TECHNICAL EVALUATION AND LIFE CYCLE COST ANALYSIS OF TRANSMISSION AND DISTRIBUTION ASSETS

by

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School of Engineering

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DECLARATION

I, Ashwin Maharaj, declare that:

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As the candidate's supervisor, I approve the submission of this thesis.

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Glossary of Terms

Term	Description
AIS	Air insulated substation
Asset Life cycle	The creation, operation, maintenance and disposal of an asset
Asset Design life	Nominal operating period expected by customer/business to satisfy economics, network security or other criteria.
CB	Circuit breaker
CT	Current Transformer
CIGRE	Founded in 1921, CIGRE, the Council on Large Electric Systems, is an international non-profit Association for promoting collaboration with experts from all around the world by sharing knowledge and joining forces to improve electric power systems of today and tomorrow.
EPRI	The Electric Power Research Institute, Inc. USA conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public.
FAT	Factory Acceptance Testing
FMEA	Failure modes and effects analysis
Failure modes	A single event, which causes a functional failure
Failure effects	What happens when a failure mode occurs.
Failure consequences	The way(s) in which the effects of a failure mode or a multiple failure matter (evidence of failure, impact on safety, the environment, operational capability, direct, and indirect repair costs).
GDP	Gross domestic product
GIS	Gas insulated substation
HAZOP	Hazard and operability study
HV	High voltage
IEEE	Institute of Electrical and Electronic Engineers USA is a technical professional organization dedicated to advancing technology for the benefit of humanity through publications, conferences, standards, professional and educational activities.
ISO9001	ISO 9001 is a widely recognized Quality Management System (QMS). It belongs to the ISO 9000 family of quality management system standards
ISO55000	ISO 55000 is an international standard covering management of physical assets. Initially a Publicly Available Specification (PAS 55) published by the British Standards Institution in 2004, the ISO 55000 series of Asset Management standards was launched in January 2014.
ITP	Inspection and test plan

LCC	Lifecycle Cost
Major plant	Large, complex and expensive plant such as: power transformers, capacitor banks, gas insulated substations.
Minor plant or equipment	Lower cost, large volume plant and equipment such as: CB's, CT's, protection relays.
MTTR	Mean Time to Repair
NPV	Net present value
OEM	Original equipment manufacturer
PPE	Personal Protective Equipment
PV	Present value
Potential failure	An identifiable condition which indicates that a functional failure is about to occur or is in the process of occurring
PAS55	PAS 55 is the British Standards Institution's (BSI) Publicly Available Specification for the optimized management of physical assets
QA	Quality assurance
QC	Quality control
ROI	Return on investment
RCM	Reliability-centred Maintenance – a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in the present operating context.
Supportability	A prediction or measure of the characteristics of an item which facilitates the ability to support and sustain its mission capability within a predefined environment and usage profile.
SCE	Safety critical equipment
SF6	Sulphur hexafluoride gas
SAT	Site Acceptance Testing
SME	Subject Matter Expert
SPAR	Single pole automatic reclosure
TPAR	Three pole automatic reclosure
T&D	Transmission and Distribution
USD	United States Dollar

Abstract

Electric Power Transmission and Distribution (T&D) Asset Managers spend on average 30% of their capital expenditure on the procurement of primary and secondary plant and equipment. Furthermore, T&D Asset Managers spend on average 50% of their operating expenditure on the maintenance and operation of plant and equipment over their useful lives which is generally 40 years for primary plant and 15 years for secondary equipment. The privatisation of T&D in many countries and emerging markets means that shareholder return is now a major performance indicator for these companies. Regulatory bodies are becoming stricter in the pursuit of efficiency and productivity, constraining expenditure. This has the effect of reducing shareholder return if not managed appropriately. In order to meet shareholder expectations whilst maintaining consumer and regulatory requirements, T&D Asset Managers must apply innovative techniques to lower their capital and operating cost while meeting regulatory requirements. Therefore, T&D Asset Managers must take optimum advantage of every opportunity for improvement. The major items for cost reduction or productivity improvement are: procurement optimization, delivery efficiency and organisational overheads. Procurement Optimization relates to the procurement of equipment, materials and services. Plant and equipment costs are a major chunk of this spend. Delivery efficiency refers to the design, construction and maintenance of T&D network assets. Opportunities for improvement can exist in design and construction process as well as smart contracting strategies. Lastly, organisational overheads relate to the organisation's cost for achieving the company's outcomes. The major costs here are the cost of internal labour and the cost of capital. This research investigation focusses on asset management, asset strategy and equipment evaluation and specification. It involves a technical evaluation of T&D assets and a life-cycle cost analysis of plant and equipment with the goal of minimizing or reducing life cycle cost and hence, reducing risk exposure. A deliberate focus on asset strategy, assessment, specification, and the supply chain will ensure that T&D asset managers deploy fit for purpose assets at the lowest life-cycle cost. Based on the results obtained from this investigation, Asset Managers must apply a structured approach and have a long term view in order to achieve the lowest life-cycle cost whilst meeting regulatory and consumer requirements, within an acceptable risk exposure. This research study provides context and proposes tools and methodologies which can be utilised for effective decision making across the full supply chain for primary and secondary T&D equipment as applicable to the electricity supply industry.

Chapter 1 - Introduction

1.1 Background

The last century has demonstrated that every facet of human development is woven around a sound and stable energy supply regime [1]. The electric power system serves to generate, transport and distribute electrical energy to consumers in an efficient, economic and reliable manner. It is made up of generating stations, transmission lines and distribution networks. The transmission and distribution (T&D) of bulk electric power is considered to be an essential service all over the world. In simple terms T&D consists of substations, poles, towers, wires and associated components. The electricity industry of both developed and developing economies are undergoing rapid and profound changes and restructuring. It has been an industrial sector that has for so long being the preserve of government monopoly institutions [2], [3]. T&D asset owners and operators have for a long time benefitted from being part of a regulated monopoly which was generally not understood by the end-users of electrical power.

In the last decade, environmental issues, regulatory and economic challenges, and changing public perception have created a radically different world for electric utilities. Consumers demand price transparency and reduction of cross-subsidies among different users. There is also a need for higher energy efficiency in technical systems of utilities and significant growth in energy demand. Governments are under pressure to raise funds for social services, balance budgets and to carry out economic reform [4]. Consumers expect greater levels of service delivery and value for money. This, compounded by privatisation is placing considerable pressure on T&D to lower electricity prices, whilst at the same time improving quality, reliability and availability of supply. Shareholders push to achieve good returns on investment; regulators demand quality, availability and reliability of supply, while consumers apply social and political pressure to lower electricity prices, making it an extremely difficult operating environment.

T&D in developing nations, although not affected extensively by privatisation, they remain highly accountable to energy regulators, governments and public. They too are required to demonstrate sustainable outcomes to consumers with a direct link to improving the quality of life for consumers. Failure to do so will make it extremely difficult to finance infrastructure projects by multi-lateral lending institutions such as The World Bank and Africa Development Bank. T&D owners and operators are required to deliver services whilst having to deal with political, economic and social pressures.

Electrification projects are being implemented at a rapid pace and there is a push to inter-connect different grids to allow bulk power to be transmitted between different provinces, and between different countries; from generation to load centres. People wish to maintain as much as possible the quality of life which they currently enjoy, and a reliable electricity supply is a key enabler for this. A fundamental aspect of the T&D industry is that they are asset-rich industries which derive an income from the provision of electricity through their assets, spread over a vast geographic area. This presents a unique situation in which these assets are required to perform their function, without the benefit of constant surveillance and monitoring, as is common in factory and process environments.

For this reason these assets require a high level of reliability and availability, since maintenance and repair crews are usually far away. T&D plant and equipment are expected to last on average 40-50 years for primary equipment and 15-20 years for intelligent devices such as protection relays [5]; and must continue to operate as required with meant times between maintenance in the 5-10 year bracket. Furthermore T&D equipment, by the nature of their function will generally cause significant disruption to end-users if a failure were to occur; if sustained over long periods and with increased frequency will have a significant impact on the standard of living [6].

1.2 Strategic Context and Delimitations of the Study

T&D network owners, spend on average 30% of their total capital expenditure on the procurement of plant and equipment and on average 50% of their operating expenditure on the maintenance of plant and equipment. In Australia alone, T&D asset managers will spend on average USD1.3bn per annum on plant and equipment procurement. Globally, T&D plant and equipment sales will tip the scales well over USD100bn per annum [7]. Moreover, the performance of the electricity transmission and distribution system has a direct relationship to the economic performance of a country. The effects of a poor performance of the electricity transmission and distribution system will be across all facets of industry and lifestyle. In Africa, it is estimated that poor performing electricity systems have a negative impact of 2% to the GDP [8]. Poor management of the electricity industry will result in a severely damaged economy and a wastage of scarce human resources [9].

In order for T&D owners and operators to extract the required reliability and availability over the design life of the plant and equipment, they must employ robust asset management techniques to strengthen decision making during the creation of assets, from specification, procurement, installation and operational life. To accurately predict performance and reliability of these assets over a period of 40 years+ is difficult and requires the use of robust asset management tools; using good information applied by working with skilled workforce. Plant and equipment must perform their function for the duration of its designed life, however premature failure will result in exorbitant breakdown costs, reliability and availability non-compliance and loss of reputation.

Equipment infant mortality, mid-life failures, common mode failures and premature ageing usually means that the asset owner has made an error in the front-end asset strategy and asset creation process. The cost of these oversights are usually passed on to consumers in the increased electricity prices. This means that insufficient upfront work and due diligence has resulted in the implementation of a sub-standard product or solution. Conversely, if plant and equipment are still in good condition at the end of the design life, this usually means that the initial solution has been over-designed. Although not generally visible to consumers and regulators, this means that assets will be decommissioned whilst still having useful life but be of no use to the T&D owner or operator. Again this over-design would indicate that too much upfront capital has been spent to create the assets, and this finances would have come from end-users through their electricity bills. Therefore, it is very important for asset owners to get it right the first time.

Beside the technical aspects of asset management, deregulation of the T&D industry will force utilities to review their processes and systems so that they are aligned with new business imperatives such as profitability and efficiency [10]. Moreover, rapid rates of technology developments as well as technology integration [11] will continue to pose challenges to T&D asset management in general.

There are many ways to improve productivity and efficiency in T&D business. The main targets are given in [12]:

(a.) Volume reductions [12], that is, reduce capital and operating expenditure. This can be achieved by applying stringent regulatory tests to project feasibility; or relaxing reliability requirements e.g. Moving from a deterministic planning model to a probabilistic planning model.

(b.) Procurement optimization [12] – Strengthening Asset Strategy, Optimization of specifications, mainly tightening of supply and delivery contracts.

(c.) Delivery efficiency [12] – improving the efficiency of internal and external delivery efficiency. This is achieved by optimizing process and procedures and eliminating wastage.

(d.) Reducing organisation overheads [12] – the main target here is the reduction of staff numbers.

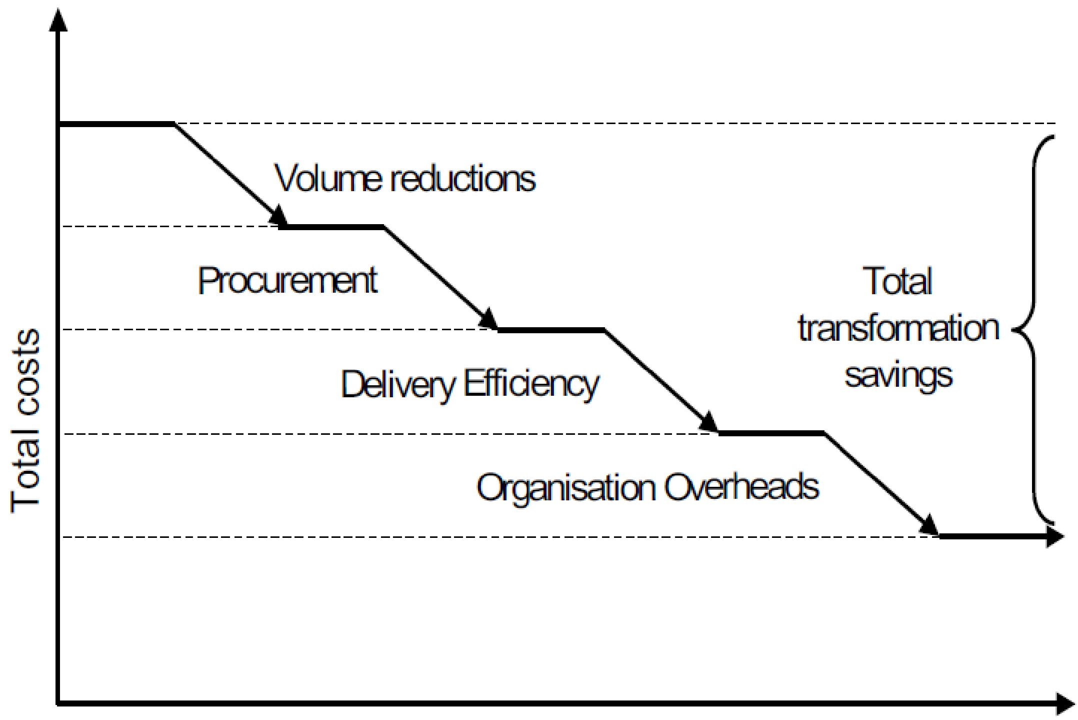

Figure 1: Productivity and efficiency improvements [12]

T&D asset owners and operators must target all avenues of business improvement if they want to be truly effective, efficient and sustainable.

This mini-dissertation (Course-work 'MSc Program') focusses only on asset management, asset strategy and equipment evaluation and specification; and addresses the technical evaluation of electric power T&D assets and a life-cycle cost analysis of plant and equipment with the goal of minimizing or reducing cost and risk exposure. The study deals with front-end asset strategy for plant and equipment, with a focus on equipment specifications, assessing suppliers and factories for factory prequalification; and assessment of plant and equipment by performing life-cycle assessments on them, with an emphasis on safety, functionality and reliability.

This requires that T&D owners and operators understand the following:

(i.) What they require in terms of functionality, reliability and availability; and develop specifications which reflect this [7].

(ii.) Have criteria and methodologies to assess suppliers and factories to be able to design and manufacture plant and equipment to meet required functionality, reliability and availability [7].

(iii.) Use appropriate tools and techniques to assess plant and equipment against functionality, reliability and availability [7].

(iv.) Have the right process, skills and capability to effectively apply the methodologies and points mentioned above [7].

In contrast to the estimated percentage spend on capital and operational expenditures which are usually planned in 5-10 year chunks and spent annually, the total cost of ownership or lifecycle cost is determined over the life of the asset. The asset lifecycle is defined as Asset Acquisition, Asset Maintenance and Operation, and Asset Disposal; this includes Asset Mid-Life refurbishment which is a tactical asset renewal strategy [13] aimed at optimizing asset management outcomes.

Asset condition information collected during the operate/maintain stage of the asset life-cycle is used to feed into asset strategy and specification. This ensures that continuous improvement occurs and lessons learned are transferred back into the intellectual property which govern further asset introduction and creation. The asset lifecycle is as shown in figure 2.

