Data analytics solutions for asset management of overhead transmission lines

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DATA ANALYTICS SOLUTIONS FOR ASSET MANAGEMENT OF OVERHEAD TRANSMISSION LINES

A Thesis by

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DATA ANALYTICS SOLUTIONS FOR ASSET MANAGEMENT OF OVERHEAD TRANSMISSION LINES

The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Industrial Engineering.

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ABSTRACT

The energy grid relies on a dependable transmission system to traverse electricity across miles through plains, mountains, and cities. The grid is in a continuous state of expansion and older lines are expected to operate for decades longer than their originally anticipated lifespan when they were installed. Each line is exposed to many different environmental modalities that cause the integrity of the line to erode. Animals, fungi, moisture and air, storms, hurricanes, car crashes, and the strain of the loaded lines all affect the transmission line’s states of degradation. Knowing how and when to replace these lines is paramount to keeping a reliable energy system functional. While the transmission system has many components that are required to perform well to keep energy flowing across the lines, there are two parts that have the most detrimental consequences, given their failure. The pole or structure and the conductor are the foundation of the transmission line and require the most attention at their demise. Repairs and replacements are heavily dependent on the budget of the utility company. The goal of this thesis is to develop analytical models that support maintenance and replacement decisions for overhead transmission lines. In collaboration with a local utility company, we develop data-driven and physics-informed predictive models for degradation of overhead transmission conductors due to environmental and operational conditions. Additionally, we develop time-based and condition-based maintenance strategies for treatment and replacement of utility poles under budget limitation using integer programming and Markov decision processes, respectively.

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LIST OF ABBREVIATIONS / NOMENTCLATURE

AC	Alternating Current
ACA/ACZA	Ammonium Copper Arsenate/ Ammonium Copper Zinc Arsenate
ANSI	American National Standards Institute
AWPA	American Wood Protection Association
Btu	British Thermal Units
CCA	Chromated Copper Arsenate
CBM	Condition-Based Maintenance
DER	Distributed Energy Resources
DOE	Department of Energy
EIA	U.S. Energy Information Administration
ERCOT	Electric Reliability Council of Texas
EPA	U.S Environmental Protection Agency
IEEE	Institute of Electrical and Electronics Engineers
IISE	Institute of Industrial and Systems Engineers
ISO	Independent System Operators
MDP	Markov Decision Process
MISO	Midcontinent Independent System Operator
NESC	National Electric Safety Code
OPGW	Optical Ground Wire
RTO	Regional Transmission Organizations
TBM	Time-Based Maintenance

CHAPTER I

INTRODUCTION

ENERGY GRID

The energy grid is one the most complex infrastructures created and is now a necessity for daily life. It links the electricity from the power plants to sockets in a home. The entire energy grid encompasses three main subsystems known as generation, transmission, and distribution. Within an electric power supply system, fuel must be expended to get electricity at a power plant. The electricity is generated as alternating–current (AC) in a 3-phase voltage, however it is inefficient to send this directly to the customer across many miles of cables [1]. Substations operate at the entry and exit of electricity to transmission lines to direct the current and change the voltages. Upon departing the power plant, electricity is stepped up to a high voltage in the tens or hundreds of kilovolts via a transformer in a substation to traverse the many miles of transmission lines. Before exiting into the distribution grid, the energy is transferred back into lower voltages where it will travel shorter distances across smaller conductors into businesses, homes, and other facilities. From household appliances to industrial equipment, there is an expectation of continuous, reliable energy. Only during times of natural disaster, is the electrical grid pardoned to stop operations. Otherwise, there’s a supposition that every time someone plugs a device into a socket it will deliver electricity without fault. This requirement does not leave room for error by utility companies.

This becomes increasingly difficult to maintain when the power grid is undergoing constant and substantial changes. Grid expansion has been rampant among population growth, the electrification of everything, and environmental pressures to increase clean energy. To combat this, the Biden Administration has invested in the Department of Energy's Building a Better Grid Initiative, which secured $13 billion to rehabilitate the energy grid [2]. This investment is in pursuit of the goal for 100% clean electricity by 2035 set by Biden-Harris efforts. It is estimated that the current transmission system needs to expand by 60% before the year 2030 if it is to support the projected demand [2]. The history of energy consumption has seen drastic changes and many more are yet to come.

Different energy resources are measured by various methods due to their physical units so the measure of heat energy, British thermal units (Btu) are a way of standardizing units for comparative analysis. The U.S. Energy Information Administration (EIA) reports in 2000, the amount of energy production in the United States was highest with coal at 22.73 quadrillion Btu then natural gas –19.66, crude oil – 12.36, nuclear – 7.86, renewables – 6.10, and natural gas plant liquids (NGPL) – 2.55 quadrillion Btu [3]. In 2021, the EIA published statistics that showed the changes occurring over the last 20 years and reported in 2020 the energy production in quadrillion Btu was natural gas – 34.72, crude oil – 23.50, renewables – 11.69, coal – 10.70, nuclear – 8.25, NGPL – 6.80. The energy mixture continues to move away from fossil fuels towards sustainable energy sources. Coal production dropped by 53%, while renewable energies saw production almost double. Renewables is a term with a large umbrella encompassing geothermal, solar, wind, hydroelectric, and biomass energy sources. As the leap towards clean energy continues to forge the future of the electricity grid, there needs to be a transmission grid that is built alongside this growth to be able to carry the generated electricity to new and further locations.

One reason for this expansion is due to the fixed locations of several renewable energy sources. Biomass is the largest portion of renewable energy being consumed in the U.S. with 37% being wood, waste, landfill gas, or other biofuels which will likely need to be transferred to a processing facility. Wind energy accounts for the next largest percentage at 29% [3]. However, the wind does not blow steadily, or reliably all year round nor does it blow the same across all regions. There is seasonality to wind as temperatures and pressures change. This resource is usually found in flatlands such as the Great Plains. With an increase in this resource comes the need for supportive materials like the transmission infrastructure to transport high voltages into densely populated areas. Similar scenarios exist with solar, hydroelectric, and geothermal energy sources.

STRAIN DUE TO ENERGY VARIATION

The stress of variability on the energy grid is exacerbated by the increase of microgrids. Microgrids are local energy sources that can store and produce electricity with the intention to function independently from the main grid or with little help. These self-maintained energy networks operate on-site and are used as a back-up measure or full-time depending on their capabilities to supplement energy. When energy bills spike or when the grid becomes unstable, microgrids provide relief. However, the voltage fluctuations caused by distributed generation units can affect the active and reactive power which can produce a quick surge in power [4]. To successfully inject microgrid energy back into the transmission or distribution grid, it needs to be in-sync with the oscillations. This requires a converter to filter in harmonic electricity from the microgrids. The main components of a microgrid are renewable energy resources, distributed generation, point of common coupling, energy storage, and a voltage source inverter. Microgrids produce DC energy while the main grid produces alternating current and therefore requires an inverter to translate the frequency and voltages. Since microgrids are individually owned and operated, there is no way to tell when owners will decide to inject energy into the grid or use energy. This increases the variation in daily load demands, which must be forecasted typically the day ahead. With so many additional concerns for running the energy grid, there needs to be a way for maintenance planning of components to be economical and efficient, so that the increase in complexity is manageable.

ENERGY MARKET STRUCTURE

The two main models of grid optimization are cost minimization and profit maximization. Cost minimization requires centralized operations to decide how servers will interact for a comprehensive total cost reduction. In the profit maximization framework individual producers, retailers, and consumers inform one another’s decisions in the quest to return their own highest profit margin [5]. This leads to two different structures in the market known as bilateral contract framework and pool markets. Bilateral contracted markets operate by retailers and producers settling on an amount of energy over a finite horizon to be purchased. An independent system operator typically mediates the transportation of energy. Within a pool market, producers submit a minimum selling price for their production currency for each hour of the finite timeline. Retailers and consumers submit a maximum buying price with their anticipated demands. This information is collected by a singular market operator and sorted by the requirements of each player to match corresponding prices and quantities of energy for consumers and producers. The pool-market structure is most relevant to the current energy operations, but combinations of these two markets also exist. Within the market producers rely upon historical data to create forecasted models of demand and supply to anticipate appropriate reactions to market prices and demands. These operations change how energy flows across transmission line and impact what the costs will be to have the lines. There must be a positive cash flow to maintain the grid in conjunction with the energy being transported and sold across it.

Energy demand forecasting strives to predict the usages of consumers across the entire grid. There are methods of day-ahead, monthly, quarterly, and annual forecasting. Day-ahead forecasts are important to their self-regulation planning. It has less to do with the market purchase and more to do with optimizing inner operation strategies. Longer-term forecasting relies on monthly and yearly analysis of consumption, supply, and expenses and provides suggestive market price agreements for utility companies, retailers, and larger consumers to make informed bids [5]. To have a successful energy delivery when consumers demand it, forecasting must be cohesive throughout independent distribution system operations, transmission system operations, commercial operators, as well as commercial and technical operators [6]. Each system operator is responsible for numerous causalities that can influence energy quality and must be aligned with the other sectors' operations. Transmission system operators require highly accurate forecasting methods in the short-term for delivering secure power [6]. It is not only important to meet production with demand, but also to optimize the expense rates to deliver such timely, anticipated energy usage.

In the United States during the 1990's the wholesale electricity market underwent a liberalization that deregulated and restructured the way power was priced and bought. Today, there are several wholesale power markets that individually operate the grid and all its components. Some federal systems are also in operation such as the "Bonneville Power Administration, Tennessee Valley Authority, and the Western Area Power Administration" [7]. The remaining consumers in the continental U.S. are serviced by ten separate independent system operators (ISO) or regional transmission organizations (RTO). These include Northwest, California, Southwest, Southwest Power Pool, ERCOT, Midcontinent, New England, New York, PJM, and Southeast. Two-thirds of all the nation's energy load is serviced within regional transmission organizations. Like ISOs the RTOs function independently and have an interconnected market of producers and consumers that offer and bid energy within the transmission system. Each power market has its own grid systems for generation, distribution, and transmission. The electric power market's intention in the U.S. to promote competition within a bid-based market system.

