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Cost-Effective Design and Maintenance of Timber Power Distribution Poles in a Changing Climate

Paraic C. Ryan
Research Academic, Centre for Infrastructure Performance and Reliability, The University of Newcastle, Australia

Mark G. Stewart
Professor and Director, Centre for Infrastructure Performance and Reliability, The University of Newcastle, Australia

Nathan Spencer
URI Engineering Pty Ltd, Australia

ABSTRACT:
There are approximately five million timber power distribution poles in service across Australia worth over $10 billion. Investment in timber power pole infrastructure is even greater in the United States, with an estimated 120 to 200 million U.S. treated poles currently in service. Despite the scale of timber power pole infrastructure assets worldwide, limited research has been carried out to better enhance network maintenance and management efficiency. This paper sets out to examine the structural reliability and performance of timber power pole networks under current and future climatic conditions. The hazards of interest are storm winds and timber decay - both of which may worsen due to a changing climate. The paper presents a case study for Brisbane, Australia, which examines the possible impacts of climate change on power distribution infrastructure. Monte-Carlo stochastic methods were utilised in the form of an event-based sequential model to estimate the climate change impacts over a period from 2015 to 2070, under various climate change scenarios. It was found that predicted climate change impacts are significant, with the analysis indicating that annual pole failures rates could increase by up to 97% under the most severe climate change scenario. The appropriateness of two climate adaptation strategies is also examined herein, via a probabilistic cost-benefit analysis. These adaptation strategies incorporate alterations to power pole design and network maintenance procedures. The analysis indicates that measured changes to design and maintenance procedures can result in cost-effective climate adaptation strategies, leading to a notable reduction in potential climate change risks.

1. INTRODUCTION

The latest International Panel on Climate Change Assessment Report (IPCC AR5) has stated that warming of the climate system is unequivocal, with many of the observed changes since the 1950s unprecedented over decades to millennia (IPCC 2013). These observed changes in climate, and perhaps more importantly projected future changes, may lead to increased risk to human life and infrastructure. One of the key means of dealing with increased climate change related risk is implementation of effective climate change adaptation strategies e.g. Stewart and Deng (2014). The work presented in this paper sets out a probabilistic framework for analysis of climate change impacts on power distribution infrastructure, and assessment of the effectiveness of different climate adaptation strategies for power pole networks. To date very few studies have employed probabilistic methods to assess possible changes in timber power pole infrastructure performance due to climate change. Existing publications in this area are limited to the work of Bjarnadottir et al. (2013). This is somewhat surprising given the International scientific community's predictions about future climate (IPCC 2013), and the scale and value of timber power pole networks worldwide. For instance, there are an estimated 120 million to 200 million treated timber poles in service in the United States (Bolin and Smith 2011) and over five million timber power poles in Australia, which have a net worth of over $10 billion (Crews and Horrigan 2000). The work described herein builds on the existing literature through i) consideration of the effect of climate change on both wind loading and on timber deterioration rates of power distribution infrastructure, and ii) incorporation of network maintenance into the probabilistic analysis, an important consideration when attempting to realistically model power pole vulnerability in a working power network over time (Ryan et al. 2014).

The framework developed herein uses Monte Carlo simulation in the analysis of structural reliability of poles, allowing climate change uncertainty to be incorporated into the assessment, together with the other forms of uncertainty associated with structural reliability modelling of infrastructure elements over time. It is widely recognised that such probabilistic methods are the most appropriate tool for the representation of processes which have high levels of uncertainty (Ryan and O'Connor 2013), and examination of infrastructure networks which have high variability among network elements (Ryan et al. 2014; Vu and Stewart 2000). The probabilistic approach utilised in this study is event-based sequential modelling. The following section of this paper presents the assessment methodology. Subsequently, a case study is presented which examines climate change impacts and the cost effectiveness of climate adaptation stratagies for a notional timber power pole network in Brisbane, Australia.