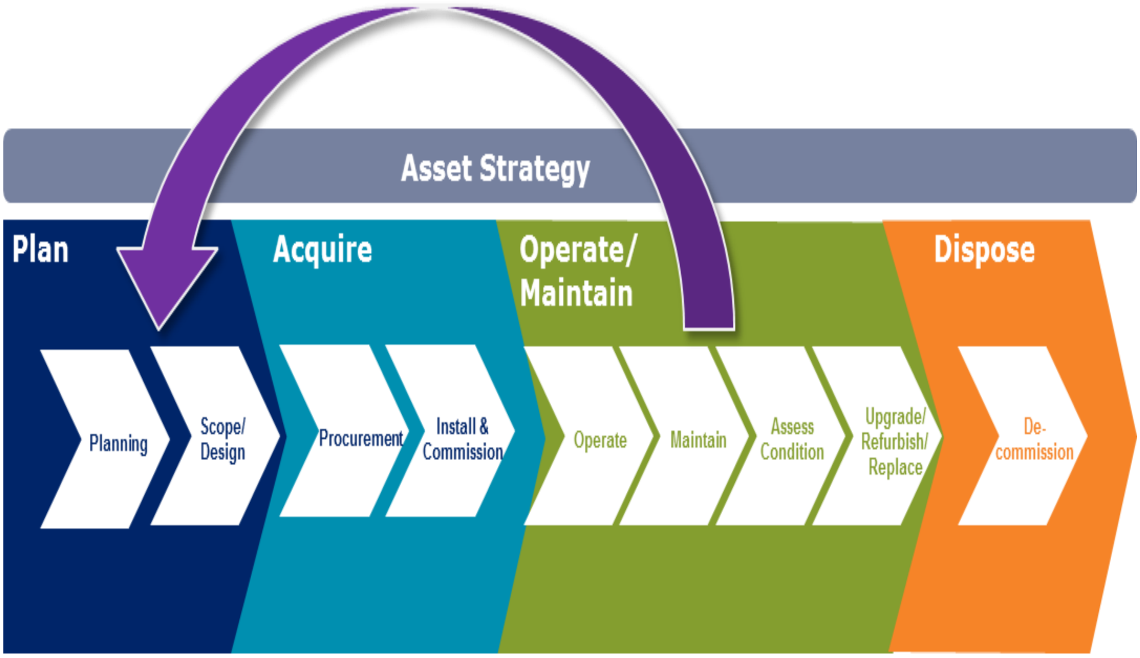

Figure 2: Asset life-cycle

The life-cycle cost across a range of different assets is split as shown in the chart in figure 2. A notable observation is that the bulk of the asset cost is part of the operate/maintain portion of the asset life. This is the case, since this is by far the longest duration of the asset lifecycle. As mentioned previously, for primary equipment around 40 years. Hence, this portion of cost must be the target for optimization – without affecting the performance and functionality.

Although the largest portion of cost is spent during the operate and maintain stage (See figure 3 [14]), Asset Managers have the greatest influence on life-cycle cost and risk at the front end-of asset strategy – during the planning stage of the asset life-cycle. This occurs long before the plant and equipment is procured, installed and operated on the network.

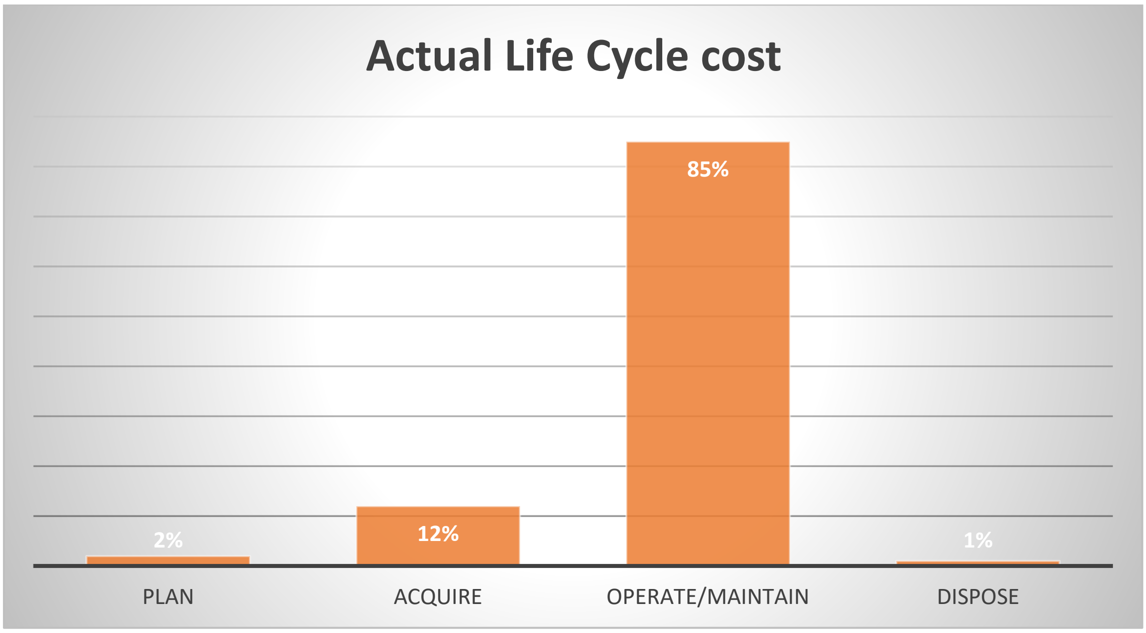

Figure 3: Total cost of ownership [14]

Once equipment is on the production line and being manufactured, it is very difficult to make changes without having a very significant impact on the cost. This progressively and exponentially diminishes as plant and equipment is installed and is put into service.

Therefore the decisions prior to acquisition and installation of the asset are the most important ones, since these are the decisions which dictate the life-cycle of the assets and therefore the cost of owning and operating these assets. This is shown in the graph of figure 4 [14].

1.3 Objectives

The aim of this research investigation is to develop a high level strategy tool for achieving the lowest life-cycle cost for T&D plant and equipment and to establish some process, tools and methodologies to achieve this. This will enable T&D asset Managers to manage risk within tolerable levels at lowest life-cycle cost for their primary plant and equipment.

The anticipated outcomes of this study include the following:

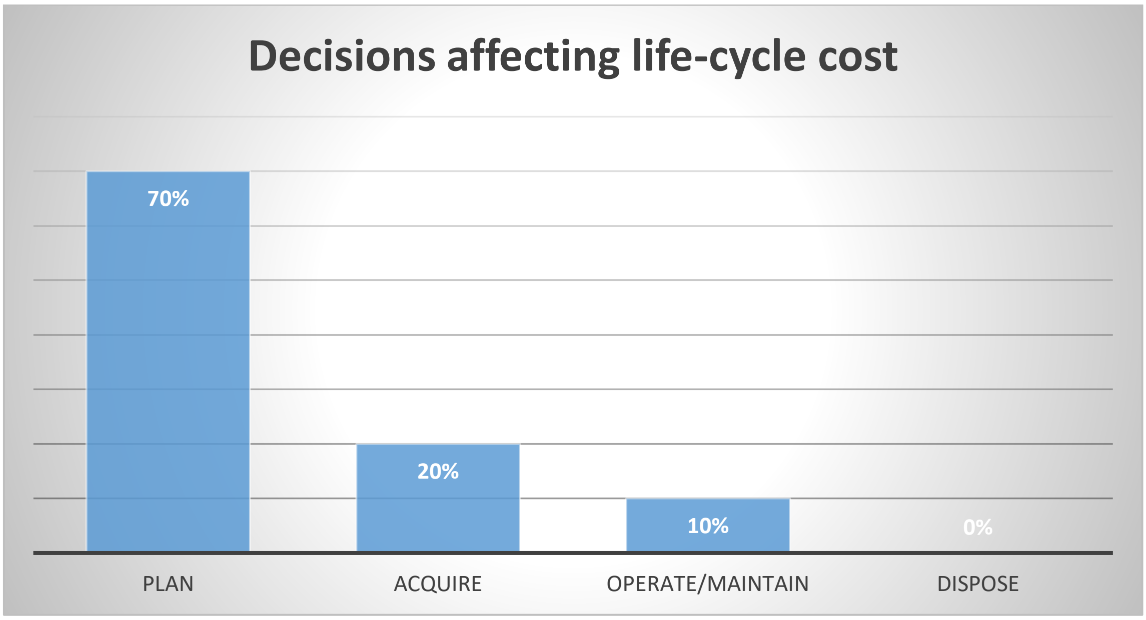

Figure 4: Decisions affecting the life-cycle cost [14]

(i) Improved asset investment decisions with respect to plant and equipment; to ensure that that the right equipment are selected for deployment, and these equipment are effectively and efficiently utilised.
(ii) Robust and fit for purpose plant and equipment which meet performance, maintainability, operability (safety) and reliability requirement's.
(iii) Best-practice methodologies to assess plant and equipment in terms of performance, maintainability, operability and reliability.
(iv) Best practice methodologies to assess and prequalify the best suppliers and manufacturers.
(v) The ability to introduced new technology in a controlled manner.
(vi) Clear accountability and responsibility for assets and their performance [15].
(vii) A discoverable document trail which demonstrates due diligence, in the event of premature failure in any particular asset class; which also assists in dispute resolution.
(viii) A consistent approach to achieving the outcomes above.

1.4 Thesis Structure

Chapter 2 covers the literature review with respect to the current industry practices with regards to plant and equipment specification, assessment and procurement.

Chapter 3 discusses and proposes methodologies and tools which can provide significant value with regards to plant and equipment specification, assessment and procurement.

Chapter 4 provides guidance on how these tools can be applied and embedded in T&D organisations.

Chapters 5 provides conclusions and recommendations.

Chapter 2: Literature Review - Current Industry Practices

This chapter reviews what T&D organisations currently do to manage their electricity Assets. The chapter assesses the development of plant and equipment specifications, how plant and equipment suppliers are assessed, and how asset information is managed.

2.1 Development of Specifications and Requirements

In the context of T&D plant and equipment, requirements generally consist of the performance criteria, functional specifications, user-specific specifications and testing requirements, that is the procurement specification. This document is the principal instrument on which suppliers and factories base their design, manufacture and essentially their cost proposal. Done well, a good specification will ensure that fit for purpose plant and equipment is procured and installed; and substandard products are easily eliminated from the procurement process. Poorly written specifications can result in the exact opposite, making it difficult for suppliers to interpret requirements which can result in incorrectly specified equipment being offered and allowing substandard products to creep into the procurement process.

Over-specifying requirements have the potential to confuse suppliers, making it difficult for them to understand what the client wants. Similarly, this can cause suppliers to focus on complying with requirements which are not essential to the fundamental function and purpose of the equipment. This places too much emphasis on unimportant issues and features, and not spending sufficient time on important requirements. Over specification also has the tendency to stifle innovation and might prevent a supplier from offering a far superior product, technology or solution. For example, a 50 page power transformer specification which has 30 pages dedicated to the tank paint specification; and 20 pages allocated to performance and functional requirements could prove detrimental. That said, it is important that operating context is understood, say, if that same transformer was to be installed in a highly corrosive environment, then a stringent paint specification might be warranted.

T&D organisations fall into various categories of maturity when it comes to specification quality. The level of maturity is usually depends on the combination of skilled and experienced personnel supported by robust technical standards and processes. Evidence suggests that only a small percentage of T&D business can be considered mature when it comes to specification development. In general most plant and equipment specifications assessed were heavily based on legacy requirements, which have been carried through the various iterations of specification updates through the years. User-specific requirements have organically grown, mostly in response to one-off problems or special preferences. Secondary system equipment specifications have followed technology advancements which have been driven by product manufacturers and developers, as is the case of today's IEC61850 based digital protection systems. Both scenarios have caused thinking and therefore specifications to veer away from equipment functional requirements – the very reason why the equipment is being procured, installed and operated.

Most T&D business today have lost key skills due to people moving-on or retiring, whilst not keeping up with development and training programs which were common in days of past. Some skilled people have moved into consulting organisations allowing them to specialise in their area of interest. Where skills and knowledge are readily available in consulting organisations, T&D organisations generally steer away from using 'expensive' consultants and will usually only call on them in the event of a major failure or emergency. This is short-sighted to say the least. Poor specifications combined with a lack of skills makes for a challenging situation for T&D businesses, and the results of this will only materialise many years into the future. These organisations are operating in an area of unknown risk and uncertainty. It is not clear to these organisations whether they are in fact making the right decisions. The outcomes of their decisions will only be known many years into the operation of the plant and equipment, and the cost of poor decisions is usually passed onto the end-users in the form of increasing electricity prices. The intellectual capital of an organisation is the key factor in the organisations profitability, sustainability and resilience. In simple terms intellectual capital consists of the knowledge contained in technical standards, systems and process as well as the tacit knowledge contained in the minds of capable and competent people. In the context of technical specification development, assessment and prequalification of supplies and factories, intellectual capital will separate top performing asset management organisations from the rest.

2.2 Assessment of Suppliers

Although some T&D organisations do this really well, most organisations are not equipped with the intellectual capital required to assess and prequalify suppliers and factories who will best meet their needs. The choice of suppliers or factories are usually driven by procurement teams which base their decisions on desktop assessments of tenders, and ultimately on up-front capital cost. The main factors considered are financial, commercial and technical compliance to specifications and usually equally weighted. For small orders and low value plant and equipment this approach is adequate, however for large volume, complex and high value plant and equipment, more due diligence is required. Even with low cost items such as protection relays, the end-result of installing substandard items on T&D networks will result in tenfold costs to resolve over the operating life of the equipment if premature failure or mal-operations were to occur.

In order to ensure that the quality, reliability and life-cycle requirements are met, the assessment must go further than a desktop assessment of the supplier, it must assess the specific factory which will be manufacturing the plant and equipment. Factories must be assessed against specific criteria ranging from quality systems to factory failure rates. Factory assessment and prequalification were common in days gone by, but seldom occur today. Company executives find it difficult to justify the cost of sending one or more people to assess a factory which is usually at an overseas location. Furthermore, with the ever dwindling capability in T&D organisations, plant and equipment engineers are not clear on what to look for; and what denotes acceptable or unacceptable factory performance. What makes things worse is that failures related to substandard equipment occur at or after mid-life (not to be confused with infant mortality failures). This means that issues will only materialise many years into the future. Considering the long operating lives of these assets, it's usually a new set of personnel that have to deal with these failures. Hence, lessons are only learned when it may be too late.

T&D businesses must have a robust set of criteria to assess suppliers and factories against, with pass/fail limits. This must be supported by adequately skilled personnel. When this skill is non-existent, this must be sourced from the market, usually from the consulting industry.

2.3 Asset Information

Asset information refers to the original specifications, drawings, test reports; and through-life asset condition and performance information. Asset information is a key enabler to the effective life-cycle management of plant and equipment. A common finding across most T&D organisations is that asset information is not managed very well. Project teams which procure and install plant and equipment are generally eager to get on to the next project, seeing asset information handover as a nuisance. Asset managers on the other hand, with the gift of hindsight are in constant angst with project teams to capture and receive asset information. Asset information associated with plant and equipment is usually created early in the project life-cycle, usually before T&D assets are constructed and commissioned. This consists of plant and equipment drawings, manuals test reports etc. It is important for project teams to capture the right information early, and store this information in the company's asset management or maintenance management system. The true benefit of having discoverable and relevant asset information will be reaped many years into the future during maintenance, breakdown situations or replacement of the assets themselves. The importance of asset information increases as the asset progresses through its life.

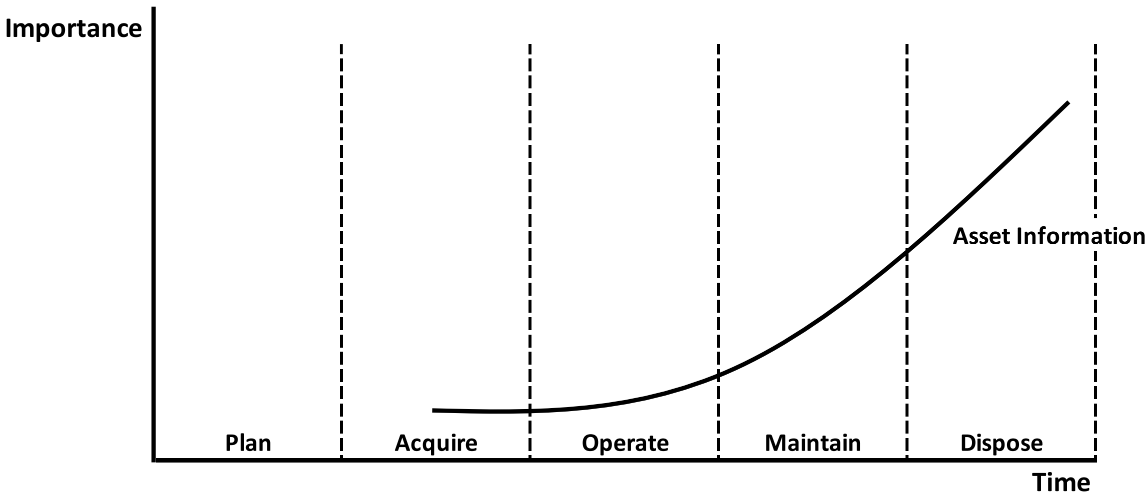

Figure 5: The importance of asset information

Asset information also consists of asset condition information. This could be oil-sample results in the case of power transformers or condition assessment information in the case of transmission line conductors. This information is collected by asset condition monitoring. Asset Condition monitoring can be done visually, intrusively or via online condition monitoring equipment. The analysis of asset condition information enables the determination of asset condition, performance, degradation and failure mechanisms, operating context and maintenance requirements [16]. If fully embraced, asset information can become the basis for effective asset management programmes [16].