GENERATION AND DISTRIBUTION

Distributed generation and electric vehicles are changing the landscape of the distribution grid. Complications such as "bi-directional flows, high power during peak loads and unpredictability" have increased with the coming technologies [8]. The distribution grid is the final stage of electricity transportation before it reaches the end user such as households, industrial facilities, businesses, and other outlets. It is comprised of poles, conductors, transformers, switch circuits, and protection circuits to deliver and use the energy safely [9]. The role of the distribution grid is to deliver safe and usable voltage, usually between 100-400 volts, apart from the multiple kilovolts transported by transmission lines. The power from transmission lines is stepped down at a distribution substation and from there is sent out at usable voltages. Electrical generation occurs by creating an electrical current, which can then be stepped up in voltage and transmitted across the grid. Nearly all the electricity produced by generators is alternating current. AC is the flow of electrical charges that continuously reverse [10]. The cyclic charge reaches a maximum, then reverses until the equivalent negative value is reached and repeats. Each generation source has its own advantages and disadvantages, which is why most power pools opt for a mixture of resources. Energy resources are produced at different frequencies and quantities. Varying costs, availability, reliability, and capacities dictate how the generated power will meet demand.

IMPACT OF RENEWABLE ENERGY ON THE GRID

The more renewable energy resources operating in the grid, the more unpredictable the resources become. Renewable energy resources including nuclear or hydroelectric are fully used and remaining resources are used to fill the gap between the demand and supply. These various generation sources and facilities can be incredibly far from their consumers while still operating reliably. Hydroelectric dams can provide a large amount of electricity to consumers but have geographic limitations. Similar issues arise not only with clean energy from solar, wind, and nuclear, but also with coal deposits and natural-gas power plants. Wind and solar generators depend upon forecasts and can vary greatly if there are scattered overcast or wind gusts. These energies are manipulated throughout the grid to support a lapse in output. Coal and nuclear power plants take a long time to begin or shutdown, whereas energy like natural gas can quickly fill in a demand gap. The cost of each of these resources is equally variable, but once the infrastructure is running, renewables are always preferred fuel since they come at no cost to produce.

There are numerous environmental benefits to be seen in conjunction with distributed energy integration. Fossil fuel reduction and operational flexibility have increased efficiency for power system stakeholders, however not without consequences to the integrity of the energy grid [11]. Transmission and distribution lines must be able to support a wide variety of generation modes under every foreseen variation without causing damage to equipment or voltaic disruptions to deliver steady energy flow to consumers. Within this balancing act, there are some predictable behaviors on both ends to expect a peak or trough that might disrupt the grid. The degree of variation to be expected or realized is known as the power quality and is measured by the deviation of voltage magnitude and angle from the rated tolerance limits set by the system operators [11]. Many emerging technologies have sought to reduce these power mismatches by utilizing energy storage systems and making the energy grid more pliable. Pumped storage hydro power has been a well-tailored solution to providing energy during shortages since the reservoir of water acts like a giant battery. Recent technological feats have brought better ways to locate power quality disturbances quickly and store energy efficiently, so it is easily accessible. Other avenues being tested for energy storage include, “flywheels, compressed air storage, molten salts, battery energy storage, superconducting magnetic storage, and super-capacitors" [11]. The effectiveness of integrating these storage systems into the energy grid is differentiated between each resource. Battery energy storage systems have proved to be a valuable asset with modern technological advancements because of their ability to discharge heavy rates of energy when supply gaps emerge, improving system inertia. Determining where to allocate battery storage is paramount to its contribution. When integrated successfully, battery energy storage systems have been shown to reduce the unpredictability caused by renewable energy generation and improve the power quality of transmission and distribution networks [11]. Furthermore, research as well as analytical studies acknowledge that the impact of the energy storage system is based substantially on where the system is connected to the grid rather than its capacity. As more consumers begin to purchase and integrate their own distributed energy storage systems, it is imperative to have predictive and quick-response measures to maintain grid resiliency.

DISTRIBUTED ENERGY RESOURCES (DER)

Distributed energy resources (DERs) make up a diverse group of energy systems at the consumer level. Various technologies such as solar photovoltaics, gas-fire distributed generation, domestic wind turbines, electric vehicles, energy storages, and demand-side management have rapidly grown in popularity among individual consumers [12]. Each of these resources has unique characteristics that make up its grid interactions within a small capacity. Traditionally, electricity allocation has been the job of a centralized energy network. With the recent and increasing integration of local and centralized distribution infrastructures, there are significant impacts seen on the distribution grid's "design, operation, organization, and regulation" [12]. Modifications to the centralized energy grid are necessary to prevent the additions of unregulated distributed energy resources from harming power quality. A lack of comprehensive planning and grid awareness can cause security issues at all three levels of the grid i.e., generation, transmission, and distribution.

Specifically for the transmission grid, the impacts of localized energy generation are broad and undefined. In the case that DERs grow to contribute an equivalent amount of energy as demand requires, the current transmission infrastructure surrounding the centralized generation facilities would need to be shifted [12]. The other scenario for transmission if DER's are capable of meeting consumer demand is a dramatic voltaic down shift, potentially near zero. Regardless of the outcome, the energy grid is volatile and subjected to drastic changes to which it needs to adapt. Current differences between the distribution and transmission grid are the impacts both qualitatively and qualitatively for the end user in the event of an outage. A failure at the transmission level has the potential to impact many more users and, in some cases, can be catastrophic, whereas distribution failures are localized, and their influence can only be felt by a local group [12]. The other main factor of differentiation is the number of assets belonging to each.

TRANSMISSION

Generation and consumption require a transmission network that can carry high voltages across multiple states. A capable transmission and distribution system infrastructure is crucial to allocating energy resources and must be able to withstand demand at full capacity. Even though demand may not reach extreme peaks often, the energy grid must be able to anticipate and support consumer needs at any time. This requires a fortified grid with additional conductors and transmission corridors to be utilized under rare circumstances. Transmission is preferred at the highest possible voltage to invoke the lowest energy transfer losses through resistance as the energy travels across the cables. This voltage is usually between 115kV to 765kV which is stepped up or down via transformers when the energy goes into a substation [13]. It is also very difficult to integrate additional transmission lines due to the expenses, land coverage, and maintenance. Each line in the system needs to be optimized before consideration of expansion [14]. Changes to the network also affect each transmission line's impedance due to Kirchoff's laws. System operators solve for the optimal power flow problem to mathematically model how assets should be utilized.

In order to improve system reliability and voltage profiles, system operators often change the grid topology as necessary. However, this is not an option for day-ahead optimization challenges due to the constantly changing market conditions. To achieve the dynamic goals for increased grid flexibility, network topology optimization attempts to use the existing transmission assets such as lines and transformers more effectively [14]. Transmission switching has been one of the control methods for problems like line overloading or voltage violations. It is also a means of protection against contingencies by having redundant lines in the grid.

It is a common debate among utility company managers to choose which type of transmission line is best. Lines can be installed underground or overhead at different capacities and expenses. Overhead transmission lines are less expensive to install than underground lines but are exposed to a much harsher environment and have been at fault to cause some wildfires. It is widely undisputed that large cities require high-voltage underground electrical transmission, while mountains, hills, or expansive planes advantageously prefer overhead transmission lines. A misfortune of underground transmission is their price tag ranging from four to ten times that of overhead lines. Material and construction methods add considerably to their cost [15]. Most companies will choose to build overhead lines because of the lower cost and maintenance associated. Currently, the nation’s largest electric transmission system is owned by American Electric Power with more than 40,000 miles [16]. They own more 765kV lines than all of the other U.S. transmission systems combined.

However, the overhead transmission lines do not lack their own difficulties in installation and management. Installing overhead lines requires an excess amount of land and constant woodland maintenance to keep trees and foliage away from charged electrical components. The National Electric Safety Code (NESC) sets forth strict proximity guidelines to ensure safe distances from the transmission line are followed and the likelihood of electric arcing is greatly reduced. Once the land has been bought and cleared for installation, the poles will be placed a certain distance apart depending upon the make-up of the pole and the tension it will experience from the conductors. A coil of conductor will gradually be unwound with caution not to bend or cause any tension on the line more than necessary to keep away from obstructions on the ground [17]. Sagging and clipping the line need to happen in the next stage. Since a majority of the power system is three phases, there is one conductor for each phase in a single circuit transmission line. The main components associated with setting up a transmission pole are the pole structure, conductor, optical ground wire (OPGW), insulator, cross arms, and earth cable.

The National Electric Safety Code (NESC) or ANSI Standard C2 defines the electrical power grid and utility system safety standards for the United States. The NESC is a document published by the Institute of Electrical and Electronics Engineers (IEEE) to ensure electrical grid components are properly installed, operated, and maintained. The rulebook is updated every five years to stay relevant with emerging technologies and industry requirements.

TRANSMISSION LINE MAINTENANCE

While transmission lines can have lifespans that exceed far past their expected operational capacity, there are many causalities for their replacement or early repair due to failed components. Exposure to the natural environment slowly erodes and degrades many components of the transmission line. The power system is also subjected to increased risks as it operates closer to its stability limits caused by market competition and the inclusion of distributed generation [18]. Each component contributes to the overall system failure probability and risks; therefore, it is beneficial to know the condition of each part in the system. Operational conditions have varying influences over each component. An expert or trained engineer usually foregoes inspections on-site and determines the conditions of transmission line parts. However, the time of the assessment doesn’t indicate a steady condition since operations, loads, and the environmental conditions are constantly changing. Historical data then becomes very important to view in conjunction with the current analysis to retain the average conditions. Transmission line risk assessments have two main evaluation criteria to be met, known as system adequacy and security [18]. System adequacy, which pertains to having sufficient utilities and hardware that coincides with demands and operational constraints. System security is the ability to compensate for dynamic and transient disturbances in the grid.

Many researchers and field experts have uncovered new procedures to address these objectives to keep the grid running smoothly. Some methods have included probability and reliability analysis, optimal power flow assessments, and contingency planning [18]. Studies about the failure risk of components have aided utility companies' knowledge in system failures and how they can fortify the grid elsewhere. These risk assessments are often based on historical statistics. Other methods weighed impacts of N-K contingencies for transmission line outages. While these works have provided valuable insights into system security and adequacy, there is also much to be gained by studying the individual components of the transmission grid as well as knowing the components at greatest risk and with the largest economic expenses. This research will focus on two major and fundamental parts to the transmission grid, wooden poles and conductors, because they can be difficult to replace and economically exhaustive.

