Modelling Substation Control and Protection Asset Condition for Optimal Reinvestment Decision Based on Risk, Cost and Performance

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SUMMARY

Risk, cost and performance are the key elements to be considered when making good asset decisions to achieve optimum return on secondary system investments. In practice, it can be very challenging to develop asset management risk frameworks and asset risk models to assess asset condition and network risk to trigger asset reinvestment decisions at the right time – the needs based timing. In an environment where there is focus on enhancing cost and efficiency, strategic asset decisions can make a significant contribution to the effectiveness and sustainability of a business. Powerlink has successfully developed an asset management risk framework and asset risk models to derive health indices, effective ages and optimal replacement timeframes for control and protection systems assets within a transmission network. These attributes have been used to determine the probability of forced outage to a network element and the resultant probability of loss of load. The process consists of three main parts. The first part includes the detailed requirements of the technical attributes, whole of life cost and how asset data are structured in an enterprise asset management system. The second part includes the methodologies and processes used to capture operation and maintenance data as well as associated costs. The third part is the asset risk model and risk assessment methodology developed to provide comprehensive asset information for making good reinvestment decisions to achieve the optimal return on investment at an affordable cost and an acceptable risk profile. This paper describes the important processes and methodologies developed by Powerlink to best utilise asset data and to derive the control and protection asset risk model. The asset and network risk model has been successfully applied to optimise asset reinvestment decisions and derive the optimal asset replacement timeframe for Powerlink's secondary systems assets based on risk, cost and performance.

KEYWORDS

Assets, Secondary Systems, Equipment, Risk, Cost, Performance, Health Index, Condition Score, Replacement, Failure Rate.

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1 Introduction

Powerlink is a State Government Owned Corporation that owns, develops, operates and maintains the high voltage transmission network in Queensland, Australia. The network extends 1,700 kilometres from north of Cairns to the New South Wales (NSW) border and comprises more than 15,000 circuit kilometres and 139 substations. Powerlink's role in electricity supply is to transport high voltage electricity, generated at power stations, through its transmission grid to distribution network customers and directly to major high voltage industrial customers, mineral processing facilities and rail companies.

Half of the transmission lines within the greater Brisbane area are expected to reach end of life within the next decade. Reflections of the situation across Powerlink's network indicates an average of 400 transmission towers are turning 50 years old each year over the next decade. Over 40% of 14,000 control, protection and ancillary secondary systems equipment installed across 139 transmission substations will need to be rationally reconfigured, refurbished or replaced over the next 10 years in order to maintain transmission system operation to an acceptable system reliability and availability standard. Similar challenging scenarios will also occur with substation high voltage and telecommunication assets. Powerlink has modified its asset management strategies to adapt to changes in the operating environment, such as changes in the reliability standard, a flat demand forecast outlook and aging assets. These strategies primarily focus on rationalising network configurations based on enduring needs and optimising reinvestment options, including non-network solutions, and replacement or refurbishment of aging assets based on a robust risk, cost and benefit modelling framework.

This paper describes the asset risk management framework, processes and methodologies that have been adopted to optimise secondary systems reinvestment decisions to achieve the desired outcomes in practice.

2 Asset Risk Management Framework

A significant proportion of Powerlink's capital expenditure previously comprised of network augmentations to meet increasing levels of peak demand. However, a number of factors, including the adoption of small scale solar photo voltaic (PV) roof top systems, consumer response to rising electricity prices, and more efficient household appliances, have seen the transmission grid demand flatten over the past five years. Powerlink's medium term outlook is that the grid demand will continue to remain flat over the next few years with a return to modest growth within a ten year outlook period.

In response to the flattening of energy and peak demand, Powerlink has developed an integrated asset management plan, which is based on the cost, risk and benefit modelling framework for transmission assets. Powerlink's approach is that individual asset reinvestment decisions are not made in isolation, but rather considered as part of the broader asset investment or reinvestment strategy. Powerlink has also established new processes for engaging with external stakeholders for the provision of non-network services, and these also form part of integrated solutions to complement network reinvestment strategies.

3 Meeting Customer and Consumer Expectations

The focus of Powerlink's asset strategies is to deliver reliable and affordable transmission network services to meet customers and consumers expectations. The works that have occurred to date aim to address the following targets:

- Reliability: The health indices of secondary systems assets and equipment servicing the transmission network have been statistically modelled based on measured functional failure rate, down time duration, physical age and environmental conditions e.g. heat, humidity and dust.