In general T&D organisations can improve their specifications, procurement processes; and apply sufficient rigour in their project delivery to realise maximum value during the useful life of their assets.

Chapter 3 – Research Methodology

This chapter assesses key asset management practices in T&D and other industrial sectors; namely life-cycle cost analysis, investment decision making, plant and equipment specification development and factory prequalification. Although most T&D organisations perform these functions in some way, this chapter provides effective ways of how this could be implemented by using proven analysis tools and standards to significantly improve asset management decision making.

3.1 Life-Cycle Cost Analysis

It is important for asset owners to have an economic view of the world. They must have a sound understanding of the total cost of ownership for their assets; or life-cycle cost (LCC). This could mean the difference between choosing a supplier over another or deciding between technology options. For example, the choice between an AIS solution and a GIS solution. Life cycle costing is the process of analysis to assess the total cost of acquisition, ownership and disposal of a product [17]. LCC considers the total cost of the asset which includes the asset acquisition capital cost, maintenance and operation cost and disposal cost; including the cost of non-availability of the asset. In T&D the cost of unavailability would typically be the cost of unserved energy due to unplanned outages (due to asset failures or performance issues). Life Cycle Cost Analysis is a useful instrument to identify the main cost drivers of a network which can be a key enabler to drive appropriate actions to reduce the costs [18]. The Life Cycle Cost equation is given as [17]

$$LCC = Cost^{acquistion} + Cost^{ownership} + Cost^{disposal} \qquad (1)$$

The table below shows the costs associated with owning a power transformer.

Table 1: Power Transformer Lifecycle costs

Capital Cost (procurement cost)	$1,000,000
Breakdown Costs (annualised)	$80,000 p.a
Routine Maintenance costs (annualised)	$30,000 p.a
Disposal Costs	$200,000
Design Life	40 years
Inflation Rate	1.5%

With the understanding that the value of money decreases with time, in order to properly determine LCC it is necessary to compute LCC as Present Value (PV). PV determines the LCC and considers the interest and inflation rates.

The equation is given as [19]

$$PV = \frac{FV}{(1+r)^n} \qquad (2)$$

Where,
PV = Present Value
FV = Future Value

R = Rate of return
n = number of periods (design life)

FV = \$1,000,000 + \$200,000 + 40(\$80,000+\$30,000)
= \$5,600,000

Therefore, $PV = \frac{\$5,600,000}{(1+1.5\%)^{40}}$ = \$3,087,068.
Therefore the PV lifecycle cost of the power transformer is \$3,087,078.

3.2 Investment Decision-Making

Asset Managers must apply financial thinking to the investment decisions. Investment decisions must take into account Lifecycle cost and Return on Investment. Net Present Value (NPV) is a valuable way in determining the viability of investments. Essentially NPV is a comparison between PV cash inflows and PV cash outflows over the design life of the asset.

$$\text{NPV} = \text{PV Cash Inflows} - \text{PV Cash Outflows} \quad (3)$$

Using the example with the power transformer above, to determine if it is beneficial to invest in owning the transformer, the PV cash inflows must be greater than the PV cash outflows, over the life of the asset. Typically, the PV benefits are calculated on a smaller timescale than the PV costs (LCC). It is generally expected that the breakeven point must occur early in the asset design life (typically before year 10 for an asset with a 40 year life), allowing asset owners to derive income from their investment for the remainder of its useful life. The breakeven point in time is referred to as NPV zero. Any NPV greater than NPV zero is referred to as NPV positive and means that the investment is sound. A NPV negative outcome means that the investment is not sound and will result in a net loss. Any NPV negative decisions must be supported by a strong case for an intangible benefit. The figure below indicated the difference between NPV positive and NPV negative.

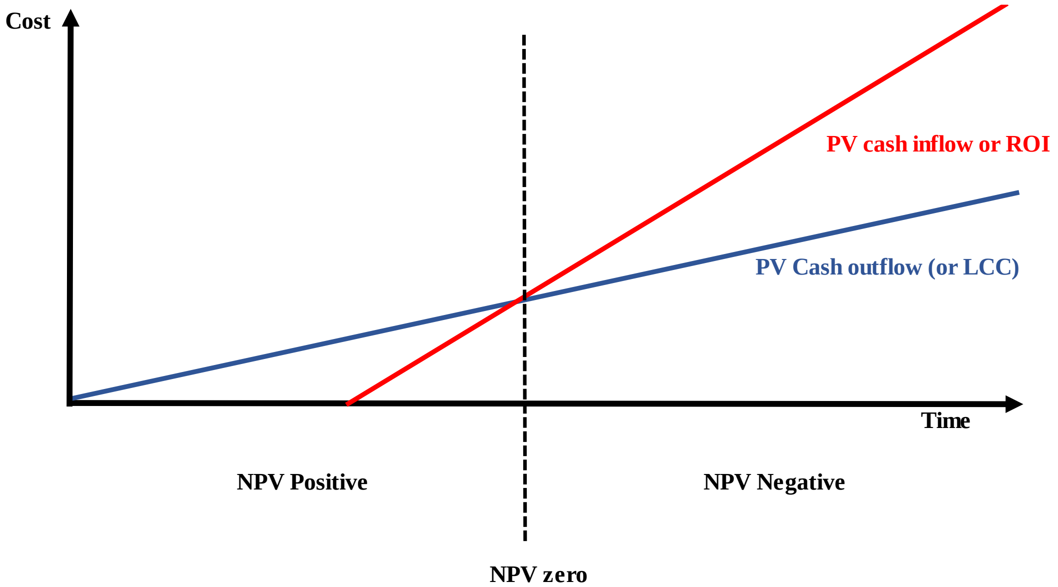

Figure 6: Net Present Value (NPV)

3.3 Plant and Equipment Specification Development

Plant and equipment specification content will typically cover 3 main areas; these are:

(i.) Industry Technical Standards
(ii.) Functional Requirements
(iii.) Technical and Performance Requirements

3.3.1 Industry Technical Standards

Industry standards consist of established norms, criteria, regulatory rules and practices. These standards are widely known and accepted in T&D, and form a crucial part of compliance. It is important to stipulate what document takes precedence in the event of a discrepancy or contradiction between the plant and equipment specification and a referenced industry standard. Usually, it is clearly stated that the customer plant and equipment specification takes precedence [20]. An example of some technical standards which apply to plant and equipment is shown in the table below.

Table 2: Industry Technical Standards

AS/NZS 3000	Electrical Wiring Rules
AS 1852	International Electrotechnical Vocabulary
AS 62271.301	Dimensional Standardisation of Terminals
AS 60044.2	Instrument Transformers – Part 2: Inductive Voltage Transformers
IEC 61869-1	Instrument Transformers-Part 1: General Requirements
IEC 61869-3	Instrument Transformers-Part 3: Additional Requirements for inductive voltage transformers
AS 4436	Guide for the selection of insulators in respect of polluted conditions
AS 1170.2	Structural design actions - Wind actions
AS 1767.1	Specification for unused mineral insulating oils for transformers and switchgear
AS 60529	Degrees of protection provided by enclosures for electrical equipment
IEC 60296	Fluids for Electrotechnical applications-Unused mineral insulating oils for transformers and switchgear

3.3.2 Functional Requirements

It is very important for asset strategy, plant and equipment engineers to first understand and be able to clearly articulate the functional requirements for the devices which they are specifying. Essentially, functional requirements are what the plant and equipment must do, over what period of time and in what operational context. There are 3 main information sources which must be interrogated and understood in order to determine the functional requirements. These are:

(a.) The asset strategy of the particular asset class
(b.) The functional, user and operator requirements
(c.) The technical and performance requirements

In line with PAS55 and ISO 55000 an asset class would generally cover a certain type of equipment or group of equipment. Examples of asset classes are:

(a.) Digital protection systems
(b.) Power transformers
(c.) Circuit breakers
(d.) Disconnectors
(e.) Transmission Line Lattice Structures and Poles

The strategy for each asset class defines at a high level the life of the asset from creation to disposal. As a minimum the asset strategy will define the following parameters which will be essential for translation into functional requirements:

(i.) The operating context
(ii.) Design life in years
(iii.) Known failure modes
(iv.) Maintenance strategy
(v.) Mid-life and end of life strategies
(vi.) Emergency replacement strategies
(vii.) Population of manufacturers, types and ages
(viii.) Reliability expectations
(ix.) Availability expectations
(x.) Expected mean times to repair
(xi.) Spares requirements

These parameters will need to be translated into functional requirements. Some asset strategy requirements will result in multiple functional requirements. The functional requirements will translate the user, operating and performance requirements into specification descriptions. These will generally cover:

(a.) Safety/Environment
(b.) Planning and design
(c.) Performance
(d.) Constructability
(e.) Maintainability
(f.) Operability
(g.) Availability/Reliability
(h.) Testing and validation requirements
(i.) Asset Interface requirements

An example for a Power Transformer is discussed. The Power Transformer has an economic and design life of 40 years.

Table 3: Functional Requirements

Asset Strategy	Functional Requirements
40 year design life	The Transformer shall perform its intended function for 40 years
8 hour MTTR	1. The Transformer shall be designed to allow for a repair and return to service 8 hours after a minor functional failure

	2. The transformer shall be designed to allow for it to be replaced by a spare unit 8 hours after a major failure

User or operator requirements are usually related to safe operation and ease of use e.g. High Voltage equipment switching, and sometimes may include continuous improvements based on past experience of operators and maintainers.

User or operability (safety) requirements must be drawn out of operators, maintainers and asset managers; and extracted from respective technical standards, codes and regulations. User and operator requirements are sometime defined in operator manuals and technical standards. Examples of user and operability requirements for a disconnector are:

(a.) Integrity of the main contact drive mechanism - If the motor drive is operated with the main HV contacts jammed, no part of the operating mechanism shall fail, slip or become misaligned other than the drive motor stalling and operating the motor overload protection.

(b.) Integrity of auxiliary contact position indication - The auxiliary contacts shall be connected directly to the main operating mechanism with no foreseeable failure modes that will cause misalignment with the main contact position.

(c.) Disconnector Position Indicators – Position indicators for the main contacts are to be marked OPEN (corresponding to the fully open position of the disconnector) and CLOSED (corresponding to the fully closed position of the disconnector).

3.3.3 Technical and Performance Requirements

Technical requirements can be dependant or independent of functional requitements and will generally cover:

(a.) System Parameters, such as System Voltage;

(b.) Technical Performance parameters, such as Fault levels;

(c.) Environmental considerations, such as Seismic requirements or pollution requirements;

(d.) Technology preferences, such as Thermally upgraded paper for transformer insulation, or SF6 arc quenching for CB’s;

(e.) Limitations, such as Physical Size or Noise Emission restrictions;

(f.) User preferred technologies or components, such a Vacuum diverter tap switch

(g.) Testing requirements;

(h.) Installation requirements;

(i.) Transport and logistics;

(j.) Documentation requirements, such as Outline drawings are to be supplied in 3D;

(k.) Installation standards which must be complied with.

Table 4 and Table 5 provide an example of technical and performance requirements for a 300kV AIS disconnector.

Table 4: 300kV Disconnector Performance Requirements (Part 1)

Description	Unit	Technical & Performance Requirement
System Details		
System Nominal Voltage	kV	275
System Highest Voltage	kV	300
Frequency	Hz	50Hz
System Neutral		Effectively earthed
Phase to earth clearance	mm	2400
Terminal Palm Height- Low Level	mm	5500
Section clearance	mm	4990
Ground clearance	mm	2440
Service Conditions		
Ambient temperature range	°C	-5 to +55
24 hour average maximum ambient temperature	°C	37
Highest altitude	m	<1000
Maximum wind speed	m/s	46
Number of phases	No.	3
Phase-phase clearance	mm	4000
Rated Insulation Level		
Switching Impulse Withstand - Phase to Earth	kVp	850
Switching Impulse Withstand - Between Phases	kVp	1275
Switching Impulse Withstand - Across Isolating Distance	kVp	700(+245)
Lightning Impulse Withstand - Phase to Earth & Between Phases	kVp	1050
Lightning Impulse Withstand - Across Isolating Distance	kVp	1050(+170)
Power Frequency Withstand - Phase to Earth & Between Phases	kV	395
Power Frequency Withstand - Across Isolating Distance	kV	435
Rated Frequency	Hz	50
Disconnector Rated Normal Current	A	>2500
Disconnector Rated short-time withstand current	kA	>31.5
Disconnector Rated short-circuit making current	kA	100

Earth Switch Rated short-time withstand current	kA	>31.5
Duration of the short-circuit	sec	>1

Table 5: 300kV Disconnector Performance Requirements (Part 2)

Description	Unit	Technical Requirement
Mechanical terminal loads		
Minimum Static load in any direction	kN	1.5
Minimum Vertical force	kN	1.5
Operating mechanism		
Method of operation – Disconnector		Power and Manual
Manual operation time – disconnector (open/close)	s	<10
Method of operation - Earth Switch		Motorised
Manual operation time-Earth Switch (open/close)		less than 1 second
Degree of protection for earth switch mechanism box		IP 65
Gland plate material for mechanism boxes		Brass
Control and Auxiliary requirements		
Control supply rating – constant value	V_{DC}	123
Number and type of spare auxiliary switches	No.	12a +12b
Locking and interlocking		
Mechanical interlocking between disconnector and earth switch	Yes/No	Yes
Limit switches to prevent overrun, when fully open and closed	Yes/No	Yes
Provision for solenoid coil interlocking, where required	Yes/No	Yes
Interlock for manual and motorised operation	Yes/No	Yes
External pad locking of earth switches	Yes/No	Yes
Electrical Switching Capability		
Maximum Electrostatic Voltage	kV (RMS)	9.5
Maximum Electrostatic Current	A (RMS)	8
Maximum Electromagnetic Voltage	kV (RMS)	17
Maximum Electromagnetic Current	A (RMS)	9.5
Structure Details		
Base plate spacing (centreline to centreline, perpendicular to phase)	mm	5000

Base plate spacing (centreline to centreline, parallel with phase)	mm	3200
Hold down bolt spacing (square arrangement)	mm	300

3.3.4 Plant and Equipment Specifications

Plant and equipment specifications consist of the combination of Industry Technical Standards, Functional Requirements; and Technical and Performance Requirements - in that order. This document will be issued to suppliers to allow them to tender against.

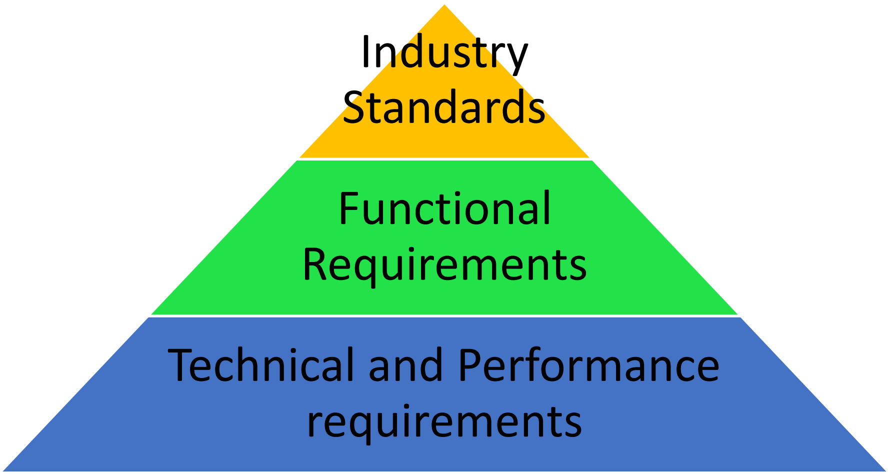

Figure 7: Plant and Equipment Specification [7]

Care must be taken to ensure that the 3 main sections of the specification (as shown in figure 6 above) are always kept separate; although they can still be part of the same document. The vendor tender response schedules which are usually at the end of the specification should also be separate and follow this sequence. This allows for these 3 sections to be assessed separately and independent; and in that sequence. The functional requirements are those which cannot be compromised at all cost, whereas some deviation to the technical and performance requirements can occur and be negotiated.