WOOD POLE MAINTENANCE

There is reason to believe the assumption that wooden poles need to be replaced after 30 years is a far underestimation of the capabilities of wooden poles ability to stand up to their environment. Oregon State University conducted a survey in 2013 with utility companies across the United States to find the average lifespan of their wooden poles. The results showed poles were living far past their 30–40-year expectations [19]. Wood pole survival is dependent on the specification, exposure conditions, and maintenance quality. Due to the wide variety of factors impacting the service life of poles there has not been any definitive long-term data yet that has produced a reliable replacement age for wooden poles. The most likely way a utility company would assess the condition of their transmission and distribution grid is to look at the records of previous inspections. Most companies will maintain a datasheet of the date of installation as well as the wood species and details of treatments. Additional information would include inspection dates and conditions at each inspection, and finally the date the pole was replaced. The pole is replaced at the point it does not conform to the standards of the American Wood Protection Association (AWPA) which is bases its minimum levels of treatment on the list of species in the American National Standards Institute (ANSI) Standard O5.1 [19]. It is generally assumed that while there are multiple treatment chemical options, they all provide a similar level of resistance to decay. They do, however, change the color of poles, the fire resistance capabilities, and the climbing characteristics for the wood species.

Wooden poles have been a long-lasting solution to the infrastructure of the transmission and distribution grids. Wood poles are able to carry energy for most use cases, but 345 kV is the typical limit for usage of wooden poles practiced by transmission line companies [20]. Wood poles have specific areas known for showing signs of degradation earliest. Depending on the type of decay, this can occur at various stages of a wood pole’s life, and it advances based on the severity of the environment. Carpenter ants, termites, beetles, and woodpeckers are common species that will shorten the lifespan of poles if infested. Chemical treatments deter animals or fungal growth, but the treatments must be timely and continued throughout the poles’ service. Some estimations of decay have been developed based off of the average monthly temperature and precipitation [21].

Another main source of decay is the moisture in contact with the pole often near the ground line. The North American Wood Pole Council classifies the environment for the United States into three categories of low, moderate and severe with moderate conditions covering nearly all of Kansas. Specifically, the report looks at regional potential for decay from ground contact. It is also acknowledged that higher concerns for decay should be placed on any pole near coastal waters, rover valleys, or banks along other waterways [19]. Southern Pine poles that have been well treated typically show decay below the groundline.

Out of the millions of wooden poles that support the transmission and distribution grid, a utility company study found that southern pine was the most commonly used, contributing to 69% of all wood poles used. The successive wood type preferred was Douglas-fir at 15% then western red cedar at 13%. Ponderosa and lodge pole pine are also used, but in limited quantities. There are several types of chemical treatments that have improved the condition of wood species resistance to decay. The most prevalent type is pentachlorophenol which was used in 63% of all wood poles. Chromated copper arsenate (CCA), copper naphthenate, and ammonium copper arsenate/ ammonium copper zinc arsenate (ACA/ACZA) are less common but make up the majority of remaining chemical treatments at 16%, 16%, and 3% respectively [20]. Recently, the EPA has issued a final registration review that pentachlorophenol will be phased out of use due to the imposed health risks to workers outweighing the benefits of using the chemical [22]. Treatments are typically applied every 10-15 years or more often if there is degradation shows that the treatment has worn off quicker than anticipated. Each treatment has varying costs associated for materials and labor, but generally the treatments are not dependent on the wood type.

Industry uses many technologically advanced methods for inspecting transmission lines as well as basic initiatives like driving out to the pole and having an expert take measurements and assess the conditions. Poles are typically inspected before going into the field through a quality check. The inspector will be looking for knots that are outside specification limits, splits, excessive spiral grain, or other defects as defined in ANSI 05.1 Standard [21]. In addition, the inspector will sample cores from a designated zone in the treated wood to see how well the preservatives penetrated the wood. These operations either happen within a wood pole manufacturing facility or at the sight of installation. In North America an inspection cycle is typically ran between eight and fifteen years, however data shows 8-12 years is best since decay risks run much higher beyond that [21]. In addition to routine inspection, some damage can be seen by drive-by parties such as cracked insulators or splits in pole tops which gives reason to inspect the pole immediately. Less telling visible signs are discoloration which gives indication that further inspection should be conducted. Areas in a dry climate can extend their inspection periods, while it is advised to shorten cycles in areas along the Gulf Coast. During the inspection, some practices include digging around the pole due the unseen decay underground, partial excavations, wood cultures for fungal decay, and internal inspections like boring and probing. The tools used for these inspections can include scaping devices, hammers, drills, increment borers, shell-thickness indicators, Shigometers, moisture meters, decay-detecting drills, acoustic inspection, X-ray tomography, ground penetrating radars, Mechanical pole testers, microscopic decay instruments, and infrared assessments [21].

Maintenance of the pole comes in many forms. Based on the status of a pole, it can be replaced, treated, or reinforced through various means. Reinforcing the wooden structures is a way to extend the life of the pole without incurring the costs of replacement. Substitute pole materials consist of steel, concrete, fiberglass, or laminated supports, with steel being the most common [20]. Safety and reliability can also be increased by installing metal trusses to the bottom of the pole where it is most vulnerable to decay from the ground's moisture.

CONDUCTOR MAINTENANCE

This thesis also considers the inspection and maintenance practices of transmission line conductors. Conductors are damaged by forces on the line occurring through string winds, energy flow, its own weight, and ice storms. Aeolian vibration is a common degradation mechanism for conductors. As steady winds blow over the surface of the conductor vibration waves are permeating through the line which creates bending stresses on the conductor and supportive hardware [23]. Galloping is another modality of wind across conductors but a speed of 15-40 mph over ice covered lines. The line experiences extreme oscillating motion putting severe levels of stress on components and increasing the likelihood of fatigue of conductor strands. Wind-induced oscillations are associated with the configuration of the bundles. Motion in the form of galloping, snaking, rolling, and breathing creates a range of torques and forces are hardware to risk severe damage. Other ways of damage to conductors are lightning strikes, flashover, direct contact, or firearms.

Inspection for conductors happens visually by relieving tension from the lines to check beneath Armor Rods or the outer strands for breaks. The number of strands that have cracked or failed is recorded for the outer and inner strands. X-ray equipment can be used to see the condition of the parts without removing the suspension clamp. EPRI Solutions also developed an acoustical signal that can be sent across hot lines to reveal broken strands and corrosion of the core [23]. In addition, visual inspections also look for the sag between the lines to exceed standards set for the distance required above the groundline to determine if the lines need tightened.

THESIS STATEMENT

The goal is to develop analytical models that support maintenance and replacement decisions for transmission lines. Specifically, we develop data-driven and physics-informed predictive models for degradation of overhead transmission conductors due to environmental and operational conditions. Additionally, we develop time-based and condition-based maintenance strategies for treatment and replacement of wood poles under budget limitation. While there are many other crucial parts of a transmission line, this work focuses on these two components due to the request for information by Sunflower Electric Power Corporation and because of their high expenses at the time of replacement.

THESIS OVERVIEW

In Chapter II, the research presents a simulation of the degradation that occurs to a conductor over time due to environmental and operational conditions. Included in the results is a sensitivity analysis to reveal how ice loading, additional amperage, and increased wind affects the conductor's sag. This work was presented and published as, "Scenario-based degradation modeling of overhead transmission lines" in the 2023 IISE Annual Conference Proceedings.

Chapter III considers the time-based maintenance of wood poles in the transmission system. In particular, we study maintenance planning strategies based on the age of the grid and the ability to find an appropriate age of replacement. Budgetary restrictions are enforced on two additional heuristic solutions. To find the optimal replacement age with budget constraints, a more systematic approach is required. The previous models, while informative, lack the ability to reduce costs and gain the most lifespan out of each pole. A mixed-integer program is formulated to account for these constraints and optimize the age of pole replacement.

Chapter IV looks at the condition-based maintenance of wood poles through the framework of a Markov Decision Process (MDP). By considering the possible actions, states, and transition probabilities between states, the MDP framework offers the best policy which determines the optimal course of action at any given state to minimize the overall maintenance cost.

Chapter V summarizes the research carried out in this thesis and discusses the key findings. It also presents possible future research extensions.

CHAPTER II

SCENARIO-BASED DEGRADATION MODELING OF OVERHEAD TRANSMISSION LINES

ABSTRACT

The U.S. transmission grid is rapidly aging with 70% of transmission lines older than 25 years. Maintenance of transmission lines has traditionally involved visual inspection of line degradation, which is costly and time consuming given the large size of the grid. The objective of this study is to model the degradation of transmission lines over time by calculating and predicting the inelastic elongation in conductors. Using inelastic elongation as a health index, we analyze the degradation of transmission lines under various environmental and operational scenarios representing the impact of climate change and large-scale electrification. We employ historical atmospheric and operational data to calculate thermal and mechanical stresses acting on transmission lines, and physics-based models to calculate inelastic elongation accumulated in a conductor given the long-term stress profile. Sensitivity analysis is performed on the severity and frequency of extreme weather events as well as the magnitude of power flow on transmission lines. The obtained results show that inelastic elongation can serve as a quantifiable and predictable health index to inform inspection and maintenance decisions. Sensitivity analysis results show that an additional increase in power flow leads to the maximum rate of increase in inelastic elongation, which is further compounded by inelastic elongation due to severe weather events.

INTRODUCTION

Overhead transmission lines are the link between the generation and distribution of electricity, carrying high-voltage electricity for hundreds of miles. During the lifetime of a line, it is repeatedly exposed to internal and external stresses due to severe weather events and power overloading. Eventually, conductors begin to show signs of aging and damage that leads to necessary replacement or repair. This is in large due to high amperage levels carried across the line, climate-induced corrosion, and extreme weather such as windstorms, heat waves, or ice accretion.