- Affordable Cost: Transmission network assets have been categorised into two groups - assets with enduring need and assets without enduring need - based on the criteria set out in Powerlink's transmission network asset decision framework as illustrated in Figure 1. For aging secondary systems assets with no enduring need but only short term need, Powerlink has developed contingency plans to minimise the system outage duration should equipment failure occur. The contingency plans for secondary system assets consist of asset risk assessment, pre-design solutions and availability of field resources to support these contingency plans.
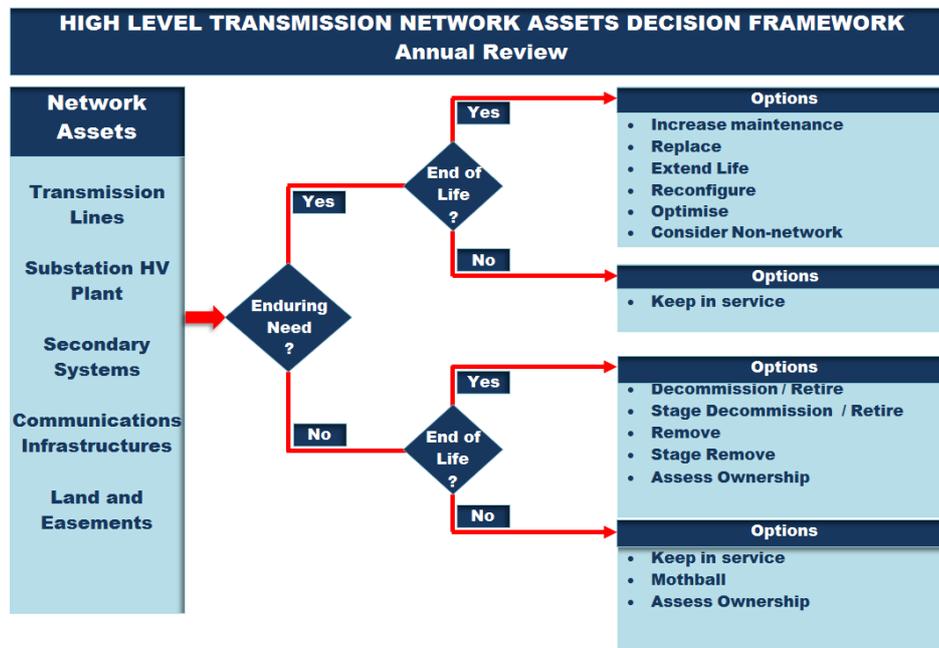

Figure 1 – High Level Transmission Network Assets Decision Framework

4   Functions of Secondary Systems Assets in Transmission Network

Secondary systems assets primarily exist to control, monitor and protect the transmission systems, network elements and associated bay equipment. These functions and services include:

- Network element protection – Duplicated X and Y systems.
- Substation SCADA – main and alternative SCADA paths - Control and monitor voltages, currents, frequency, active and reactive power, system alarms and events.
- Control and monitor network elements – feeders, transformers and reactive plant.
- Automatic Voltage Regulation (AVR) and Emergency Voltage Regulation (EVR).
- Autoreclose – Single Pole (SPAR) and Three Poles Autoreclose (TPAR).
- Control and regulate network voltages.
- Power systems voltage and frequency control.
- Generator Automatic Governor Control (AGC) SCADA link to the Australian Energy Market Operator (AEMO).
- Power measurement and monitoring such as Harmonics and Negative Phase Sequence, Synchro-phasors, Power Oscillation Damping (POD), Transient Recorders and Fault Recorders.

The secondary systems asset risk, cost and performance referred to in this paper are only at the equipment and sub-system level, i.e. not at bay, substation or network level.

4.1 Powerlink Secondary Systems Asset Performance – Risk, Cost and Performance

The secondary system assets discussed in this paper are the financial assets associated with a substation switching bay or a transmission network element. Each secondary system asset consists of a number of equipment (e.g. control and protection equipment) integrated to provide control, protection, SCADA and monitoring functions to the power system, and network elements such as transmission lines, power transformers and reactive plants (SVCs, capacitors and reactors). Based on an analysis of 16 years of historical fault data and application of the new secondary system asset risk model, it was found that:

- The reliability and availability of secondary system assets do not correlate well with the average secondary systems' asset physical age. However, there is a very close relationship between ageing equipment and increased component failures, extended functional failure duration and decreased secondary systems availability and reliability.