2. ASSESSMENT METHODOLOGY

The basis for the model used has been developed in detail in a previous paper by Ryan et al. (2014), which examined the existing risk to power poles without considering climate change effects. This section presents a brief description of the model, with a focus on how predicted climate change is incorporated into the assessment. The reader is referred to the previous paper for more detailed discussion on the model development and probabilistic model parameter selection (Ryan et al. 2014).

A structural reliability assessment requires consideration of structural resistance of the element being considered (R), and the load the element is subjected to (S), in order to calculate the probability of a given failure event. In the case of power distribution pole networks the load and resistance are time-dependent, especially when considering the possible effects of climate change over a period of 50 to 100 years. For the study herein the limit state failure event is defined as the bending failure of a power pole under wind loading, the most common failure mode for timber power poles (Winkler et al. 2010). Consequently, the time-dependent resistance, ($R(t)$), will be the bending resistance of a power pole in a network at a given time t. The time-dependent load, ($S(t)$), will be the annual maximum wind load at year t.

2.1. *Sequential Event-Based Modelling*

The sequential event-based modelling approach used herein allows power pole network performance over time to be assessed, considering both maintenance and climate change effects. The uncertainty and variability associated with a) climate change predictions, b) structural capacity, c) structural loading, and d) deterioration with time are incorporated in the analysis. The sequential aspect of the model relates to the fact that each Monte Carlo iteration runs on a year-by-year basis from the year 2015 to 2070. Each yearly step includes; calculation of $R(t)$ and $S(t)$, accounting for climate change effects on deterioration and wind load, in addition to simulation of network maintenance if appropriate. This time-dependent modelling approach simulates the actual stochastic behaviour of the system over time, thus creating "an artificial history" of infrastructure network performance. The event-based aspect of the probabilistic model refers to the fact that the occurrence of certain events over the monitoring period can influence the course of a given sequential Monte Carlo simulation. The two key events which can occur are a) violation of the limit state, whereby the annual wind load exceeds the deteriorated pole capacity and the pole fails, and b) the condemning of a pole as a result of the network inspections and maintenance programme. Upon occurrence of a wind failure or the condemning of a pole, the pole in question is replaced by a new pole in the Monte Carlo simulation. This pole is assigned new properties generated from the appropriate distributions i.e. pole diameter, pole bending strength, sapwood depth etc. The process of deterioration then restarts for this new pole, and the sequential Monte Carlo process continues for the iteration in question up to the year 2070. This sequential event-based approach means that, in effect, each Monte Carlo iteration represents one pole location in a network of poles, whereby if this pole fails at a given location it must be replaced to prevent a break in the power supply system.

2.2. Time Dependent Load and Resistance

The initial bending resistance (*R(0)*) of a timber power pole at time $t = 0$ can be represented based on established bending theory as follows;

$$R\ (0) = f_b\ .\ {\pi . D^3}\Big/{32} \qquad (1)$$

where f_b is the bending strength of the timber, and D is the ground line diameter of the distribution pole. It is noted however that this initial bending resistance (*R(0)*), will tell us little about the performance of timber power poles in service, which undergo significant deterioration over their service life. Thus, for timber power pole networks, as with any infrastructure network analysis, infrastructure element deterioration must be incorporated into the probabilistic model. Timber deterioration was incorporated herein based on the work of Wang et al. (2008), who developed a timber decay model based on 35 years of field data for 77 timber species. The Wang et al. model represents decay progress as an idealised bilinear relationship, characterised by a decay lag time, t_{lag} (years), and a decay rate, r (mm/yr). These r and t_{lag} values can be calculated as;