Climate change has provoked the power industry to reprioritize itself toward grid decarbonization and replacement of fossil fuels with renewable energy. To support a widening dispersion of energy sources such as wind, hydroelectric, solar, and nuclear, the power grid will need to expand rapidly to meet demand. However, the United States power grid is rapidly aging. The Department of Energy reports around “70% of transmission lines are 25 years or older” [24]. These lines will continue to require more frequent maintenance amidst a limiting budget and workforce. Inadequate knowledge of transmission-line conditions can have catastrophic consequences. A California wildfire due to a PG&E transmission line failure caused 86 fatalities, turned 528 commercial buildings to ash, and damaged thousands of homes and structures [25]. To avoid further deplorable events, it is vital to transition current strategies from reactive to proactive to maintain the transmission grid while meeting the increasing need for electricity. This has never been more imperative than now when severe weather events are intensifying in strength and frequency due to climate change. It is projected that many global locations will see substantial increases in heat waves, with less precipitation brought by more intense storms [26]. Across the country, extreme weather events have caused power outages to double within the last two decades [27]. These severe weather conditions will continue to accelerate the degradation of the transmission grid. Practical and rapid solutions are necessary for the growth and maintenance of an expanding transmission grid.

Visual inspection is the most common method of assessing transmission-line conditions. Recent advances in transmission maintenance employ robotic and drone technologies to inspect transmission lines, which has increased the speed of search and repair processes [28]. Nevertheless, this comes with a high cost for modern technology and skilled workforce to support the robotic inspection of the power grid that can be thousands of miles long. Hence, it may be cost prohibitive to frequently inspect transmission lines using robotic and drone technologies. To mitigate safety risks and financial losses due to transmission-line failures, it is necessary to have a method of preventative maintenance by following a calendar schedule or adopting condition-based maintenance practices. Asset condition monitoring requires a health index to quantify the asset health status for maintenance, repair, or replacement.

This research aims at investigating the employment of permanent elongation in the conductor as a quantifiable and predictable health index to support condition-based monitoring and maintenance of transmission lines. In this study, permanent elongation, also known as creep, is estimated by calculating the time-varying mechanical and thermal stresses acting on the conductor over a period of interest. For proof-of-concept illustration, we apply the proposed method to a transmission-line segment in central Kansas to determine whether ground clearance violation occurs under different weather and operational-condition scenarios.

PROBLEM DESCRIPTION

The main component of a transmission line is the conductor, which is suspended by towers or poles. The sag in the conductor is defined as the vertical difference between the highest and lowest points of the conductor between two adjacent poles. Several factors affect conductor sag, namely, conductor weight, span, tension, temperature, and wind. The conductor is continuously exposed to mechanical and thermal stresses due to atmospheric and operational conditions. This leads to both elastic and inelastic elongation of the conductor, contributing to the sag. Elastic elongation is temporary and disappears once the stress is removed, whereas inelastic elongation is permanent. An important factor of transmission-line maintenance is ensuring conductors do not experience ground clearance violation due to excessive sag, which is set in place by the National Electric Safety Code (NESC). Excessive sag may violate the minimum safe clearance between the energized conductors and the terrain or nearby objects, such as trees. This degradation requires immediate maintenance to prevent potential electrical fires or safety hazards. Given the current permanent elongation in the conductor, also known as creep, we calculate sag and, in turn, the remaining time to ground clearance violation as a quantified health index under different atmospheric and operational conditions.

RELATED RESEARCH

Several health indices have been proposed to monitor and predict the degradation of the transmission grid, particularly transformers [29]. Those health indices combine historical operational and maintenance logs with different diagnostic test results, such as the dissolved gas analysis, to assess and monitor the health condition of transformers and predict failure times. However, there are no similar quantitative health indices for transmission lines. Relevant health indices in the literature are mainly based on visual scoring of the status of transmission lines [30]. This study investigates the application of creep in conductors as a quantitative and predictable health index to inform inspection, maintenance, or replacement decisions. Laboratory testing on the nature of conductors has provided the relationship between creep and mechanical and thermal stresses through empirical laws [31].

Understanding the condition of overhead transmission lines has been a long sought after answer. Tsimberg et al., estimate the remaining lives of conductors and their condition. The question they pose is whether visual inspection and age are sufficient determinants of the conductor's condition or if other tests are necessary making the condition more expensive [32]. Other studies have focused on several different inspection techniques. From the latest technology to optimizing what has been long practiced, overhead line deterioration can be tracked by several methods.

Modern inspection techniques can often be expensive and time consuming, but one metric that has been deemed valuable in knowing the condition of the conductor is the sag. Mahin et al., created an extensive review on the literature using optical and physical properties for measurement techniques [33]. State equations were developed by Polevoy to find transmission line sag based on creep, operational factors, and other properties of the material [34]. A least squares estimation approach was also used by Ramachandran, P., et al. [35].

Various types of conductors were tested for carrying high voltages while incurring less sag [36]. Since tension can be used to estimate the sag of the conductor, a sensor was made and tested to tell the tension of the line and in turn find the sag through calculations. The sensor is known as a fiber Bragg grating based sensor [37]. Other types of sensors include measuring for the vibration because a higher vibration frequency translates to a lower sag [38].

METHODOLOGY

DATA COLLECTION

We present a proof-of-concept illustration of the proposed health index for monitoring the condition of a 115kV transmission line segment located in central Kansas between May 2014 and October 2022. The line is operated by Sunflower Electric Power Corporation, a Kansas utility company, who provided the initial installation condition and average operational data for the line. Atmospheric and operational data are utilized to evaluate the condition of the conductor over the period of interest. The operational data provided was limited to the average amperage measured on the line segment. The conductor type is Hawk 477, which was initially strung at 20% of the rated strength. The characteristics of the Hawk conductor are shown in the table below (CME Wire and Cable Company standards [39]):

TABLE 1: CME WIRE AND CABLE STANDARDS FOR HAWK 477

Type	Alum. /Steel Ratio	Cross-Section Area (m^2)	Rated Strength (kg)	Unit Weight (kg/m)	Resistance at (Ω/m)	
Hawk	26/7	2.2808×10^{-4}	8845.05	0.97519	25 °C	75 °C
					7.283×10^{-5}	8.688×10^{-5}

The latitude and longitude of the transmission line allow accurate weather data to be retrieved as well as time allocation for sun exposure. The weather data was obtained from "visualcrossing.com", which includes the hourly temperature, amount of precipitation, precipitation type, wind speed and angle between May 2014 to October 2022. With the elevation above sea level and ambient temperature, we can calculate the air density, air viscosity, and the thermal conductivity of air that is acting on the line [40]. These three equations are in the IEEE Std 738-2006 as they each rely upon conductor temperature for calculation.

CREEP MODELING AND CALCULATION

To estimate permanent elongation in the conductor, also known as creep, we simulate the elongation of the conductor over a period of interest starting from the initial installation [31]. This involves dividing the period of interest into equal time intervals (e.g., hours) during which atmospheric and operational conditions are fixed. At the beginning of each time interval, given the corresponding atmospheric and operational data, we first calculate the conductor temperature as well as the mechanical forces due to conductor weight, wind, and ice accretion (if any) acting on the conductor during that interval. We then simulate the elongation of the conductor during that interval by iteratively calculating the tension and stress in the conductor and the resulting permanent elongation. In what follows, we provide more technical details related to each simulation step.

Given the atmospheric and amperage data during a time interval, the first step involves finding the conductor temperature, which is calculated based on the heat-balance equation as described in IEEE Standard 738 [40]:

$$q_c(\tau) + q_r(\tau) = q_s + I^2 R(\tau) \tag{2.1}$$

Here, τ denotes the conductor temperature, $q_c(\tau)$ and $q_c(\tau)$ are the rates of convection and radiation heat loss, respectively, and q_s and $I^2 R(\tau)$ are the rates of solar and power loading heat gain, respectively. The underlying premise of the heat-balance equation is that in the steady state, the rates of heat loss and heat gain in the conductor must be equal. Specifically, heat loss can occur via both heat convection and radiation. Convection heat loss occurs as the air around the transmission line circulates hot air away. This calculation uses parameters of the surrounding air particles and the presence of wind. Radiated heat loss gauges the level of heat dispersion by material properties like the conductor emissivity and diameter. The right-hand side of the heat-balance equation describes the rate of heat gain in the conductor. The location, time of day and year, material absorptivity, and cloud conditions all affect the conductor's ability to experience solar heat gain. Finally, power loading heat gain is due to conductor resistance $R(\tau)$, which is typically reported for 25 °C and 75 °C and is linearly interpolated for other temperature values. The conductor temperature is obtained by transforming the heat-balance equation into a root-finding problem and is solved using numerical methods.

The second step of the simulation process is to calculate the forces affecting the conductor, including the gravitational pull and wind [41]. The gravitational pull is due to the weight of the conductor w_c as well as the weight of any ice accretion w_i. The wind force F_w is calculated as a perpendicular force in accordance with the air pushing orthogonally against the projected surface area of the conductor expanded by any ice accretion. Therefore, the total force affecting the line is calculated as

$$F = \sqrt{(w_c + w_i)^2 + F_w^2} \tag{2.2}$$

Ice accretion requires certain atmospheric and operational conditions to yield sub-freezing temperatures in the conductor during a freezing rainstorm. Several models have been proposed to estimate the thickness of the ice accumulation on transmission lines during freezing rainstorms. In this study, we use the model proposed by Atmospheric Research 46 (1998), which calculates the ice thickness, denoted by R_{eq} , for a freezing rainstorm lasting N hours as follows [42]:

$$R_{eq} = \frac{1}{\rho_j \pi} \sum_{i=1}^{N} [(P_i \rho_0)^2 + (3.6 Z_i V_i)^2]^{\frac{1}{2}} \tag{2.3}$$

In the equation above, P_i, Z_i , and V_i are the precipitation rate, liquid water content, and wind speed during hour i, respectively. The density of water is referenced as ρ_o and ice as ρ_j. The first term corresponds to ice accretion due to the rain directly falling on the line, whereas the second term is due to windblown rain.