- The performance, i.e. reliability and availability, of secondary system equipment is not linear with the physical age of the equipment. Electronic and microprocessor based equipment installed in a clean air conditioned environment have a very high availability during the first ten years then it gradually declines from ten to fifteen years and rapidly reduces after that at a doubling rate as shown in Figure 2.
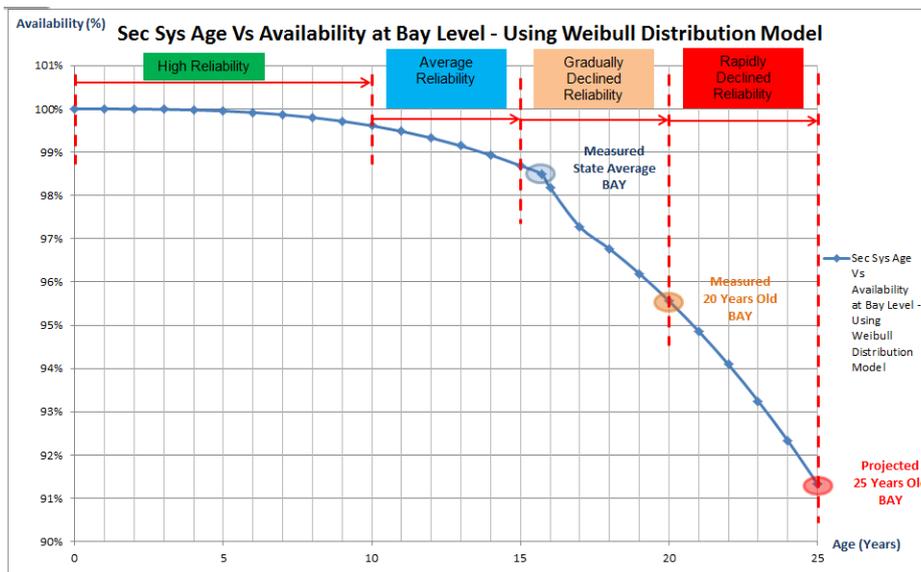

Figure 2 - Secondary System Age Vs Availability at Bay Level – Weibull 2 Parameters Distribution Model

- The sharp decline of functional availability after 15 years of service is primarily due to equipment, software and firmware obsolescence issues. For example: A failure of a protection relay beyond this time generally means that a direct replacement is not available and that some degree of re-design or re-engineering is required to install an alternative relay. The older the relay the more likely it will require a substantial re-design of the protection system, including changes at the remote end. This is what drives the substantial increase in expected outage duration as secondary systems age. The secondary system functional outage duration is plotted against the equipment age profile as shown in Figure 3.

- The secondary system asset risk model projects that by increasing the Mean Replacement Age of approximately six percent (6%) of total installed assets from 20 years to 25 years, the yearly secondary system maintenance cost increases by 19.4%. The functional availability of the extended replacement age assets reduces from 95.5% to 91.3%.

- The network risk, availability and reliability are directly affected by the increase of secondary systems functional downtime, which is directly linked to the equipment obsolescence issues and

the effective age taking into account the operating environmental conditions such as dust, humidity and temperature.

- The use of average asset ages to assess secondary system reliability, availability and network risk assessment can lead to inefficient risk mitigation and reinvestment decisions. For example: the secondary system asset of a feeder bay comprised of 20 years old bay control unit, one year old X protection relay (e.g. recently replaced as part of remote end replacement) and ten years old Y protection relays. The average asset age is 10.3 years and in theory the reliability and availability of the secondary systems should be high or very high. However, in practice the bay control unit has already reached the rapid decline of functional reliability and availability. Therefore, the overall reliability and availability of the secondary system asset for the bay is low due to poor performance of the bay control unit.