Therefore if cost savings are to be found these should be targeted at the technical and performance requirements, and not the functional requirements. Asset Strategy and Plant engineers are able to apply value engineering techniques [21] to the technical requirements to enable cost savings, and can rest assured that functionality, safety and operability won't be affected. This is also another reason for technical specifications to clearly stipulate that functional requirements are mandatory.

The fact that the specification and response schedule have clearly separated the Functional Requirements and Technical and Performance requirements means that tenders can be assessed quickly and effectively. This also allows for the Functional Requirements and Technical and Performance criteria to be assessed by different personnel and in parallel. Typically:

(a.) The Functional Requirements of a specification should be developed; and similarly this portion of a tender response schedule be assessed by personnel in charge of Asset Strategy and Asset Maintenance; and (b.) The Technical and Performance Requirements of a specification should be developed; and similarly this portion of a tender response schedule be assessed by personnel in charge of Plant and Equipment design, application and integration.

Suppliers and vendors will also find it easy to respond to a clear and well defined specification with the benefit of knowing what the non-negotiables are, and allowing them to focus more effort on achieving the mandatory outcomes. It is also useful to be able to first compare different supplier responses against the Functional (mandatory) requirements and eliminate those suppliers from competing early in the procurement phase. This inherently allows more time to evaluate the compliant tenders on the remaining technical, financial and commercial criteria. This is illustrated below in a 2-staged tender review process below.

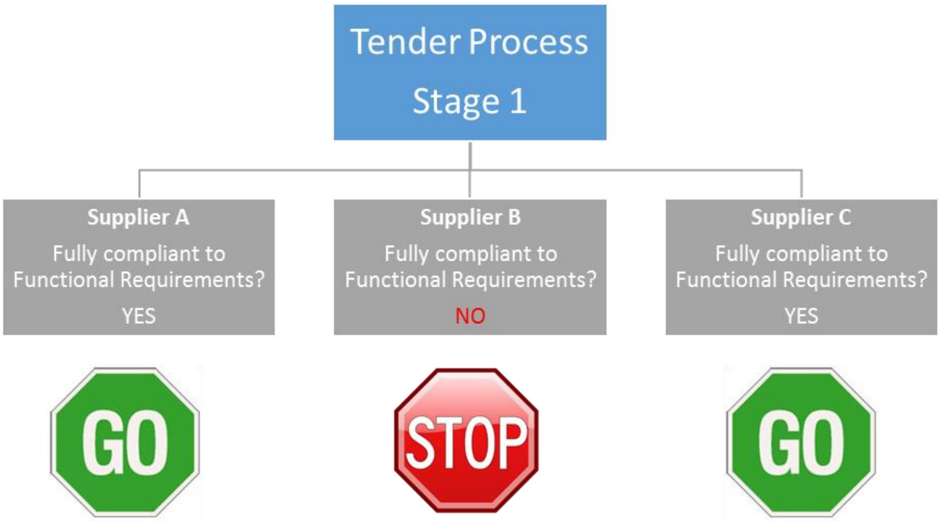

Figure 8: Stage 1 Tender Assessment (Functional Assessment)

Supplier 2 is disqualified at the stage 1 tender review since full compliance to functional requirements have not been achieved. Since there aren't as many functional requirements, the stage 1 tender assessment can be completed quickly. This is especially helpful if there are a large number of tenders which must be assessed. Supplier 1&3 can be progressed to the stage 2 tender assessment which will consider the Technical and Performance Requirements, Commercial criteria and financial criteria; in that order (See Figure 8).

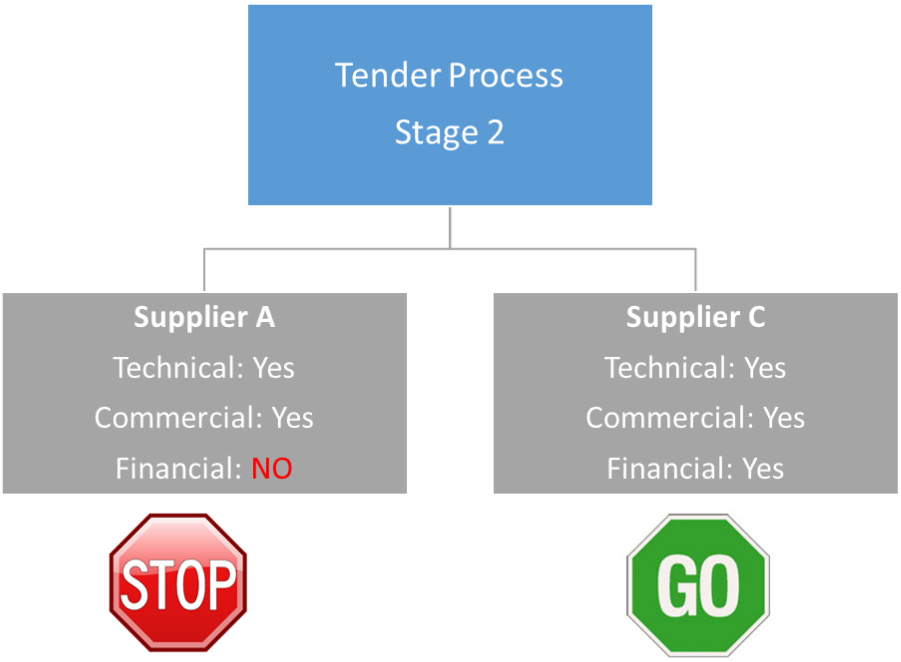

Figure 9: Stage 2 Tender Review

As a rule of thumb the amount of content in the technical specification will vary depending on the cost and complexity of the plant of equipment. It is generally accepted that specifications for major plant items such as: Power Transformers, GIS substations; will contain significantly more information to that of minor plant. Minor plant and equipment would generally be items such as circuit breakers, instrument transformer and protection relays. This does not mean that more effort should be spent on one and less on the other.

Although major plant items are significantly more complex, and the consequence of the failure can be severe; minor plant is deployed in large volumes over longer periods of time. Period contracts for minor plant and equipment usually span 4-6 years. This means that there still a significant amount of risk exposure associated with the cost of 'common mode failure' issues across entire fleets of minor plant and equipment. This supports to a greater extent the requirement to develop well thought out technical specifications and to use these as a first line of defence as part of plant and equipment procurement due diligence.

The opportunity to create value diminishes as we progress through the various stages of asset strategy development to the development of functional requirements, the development of technical and Performance requirements and so on. The reason for this is because good asset strategy might define a technology choice or eliminate waste, whereas the functional and technical requirements are bound by the confines of the asset strategy.

It must be noted, that only the value that has been created in the early stages of asset development and creation can be realised during operation of the plant and equipment.

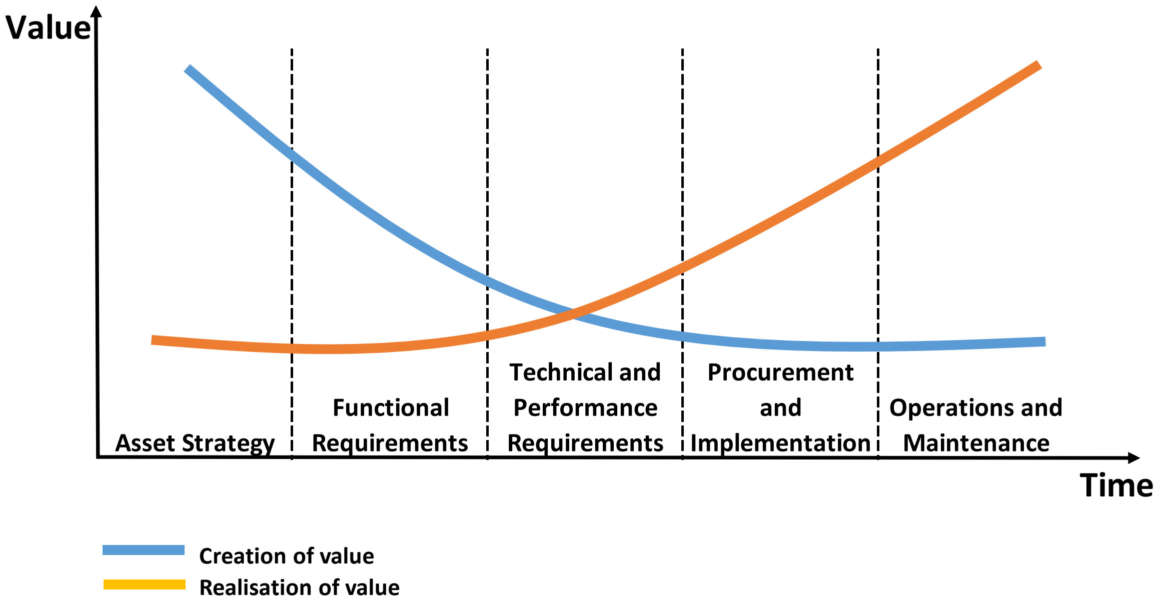

Figure 10: Creation and realisation of value

3.4 Factory Assessment and Prequalification

As mentioned above, T&D asset managers procure large, complex and expensive assets; as well as large volumes of relatively low value assets. Each scenario has long term risks and consequences which must be effectively managed. Desktop assessments of suppliers and factories is not considered as good practice just by itself. The quality of factories and their products vary widely, and similarly the performance and reliability requirements of T&D asset managers and their organisations vary widely. T&D asset managers must convince themselves that suppliers and factories are as good as they say they are on paper. Considering the long term cost and risk which must be managed, it is worth the additional effort to properly assess the capability of suppliers prior to plant and equipment procurement. It is important for T&D asset managers to have the tools, methodologies and capabilities to be able to properly assess factories against their specification requirements. The main criteria against which factories are evaluated are [7]:

(i) Material supply chain, storage and handling
(ii) Equipment Design process
(iii) Equipment Manufacture process
(iv) Testing Capability
(v) Quality systems
(vi) Warranty and after sales services

It is prudent for T&D asset managers to send appropriately experienced and skilled personnel to one or more shortlisted factories in order to assess the factories against the criteria listed above. The cost of this exercises is insignificance when compared to the cost of the plant and equipment (whether it be a single piece of large plant or a large fleet of smaller equipment). Furthermore, it would be too late if quality or performance issues are realised during operation of the plant and equipment. Where T&D organisations don't have the experience, skills and capabilities to adequately assess plant and equipment factories, this can be sourced from the market.

3.4.1 Material Supply Chain, Storage and Handling

This applies to all materials and components which the factory buys in order to manufacture their products. The way in which they manage their own internal supplier chains are very important in assuring that their end product is able to meet quality and reliability requirements. As a start it is important that all materials and components are appropriately stored, systematically and methodically catalogued, tested and tagged where appropriate with traceability to their Quality Management system (QMS). Considering that T&D equipment will be subjected to high voltages in most cases, cleanliness of stored materials and equipment is paramount. Dirt and dust, if not managed well, will almost always have long term detrimental effects on the equipment being manufactured. The following points should be verified:

(a.) Valid and up to date material specifications (The factories specifications for the materials which they procure) [22]
(b.) The contracting mechanism between the factory and its suppliers [22]
(c.) The mechanism in which the factory manages quality issues with its suppliers
(d.) The basis of procurement decision making for material procurement e.g. If the factory procures materials purely on the lowest price, this might be an avenue for substandard quality to creep in [22].
(e.) The capability and commitment of the Quality Management staff, particularly the Quality Manager.

3.4.2 Equipment Design Process

It is important to evaluate the plant and equipment design process. This will generally cover the:

(a.) Design management and design review process, ensuring that there are sufficient checks and balances
(b.) Design software for Plant and Equipment Electrical design, mechanical design, CAD drawing software etc. Check that the most up to date design tools are being utilised and drawing requirements and standards can be complied with.
(c.) The use of relevant international and internal factory-specific technical standards to guide their design such as IEC or IEEE. [22]
(d.) Workforce capability. This is to ensure that the people producing the design are appropriately skilled and qualified. This is usually a qualitative assessment since T&D personnel typically don’t have the knowledge and skills required to assess competencies of factory personnel.
(e.) Continuous improvement, taking into account lessons learned from manufacture, and operations of the plant or equipment being manufactured, including industry-wide innovations.

3.4.3 Equipment Manufacture Process

The manufacture process is required to be documented in detail, again in line with the factory QMS. The following will need to be assessed or cited:

(a.) Manufacturing methods are in line with industry standards and practices [22].
(b.) Documented manufacturing procedures and work instructions [22].
(c.) Appropriate tools to do the work [22].
(d.) A clean and ergonomic workspace with good lighting [22].
(e.) Evidence of QA and QC must be obvious on the production line. Inspection and verification is supported with the use of QC cards or other system.

(f.) Manufacturing machines are up to date, in good condition and working order and are within calibration. Calibration is to be verified by citing the calibration sticker on the machine and relevant calibration certificates.
(g.) Good communication between factory workers, factory inspectors and designers.
(h.) Evidence of a skilled workforce.

3.4.4 Testing

Testing generally refers to mechanical and electrical testing against the performance requirements listed in the technical specification. It is important to verify that the factory can comply with the testing requirements contained in the technical specification. This applies to the testing equipment and the process for testing. It is important to check that testing equipment are within calibration dates. There are known cases during factory testing it was discovered that the factory testing equipment did not have the capability to perform one or more tests. At this point it is too late, and T&D asset owners are forced to accept plant and equipment at risk or pay for testing at a different testing laboratory.

Typically, the following can be verified:

(a.) The location of the test lab. In the factory or elsewhere [22].
(b.) The test lab capability to perform all required tests.
(c.) Site testing capability, that is, at the site installation.
(d.) Capability of the test engineers and technicians.
(e.) The standards to which the lab is capable of testing such as IEC.
(f.) Test reports and documentation management.
(g.) Failure investigation capability and process.

Note. If a factory does not have the capability to test a major plant item, then they generally won't have the capability to design and manufacture it.

3.4.5 Quality Systems

The quality system consists of a combination of QA and QC activities which span across the entire supply chain and production process of the factory; including dispatch and on-site installation. It is important to ensure that the factory has a robust and mature quality management system which covers the end to end production process. This must be tested by tracing components through the entire production life-cycle. Evidence of continuous improvement and certification to ISO9002 or other accredited bodies provides an added level of comfort.

It is also important to compare the factories in-factory and in-service failure rates of the equipment being assessed against industry benchmarks. In-service equipment failure information is usually accessible from international technical organisations such as CIGRE, IEEE and EPRI to mention a few.

3.4.6 Warranty and after sales service

Most T&D organisations have warranty requirements. This applies to major and minor plant and equipment. It is prudent for T&D asset managers to assess and negotiate the warranty duration, terms and conditions prior to awarding procurement contracts.

Similarly it is important to understand how a warranty claim will be handled should any issues occur. Access to local sales and technical support is always an advantage. Where local support is not readily available, it must be understood how the factory intends to manage defects and warranty claims.

3.4.7 Factory Evaluation Checklist

The outcome and decision from a factory evaluation is usually a factory prequalification report which concludes in one of 3 outcomes:

(i) Unconditional prequalification: The factory meets all criteria
(ii) Conditional prequalification: The factory meets all mandatory criteria, however needs to make some minor improvements to meet some lower level criteria
(iii) Disqualification: The factory does not meet one or more mandatory criteria

It must be noted that factory prequalification is only the first step largely focussing on the factory's quality, design and manufacturing processes. This does not mean that anything can be procured at this stage. The next step is to assess the specific equipment class against the functional and technical requirements. This is described in the next section.

Below is an example of a factory evaluation checklist which has been tabulated. This checklist could be filled-in during the factory evaluation via a combination of inspections, shop-tours and meetings with factory specialists. The checklist will form a vital input to the factory prequalification report. The factory prequalification report is a vital tool to communicate recommendations to decision makers; and is a discoverable document which could be referenced and interrogated down the track if problems with the equipment or factory are encountered.