At each time interval, given the conductor temperature τ and force *F*, we divide that interval into subintervals such that the conductor length remains unchanged during each subinterval and only increases when transitioning to the next subinterval. Within each subinterval, given the current permanent elongation ε_c, we first calculate tension *H* by solving the following equation [41]:

$$l + \frac{F^2 l^3}{24H^2} = \left(l + \frac{w_c^2 l^3}{24H_o^2}\right)\left(1 + \alpha(\tau - \tau_o)\right)\left(1 + \frac{H - H_o}{EA} + \varepsilon_c\right) \tag{2.4}$$

where l is the span (horizontal distance between poles), *E* is the Young modulus of elasticity, α is the coefficient of thermal expansion, *A* is the cross-sectional area of the conductor, and H_0 and τ_0 correspond to the initial stringing tension and conductor temperature at the time of installation, respectively. The stress σ is found by dividing the calculated tension by the cross-sectional area. Given the conductor temperature τ and stress level σ, we then calculate the additional permanent elongation that occurs during the current subinterval. It has been empirically shown that the relationship between creep and conductor temperature, stress, and time duration follows a power-law equation as shown below:

$$\epsilon_c = K e^{\phi\tau} \sigma^{\beta} t^{\mu} \tag{2.5}$$

where the parameters $K = 1.9$, $\phi = 0.024$, $\beta = 1.83$, and $\mu = 0.23$ are all experimentally determined for ACSR Hawk 477 kc/mil [31].

RESULTS AND ANALYSIS

We start our computational experiments by running the simulation model for the given line segment to obtain the progression of creep in the conductor from the point of initial installation, which establishes our baseline scenario. We then perform sensitivity analysis by considering three groups of scenarios corresponding to harsher weather and operational conditions compared to the baseline scenario. When running the creep model under each scenario, we also calculate and track conductor sag and report whether the required NESC ground clearance is violated at any point during the simulation.

An engineering drawing provided by Sunflower Electric informed the conductor sag value began at 1.8 meters from the attachment points on the adjacent poles to the lowest point of the suspended conductor. It also shows that a sag value beyond 4.6 meters will violate ground clearance. The trials range from 05/02/2014 at 12:00 PM to 10/13/2022 at 11:00 PM. Model implementation via MATLAB used the initial hanging parameters, hourly weather data provided by “visualcrossing.com,” and constant amperage value of 353.5 to form the input data. Results of the simulation describe how the transmission line interacts with operational and environmental conditions. The first scenario in section 3.1 reports the baseline creep that the conductor has experienced without altering the raw data. Sensitivity analysis’ in section 3.2 discovers how the degradation was affected under scenarios of climate change and large-scale electrification. A concern for many transmission utility companies is the destruction left in the wake of ice storms. Using the creep simulation model, section 3.3 uses average conditions of the five worst Kansas ice storms on record in the winters of 1984, 1998, 2002, 2005, and 2007 and inserts the ice storm(s) uniformly [43].

COMPUTATIONAL EXPERIMENT

Figure 1(a) shows how the creep compounds hourly, while Figure 1(b) depicts the varying phases of sag per hour. The yellow line running through the sag calculation is the linear incline of the average value of sag over time. The base shift in the sag is due to the increasing conductor creep. The conductor experienced 592.9 mm/km of creep in total without reaching a violation in sag.

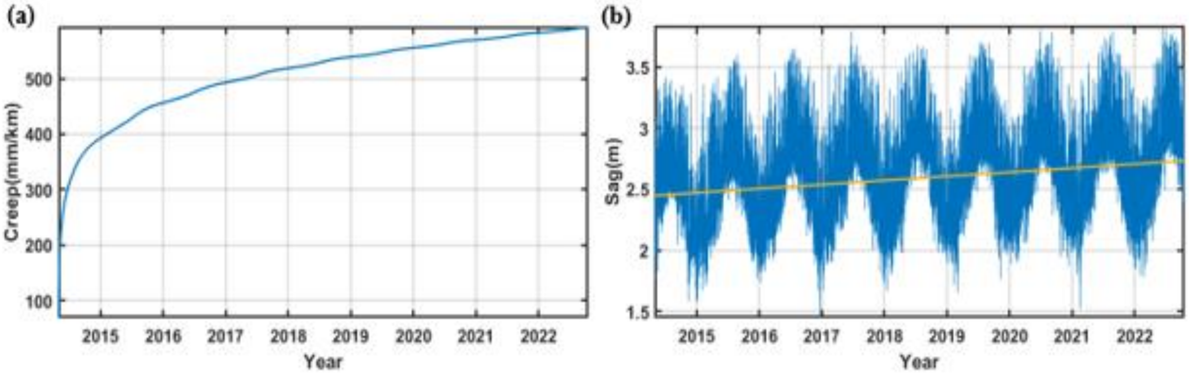

Figure 1: Example figure shows (a) conductor creep (mm/km) over time and (b) conductor sag (meters) over time.

SENSITIVITY ANALYSIS

Figure 2(a) shows the rise of sequential creep with increased amperage factors. At an amperage value of 647 Amps, 1.83x the original, the line exceeds sag of 4.6 m for the first time at 6/11/2022 at 2 PM. The markers in Figure 2 are the first hour sag exceeded the ground clearance. As the environment extremes are increased, the moment of sag violation comes gradually earlier. This is shown through the relationship in Figure 2(b), where an increase in amperage requires less time for the maximum sag value to surpass a sag limit of 4.6 m. Within Figure 2(d), the creep only exceeds ground clearance when conductor temperature increases are involved via amperage which leads us to conclude that inelastic elongation was likely the cause. An increase in wind requires higher multiplicative factors, as seen in Figure 2(c) to invoke a violation over this time.

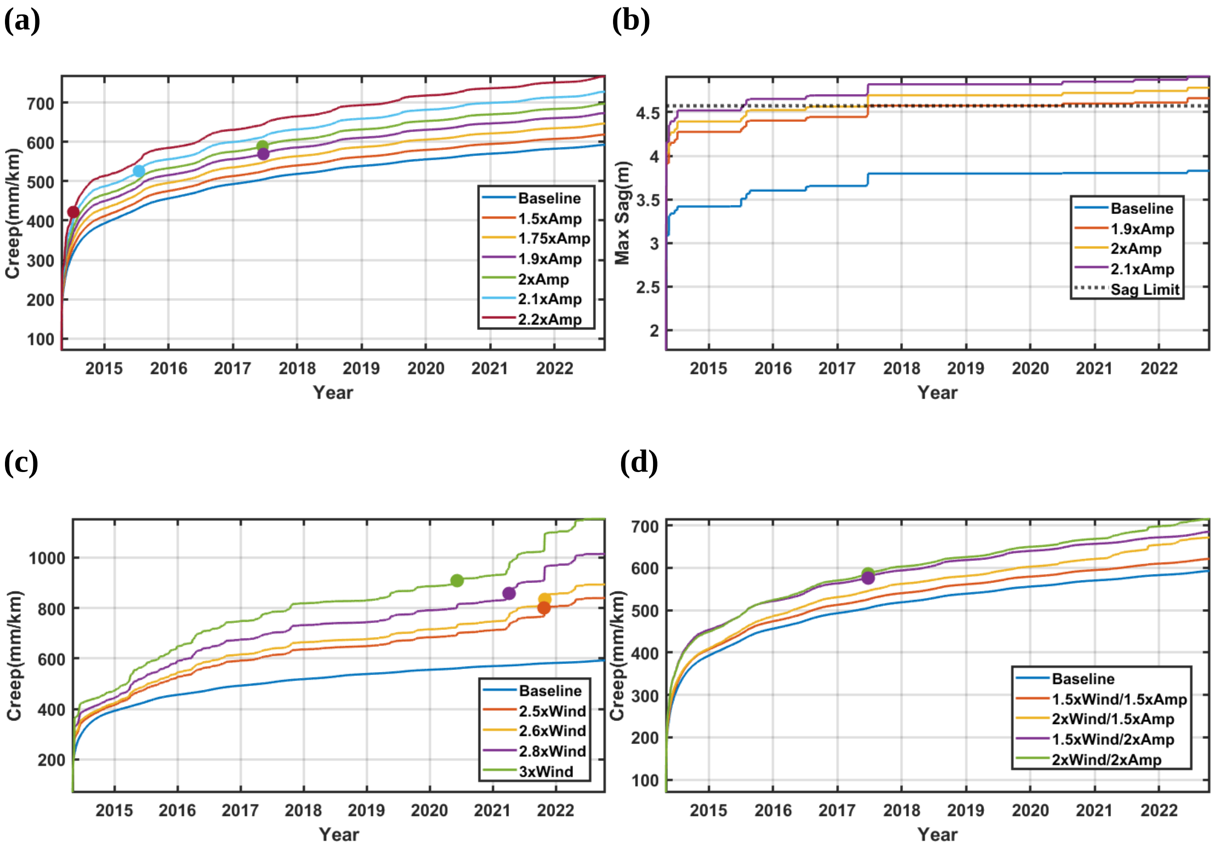

Figure 2: Example figure shows (a) creep under various amperage scenarios (b) max sag value over time (c) creep under various wind speed scenarios, and (d) creep under various weather-operations scenarios.

ICE ACCRETION

The simulation quantified the average severe ice storm event and study the results as seen in Figure 3. Ice storms began on January 15th of each year and were inserted into the simulation in 2018 for one storm and in 2016, 2018, and 2020 for three storms. The maximum radial ice thickness for each ice storm is 0.0202 meters. Ice remains on the line until an hour passes above freezing, whereafter the radial ice thickness is removed from the next hour’s calculations. Many transmission lines experience extreme damage during this type of ice storm; however, the data suggests other factors besides creep contribute to failures since sag did not surpass ground clearance requirements. The most significant differences are the immediate spike in creep at the time of the storm. Ice storms cause less creep in a later stage of life because the rate of cumulative creep is declining. The maximum sag ranged from 3.83-3.84 m and creep from 596.8-604.2 mm/km for the three scenarios. The three-storm simulation showed that the 2016, 2018, and 2020 ice storms jumped in creep by 14.1, 7.5, and 5.5 mm/km respectively.