$$r = k_{wood}\ .\ k_{climate} \qquad (2)$$

$$t_{lag} = 5.5 r^{-0.95} \qquad (3)$$

where k_{wood} is the wood parameter and $k_{climate}$ is the climate parameter. The Wang et al. (2008) publication provides formulas for k_{wood} for both hardwood and softwood timber which relate to the durability class of the timber and the section of the timber cross section being considered, in addition to providing adjustments for treated timbers. The uncertainty associated with the decay model is incorporated using a model error factor for decay, ME_{decay} (Wang et al. 2008). Of primary interest, however, in the context of the effects of climate change, is the $k_{climate}$ parameter. This parameter value is determined based on annual average temperature and yearly rainfall at the location considered. As shown by Wang and Wang (2012) the influence of climate change predictions on this parameter can significantly affect the rate of timber deterioration. Predicted changes in temperature and rainfall to the year 2070 (CSIRO 2007) were incorporated into the calculation of the $k_{climate}$ parameter herein. This allowed the effects of predicted climate change on deterioration, and the resulting time dependent resistance (*R(t)*), to be considered in the analysis.

2.3. Time Dependent Wind Loading

Possible changes in wind speed are an important consideration for power distribution infrastructure as increases or decreases in the annual maximum wind speed will reduce or increase the reliability performance of power pole infrastructure, respectively. The wind field for the case study location in this paper (the

Queensland capital city, Brisbane) is dominated by non-cyclonic synoptic weather systems. These non-cyclonic gust wind speeds are modelled using the Gumbel distribution, with the annual maximum non-cyclonic peak gust speed as follows (Wang et al. 2013);

$$F(v) = e^{-A} \text{where } A = e^{-\left(\frac{v-v_g}{\sigma_g}\right)} \tag{4}$$

where v_g and σ_g are the location and scale parameters for the Gumbel distribution. Values for these location and scale parameters for a range of locations in Australia have been developed by Wang et al. (2013) based on data recorded from 1939 to 2007. Thus, this wind field does not account for the possible future reductions or increases in wind field magnitude due to climate change. A modification to Eqn. (4) has been suggested by Stewart (2014) to allow climate change related effects to be incorporated into the Gumbel distribution. Eqn. (4) thus becomes;

$$F(v) = e^{-A} \text{where} \quad A = e^{-\frac{\left(\frac{v}{1+\frac{\gamma_{mean}(t)}{100}}\right)-v_g}{\sigma_g}} \tag{5}$$

where $\gamma_{\mathrm{mean}}(t)$ represents the time-dependent percentage change in gust wind speed for a given Monte Carlo simulation. The Wang et al. (2013) statistical parameters for the Gumbel distribution are assumed to reflect pre-climate change wind speeds (i.e. 1990 levels). Having established an expression which probabilistically represents the time-dependent wind speed incorporating climate change, the work of Henderson and Ginger (2007) was used to calculate the time-dependent wind load *S(t)*, as described in Ryan et al. (2014). This model allowed uncertainty and variability to be incorporated into predictions for the wind load on the power poles, conductors etc. for a given wind speed *v*, at a given time *t*. Details of the statistical properties used for the model variables are provided in Table 2.

2.4. *Probabilistic Cost-Benefit Analysis*

The probabilistic cost-benefit analysis was carried out in this study based on a framework developed by Stewart (2014), whereby, the probabilistic Net Present Value (NPV) of a given climate adaptation strategy is:

$$NPV = \sum E(L)\Delta R + \Delta B - C_{adapt} \tag{6}$$

where ΔR is the reduction in risk caused by climate adaptation measures, C_{adapt} is the cost of adaptation measures including opportunity costs that reduces risk by ΔR, ΔB is the expected co-benefit of adaptation such as reduced losses to other hazards, increased energy efficiency of new materials, etc., and E(L) is the 'business as usual' expected loss (risk) given by the following equation:

$$E(L) = \sum \underbrace{Pr(C)\Pr(H|C)}_{\text{HAZARD}} \underbrace{\Pr(D|H)}_{\textit{VULNERABILITY}} \underbrace{\Pr(L|D)}_{\textit{CONSEQUENCES}} \tag{7}$$

where Pr(C) is the annual probability that a specific climate scenario will occur, Pr(H|C) is the annual probability of a climate hazard (wind, heat, etc.) conditional on the climate, Pr(D|H) is the annual probability of infrastructure damage or other undesired effect conditional on the hazard (also known as vulnerability or fragility) for the baseline case of no extra protection (i.e. 'business as usual'), Pr(L|D) is the conditional probability of a loss (economic loss, loss of life, etc.) given occurrence of the damage. The summation sign in Eqn. (7) refers to the number of possible climate scenarios, hazards, damage levels and losses. If the loss refers to a monetary loss, then E(L) represents an economic risk.