Table 6: Factory Evaluation Checklist

Description	**Score**	**Comments**
Quality Systems		
Works procedures and instructions		
Continuous improvement and International compliance		
QA plans and QC plans		
Audit and failure review process		
Quality Certification (such as ISO 9002)		
Manufacturing Methods	**Score**	**Comments**
Insulation impregnation and dry-out methods		
Coil winding methods		
Individual part manufacture process		
Active part and assembly methods		
Workshop Practice	**Score**	**Comments**

Clean conditions, tool control and hygienic safety		
Calibration and instrumentation		
Environmental Controls		
Design Practices and Application	**Score**	**Comments**
Design criteria basis and guidelines		
Design process flow		
Interface with procurement and manufacturing		
Design tools and competence		
Date of Last design review		
Testing Facility and Practices	**Score**	**Comments**
Calibration of equipment		
Test capabilities		
Competence		
Timeliness and Quality of Test Reports		

Factory Evaluation Checklist (Table 6)

Raw material Procurement, Storage and Sub-Contractor Practices	**Score**	**Comments**
Supplier and subcontractor assessments and reviews		
Spot check / inspections on materials and subcontractors		
Control Systems and customer participation/notification / transparency		
Site and other Service	**Score**	**Comments**
After Sales Services		
Spares		
Emergency response time		
Manuals		
Training, technology transfer		
Site Tools and Plant		
Site clean conditions, tool control and hygienic safety		
Investigations and failure reports		
Calibration site of Instrumentation		
Factory Performance	**Score**	**Comments**
In-service Failure Rate (%)		
Factory Test Failure Rate (%)		

3.5 Plant and Equipment Safety, Reliability and Operability

Three key methodologies and studies are used to ensure life-cycle plant and equipment functionality, reliability and operability (Safety). These are Failure Modes and Effects Analysis (FMEA), Reliability Centred Maintenance (RCM) and Hazard and Operability Studies (HAZOP). These methodologies represent best practice from various industries, and used in conjunction with each other can be very powerful if applied correctly. The main origins of these methodologies are:

(i.) FMEA: Developed in the Manufacturing Sector, with input from Six-Sigma.

(ii.) RCM: Developed in the Aviation Sector, in response to failures related to maintenance issues.

(iii.) HAZOP: Developed in the Oil and Gas Sector, with input from process safety.

These studies are summarised in Table 7.

Table 7: FMEA, RCM, HAZOP summary

	FMEA	RCM	HAZOP
Scope of study	Asset reliability	Reliability/Cost	Safety
Study outcome used to support	Plant and equipment engineers, designers	Operators and Maintainers	Operators and maintainers
People who provide key input into study	Plant and equipment engineers, designers	Asset Managers	Operators and maintainers
Study outcome used to improve which asset phase	Manufacturing phase	Operation, In-Service	Operation, In-Service
Study Focus area	Asset Functions	Asset Functions	Asset Design intent
Study outcomes	Failure modes, causes and consequences	Functional Failures, causes	Potential for hazards to occur (Design deviations), Causes

3.5.1 Failure Mode and Effect Analysis (FMEA)

Evaluating the specific plant or equipment is equally important as evaluating the factory as described in the section above. In this section it is assumed that the equipment being evaluated complies with the Functional and Technical requirements. This section will focus on the application of FMEA and RCM principles to the equipment. This is a robust way of checking that the equipment complies with the safety, operability and reliability requirements. The outcome of the FMEA is used to conduct the RCM analysis; and are usually performed together and in that order. The most effective FMEA exercises are done in a workshop setting using the combined knowledge of factory specialists and T&D personnel. For this reason, it is efficient and opportunistic to combine factory prequalification's with FMEA/RCM analysis.

The use of complex tools such as of FMEA in equipment evaluation is fairly standard in mature industries such as defence or manufacturing. FMEA is now being utilised more frequently in industries which are required to drive up value and reliability whilst driving down costs. In one sense this is a necessity, however this is also an indicator of organisational maturity, or the progression thereof.

The process of FMEA as applied to T&D consist of 7 steps:

(a.) Functional Components: Split the plant or equipment into its functional components. For minor plant or equipment functional components should be split at the first level only. Such as, a current transformer could be split into the Primary terminal Contacts, Main insulation, Active Part (transformer), Secondary Terminal contracts and stands. For major plant functional components can be split down to 3 levels. Such as, for a power transformer, the main components could be the active part, the tap-changer, the insulation systems etc. Each of these components should be split into sub-components. Such as, the active part could be split into the core, the main windings and the compensation windings. This can be done one level further if required.

(b.) Failure modes: Determine the potential failure modes for the various functions are derived in the step above. Usually there are many known failure modes based on past experience, and some functions can have many failure modes [23].

(c.) Failure Effects: Determine the effect of the failure mode, that is, what will happen if the failure mode were to occur. In some cases the failure mode will result in the plant or equipment not being able to perform its primary function and need to be taken out of service; this is a full functional failure. In some cases the plant or equipment would still be able to perform its primary function; this is a partial functional failure. It is important to have a good idea of which of these 2 effects the failure mode falls into.

(d.) Failure Occurrence (O): Determine how often this type of failure mode is expected to occur within the life of the equipment based on historical manufacturing and maintenance information. For simplification, less than 2% failure rate per annum will be applied a score of 1 and greater than 2% per annum applied a score of 2.

(e.) Failure severity (S): The failure severity has a direct link to the failure effect. For a partial functional failure a score of 1 is achieved, whereas a full functional failure attracts a score of 2.

(f.) Failure detectability (D): This is an indicator of the failure mode is detectable or not. A failure mode can be detected by condition monitoring (including online condition monitoring). Some failure modes cannot readily be detected, such as CB contact wear. Detectable failure modes achieve a score of 1 whereas undetectable failure modes achieve a score of 2.

(g.) Risk Priority number (RPN): The RPN is calculated as RPN = O x S x D [23]. The RPN allows the failure modes to be prioritised to allow for the higher risk items to be assessed first.

The disconnector picture below (minor plant example) shows the main functional components in different colours, and their sub-components shown by the numbers.

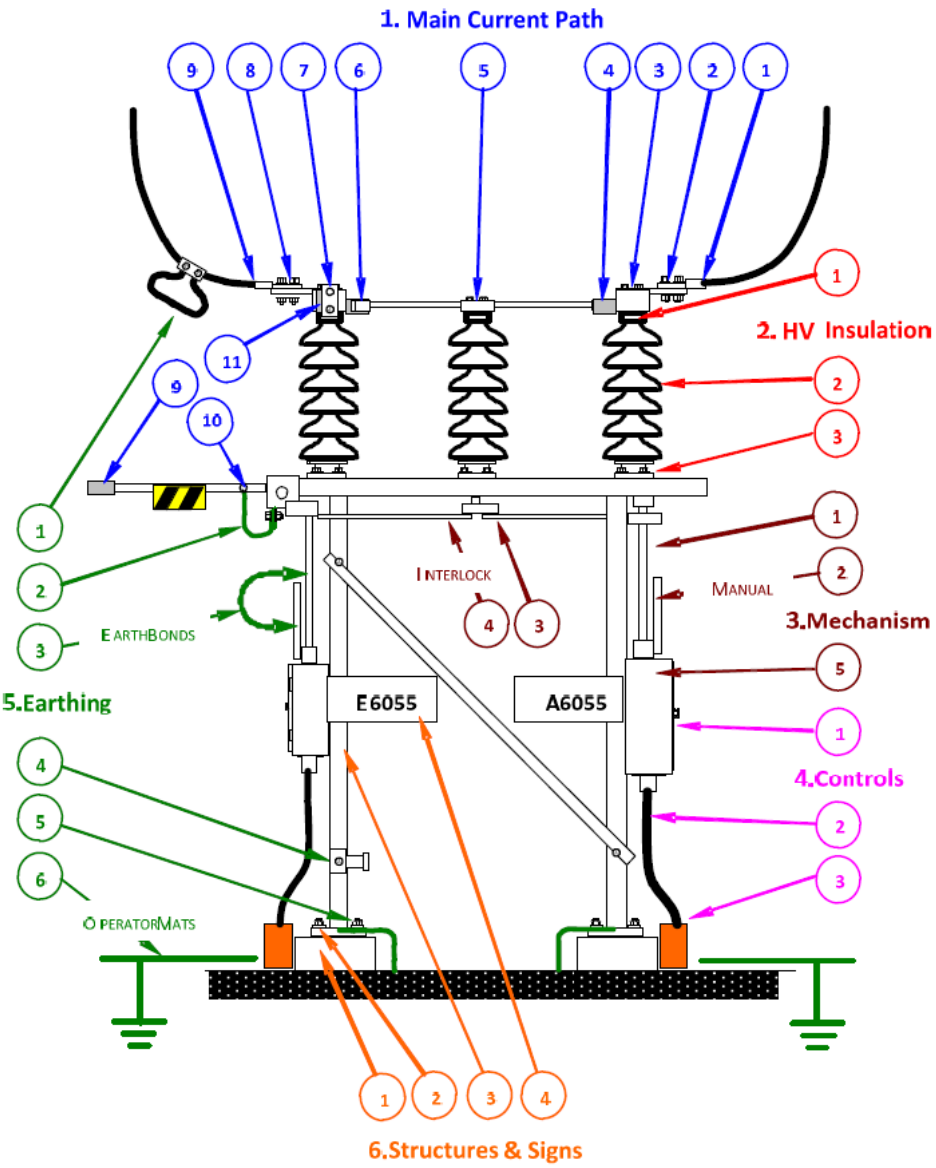

Figure 11: Disconnector functional component diagram [24]

A major plant item, being significantly more complex will have more functional components, and hence will be subject to more failure modes. Similarly the consequence of failure is generally much higher.

The diagram of the power transformer illustrates different functional components as shown in figure 12.

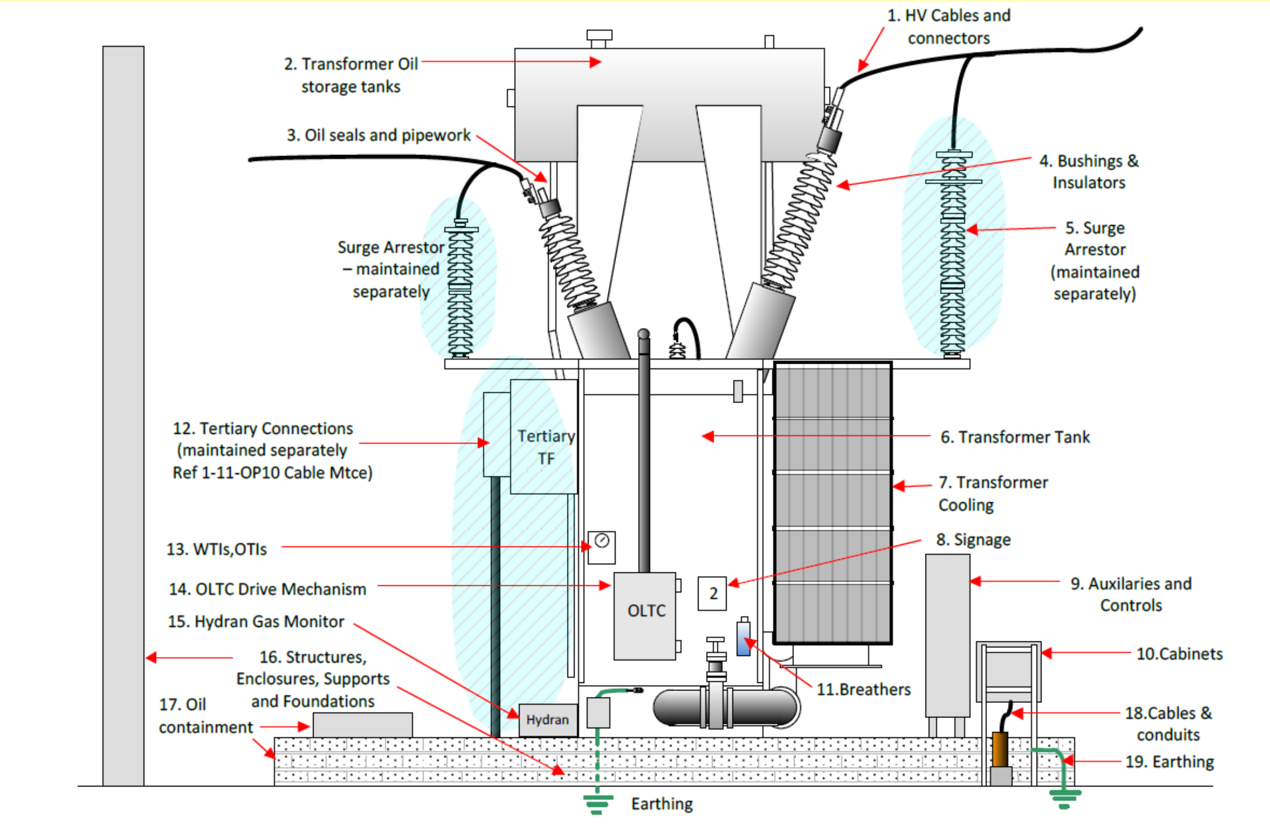

Figure 12: Power transformer functional component diagram [25]

It must be noted that each component and sub-component will have more than one failure mode. During the FMEA workshop(S), using visual aids as above helps easily identify the functional components and then determine the failure modes and effects.

The FMEA is required to be performed by the following personnel:

(a.) The Factory equipment subject matter experts.
(b.) The T&D equipment subject matter experts.
(c.) The T&D operation and maintenance personnel.
(d.) A trained FMEA facilitator (as necessary).

Usually, the FMEA worksheet is pre-populated by the personnel listed above and then finalized during the workshop. The scoring mechanism is prescribed as 'low' score and a 'high' score. Although complex industries such as Defence or Aviation may choose to apply a more detailed approach, a high/low differentiator is usually sufficient for T&D.

Table 8: Risk Priority Number (RPN) scoring

Criteria	Low score	High score
Failure Occurrence (O)	1	2
Failure Severity (S)	1	2
Failure Detectability (D)	1	2

Therefore, depending on the different permutations, this would provide a RPN score between 1 and 8. This is a very simplified and crude way of determining the RPN score. Typically, the higher end of RPN scoring, such as 8 signifies a dominant failure mode, a midway RPN score, such as 5 signifies a non-dominant failure mode and a low RPN score such as 1 signifies an obscure failure mode. Dominant failure modes are deemed important because of their frequency or severity. Non-dominant failure modes occur occasionally with moderate consequences. Obscure failure rarely occur, and generally there isn't any history of this failure mode having occurred in the particular T&D organisation.

A completed FMEA allows for T&D organisation to properly understand the risks associated with the plant and equipment. Some show-stoppers might be identified during the FMEA. This might significantly influence the procurement decision or might prompt changes to asset strategy such as Technology Change - A change from an AIS solution to a GIS solution.

Also of significant importance, the FMEA provides input parameters for the following assessments to be conducted:

(a.) Reliability assessment.
(b.) RCM assessment.
(c.) HAZOP Assessment.

Refer to the FMEA example below for a fixed series capacitor (FSC).