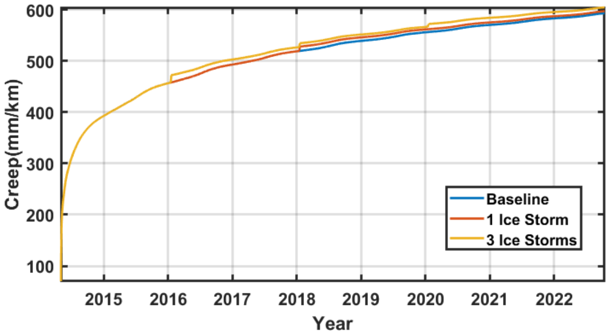

Figure 3: Example figure shows creep with inserted ice storm(s).

DISCUSSION AND CONCLUSION

Overhead transmission lines are exposed to many natural and manmade conditions, namely, mechanical and thermal stresses, corrosion, fatigue, corona discharge, and lightning strikes that may lead to line degradation or failure. Conductor degradation can cause excessive sag posing fire and safety hazards. By defining the health degradation factor as creep, this research can aid in cost reduction by informing maintenance personnel to prioritize inspection of transmission lines based on conductor’s sag and expected time to ground clearance violation. The simulation framework tests multiple scenarios and predicts when a ground clearance violation will occur. Using data for a conductor in central Kansas, we identify the line behavior in response to ice accretion, increased power loading, and severe weather. The most notable factor exceeding sag limits is amperage. Model validation requires field measurements to compare predicted and actual sag values for different transmission-line segments at the present time and performing model calibration accordingly. Future work will combine this health degradation index with a criticality index to create a condition-based maintenance planning strategy for utility companies.

CHAPTER III

TIME-BASED MAINTENANCE PLANNING FOR WOOD POLES BASED ON AGE AND DEGRADATION

ABSTRACT

Overhead transmission grids contain lines spread hundreds of miles across various environments and are exposed to many different degradation factors. Due to the nature of wood poles and their ability to withstand decades of usage many transmission companies have aged grids now that will require constant maintenance including treatments, repairs, and replacements. This research helps to provide a high-level vantage point on the age of the entire grid. It offers analytical solutions to the maintenance planning problem for wood poles to find the best treatment and replacement strategies under budget constraints. In this chapter, we first consider engineering economy analysis of wood-pole maintenance, where the net present value is found over a given planning horizon encompassing treatment and replacement costs for a transmission grid based on pole age. Two heuristic solutions are then shown to compare the impacts of target ages for treatment and replacement on the range of ages for the grid under budgetary restrictions. An optimization framework is finally presented to schedule replacement and treatment of wood poles within budget limitations. The proposed methods are applied to the data supplied by the Sunflower Electric Power Corporation.

INTRODUCTION

The transmission grid is vital to society for daily life. Although generation gets the most coverage for its transition into renewables and other various resources, it is the transmission grid that allows for the hundreds of thousands of generated watts to reach consumers as it is needed. The rapid growth of generation requires the transmission grid to support it and thus new lines are being put in or older lines are being pushed toward their carrying capacities. The age over 70% of the United States transmission grid is around 25 years or older meaning that many lines require more frequent maintenance [24]. Of the transmission line, there are a few components that will lead to catastrophic failure if not maintained properly, namely the wood pole and the conductor. Weather and operational conditions degrade the transmission line through several modalities and require regular inspection.

Sunflower Electric Power Corporation provided information about the age of their transmission grid with around 19,000 wood poles making up the system. The range of poles in the dataset reaches all the way back to the 1940's with the most recent removal and installation of a wood pole in the year 2021. This means the oldest pole is 74 years old and the youngest pole is two. However, the transmission grid is aged due to the longevity of the poles and constant addition of transmission lines. With over 13,000 poles at or above the age of 40, 70% of the poles are due for replacement according to traditional wood pole failure assumptions. Assuming each pole is a single circuit transmission line with a price tag of $45,894.34, this would equate to $596,626,420 in total replacement expenses. This highlights how crucial it is for maintenance to be timely and economically efficient with such extreme costs. It also highlights that pole replacement activities may strain utility budgets and resources. However more recent studies by Oregon State University looked at pole removal data for 86 different utility companies and concluded that poles in many cases were in service for up to 80 years [19]. While every pole has variation in the way it will degrade due to the exposure to its environment, there needs to be a reliable methodology to know the probable lifespan of the pole if it is properly treated and maintained throughout its life.

Due to the complexity and uncertainty of degradation factors, another approach utility companies can take to justify the replacement of pole removal is to operate by their constraints. It is not possible that a utility company replace poles at a young age due to the size of the transmission grid and the associated costs. Budget and labor limitations require that pole replacement be agile and economical, unless replacement is urgent as in the case of a pole failure. By creating a framework that takes into consideration the age and costs of the poles, transmission maintenance planning can make informed decisions by how many poles the budget allows for replacement. It also provides awareness on the future costs to ensure other aging poles are included into the budget's timeframe.

This research aims to provide two methods of analysis, each with a unique intention and focus. The engineering economy analysis provides the net present value of replacement and treatment costs over a specified planning horizon. The results discussed include data from Sunflower Electric Corporation that operates and maintains the transmission grid on the western side of Kansas. The analysis offers an overview of the state of the system and helps determine a reasonable replacement frequency within budgetary restrictions. The proposed optimization approach provides a robust maintenance strategy by informing not just the overall number of lines that need attention, but the exact action to be taken for each line in the grid.

PROBLEM DESCRIPTION

Utility companies work to prevent emergency repairs and unnecessary expenses, while maintaining a reliable transmission grid. One vital component of the transmission line is the structure holding up the conductor, which in many cases is a wooden pole. Wood poles can last in service for many decades, but eventually surpass a safe-operating level of degradation and require replacement. The age of the transmission grid has reached the point where a large population of wood poles will need serviced or replaced at a high frequency. Utility companies must have knowledge not only about the age of their transmission grid, but also about the age for optimal replacement. Poles above this replacement age need to be replaced at a rate manageable by the budget and labor restrictions of the company. This research provides an engineering economy analysis to inform utility companies on the net present value of replacements and treatments over a planning horizon. It also offers an optimization framework to find the optimal replacement and treatment schedule of wood poles considering a targeted replacement age while not exceeding the budget limitations.

RELATED RESEARCH

Wood pole maintenance has been a research topic for many years but has since become a growing concern as the older age of the transmission grid leads to more required maintenance and failures. In-service pole inspections are typically performed on a scheduled basis. The time variation can depend on wood species, initial treatment, chemical treatment types, geography, and the local climate. Historical data from the typical inspection cycles in North America shows that eight to twelve years is the best timeframe to check wood poles in the field since the risk of decay for waiting beyond that increases significantly [21]. Other studies conducted by Oregon State University looked to find the average lifespan of wood poles to narrow down a replacement age. Their study found that wood pole lifespans are reliant on the specification, exposure conditions, and maintenance quality [19]. With these factors in mind, the poles live far past the previously expected 30-40 years and a different method must be used to find a more accurate conclusion on the potential service life of wood poles. While it is critical to understand when the pole's age suggest failure, it is also important to know the limitations of the utility company that is operating those assets. A more informed model to show how utility companies should maintain their grid must be based on the age as well as the budget or labor limitations.

Comprehensive asset management focuses on the life-cycle costs of equipment. This can be either individual components or the asset as a whole, but the objective remains to obtain the optimal usage out of the assets while being conscientious of its reliability and return on investment. For long-term economic success, companies can utilize four possible approaches to maintenance: condition-based, reliability-centered, corrective, and time-based maintenance [44]. Of these four techniques, this chapter created a time-based maintenance strategy which considers the importance of the line, but not the condition.

We first consider the methodology of preventative maintenance and corrective maintenance among components. In some cases, it is much more costly to operate under corrective maintenance since failure can occur unexpectedly, therefore establishing preventative actions at the appropriate time in the part’s life is critical to reduce consequences. Dekker et al. show the effects of economic dependence on multi-component maintenance models using several grouping techniques [45]. Knowledge about when to monitor the assets, and if it is accessible on a discrete or continuous bases changes how maintenance planners will operate. This includes when it is possible to replace, maintain, repair, inspect, or monitor the asset. Jonge et al., provide a maintenance optimization review that covers these topics extensively from 2001 to 2018 [46].

The research by Schneider et al., shows proactive strategies of asset management in the transmission grid by modeling the life of transformers including their aging mechanisms for its main functional components [44]. Kundamal, et al., writes about the time-based maintenance practices of utility companies in water and power and how they might be improved through risk-based maintenance instead [47]. Repairs and replacements have previously been informed by a scheduled cycle; however, Kundamal argues that cost reduction can be achieved at the operational and capital level. This is done by incorporating the probability of failure into the assets instead of purely by time informed schedules. Finally, a process model was adapted to be informed by the risk probabilities as the condition of the asset changes and inform workers how to manage the assets accordingly. This model requires an extensive amount of data that will need to be regularly updated for a dynamic risk computation. From there decay curves will be fit to the data for each component. The type of decay factor occurring to the asset will inform an intelligent algorithm that creates an overall asset score to be compared against the state of other assets. This model gives utility providers good insight to the state of their grid if all this information is readily accessible. However, most companies would find it equally if not more expensive to have this level of condition monitoring on their equipment that it is worth.

Mixed-integer programming has been a versatile tool in solving what is known as parallel equipment replacement problems, which is the allocation of the asset replacement with fixed and variables costs within a timeframe. By utilizing integer programming with asset management, limitations can be incorporated with knowledge of aging and degradation factors. With assets operating independently from one another physically and economically, the components need to be optimally maintained to reduce the costs and possibility of failure. Multiple studies have been done to optimize maintenance decisions on components like offshore windmills [48] or commercial aircraft [49], each with varying needs and costs in scheduling [50].

To find an improved scheduling system for maintenance and repairs of Saab, a Swedish aerospace and defense companies' aircraft fleet, Obradović writes to address the simultaneous scheduling of preventative maintenance for Saab's assets [50]. The mathematical models were derived from a mixed-binary linear optimization framework. Preventative maintenance practices are scheduled with generated interval costs over a discrete time horizon. This work was also extended to the flow of components in the repair workshop which are included as either aggregated parts, individual components, or generically as jobs. The relationship between the repair shop inventory and the aircraft operator is shown through a bi-objective optimization solution.