3. CASE STUDY DETAILS

A typical Australian power distribution pole layout, as detailed in Ryan et al. (2014) was used for the illustrative example herein. In order to investigate the climate change impacts on structural reliability of a typical newly installed Australian power pole subject to extreme winds, an appropriate pole diameter must be obtained for the pole set-up in accordance with existing

Australian design standards (Standards Australia/New Zealand 2010; Standards Australia/New Zealand 2011). For this case study the power distribution pole was designed for the general case, whereby possible shielding and directional effects were not considered (M_s & M_d = 1.0), and the pole was assumed to be on flat ground in the Brisbane Region of Queensland, Australia. The timber type used for the design was spotted gum, the most popular power pole timber species in South-East Australia. The pole was assumed to be CCA treated in line with current practice in the Australian power industry. Given the timber type and the wind loading conditions a required pole design ground line diameter of 241mm was obtained. The appropriate available pole sizing grade for this design ground line diameter ranges from 250 mm to 295 mm i.e. pole ground line diameter uniformly distributed from 250mm to 295mm. Inspection intervals were set at 5 years, with first inspection at 20 years (Standards Australia/New Zealand 2010). In accordance with common industry practice in Australia, inspection failure, or pole condemning criteria, was set at 50% of original pole capacity based on loss of section modulus (Z), meaning if inspection revealed that the pole moment capacity was less than 50% of the original pole moment capacity the pole failed the inspection and was condemned and replaced.

The climate change predictions used in this paper are the IPCC AR4 predictions for Brisbane, which were published by CSIRO (CSIRO 2007). Three climate change scenarios were considered for the time period from 2015 to 2070, namely; 1) no climate change, 2) B1 (medium) climate change scenario and 3) A1FI (worst) climate change scenario. The IPCC AR4 probabilistic parameters for predicted change to the year 2070 for wind, rainfall and temperature are presented in Table 1 for the B1 and A1FI climate change scenarios. The statistical details for the remaining probabilistic parameters used in the illustrative example are presented in Table 2. Due to space constraints the detailed discussion on the nature, definition, and source of each parameter is not provided herein, but can be found in Ryan et al. (2014). All results presented in this paper are based on one million Monte Carlo simulations, each of which ran from the year 2015 to 2070 in steps of one year.

Table 1. IPCC AR4 predicted climate changes to 2070 for Sydney Region

Parameter	B1 10th P[1]	B1 50th P	B1 90th P	A1FI 10th P	A1FI 50th P	A1FI 90th P
Temperature (°C)	+1.1	+1.6	+2.3	+2.1	+3.1	+4.4
Rainfall (%)	-18	-5	+9	-33	-9	+17
Wind speed (%)	-1	+3	+10	-2	+6	+19

[1] P = Percentile

Table 2. Statistical parameters for probabilistic model

Property	Units	Distribution	Mean	COV
Pole ground line diameter	mm	Uniform (250 - 295)	273	-
Sapwood depth	mm	Uniform (25 – 50)	37.5	-
Corewood depth	Growth rings	Uniform (5-10)	7.5	-
f_b Spotted Gum	MPa	Normal	104.1	0.14
Conductor diameter	mm	Normal	13.5	0.06
Street lighting wire	mm	Normal	9.0	0.06
Pole height	m	Normal	10.7	0.03
High voltage wires	m	Normal	10.95	0.03
Low voltage cables	m	Normal	9.5	0.03
Communication wire height	m	Normal	8.1	0.03
Wind speed (Brisbane, Qld)	m/s	Gumbel	24.276	0.13
ME_w	-	Lognormal	1.00	0.05
ρ_{air}	kg/m^3	Lognormal	1.2	0.02
$M_{z,cat}$	-	Lognormal	0.95	0.10
$C_{d\ pole}$	-	Lognormal	1.2	0.05
$C_{d\ wires}$	-	Lognormal	1.0	0.05
G (poles)	-	Normal	0.96	0.11
G (wires)	-	Normal	0.81	0.11
ME_{decay}^{a} (durability class 2)	-	Lognormal	1.00	0.92