Table 9: Failure Mode and Effects Analysis example

FMEA										
Component	**Function**	**Failure mode**	**Failure effect**	**Failure Consequences**	**Detection method or symptom**	**Redundancy provided**	**S**	**O**	**D**	**RPN**
Capacitors	To produce reactive power	Element failure	Faulted element (and parallel group) is short-circuited	Unit produces less reactive power, higher unbalance current	Higher unbalance current, offline capacitance measurement	No	1	1	1	1
		Leakage in bushing or welding seam	Element voltage withstand capability decreases	Element short-circuit, environmental concerns	Higher unbalance current, offline visual inspection	No	2	2	1	4
		Loose connection in inter-rack wiring	Connection resistance increases	Hot spot	Higher unbalance current, thermography	No	2	2	2	8
MOV	To protect capacitors from overvoltage	Moisture inside housing	Leakage current increases, finally short-circuit	MOV failure protection operates, bypassing of FSC	Online varistor unit leakage current monitoring	No	1	1	1	1
		Degradation of varistor elements	One varistor units conducts before others during failure	MOV failure, bypassing of FSC	Offline varistor unit voltage measurement	No	2	1	2	4

		External insulation dirty	Uneven voltage distribution may damage individual disks	MOV failure, bypassing of FSC	Visual inspection	No	1	1	1	1
Current transformer	To measure current on platform	Internal insulation failure	Incorrect measurement result, finally CT destruction	Fault-to-platform protection operates, bypassing of FSC	Insulation resistance measurement	For secondary coil yes	1	1	1	1
		Loose connection in connection box	Incorrect measurement result, hot spot	One measurement missing from one P&C system -> One P&C system failure	Visual inspection	Yes	1	1	1	1
	To power platform electronics	Internal insulation failure	No power from transmission line	Fault-to-platform protection operates, bypassing of FSC. If not fault-to-platform fault, power still supplied from ground level via laser	Insulation resistance measurement	Yes	1	1	1	1
		Loose connection in connection box	Hot spot in connection box	May damage connection. If so, power supplied only from ground level via laser	Visual inspection	Yes	1	1	1	1
Spark gap	To bypass FSC if MOV is to be overloaded	Housing leakage / severe abnormal environmental condition	Voltage withstand capability decreases, spark gap self-ignition	Bypassing	Visual inspection	No	1	1	1	1
		Animal inside	Voltage withstand capability decreases, spark gap self-ignition	Bypassing	Visual inspection	No	2	2	2	8

		Graphite electrodes fault	Voltage withstand changes, spark gap self-ignition / forced triggering fault	Bypassing / MOV damage	Visual inspection	No	1	1	1	1
		Damping resistor insulation erosion	Resistance decreases	Higher discharge current for the trigatron. The Trigatron can withstand this and operates normally	Visual inspection	No	1	1	1	1

Once the FMEA is complete, several failure modes which may not have been known before, or had not been deemed serious before are now at the fore-front of thinking. These failure modes could be show-stoppers in terms of moving forward with this specific type of equipment, or could result in modifications to the original specifications allowing the manufacturer to eliminate these specific failure modes in their design.

3.5.2 Reliability Centred Maintenance (RCM)

Successful asset management relies heavily on the use of information and data to facilitate the decision making process. Decision making is improved if the process uses information from a variety of sources including from within the organisation, operating environment, technical groups, manufacturers, maintainers and repairers [26]. Equipment reliability and life-cycle cost is a key factor in effectively managing plant and equipment assets. It is usually very difficult to assess the effectiveness of RCM at its inception, when data is inadequate or when it is implemented on a large population of assets [27], however over time it becomes evident that application of RCM delivers value over the life of the asset. Failure of assets are undesirable from an economic standpoint but can also be hazardous and catastrophic in some cases.

A RCM study is one that could radically assist in predicting and preventing asset functional failures. The RCM study aims to create intelligence to fix a functional component before it fails. RCM analysis will result in a cost effective maintenance program, improved maintenance policies and effective asset management. Prior to understanding RCM, it is required to understand maintenance in general. Preventive maintenance refers to maintenance tasks which are performed periodically to prevent failures. This consists of routine maintenance (such as Lubrication, alignment, calibration) and corrective maintenance (such as Repairs). The basis and frequency of corrective maintenance tasks are derived through the RCM process.

The crux of RCM is to:

(a.) Define specific maintenance inspection tasks which are specially looking for the onset of known failure modes
(b.) Prescribe the frequency of these inspections so that they occur before the failure mode eventuates

If known failure modes are detected these then trigger a corrective maintenance task. The RCM will typically result in 4 different types of maintenance tasks, namely:

(i.) On-Condition Task [14]: A scheduled inspection or test to determine if a component is in a satisfactory condition and will remain in this condition till the next scheduled maintenance.
(ii.) Failure-finding task [14]: A scheduled inspection to find functional failures which have already occurred but were not evident to operations staff.
(iii.) Re-work task [14]: Scheduled removal of an asset to perform maintenance to ensure that the asset meets condition and performance standards
(iv.) Discard task [14]: Scheduled removal of an asset to perform maintenance to discard one or more of its components which is deemed end-of life.

The FMEA outcome is a key input parameter which is used to perform a RCM analysis. The actual analysis is conducted by applying decision trees (yes/no) to each of the FMEA failure modes to determine which type of maintenance tasks, if any, will be required. Decisions are usually divided into safety, operational, economic, and hidden failure detection. An example of the decision tree question could be:

(i) Is the occurrence of a failure evident to the operating crew during normal operation?

(ii) Does the failure cause a loss of function or secondary function?

Application of RCM will result in asset management and maintenance policies; including a list of maintenance tasks which could be grouped for efficiency. Where maintenance tasks cannot be identified, a redesign or change in technology choice might be warranted (such as the choice between an oil-filled CT and a SF6 filled CT). Examples of maintenance tasks might be lubrication, On-time condition monitoring, failure finding task. The development of asset maintenance policies using RCM is a major element in an asset management system implementation [15].

Determining the list of tasks is only half of the maintenance strategy, which in this case is RCM. It is also important to determine the frequency of maintenance (usually in years). The key to calculating the RCM frequency is to calculate the P-F interval, where:

(i) P – Potential failure. The onset of a failure [28].

(ii) F – Functional failure. The point at which functional failure occurs [28].

The P-F interval is the time taken from potential failure to functional failure. The P-F interval must be long enough such that the On-Condition tasks can detect the potential failure before it becomes a functional failure. Figure 13 illustrates the P-F interval. Asset maintenance must occur within the P-F interval to ensure that functional failures are detected and repaired before they occur. Calculation of the maintenance frequency, which is the duration between each asset maintenance cycle is key to maintenance strategy. RCM analysis provides data which enables asset P-F intervals to be calculated for each asset class.

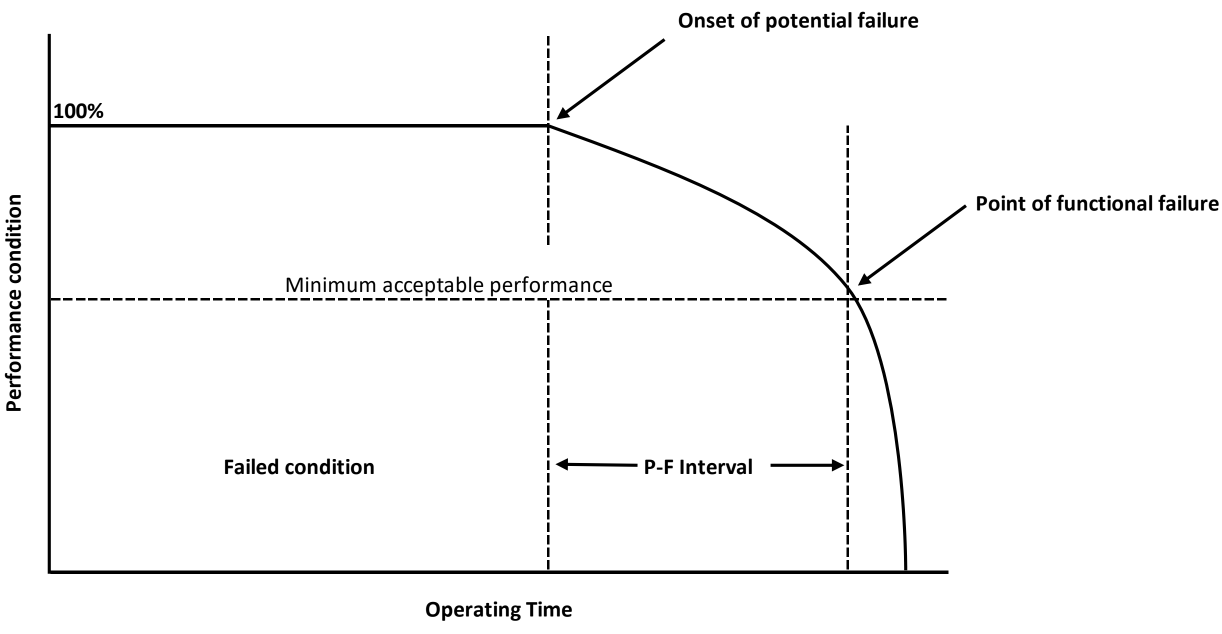

Figure 13 Potential failure to Functional Failure interval [28]

The formulae to calculate the P-F interval is shown in [28]

$$\text{P} - \text{F Interval} = \frac{Task\ Frequency}{2} \quad (4)$$

Where,
(i) P-F Interval is the duration between the onset of a functional failure and the point at which the functional failure occurs; and
(ii) Task Frequency is the duration between the specific maintenance tasks which have been implemented to detect the functional failure.
This allows for the maintenance task to be scheduled before the functional failure occurs.

Knowing the P-F interval and the maintenance tasks means that the maintenance over the life of the asset can be calculated as the sum of:

(i.) Asset acquisition Cost.
(ii.) Asset Maintenance cost (over the lifecycle).
(iii.) Asset Disposal Cost.

It is very important for asset owners to have a clear understanding of life-cycle cost since this drives effective decision making and results in predicable asset performance and cost. Refer to Table 10 for a RCM example which was performed for a transmission line conductor.

Table 10: Reliability Centred Maintenance (RCM) example

Function	Functional Failures	Failure Modes	Predominant Failure Consequence Category	Maintenance Task Summary
1. To conduct current between two substation gantries at up to the maximum static current rating under normal operating conditions.	2	30	SAFETY – conductor failure resulting in contact with ground/fire start.	ON CONDITION – Conductor assessment for corrosion ON CONDITION – Conductor inspection for damage ON CONDITION – Joint resistance test ON CONDITION – Corona/Thermographic inspection REDESIGN – Conductor Joint construction
2. To maintain conductor position above minimum required clearances.	1	8	SAFETY – conductor clearance not maintained/ electrical hazard.	ON CONDITION – Clearance check
3. To operate within acceptable noise and EMI limits in accordance with LDM section 20.	1	3	ENVIRONMENT – Electromagnetic interference	ON CONDITION – Corona Inspection
4. To indicate the presence of overhead conductors to persons not performing intentional or legal low-level flying operations in accordance with AS/NZS 3891 without damaging the conductor.	1	3	SAFETY – Aviation Hazard	FAILURE FIND – Marker Ball inspection

3.5.3 Hazard and Operability Study (HAZOP)

The purpose of a HAZOP study is to identify hazards associated with the plant and equipment during the installation, operation, maintenance and disposal [29]. This also includes environmental hazards. A key benefit of the HAZOP study is that the outcome can be used to develop appropriate remedial measures to eliminate or control the hazards. The steps involved in a HAZOP study are as follows:

(i.) Perform a FMEA analysis.

(ii.) Conduct a HAZOP workshop [29] with subject matter experts from various discipline areas with the T&D organisation, particularly maintenance and operations. If it is possible for factory SME's to be present, this is an advantage. The HAZOP workshop should be facilitated by a trained HAZOP facilitator.

(iii.) The FMEA should be used as a starting point to identify potential hazards associated with the plant or equipment functions or failure modes. The use of guide-word is also useful to stimulate productive thought processes. Examples of some common guidewords are 'temperature', 'flow' and 'pressure'. Hazards are to be identified for all phases of the asset life-cycle, installation, operation, maintenance and disposal.

(iv.) Using a brainstorm type approach [29], hazards are identified and recorded on the HAZOP record for further assessment.

(v.) The identified hazards must be passed on to plant and equipment engineers as well as designers to allow them to eliminate the hazards modifying specifications or designs. It is not the responsibility of the HAZOP workshop group to determine solutions [29].

The hierarchy of controls can be applied to individual or group hazards such that they can:

(i.) Be inputted into plant and equipment functional and technical specifications to be eliminated

(ii.) Be inputted into the overarching system design to substitute the hazard, such as the use of a different technology

(iii.) Be inputted into overarching system design to be engineered-out

(iv.) Be inputted into operation and maintenance processes to change the way people operate or maintain the equipment

(v.) Be inputted into process to build in guards or require people to use personal protective equipment when operating or maintain the equipment.

The hierarchy of controls is shown in figure 14.

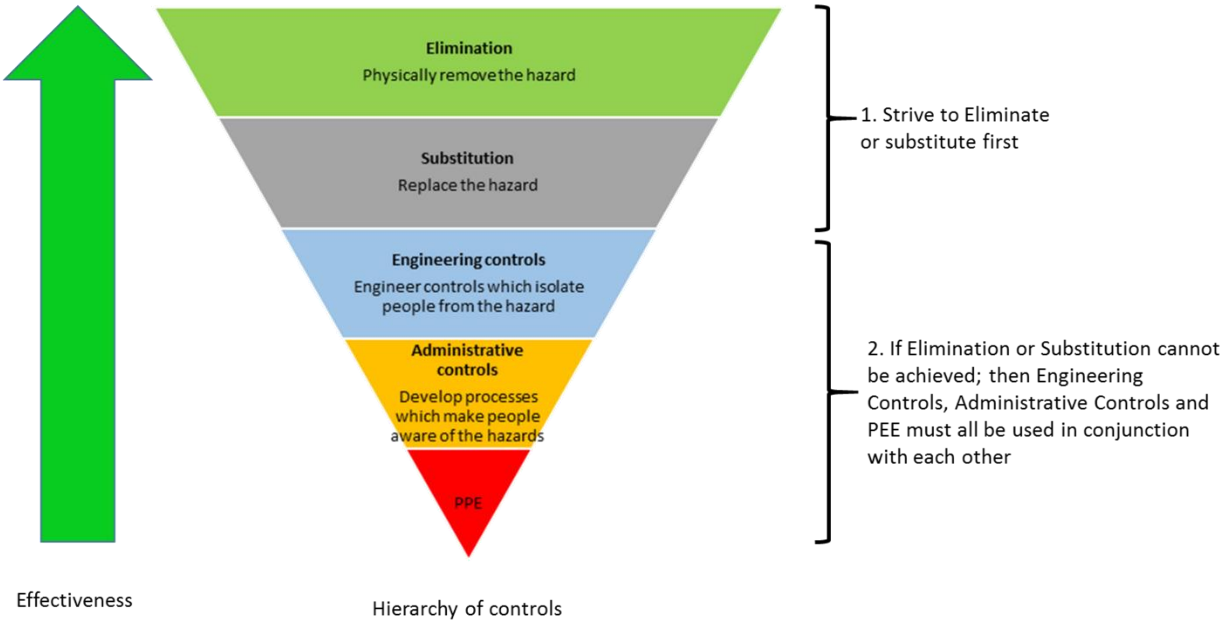

Figure 14 Hierarchy of controls

A completed HAZOP workshop example is shown in Table 11.

Table 11: Hazard and Operability Study (HAZOP) example

HAZOP WORKSHOP Record						
Item	**Guideword / Hazard**	**Causes**	**Consequences**	**Safeguards**	**Action**	**Responsible person**
1	Earth switch	Mechanical lock off facility	Pinch point when access mechanical lock off facility located on top of the earth switch mechanism box	none	Provide operator access to reach lock off mechanism	
2	Earth switch	Manual operating handle is stored in the mechanism compartment	Possible to make electrical contact with control wiring or risk of abrasion or cuts when accessing	none	Relocate handle to the door as per adjacent mechanism box	
3	Earth switch	Terminology of open close (O/I)	Incorrect interpretation of position	none	Ensure correct indication	
4	Earth switch	Main Contacts - greasing	Contacts may bind if incorrect grease is applied	Routine maintenance task	Ensure O&M manuals are available for the maintenance porvider	

Item 4 indicates that a typical hazard on this earth switch is ‘binding of the main electrical contacts’; and that a typical cause is ‘application of incorrect grease during maintenance’. The most appropriate safeguard to prevent this is the routine maintenance task associated with maintenance of the main electrical contacts. The key action is to ensure that the maintenance provider has the ‘operation and maintenance manual’, which will ensure that they know which grease to use.

3.5.4 Safety Critical Equipment (SCE)

Safety critical equipment (SCE) is equipment which has a primary function to protect people (workers or the public) or prevent a major accident event. SCE in comparison to all other plant and equipment therefore receives:

(i) An elevated level of scrutiny and evaluation during equipment procurement and application (specification, evaluation e.g. FMEA, RCM, HAZOP etc),

(ii) More focus and checking during installation and commissioning with a focus on functionality and operability.