Similarly, an aircraft maintenance scheduling model was created instead for airlines by optimization frameworks [49]. With the flight schedule at hand decision makers need to prioritize when each aircraft different level of maintenance scrutiny which is required by the Federal Aviation Administration. This objective aims to lower the cost of maintenance by deciding when airlines will be checked for a mid-sized airline. Several other industries look to use optimization for the management of their assets. In the chemical industry, over one fourth of the tasks are related to maintenance operations [51]. Additionally, many companies struggle to reduce costs and be competitive in their markets due to inefficient maintenance policies [52].

For multi-unit systems, various optimization methods have been created, but with heavy focus toward state definition and less on the combination of time-based management and the optimization of replacements. Some models assume a fixed cost for maintenance setup, regardless of the number of times the asset is acted upon while others require an inspection to identify failure and to incur costs [46]. Lutigheid et al., assigned the state of the system to be the weighted sum of the ages for each asset in the planning horizon to determine the next maintenance procedure done [53]. Several different grouping mechanisms can be accounted for by determining which assets are dependent upon one another. Thus when one component suggest failure or indicates it needs to be replaced other components will undergo the same actions even if they did not signal it was required. We see a void in the literature to find how the budget might inform the age of replacement and treatments to a large-scale asset problem, particularly in the analysis of the transmission grid and wood pole maintenance.

METHODOLOGY

Not only is it a utility company’s goal to have a reliable operational grid but they must achieve this under budgetary limitations. This means that each year only a certain number of poles can be replaced or treated, and other poles will have to sustain their current condition for at least another year. Since poles degrade in a variety of ways, it can be difficult to know how the rate of each pole’s future condition align with budgets. Transmission grids are built incrementally and thus all require maintenance at different times based on their age and environmental exposure. The MISO Transmission Cost Estimation guide provided the individual pricing for the transmission lines under various circumstances [54]. Since the wood pole types are unknown for the data used in the model, an assumption is made for every pole to have the following costs associated.

TABLE 2: MISO TRANSMISSION COST ESTIMATES FOR WOOD POLE REPLACEMENT.

Item	Price
Retirement/Removal	\$14,691
Shield Wire	\$1.35 /foot
Optical Ground Wire (OPGW)	\$6.09 /foot
Conductor	\$2.60 /foot
Wood Pole	\$25,933

Additional assumptions for the transmission lines were that every line was 115 kV tangent structure, single circuit, with a span of 160 meters (about 524.93 feet) for a single circuit. The span is priced for a 477 kcmil Hawk conductor. Therefore, the total cost to replace one pole, denoted by $C_{i,t}$ in year t is \$45,894.34. Treatment operations were set to be every 10 years at a cost of treatment per pole, denoted by $D_{i,t}$, of \$2,500 for labor and materials [55].

The net present value calculations inlcude an interest rate of 3%, an inflation rate of 2%, and adjusted rate found by incorporating both rates for a final rate of (1+0.02)/ (1+0.03) = 0.99029. The year in which the net present value will be first calculated is based on the current age of each pole plus the remaining years until replacement. There is also a treatment calculation for every ten years until that next replacement. If the treatment occurs on the replacement year, it is not factored into the costs. The net present value is found using the following equation for a geometric series. The variable, α, represents the present cost of the replacement or treatment, r is the compounded rate, and n is the number of times the pole is replaced or treated. This equation was used for finding both the net present value of the treatment and the replacement costs.

$$NPV = \alpha * \frac{1-r^n}{1-r} \tag{3.1}$$

Based on the reports of the Los Angeles Department of Water and Power in 2014 that many of their poles in service had exceeded 90 years, the maximum lifespan under any environmental circumstances, denoted by L_i for pole i, was set to be 100 years old [19]. Annual budgets for replacements and treatments depend on the operating budget of the utility company. While Sunflower Electric did not express their annual budgets for these categories, the anticipated replacement budget, denoted by B_t, was set at \$20,000,000 and the treatment budget, denoted by O_t, at \$5,000,000. The treatments will also be governed by a maximum time allowed between consecutive treatments, denoted by τ_i, so that pole does not remain untreated past the point of significant damage to occur.

A target replacement age for the pole is one such that the residual strength is not compromised past 2/3 of its original strength, but just before that [19]. Based on the power model for the rate of decay in a pole, the residual strength should be compromised at around the age of 80, but this is not without significant variance for each pole. 80 years is used as the target replacement age, denoted by, W_i.

For each pole i, a pair of binary decision variables $x_{i,t}$ and $y_{i,t}$ are used indicating whether that pole will be replaced, or treated during year t, respectively. The optimization model will decide which poles are replaced or treated at each year within the planning horizon. This in turn, affects the age of the pole for that year, denoted by $Z_{i,t}$, and the years that have passed since the last treatment, denoted by $V_{i,t}$. The following formulation describes a time-based maintenance strategy for wood poles by reducing the budget spikes and finding optimal times for treatments and replacements of each pole to meet monetary restrictions. To model the dynamics between the pole age, the time passed since treatment, and the decision variables, updating equations are used. The age of pole i must increase by one every year or be reset to zero due to its replacement. The age of every pole must also be within the bounds of the maximum age and 0.

$$Z_{i,t+1} = \begin{cases} Z_{i,t} + 1, & x_{i,t} = 0 \\ 0, & x_{i,t} = 1 \end{cases} \tag{3.2}$$

$$0 \leq Z_{i,t} \leq L_i \quad t = 1, \dots, T, i = 1, \dots., n \tag{3.3}$$

The piecewise function in equation (3.2) is reformulated into linear constraints, as shown in equations (3.4) and (3.5). More specifically, when no replacement occurs during year t, i.e., $x_{i,t} = 0$, the variable $Z_{i,t+1}$ needs to be incremented by one time unit. In that case, the constraint in equation (3.4) leaves a lower bound of zero and a relaxed upper bound of M. The second constraint in equation (3.5) sets the value of $Z_{i,t+1}$ to $Z_{i,t} + 1$. In the opposite scenario, where the pole is replaced during time step t, i.e., $x_{i,t} = 1$, the variable $Z_{i,t+1}$ needs to be set back to zero. In that case, the constraint from (3.4) will set the value of $Z_{i,t+1}$ to zero. Constraint (3.5) will be relaxed so that $Z_{i,t+1}$ is between a large negative and positive value of M.

$$0 \leq Z_{i,t+1} \leq M * (1 - x_{i,t}) \tag{3.4}$$

$$Z_{i,t} + 1 - M * x_{i,t} \leq Z_{i,t+1} \leq Z_{i,t} + 1 + M * x_{i,t} \tag{3.5}$$

The initial ages for the poles $Z_{i,t=0}$ are set based on the current age of the wood poles. The current age of each pole at the start of the planning horizon is found by tracking the years back to its installation. The time since the last treatment is also updated annually or reset after every treatment or replacement. Additionally, the time since the last treatment cannot be below zero or above the maximum allowed number of years between replacements. The variable $V_{i,t}$ is initialized based on the time passed since the last treatment of each pole at the beginning of the planning horizon. Therefore, the updating constraints for the treatment age are as follows:

$$V_{i,t+1} = \begin{cases} V_{i,t} + 1, & x_{i,t},\ y_{i,t} = 0 \\ 0, & x_t \ or\ y_t = 1 \end{cases} \tag{3.6}$$

$$0 \leq V_{i,t} \leq \tau_i \quad t = 1, \dots, T, i = 1, \dots., n \tag{3.7}$$

Similar to the constraints for the age of the pole, the piecewise function in equation (3.6) is reformulated into linear constraints of (3.8) and (3.9). The only different is that because the time since last treatment, $V_{i,t}$, is dependent on a replacement or treatment occurring, both binary variables $x_{i,t}$ and $y_{i,t}$ are considered in the constraints.

$$0 \leq V_{i,t+1} \leq M * (1 - x_{i,t} - y_{i,t}) \tag{3.8}$$

$$V_{i,t} + 1 - M * (x_{i,t} + y_{i,t}) \leq V_{i,t+1} \leq V_{i,t} + 1 + M * (x_{i,t} + y_{i,t}) \tag{3.9}$$

Each year, a pole may undergo replacement or treatment but not both and thus the sum of the corresponding binary variables must be less than or equal to one. Based on the age of the pole the variables $y_{i,t}$ and $x_{i,t}$ will be initialized at the start of the planning horizon by whether the pole needs immediate replacement or treatment, budget permitting.

$$y_{i,t} + x_{i,t} \leq 1 \quad t = 1, \dots, T, i = 1, \dots., n \tag{3.10}$$

The annual budget limitation for replacement and treatment is expressed as the sum of the costs for replacements and treatments within that year set to the limitation of their respective budgets.

$$\sum_{i=1}^{n} C_{i,t} x_{i,t} \leq B_t \quad t = 1, \dots, T \tag{3.11}$$

$$\sum_{i=1}^{n} D_{t,i} y_{t,i} \leq O_t \quad t = 1, \dots, T \tag{3.12}$$

The objective function aims at minimizing the total squared tardiness associated with pole replacement past their targeted age as seen in equation (3.13).

$$\min \sum_{i=1}^{n} \sum_{t=1}^{T} \gamma_i * \max\left(z_{t,i} - W_i, 0\right)^2 \tag{3.13}$$

To linearize the max operator in equation (3.13), the constraint (3.14) is added along with the auxiliary variable $P_{i,t}$ which serves as a measure of total tardiness.

$$Z_{i,t} - P_{i,t} \leq W_i \tag{3.14}$$

Thus, the reformulated objective function is:

$$\min \sum_{i=1}^{n} \sum_{t=1}^{T} p_{i,t}^2 \tag{3.15}$$

$P_{i,t}$ is squared to increase the weight of the tardiness the longer a pole goes without being replaced above the replacement age.

$$Z_{i,t} - P_{i,t} \leq W_i \tag{3.16}$$

The value of γ for each pole serves as a weighting factor in the case that utility companies need to prioritize the maintenance of some poles over others. This mixed-integer program was implemented in Python and solved using the Gurobi optimization solver.