a: ME_{decay} distribution truncated at 10.0

4. CLIMATE CHANGE IMPACTS

Figure 1 presents the cumulative power pole failures due to wind loading over the period of 2015 to 2070, under the three climate change scenarios for the notional network of one million Brisbane poles. Firstly, considering the nature of the output, it is noted that initially the curves are influenced by the age of the poles, and then by the network maintenance actions. As seen in Figure 1, few failures occur in the first 15 years, followed by a steep rise from 15 to 20 years. After this point the annual failure rate (slope of curve) initially drops and then rises to a peak every five years. This cyclical nature of wind failures is due to the influence of the maintenance inspection intervals. The maintenance actions occur at the end of every fifth year, leading to the replacement of the most decayed poles, which are most vulnerable to wind failure. Thus, in the year following the inspection the network is most resilient to wind failure, meaning failure rates are low, while just before inspection wind vulnerability is increased, meaning failure rates are highest.

The predicted impact of climate change on power pole network performance can be observed from Figure 1 and from Table 3, which presents the impact of the climate change scenarios on both wind failures and pole condemnings over the 2015 to 2070 period. Both the B1 and A1FI climate change scenarios result in substantial increases in wind failures, with percentage increases of 60% and 97%, respectively. This is a significant increase when considered in the context of the consequences of power pole wind failures, which range from loss of power to business and homes, to catastrophic wildfire events with significant loss of life and infrastructure. Impact on pole condemning rates, brought about by increased timber decay rates are also substantial at 18% and 23% for the B1 and A1FI scenarios, respectively. Preliminary cost estimates obtained from industry indicate that the typical cost of pole condemning and subsequent replacement is in the region of $7,500, while the typical cost associated with power pole wind failure is thought to be in the region of $60,000. These preliminary costs estimates would indicate that climate change impacts for one million poles in the Brisbane area from 2015 to 2070 could be in the region of $800 million to $1.1 billion, depending on climate change scenario considered. It is noted that as part of the research project under which the study herein was carried out, climate change impacts on timber power pole infrastructure for five Australian cities were examined, with Brisbane found to have the greatest predicted climate change impacts. Melbourne was found to have a very slightly positive climate change impact, illustrating the highly spatially variable nature of climate change impact analysis.

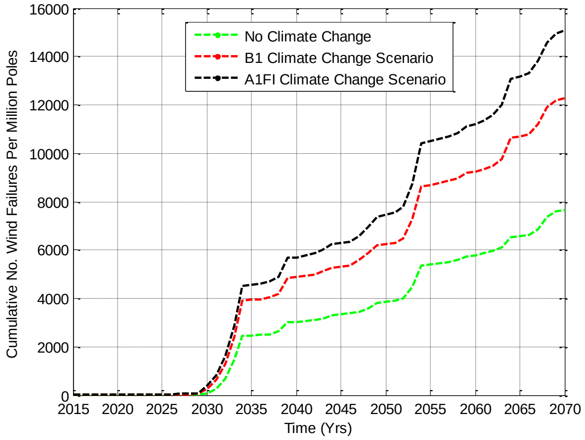

Figure 1. Cumulative power pole failures from 2015 to 2070 for network of one million power poles

Table 3. Impacts of climate change scenarios on power pole wind failures

Climate Change Scenario	Total Wind Failures	% Change in Wind Failures	Total Poles Condemned	% Change in Poles Condemned
No Climate Change	7,671	_	388,074	_
B1 Scenario	12,260	+ 60%	458,172	+ 18%
A1FI Scenario	15,075	+ 97%	478,805	+ 23%