- Extending the replacement age of secondary systems beyond the optimal replacement timeframe will result in lower secondary systems functional availability and reliability, and higher maintenance costs. However, it does not directly translate to higher forced outages of network elements, but increased network and compliance risks due to extended functional failure duration of secondary systems. It implies that secondary systems fail to meet the minimum acceptable reliability and availability standards required to support the network under all network conditions.
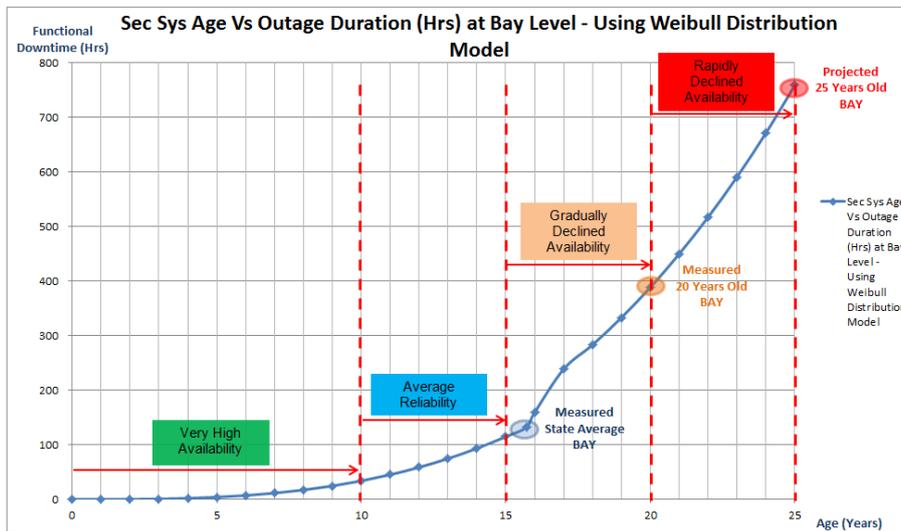

Figure 3 - Secondary System Age Vs Outage Duration (Hrs) at Bay Level - Weibull 2 Parameters Distribution Model

4.2   Secondary System Exposure Factor and Risk Model Components

For secondary system assets, the exposure factors represent the probability of equipment functional failures that lead to an adverse network risk event occurring. The ten year average probability of secondary system equipment failures that result in forced network element outage is 2.36% (excluding human error). This is defined as the secondary system equipment exposure factor. Statistically, it means that for every secondary system functional failure event there is 2.36% chance that it will result in a network element outage event.

The risk cost provides a measure of the expected or long term equivalent cost associated with the risk event over a defined period of time. The risk cost is defined as the probability weighted cost of the consequence associated with the risk event. The risk cost is defined as:

Risk Cost = Likelihood of Failure (LOF) x Consequence of Failure (COF)

The quantitative risk model requires that both the likelihood of failure (LoF) and consequence of failure (CoF) be calculated. This section outlines the method used to determine these values.

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The likelihood of failure (**LoF**) comprises two components – the **probability of failure** and the **exposure factors**.

4.2.1 Secondary System Equipment Probability of Failure

The probability of secondary system equipment functional failure is defined according to [1] based on the equipment functional failures captured in an enterprise asset management system. An exponential distribution function has been used to calculate the equipment failure rate from field data and the results must be interpreted statistically [3] and moderated against the operating environmental conditions and network element outage events (Forced Outages Data - FOD). The Secondary System Equipment Functional Failure Rate can be calculated:

$$\lambda = \frac{r}{T_a} \tag{1}$$

r   Number of failures

$T_a = \sum_{i=1}^{n} t_i$ Accumulated operating time when failed items are replaced (or functional failures are

                 resolved)

n   Number of units in service, or items under test (at the beginning)

t   Operating time of each unit in service or in Time (at the beginning)

4.2.2 Consequence of Failure (CoF)

Depending on the value framework of each organisation, there may be a range of consequences associated with a risk event, including financial, stakeholder, safety, network and environmental impacts. Powerlink examines the consequences of failure in accordance with the categories outlined within its Corporate Risk Framework. These categories include: Financial, Legal and Compliance, Stakeholder, Projects, Network Operations, Safety, and Environmental.

4.2.3 Assigning Costs to Consequences

Under a quantitative risk assessment framework, it is necessary to assign financial costs to consequences. The Powerlink corporate risk framework assigns dollar values for the financial and contractual category of consequence. These same costs have been extrapolated and are used as a basis of equivalence for the other consequence categories, such as safety, stakeholder, network and environment.

