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A practical approach to electricity network hardening decisions

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Abstract: Bushfires destroy wooden power poles with a probability that varies principally with wood species, fire intensity, and fuel load. The destruction of a pole cuts the electricity supply to dependent customers. Electricity supply can be maintained when fires impact powerlines if wooden poles are replaced by non-combustible poles. However, replacing wooden poles before they reach the end of their life brings additional costs to networks and consumers. The selection of which wooden poles to proactively replace is primarily a tradeoff between gains in electricity supply reliability and the costs of proactive replacement. We consider the problem of optimizing the proactive replacement of wooden poles to improve supply reliability, from a mathematical perspective and in the reality of Australia's regulated electricity system.

Keywords: *Electricity networks, wildfire, wildfire simulation, combinatorial optimization*

1 INTRODUCTION

Rural electricity distribution networks are radial. Distribution powerlines ("feeders") extend outwards from facilities known as zone sub-stations. Feeders branch at various points to cover customer locations, and in sparsely populated regions can extend up to 600km in total length. Zone sub-stations are connected by sub-transmission lines to terminal stations on the national grid. Few rural customers can be reached via more than one distribution system path, meaning that the distribution system has no redundancy from most customers' perspectives. Feeders are formed into sections by fault-detecting and isolating devices. If a pole within a section succumbs to fire, then customers from the previous isolating device back to the zone sub-station will remain supplied. In contrast, all customers from the device onwards will lose supply until the network is repaired. Our focus here is on the Powercor electricity distribution network in the western half of Victoria. In collaboration with Powercor and Blunomy, we have addressed the proactive replacement of wooden poles. The results were used in seeking regulatory approval for a pilot program involving 1576 wooden poles, see pp. 64 in Powercor (2025). Overall, there are about 1200 sections and 197,000 poles with bushfire relevance within Western Victoria.

Australian hardwood power pole survivability in wildfires is not well documented in the literature. Some studies address the occurrence of wildfires that are caused by pole breakage due to wind loading (Mitchell, 2013), but this is the inverse of our focus here. Proprietary information is held by electricity businesses in Australia. The loss rate of wooden poles in forested areas approached 50% in NSW during the Black Summer 2020 fires, whereas fibreglass and concrete poles almost universally survived. In predominantly grassland fires in the central west of Victoria between January and March 2024 (impacting in excess of 29,000 Ha), the average chance of wooden pole destruction was approximately 5%. Bushfire reconstruction and data analysis relating to this period indicate that the probability of a pole succumbing to fire impact can be explained by factors such as pole material, fuel load, and the estimated fireline intensity. Under severe grassfire conditions (fireline intensities near 10 MW/m), the rate of wooden pole loss was around 15%.

Bushfires propagate over the landscape under the influence of wind, terrain, and the availability and structure of vegetation fuel. When a fire impacts a feeder, it will make contact with one or more sections, depending on how the fire evolves under these conditions. Some fires might only contact one or a few sections, while others might visit nearly every pole on a feeder. Pole destruction is not assured when a fire visits. The combination of probabilistic fire outcomes, radial section dependence, and fire footprint variability makes optimization of pole proactive replacement challenging.

2 SIMULATIONS

The generation of data for pole replacement prioritization requires bushfire simulations and statistical experiments. For Western Victoria, 6.1 million bushfire simulations were executed using CSIRO Spark, each covering 18 simulated hours of fire event. Each simulation has one of 88,300 fire ignition locations in at least 2Ha of burnable vegetation, and spaced at most 1.5km apart. On average, 76 different weather streams were run for each ignition location. These streams provided 30-minute resolution time series data on wind, temperature, and humidity, which were extracted from historical records. Each weather stream represented a unique combination of fire danger rating, wind direction, and wind speed. For every simulation, predicted fire arrival times and intensity data were obtained at a spatial resolution of 30 metres. Further processing of the outputs to account for potential firefighting successes, informed by the findings of Plucinski et al. (2023), expanded the corpus of simulations to 15 million members. Annual probabilities of occurrence were computed for each member for epochs up until 2060 under two climate scenarios: RCP4.5 and RCP8.5. This provides a comprehensive dataset on bushfire possibilities in Western Victoria.

A mapping of simulation j to the pole locations it impacts was formed, and the fuel load and fireline intensity were recorded. We conducted 100 Monte Carlo (MC) simulations of each fire j that impacts the electricity network. Within each MC simulation, the loss or survival of each individual pole was determined by sampling from the aforementioned pole loss probability function. The resulting state of each section was recorded as either intact (supply maintained) or damaged (supply cut). From the 100 MC simulations (for each of 15 million simulated fires), we gain an estimate of the probability of each section s being damaged while no dependent sections are damaged, $p^0_{s,j}$, and where s and at least one of its dependent sections is damaged, $p^1_{s,j}$.

3 OPTIMAL AND PRACTICAL APPROACHES TO DECISIONS

We can formulate an optimization problem where we select a subset of sections to "harden" (replace wooden poles) to maximize the Net Present Value (NPV) of reliability gains minus capital costs over a planning horizon. Data regarding the gains and costs can be pre-computed for each section. All of the potential reliability gains for a given section are only realized if all the sections it depends upon are also hardened; otherwise, only partial hardening gains can be realized. In a mathematical programming context, evaluating these conditional gains requires a set of constraints that grows exponentially with the number of sections in the feeders.

Model transparency, repeatability, and interpretability are crucial in the real world of electricity businesses, consumers and regulators. Decisions are made in a hierarchical and iterative manner as data is shared among subject matter experts and stakeholders. This process includes review, consultation, and testing of models, allowing them to be scrutinized and challenged. In this context, a black box optimization model is largely incompatible with the multi-stage and multi-party processes, as its outputs can be unintuitive, vary markedly due to minor changes in input data, and be difficult to verify and validate.

When a radial distribution network has no branches and is hardened in one stage from the zone sub-stations outwards, the NPV of hardening a section s can be expressed as $\sum_j r_j \{p^0_{s,j}.V_0 + p^1_{s,j}.V_1\} - C_s$. In this expression, V_0 is the benefit (with annual discounting) of maintaining supply to all customers within section s and beyond for the duration of the planning horizon; V_1 is the corresponding benefit of maintaining supply to the customers in s only; C_s is the discounted excess cost of hardening s before wooden pole end-of-life; and r_j is the likelihood of a fire represented by simulation j occurring during the planning horizon. A Pareto frontier between NPV gains and total expenditure can be formed by progressively selecting sections based on the ratio of NPV to C_s, subject to the zone sub-station outwards hardening rule. This specific algorithm can also be applied heuristically to branching networks with the zone substation outward hardening rule relaxed. This approach is the basis on which Powercor has selected poles and feeders for proactive replacement.

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