5. COST EFFECTIVENESS OF CLIMATE ADAPTATION STRATAGIES

Research is ongoing at the University of Newcastle to assess the cost effectiveness of a number of climate adaptation strategies using probabilistic cost-benefit analysis. This section presents preliminary probabilistic cost-benefit analysis results for two climate adaptation strategies. It is noted however that the direct and indirect costs used in this analysis were approximated based on the experience of industry partners. Further work is required to develop more robust statistical parameters for the direct and indirect costs associated with power pole failure, and the direct costs associated with pole inspections and scheduled pole replacements. Consequently, the results presented in this section should be taken as preliminary indications of the appropriateness of the adaptation strategies. The NPV of the adaptation strategies was derived in a probabilistic context using the formulae presented in Section 2.4, though comparison with the "business as usual" case. The results for Brisbane, Australia under the A1FI climate change scenario are presented herein. A discount rate of 4% was used for the illustrative example. The "business as usual" case and the adaptation strategies, which are a mix of design and network maintenance alterations, are as follows:

- Business as Usual (BAU): Pole diameter design in accordance with AS/NZS standards, inspection intervals set at 5 years, and pole condemning criteria set at 50% of original pole capacity
- Adaptation Strategy 1: Same as BAU with exception that pole condemning criteria increased to 60% of original capacity. This means that poles are replaced at an earlier stage of deterioration, reducing the vulnerability of the network to power pole wind failures.
- Adaptation Strategy 2: Same as BAU with exceptions that both original poles and replacement poles are one size grade larger than required under the existing AS/NZS design procedure, and pole condemning criteria is reduced to 45%.

Values for the 10th percentile NPV, mean NPV and 90th percentile NPV are presented for each adaptation strategy in Table 4. These preliminary results indicate that Adaptation Strategy 1 (increasing pole condemning criteria) is unlikely to be cost effective. This strategy reduced wind failures to 115% of failures under the no change scenario, however this came at a cost of a 27% increase in pole condemning rates. The results did however indicate that Adaptation Strategy 2 would be cost effective, with a mean NPV of $263 per pole i.e. $263 million for the pole network. This option reduced annual pole failure rates to within 11% of no climate change condition, and reduced pole condemning rates to 93% of those under current climactic conditions. Although, these reductions came at the expense associated with increasing pole size, the notable reductions in pole failures and condemnings mean the strategy is likely to be cost effective. As previously mentioned however, further work is required in the area to establish more robust statistical parameters for costs.

Table 4. Effectiveness of climate adaptation strategies for A1FI climate change scenario

Climate Adaptation Strategy	10th Percentile NPV per pole ($)	Mean NPV per pole ($)	90th Percentile NPV per pole ($)
Strategy 1	-1066	-243	0
Strategy 2	-154	+263	+924

6. CONCLUSIONS

A probabilistic event-based sequential model has been developed herein to facilitate assessment of the impacts of predicted future climate change effects on the performance of power distribution infrastructure. A case study has also been presented which utilised the model developed to assess the possible climate change related implications for power distribution infrastructure in the Brisbane region of Australia. The assessment indicated that the impacts of climate change to the year 2070 on power pole network performance for Brisbane, Australia are likely to be significant. Wind failure rates were predicted to increase by 60% and 97% as a result of the B1 and A1FI climate change scenarios, respectively. This could have a large societal impact, given the consequences of power pole failure, which range from loss of power, to loss of life. Pole condemning rates were also predicted to notably increase under the B1 and A1FI climate change scenarios. A preliminary cost-benefit analysis, aimed at examining the appropriateness of climate adaptation strategies, indicated that measured adjustments to design and management procedures can be used to develop cost-effective climate adaptation strategies, helping to mitigate the negative effects of climate change on power pole infrastructure performance.

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