These costs are not considered to be calibrated to the expected cost of safety, stakeholder, network and environmental events, but are a proxy for the relative impact of each consequence. This is appropriate as Powerlink's quantitative risk framework is used to describe the relative levels of risk across different assets in order to inform the priority of asset reinvestments. It is not used as an economic decision-making framework.

Table 1 – Corporate Risk Matrix Consequence Scale

Consequence	Description	Range	Cost
7	Catastrophic	> $80M	$225M
6	Extreme	$15M to $80M	$45M
5	Major	$3M to $15M	$9M
4	Moderate	$600K to $3M	$1.8M
3	Minor	$120K to $600M	$360K
2	Insignificant	$30K to $120K	$72K
1	Negligible	< $30K	$14.4K

4.2.3.1 Network Consequences

A quantitative approach for assessing network consequences associated with transmission element outages needs to consider a number of factors. One primary network consideration is the potential for

interruption of customer supply, however there are other impacts including transmission system congestion which can impact on the efficient operation of the National Electricity Market (NEM), disconnection of generating units from the grid, and delays to planned project and maintenance works.

A quantitative model for interruption of customer supply can be developed by examining the Unserved Energy (USE) and Load at Risk (LAR) components. The Unserved Energy (USE) component is assessed by examining the expected magnitude of lost load, the duration of the outage, and the value of customer reliability. When calculating the expected loss of load over the year, it is usually necessary to include an additional factor to account for changes in load profile (load factor).

The Unserved Energy (USE) component is:
USE Component ($) = Load Factor (%) x Magnitude of Lost Load (MW) x Restoration Time (Hours) x Value of Customer Reliability ($/MWh).

The restoration time may be the duration for Network Operations to restore load through switching and/or network reconfiguration. Where it is not possible to restore load through switching, the restoration time may need to represent the time to replace failed equipment.

The Value of Customer Reliability (VCR) represents the value that different types of customers place on reliable electricity supply. For example, industrial customers may place a higher value on network reliability than residential customers. The Australian Energy Market Operator (AEMO) conducts surveys of customers to determine VCR across different customer categories and locations. Further information is available on their web-site (www.aemo.com.au). The VCR for a particular connection point can be estimated by taking the weighted average of the VCRs for the different customer categories supplied by that connection point.

The Load at Risk (LAR) component is calculated by determining the expected loss of load under prior outage or subsequent network contingency conditions. The probabilities of these occurrences need to be estimated for these models.

LAR Component ($) = Co-incidental Network Outage (%) x Load Factor (%) x Load at Risk (MW) x Restoration Time (Hours) x Value of Customer Reliability ($/MWh).

The network consequence may also need to incorporate the impact of outages on the efficient operation of the National Electricity Market. Network constraints arising from element outages can result in an economic cost to consumers, since higher cost generating plant may need to be dispatched to replace constrained off generating sources. These impacts can be difficult to quantify for highly meshed grids with multiple sources of generation, and market simulation models may need to be considered.

This method only considers the consequence from a protection failure that results in tripping. It does not consider other potential consequences such as a failure that may result in an element being directed to be switched off due to having protection out of service for too long or a hidden failure that results in ineffective protection. As such the results may be viewed as conservative.

4.2.4   Equipment Condition Scores (Health Indices), Effective Age and Replacement Age

The failure rate and reliability of electronic equipment in electrical substations depend on factors such as physical age, duration of voltage and current stresses, temperature, humidity and air pollution. The Two Parameter Weibull probability distribution, shown in equation (2), has been adopted to calculate equipment health indices based on functional failures. The equipment effective age can be estimated from the health index taking operating environmental conditions into account. In the absence of field data to accurately model the deterioration of electronic equipment due to temperature, humidity and air pollution, a linear model was used to calculate equipment effective age from condition scores based on the environmental conditions as shown in Figure 4. This linear model should be further reviewed and recalibrated in the future when sufficient environmental data can be obtained.

$$f(t,\beta,\eta) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{1}{\eta}\right)^{\beta}} \qquad (2)$$

β   Is the Shape Parameter (or Slope). β = 4 to reflect higher increase of functional failure rate for equipment that has been in service for 20 years or more.