SCE will have a more stringent maintenance plan during its useful life, since it is imperative that this equipment maintain its primary function for as long as it is in service.
An example of a SCE list is:

Table 12: Safety Critical Equipment (SCE) list

Asset Category	Sub Category	Asset Class
Substations	Switchgear	High voltage disconnectors & Earth Switches
		High voltage Isolating links
		Switchgear mechanical Lock-off Points
		Switchgear status indication
		Indoor board arc containment and venting
	Reactive Plant	Capacitor discharge equipment
	Infrastructure	General Earthing and bonding
		Substation Earth grid
		Flexible Earth leads
		Fencing & Gates
		Access roads
		Fire Protection Systems
		Signs
Secondary Systems	Protection System	Protection Schemes
		Electronic and Protection logic Interlocking
Transmission Lines	Earthing	Tower earth grid
		General earthing and bonding
	Structures	Tower Anti-Climb
		Tower & Pole fall arrest systems
	Conductor	Aerial Marker balls

3.6 Design Review

Once a decision has been made to procure a major plant item or a fleet of minor plant and equipment, it is expected that the factory will start its design. This is a critical part of the asset life-cycle since T&D asset managers will have the opportunity to confirm the design against the specification which they would have issued to the supplier at an earlier stage. The level of design review required for major plant will greatly differ when compared to that of minor plant and equipment. Major plant design review is expected to be more onerous simply because the plant is much more complex and expensive when compared to minor plant and equipment. The consequence of something going wrong with major plant is much more severe. Where minor plant design reviews may be conducted at the premises of the T&D asset manager's premises, major plant design reviews usually occur at the manufacturer's factory. The main purpose of the design review is to:

(i) Ensure clear and mutual understanding of the functional and technical specification requirements between the T&D asset manager and the factory [30].
(ii) To verify that the factory's design complies with the functional and technical specification requirements [30].
(iii) To verify any special requirements such as project or delivery dates which must be met [30].

This is also an opportune moment to make any last minute design changes without adversely affecting cost; or bring in modifications which were not thought of before.
The requirement and schedule for design reviews must be driven by the T&D asset manager. Contract placement must only occur after satisfactory completion of the design review. In general, the following items must be verified in accordance with the specification:

(i) The design has adequately covered the functional and technical requirements;
(ii) The design has adequately meets performance criteria;
(iii) The design has adequately covered the local conditions e.g. Seismic, pollution;
(iv) Wiring schematics are adequate;
(v) Special requirements are understood e.g. Painting and paint colour;
(vi) Transport, logistics, installation and erecting has been adequately catered for;
(vii) Special requirements have been catered for e.g. Specific labelling and indication;
(viii) Spares requirements have been allowed for.

The design review meeting is also a good time to discuss and agree on the inspection and test plan in terms of schedule and steps. This is useful for the T&D asset manager, particularly if factory testing is intended to be witnessed. It is typical for the T&D asset manager's subject matter expert to check the following:
(i) Drawings, reports and schematics;
(ii) Electrical, mechanical and structural calculations (this is usually done with specialised software).

Any deviations to the specification must be clearly articulated and noted, if it is agreed that this deviation will be accepted by the T&D asset manager. All points covered during the design review meeting must be clearly minuted and signed off by both parties. It is important that the design review meeting minutes are discoverable should any issues arise in the future. A simple template for design review record or minutes is shown in Table 13.

Table 13: Design review record/minutes example

Design Review record and minutes

Factory/Supplier ______________________

Client ______________________

Equipment ______________________

Factory SME(s) ______________________ **Factory SME(s) signatures** ______________________________________

Client SME(s) ______________________ **Client SME(s) signatures** ______________________________________

Date ______________________

Item Examined	Document reference	Recommendations (if corrective action required)	Description Of Corrective Action Taken	Corrective Action Taken By	Signed off

3.7 Testing

Plant and equipment will be tested at the factory once manufactured and then again on site. As the names suggests, this is referred to as Factory Acceptance testing (FAT) and Site Acceptance testing.

3.7.1 Factory Acceptance Testing

The main purpose of factory acceptance testing (FAT) is to verify that the plant and equipment meets technical and performance requirements; and performs the functions that it has been designed for. For major plant, FAT will consist of type tests and routine tests:

(i) Type tests are performed to prove the plant and equipment design; and
(ii) Routine tests are to confirm that performance parameters can be achieved.

It is good practice for the T&D SME's to witness FAT's, particularly for major plant. Witnessing of FAT for minor plant and equipment only needs to occur at the front-end of period contracts, or if there is a change in the design or other technical aspect during a period contract. Although undesirable, if plant or equipment were to fail, the most appropriate time for this to occur is during FAT. At this point in time, it is possible to quickly fault-find, find the root cause effect a repair. A failure during SAT would incur adverse costs to determine the cause of failure and to administer a repair. Sometime the cause cannot be determined. The cost of a failure gets exponentially higher as the plant or equipment progresses through to operation and the remainder of its life.

It is good practice the T&D asset owners to prescribe the 'approval to dispatch' as a hold point for major plant. This occurs when the plant item has successfully completed all required factory tests. This will ensure that there is sufficient time for all relevant testing requirements and test reports to be scrutinised before the equipment leaves the factory. This is done by citing all test reports and test certificates and comparing these against the requirements which were stipulated in the specification.

3.7.2 Site Acceptance Testing

The main purpose of Site Acceptance Testing (SAT) is to confirm site integration requirements and to verify that the plant and equipment has not been damaged during transport to site. Site acceptance test results must be compared with the results obtained from the FAT, in particular HV test results. Care must be taken provide compensation to test results to account for changes in temperature, humidity etc. SAT test equipment is to be in working order and have valid calibration certificates. It is also important to ensure that testing is being performed by qualified personnel.

3.7.3 Inspection and Test Plan

It is good practice to agree the inspection and test plans (ITP's) for FAT and SAT. The FAT ITP's are required to be negotiated with the factory and the SAT ITP's are required to be negotiated with the site installation and commissioning team. The ITP's clearly articulate the tests which must be performed and the sequence in which they must be performed. The ITP also defines the hold and witness points:

(a.) Hold point: These are points which must be confirmed and approved by SME's before any further testing can occur.
(b.) Witness point: These are points which must be confirmed by SME's but testing can continue without approval.

An example of an ITP is shown in table 14.

Table 14: Secondary System ITP example

Equipment	Test Description	Drawing Number	ITP Number	Hold Point	Witness Point	Test Completed By (Contractor)	Test Witnessed By (Client)	Completion Date
DC System Tests	Initial Charge Tests			Y / N	Y / N			
	Inter-Cell Voltage Tests			Y / N	Y / N			
	Performance Tests			Y / N	Y / N			
Feeder Integration Tests	X Protection Function Tests			Y / N	Y / N			
	X Protection End to End Tests			Y / N	Y / N			
	Y Protection Function Tests			Y / N	Y / N			
	Y Protection End to End Tests			Y / N	Y / N			
	BCU Function Tests			Y / N	Y / N			
Feeder Integration Tests	X Protection Function Tests			Y / N	Y / N			
	X Protection End to End Tests			Y / N	Y / N			
	Y Protection Function Tests			Y / N	Y / N			
	Y Protection End to End Tests			Y / N	Y / N			
	BCU Function Tests			Y / N	Y / N			
Transformer 1 HV Integration Tests	X Protection Function Tests			Y / N	Y / N			
	Y Protection Function Tests			Y / N	Y / N			
	BCU Function Tests			Y / N	Y / N			
Transformer 1 LV Integration Tests	X Protection Function Tests			Y / N	Y / N			
	Y Protection Function Tests			Y / N	Y / N			
	BCU Function Tests			Y / N	Y / N			
	AVR Tests			Y / N	Y / N			
Overall Scheme Tests / Final Trip & Alarm Tests	Para feeder Trip, CBF & AR Tests			Y / N	Y / N			
	Blyth West Feeder Trip, CBF & AR Tests			Y / N	Y / N			
	Transformer 1 Trip, CBF & AR Tests			Y / N	Y / N			
Feeder CVT	X Protection Voltage Injection Tests			Y / N	Y / N			
	Y Protection Voltage Injection Tests			Y / N	Y / N			
	BCU Voltage Injection Tests			Y / N	Y / N			
Feeder CVT	X Protection Voltage Injection Tests			Y / N	Y / N			
	Y Protection Voltage Injection Tests			Y / N	Y / N			
	BCU Voltage Injection Tests			Y / N	Y / N			
Transformer 1 HV CVT	X Protection Voltage Injection Tests			Y / N	Y / N			
	Y Protection Voltage Injection Tests			Y / N	Y / N			
	BCU Voltage Injection Tests			Y / N	Y / N			
Transformer 1 LV VT	X Protection Voltage Injection Tests			Y / N	Y / N			
	Y Protection Voltage Injection Tests			Y / N	Y / N			
	BCU Voltage Injection Tests			Y / N	Y / N			
Primary Injection Tests	CT8011 Primary Injection & Burden Tests			Y / N	Y / N			
	CT8013 Primary Injection & Burden Tests			Y / N	Y / N			
	CT8015 Primary Injection & Burden Tests			Y / N	Y / N			
	CT5736 Primary Injection & Burden Tests			Y / N	Y / N			
	CT8011 - CT8015 Summation Tests			Y / N	Y / N			
	CT8013 - CT8015 Summation Tests			Y / N	Y / N			
	CT8011 - CT8015 Summation Tests			Y / N	Y / N			
	Transformer 1 400V Stability Test			Y / N	Y / N			
NGM Calibration Tests	Meter Secondary Injection Tests			Y / N	Y / N			
	Metering CT & VT Injection Tests			Y / N	Y / N			
DNSP Interface Tests	Intertrip Send / Receive Tests			Y / N	Y / N			
	CT5736 Line-Up Tests			Y / N	Y / N			
HV Tests	Primary HV Tests			Y / N	Y / N			
	Transformer SFRA Tests			Y / N	Y / N			
	Transformer Oil Tests			Y / N	Y / N			
Site Off-load Test Completion Certificate Issued				Y	Y			

3.7.4 Test reports

Test reports are required for all tests which have been performed- this includes FAT and SAT. The tests should explicitly stipulate a pass or fail result. Any noncompliance and its resolution must be recorded. Test reports are to be retained and stored with relevant asset information for future reference (if any).

Chapter 4 – An Effective Asset Management Strategy

4.1 Strategy, Policy and Capability

Asset Management is defined as Systematic & coordinated activities and practices through which an organization optimally manages its physical assets and their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organizational strategic plan [31]. For best results the strategy and tools mentioned in the previous sections must be developed and implemented in its entirety that is all tools implemented, however selected portions can be chosen for application based on known gaps in a particular organisation. For best results, a top-down implementation approach is recommended.

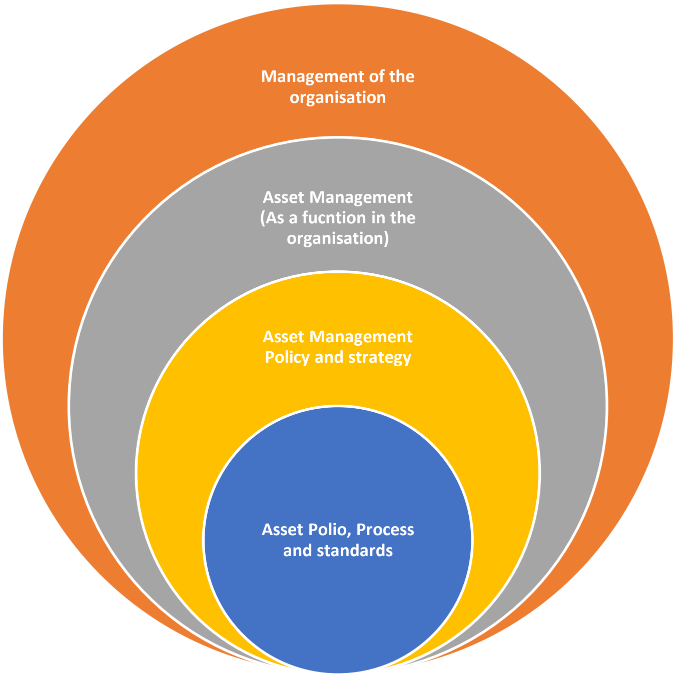

Figure 15: Implementing Asset Strategy [32]

A 3-step approach will ensure that effective asset management for plant and equipment can be successfully deployed:

(a.) Develop and embed Strategy, Requirements and standards
(b.) Develop and embed Policy and process
(c.) Develop Competency and Capability

It is important to develop an asset strategy, functional, technical requirements and design standards for the asset classes which are deemed important. These documents are highly technical in nature. An individual suite of documentation will need to be developed for each asset class such as Power transformers.

(a.) Asset Class Strategy: The asset class strategy will consider the life-cycle requirements of the asset class from creation to disposal; and will stipulate the performance criteria for the asset class.
(b.) Functional and technical requirements: These documents will define in detail the assets functional and user functional requirements as well as the detailed technical performance requirements for the assets (including design standards requirements).

(c.) Inspections and test plans (ITP's): The ITP's will define the inspections and test plans required to verify and test the functional and technical requirements.

Effective policy, procedures and tools will support the application of asset strategy. This is defines as:

(i.) Policy: Policy will define the high level requirement which would state why asset strategy must be implemented, as well as direct personnel to comply. This will make clear requirements such as Factory Prequalification's, the need to perform equipment assessment studies (such as FMEA).

(ii.) Process and procedure: Procedures, in line with policy will state what must be done, at what point in time and by whom. This will ensue that there is consistency in results. The assessment tools are also captured in procedure documents (such as HAZOPs)

Having effective strategy, standards, policy and process is only as effective as the people applying them. It is important that the people responsible for applying strategy, standards, policy and process have the requisite level of experience and knowledge. It is good practice for T&D organisations to know what competencies they require and to assess their people against those competencies. Gaps identified can drive development plans; and the fact that this is done will in general drive a culture of continuous individual development.

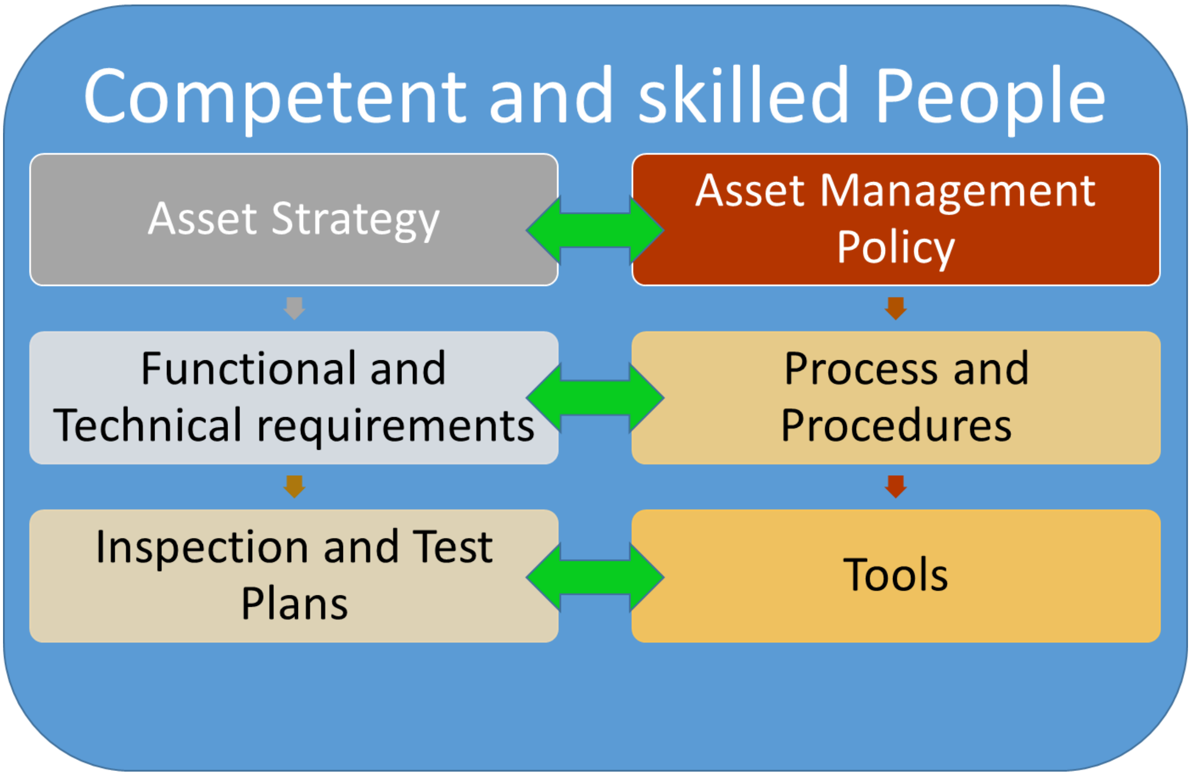

Figure 16: Strategy, policy and capability

4.1.1 Prioritisation of Asset Classes for Asset Strategy Implementation

It can be a daunting task for asset managers who are embarking on a journey towards implementing effective asset strategy in deciding where to start. The main consideration is to determine which asset classes to consider first; and the understanding that some asset classes will not require a detailed level of focus; and some no focus at all. As a rule of thumb, the key factor in determining the priority of asset classes to focus on must be based on life-cycle cost; in particular highest to lowest. This will typically follow this sequence:

(i.) Transmission/Distribution Line towers and insulators
(ii.) Transmission /Distribution Lines overhead line conductors
(iii.) Power transformers
(iv.) Substation infrastructure
(v.) Circuit Breakers
(vi.) Disconnectors
(vii.) Protection and Automation equipment
(viii.) Instrument transformers

Figure 17 is an example of lifecycle cost for the major asset classes.

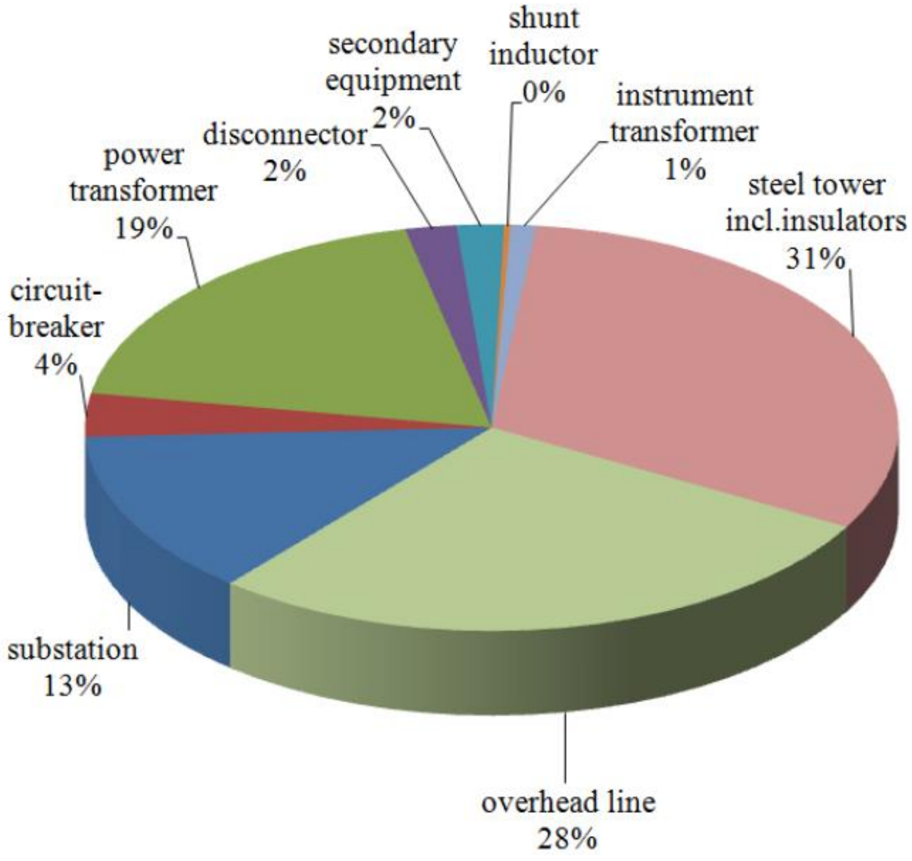

Figure 17: Lifecycle cost of major asset classes [18]

4.1.2 Support from External Specialists

Strategy development, Specification development, Factory Assessment, Plant and Equipment Assessment, Design Review and the witnessing of factory acceptance testing are functions which require a good degree of subject matter knowledge complimented by the skillsets required to administer and facilitate the procedural aspects related to these functions. It is imperative that the people responsible to execute these tasks are adequately qualified and experienced.

Large T&D organisations are sometimes fortunate enough have SME's with detailed plant and equipment knowledge and experience. This makes it easy to apply the requisite procedural requirements such as Factory prequalification and equipment assessment studies, in order to obtain best outcomes. Smaller organisations may not have the requisite specialist skills required to execute these functions adequately. It is not uncommon for these organisations to obtain these skills from the consulting market to help perform one or more of the required functions. Sometimes, even if there is a requisite level of skill and experience in the T&D organisation, it is a good practice to obtain specialist consultant support. This allows for an independent view and an opportunity to sound-out any concerns. These skills are readily available in big design houses and also via small specialist consultancy firms.

4.1.3 Organisation Maturity and Resilience

Resilience is a function of an organisation's situational awareness, management of risk and vulnerabilities and its ability to adapt and manage change [33]. An organization with a heightened resilience is one that is more likely to weather both the problems of day-to-day business and successfully navigate the issues that arise in a crisis [34], that is, the organisations ability to bounce back after a major asset failure or a crisis. Moreover, organisations with a more resilient leadership and culture [35], and workforce are more likely to be more competitive in a challenging environment.

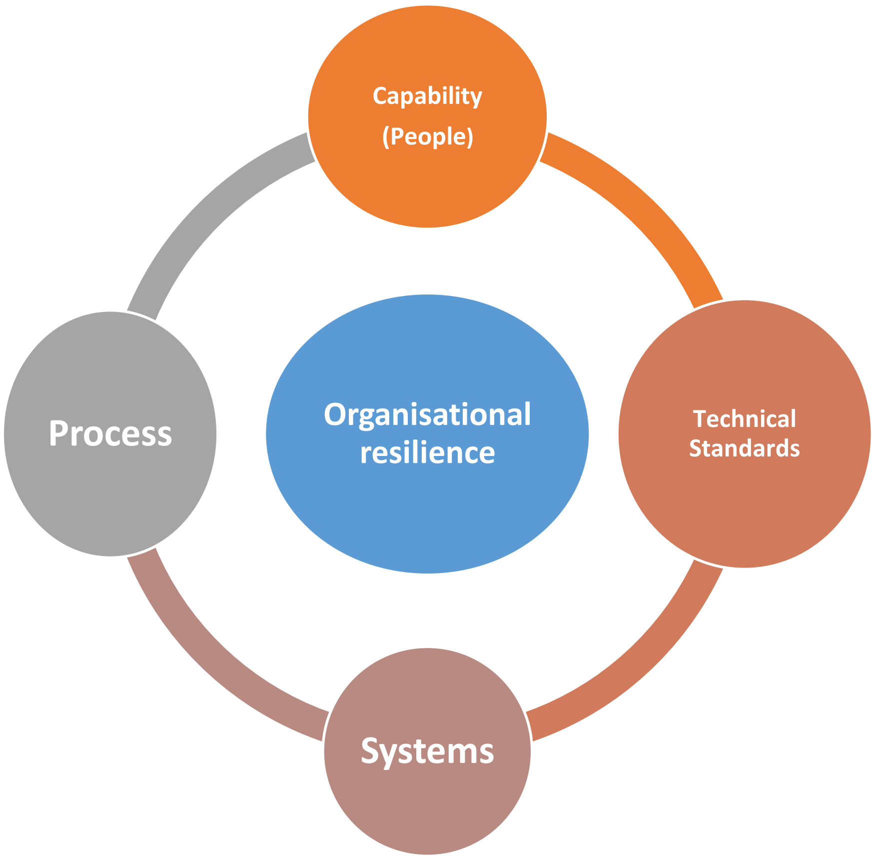

Figure 18 Organisational resilience

In the context of T&D Asset Management, application of the strategies and tools covered in this theses, and continuous improvement will make organisations more mature and competitive. This will generate more value in the long term and allow utilities to extract more out of their assets. The introduction and application of the strategies, principles and tools will inherently start the organisation on a journey of continuous improvement and development. This will create and develop intellectual capital in the form of up-to-date and relevant technical standards, process and capability (people) and ultimately make for a more resilient organisation.

4.1.4 Benefits of an Effective Asset Management Strategy

As detailed in previous sections, specific benefits of an effective asset management strategy are:

i. Achieving lowest life cycle costs.
ii. Improved asset reliability, integrity and performance.
iii. Organisational maturity and resilience.

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

Owning, operating and the utilization of T&D assets is the primary mechanism from which T&D organisations derive revenue. Furthermore, the electric power transmission and distribution system has a direct correlation to a country's economy and Gross Domestic Product (GDP). This by itself implies that the effectiveness of the asset management strategy and its application is not only directly proportional to productivity of the T&D organisation but also of the country. This thesis provides:

(i.) Insight into best practice T&D asset management techniques and strategy as related to high voltage plant and equipment;

(ii.) Tools and methodologies for T&D asset owners to make effective judgments and decisions related to the selection, specification and application of plant and equipment, resulting in lowest lifecycle cost;

(iii.) The ability to perform a technical assessment T&D asset suppliers and factories, and the criteria for this;

(iv.) A practical approach to application of the methodologies tools and equipment covered in this thesis;

(v.) The ability to ensure predictable asset performance and reliability over its lifecycle;

(vi.) The means to replicate favourable outcomes in different T&D organisations regardless of location or regulation.

A key finding of this thesis is that equipment infant mortality, mid-life failures, common mode failures and premature ageing usually means that the asset owner has made an error in the front-end asset strategy and asset creation process. The cost of these oversights are usually passed on to consumers in the form of increased electricity prices. What this means is that insufficient upfront work and due diligence has resulted in the implementation of a sub-standard product or solution. Conversely, if plant and equipment is still in good condition at the end of the design life, this usually means that the initial solution has been over-designed. In order for Asset Managers to develop and apply an effective asset management strategy, they must:

(a.) Understand what they require in terms of functionality, reliability and availability. It is possible to develop this understanding with the use of the tools covered in this thesis, that is FMEA, RCM, HAZOP. This information must be translated into equipment procurement specifications and maintenance strategies.

(b.) Procurement specifications must contain relevant information in line with point a. above. Over specification has a tendency to increase equipment cost (for functionality which may not be necessary) and could also confuse factory sales personnel in terms of understanding what is important for consideration during manufacture.

(c.) T&D organisations must be selective on the factories which will supply them with plant and equipment. The investment of time, prior to contract award, to properly evaluate factories against equipment specification and quality requirements is a key factor in attaining lowest lifecycle costs whilst mitigating risks like plant and equipment infant mortality and mid-life failures.

(d.) T&D asset owners must ensure that they have the right methodologies, process, technical standards and skilled people to effectively apply the points covered above. Where there are skill gaps, this must be addressed by implementing targeted or organisation-wide staff competency and skills development programs; and supporting this with the use of external industry specialist consultants.

Effective and well thought-out asset management will ensure that performance and life-cycle requirements are achieved at lowest costs whilst managing risk exposure. Value is created early in in the asset life-cycle process, which is during the development of the asset strategy; and the opportunity to create value diminishes as we progress through the asset life-cycle, that is during specification development, procurement and installation. The move from overly prescriptive specifications to functional specifications will ensure that functional and user-requirements are met, thus keeping upfront capital costs down. The application of strong asset management tools such as FMEA's, HAZOP and RCM prior to asset deployment, will ensure that effective maintenance strategy is deployed, thus keeping maintenance costs at a minimum. This allows asset managers to make sound investment decisions whilst understanding risk. The procurement or supply chain process is broadly covered below.

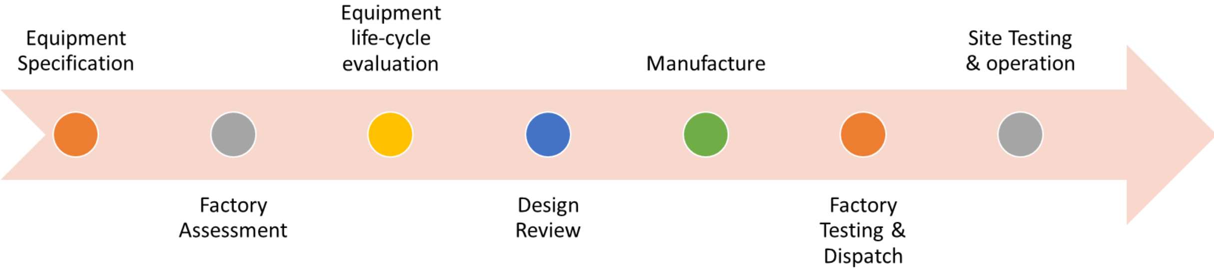

Figure 19: Plant and equipment supply chain

Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining stakeholder needs and required functionality early in the development cycle, documenting requirements, then proceeding with design [19]. Application of systems engineering principles to the plant and equipment supply chain process ensure that relevant checks and balance occur at the right time. Systems thinking helps in showing synergies in complex systems so that a holistic optimization approach can be applied to the systems [34].

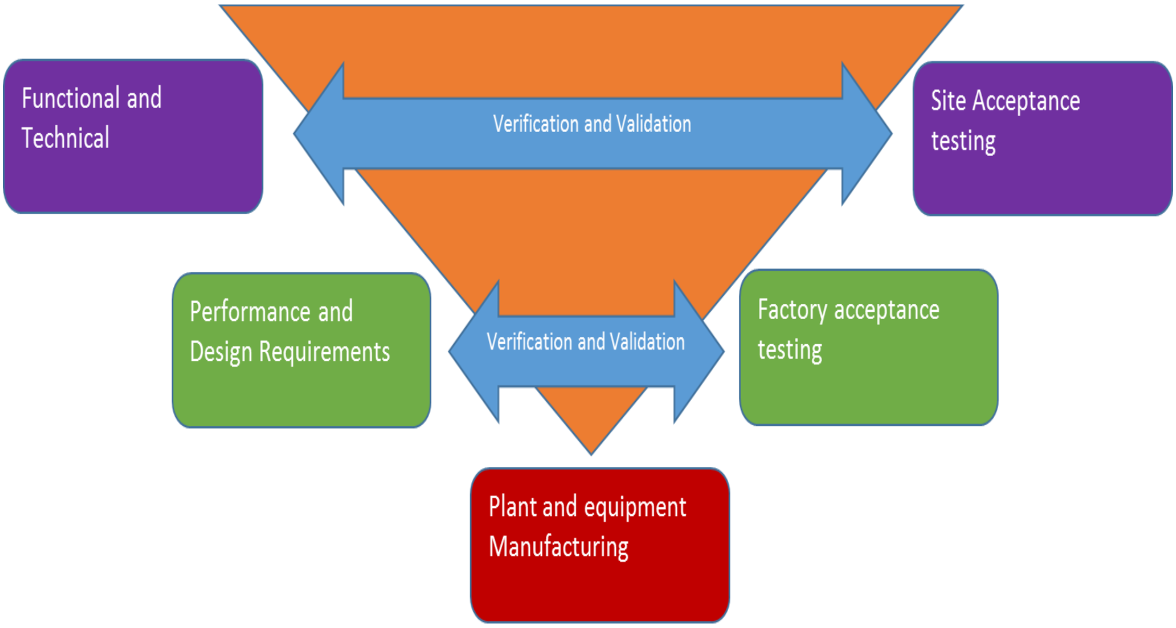

Figure 20: Verification and validation of requirements [7]

5.2 Recommendation

It is recommended that T&D organisations apply the strategy, systems, principles and tools covered in this thesis to their organisations. Best results will be obtained by full application of all aspects mentioned in this thesis. Where full application cannot be applied, a gap-analysis will identify the most significant areas for improvement and thus allow the partial application of the strategy, systems, principles and tools covered in this thesis.

T&D organisations which are government owned, privatised, in first world and third world environments will all benefit from the approach, philosophy and methodologies covered in this theses. However most benefit will be gained in T&D organisations in developing and third world environments. This is mainly due to the fact that these T&D organisations will see the most growth, and thus will be investing more in asset and infrastructure development.

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