η   Is the Scale Parameter or Equipment Characteristic.

The Distribution Function has been modelled to reflect the field data obtained from fault notifications, work orders and equipment repair registers over the last 16 years. Equation (2) has been simplified as:

$$\text{Equipment Failure Rate} = \lambda = 3.923333 \times 10^{-4} \times (t)^3 \qquad (3)$$

t   Is the Predicted Condition Score (or Health Index) of the equipment [0-10] = [Best – Worst]

$$Condition\_Score = Health\_Index = t = 13.659923 \times \sqrt[3]{\lambda} \qquad (4)$$
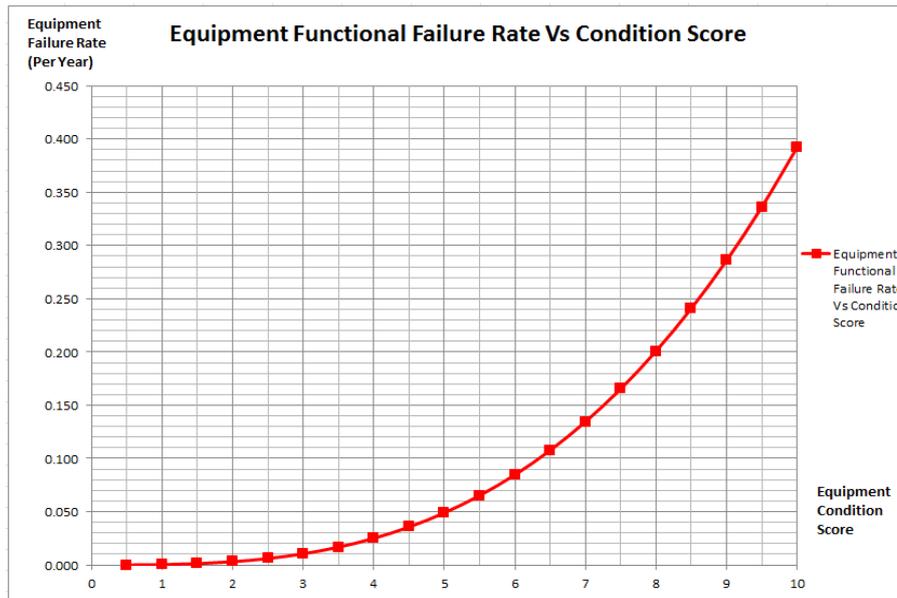

Figure 4 – Equipment Functional Failure Rate Vs Condition Scores

Based on the Condition Score of the equipment in the current year and taking into account the Operating Environment, the Effective Age in the current year can be calculated in Table 2 and illustrated in Figure 5 below.

**Table 2 –Effective Age of Secondary System Equipment Based on
Current Year Condition Score and Operating Environment**

Operating Environment		Effective Age of Secondary System Equipment	
Air Condition	Dust	20 Years Lifespan Equipment	10 Years Lifespan Equipment
Yes	No	$T_{Effective\_Age} = 2 \times t_{Condition\_Score}$	$T_{Effective\_Age} = t_{Condition\_Score}$
Yes	Yes	$T_{Effective\_Age} = \dfrac{20}{8.5} \times t_{Condition\_Score}$	$T_{Effective\_Age} = \dfrac{10}{8.5} \times t_{Condition\_Score}$
No	No	$T_{Effective\_Age} = \dfrac{20}{6.5} \times t_{Condition\_Score}$	$T_{Effective\_Age} = \dfrac{10}{6.5} \times t_{Condition\_Score}$
No	Yes	$T_{Effective\_Age} = \dfrac{20}{5} \times t_{Condition\_Score}$	$T_{Effective\_Age} = 2 \times t_{Condition\_Score}$

The condition scores of the equipment in the future years can be projected based on the age of the equipment and the environmental conditions in the future years as shown in Table 3 below.
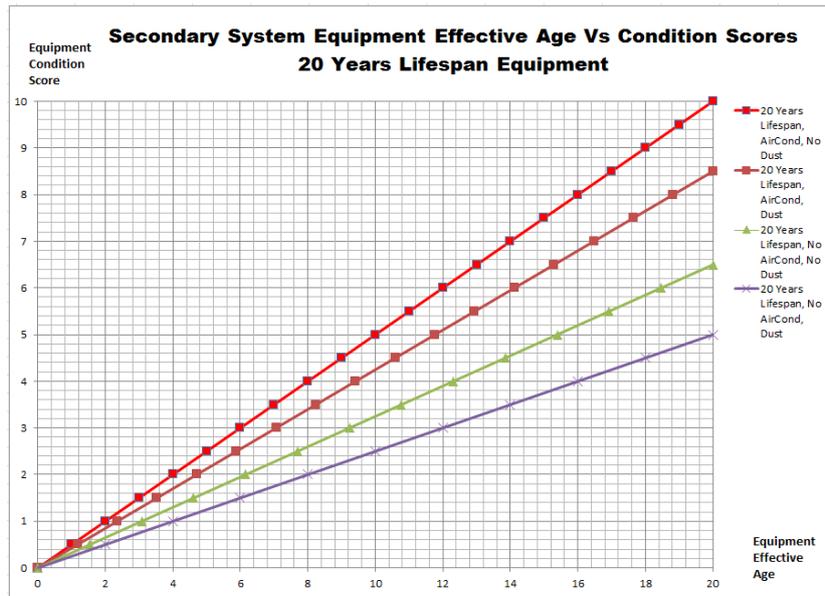
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Figure 5 – Equipment Condition Scores Vs Effective Age – 20 Years Lifespan Equipment

Table 3 – Future Year Condition Score based on Future Age of Secondary System Equipment and Operating Environment

Operating Environment		Effective Age of Secondary System Equipment $$t_{HI\_Yr(x)} = \frac{Max\_HI \times T_{Eff\_Age\_Yr(x)}}{LifeSpan \times (1 - Reduction\_Factor)}$$		Reduction Factor
Air Condition	**Dust**	**20 Years Lifespan**	**10 Years Lifespan**	
Yes	No	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{20}$	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{10}$	0%
Yes	Yes	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{2 \times 8.5}$	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{8.5}$	15%
No	No	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{2 \times 6.5}$	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{6.5}$	35%
No	Yes	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{2 \times 5}$	$t_{HI\_Yr(x)} = \dfrac{10 \times T_{Eff\_Age\_Yr(x)}}{5}$	50%

5   Conclusion

Powerlink has adopted asset management strategies to overcome challenges and deliver reliable and affordable transmission services that are valued by customers, consumers and shareholders. These strategies include assessment of the enduring need for network assets and associated equipment. The Quantitative Asset Risk Framework provides a solid foundation for quantifying asset risks using standardised engineering methodologies to model network, asset and equipment risks.   The optimal replacement timeframes for secondary systems assets have been modelled based on risk, cost and performance.   This model has been used to calculate the reliability, availability, health index, effective age and optimal replacement timeframe of all secondary system assets and equipment in the network. This model also enables Powerlink to quantify the trade-off between reinvestment cost versus availability and reliability for secondary systems.

Delaying replacement of secondary systems assets beyond the optimal replacement time frame does not always necessarily result in higher mal-tripping of network elements, but definitely lowers

secondary systems availability and reliability. It is important to note that not every functional failure will necessarily result in an outage to a network element, but it does represent the loss of some of the normal functions of the protection and control system[1] and can contribute to forced outage events of network elements. This model projects that the effect of extending the mean replacement age of secondary system assets from 20 years to 25 years is a near doubling of the annual duration of secondary systems outages due to functional failures. In addition, by increasing the mean replacement age of 6% of secondary system assets from 20 to 25 years, the yearly operation and maintenance cost for secondary system assets is expected to increase by almost 20% without considering the additional demands on field staff resources. The conclusion is based on Powerlink data and is a direct reflection of Powerlink's environment, including the types of relays purchased, the conditions in which they are installed, the maintenance regime used, and the quantity of spares held.

The significant decrease of system functional availability and reliability coupled with forced network element outages for extended periods of time increases the risk that such failures will occur coincidently with other network events, whether planned or unplanned, and result in reduced reliability outcomes for consumers. Optimal secondary system replacement ages and the associated costs must be evaluated taking into account minimum acceptable equipment reliability, network performance, and other risks across the transmission system.

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[1] *The functions that could be unavailable include auto-reclose, automatic voltage control, emergency voltage control, protection signalling, SCADA, remote control or others.*