RESULTS AND ANALYSIS

ENGINEERING ECONOMY ANALYSIS

An engineering economy analysis is first performed of the net present value corresponding to various replacement ages over a planning horizon of 100 years. The intention of this analysis is to provide a quick and easily adaptable cost calculator showing how different treatment and replacements ages affected the yearly net costs and age of the grid. The main goals are to first see what budget is appropriate and then secondly, how to maintain the grid on a more consistent budget. This next section of the results considers a scenario in which budget limitation is neglected completely and instead focus is drawn to the changes occurring via replacement age frequencies. The histogram below shows the initial age distribution of wood poles operated by the Sunflower Electric Corporation.

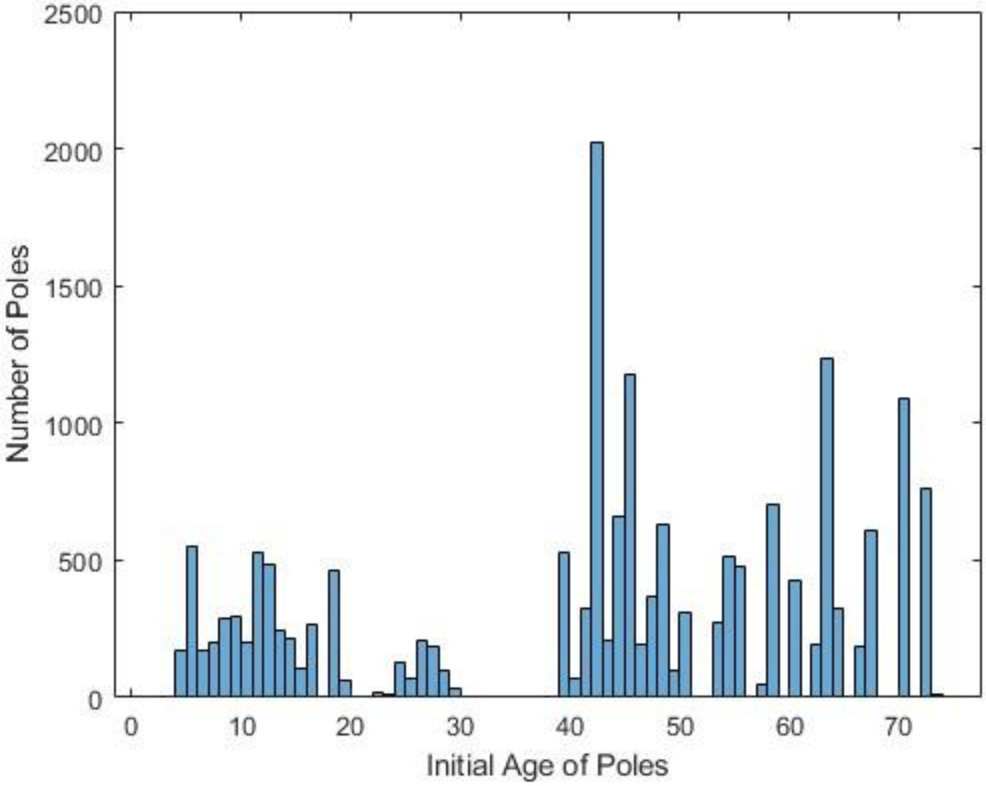

Figure 4: Histogram shows the input data of transmission line ages provided by Sunflower Electric Power Cooperation.

For ease of implementation, the time to the next replacement for each pole was first calculated. If the current age of the line exceeded the replacement age input by the user, then this value was set to zero otherwise the remaining years left to the replacement age were shown. Given the time to first replacement, the number of treatments that would occur until the first replacement can also be calculated. Total expenses are then calculated for that pole until the end of its service life. From there, the number of years left in the planning horizon for each pole and the number of replacements that would happen in that timeframe could be calculated along with the treatments. These costs were discounted and summed to produce the total net present value of maintenance costs for the transmission grid.

This framework gives utility companies a quick overview of the status of their grid without any required extensive implementation. All that it requires is the age of the poles. Finding the optimal replacement age using this tool requires an exhaustive search over every decade in a pole's life.

Analysis of the treatment and replacement costs based on a 100 year planning horizon is depicted below to show how the replacement, treatment, and cumulative costs change as we change the replacement age. The net present value for replacement costs is a factor of 10x larger than the treatment costs and therefore is the dominant cost in the cumulative cost line shown in black.

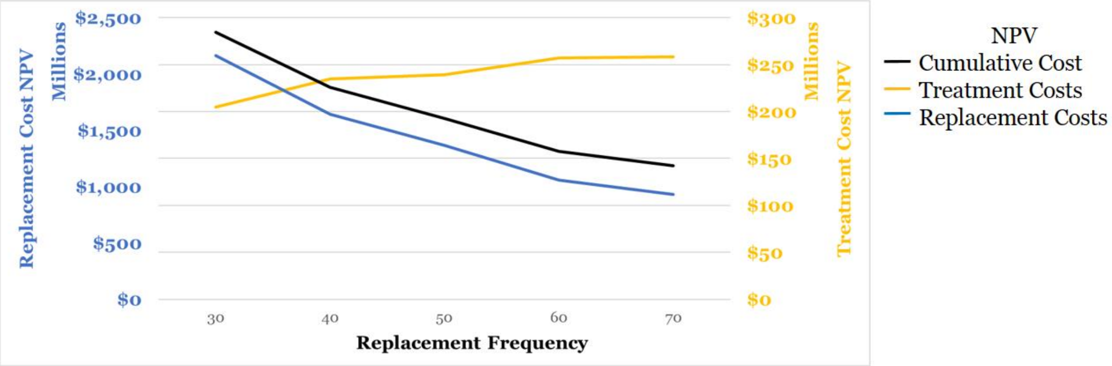

Figure 5: The number of replacement, treatment, and cumulative costs over the increasing replacement age frequency.

The net present value of the cumulative replacement costs per year is dependent on the number of replacements and is portrayed in the graphs below, however due to adjusted rate and the time value of money, the cost in the present value of future replacements is less than the cost today. Because transmission lines start with different initial ages, there are spikes when a large portion of the grid that was installed at the same time is due for replacement. This is a challenge that will require factoring these spikes into the future budget by either letting the poles age further or replacing them earlier when there is a lull in the replacement costs.

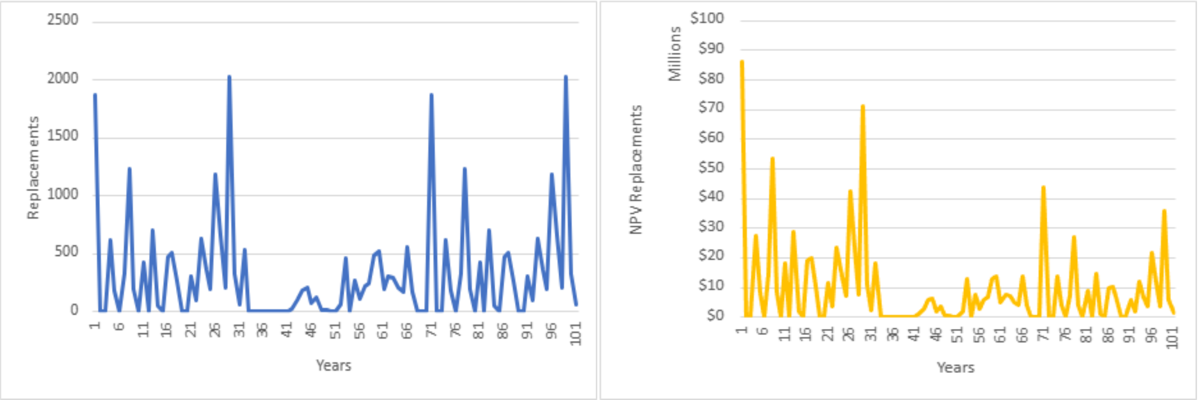

Figure 6: Left graph is the number of replacements over planning horizon and right graph is the replacement costs over the planning horizon for a replacement age of 70.

Similarly, the number of treatments and their corresponding costs are shown in the graphs below. The treatments still have spikes but are much more concentric because they are occurring more frequently than the replacement costs.

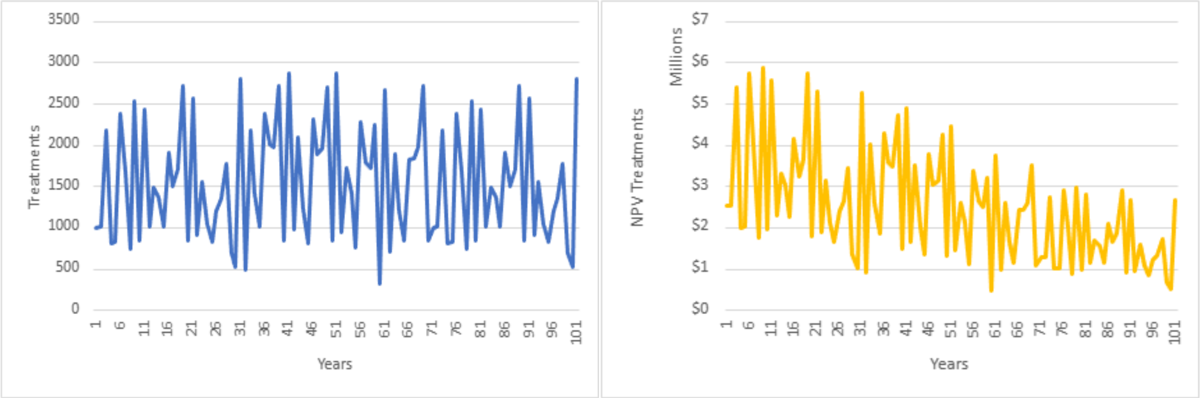

Figure 7: Left graph is the number of treatments over planning horizon and right graph is the treatment costs over the planning horizon.

Different replacement ages can provide a means to reduce the spikes in the budget and will depend on what the current age of the transmission grid is. Since the dataset we have has a large population of wood poles with a current age above the replacement age of 50, the right graph below shows the resulting spike of immediate replacements.

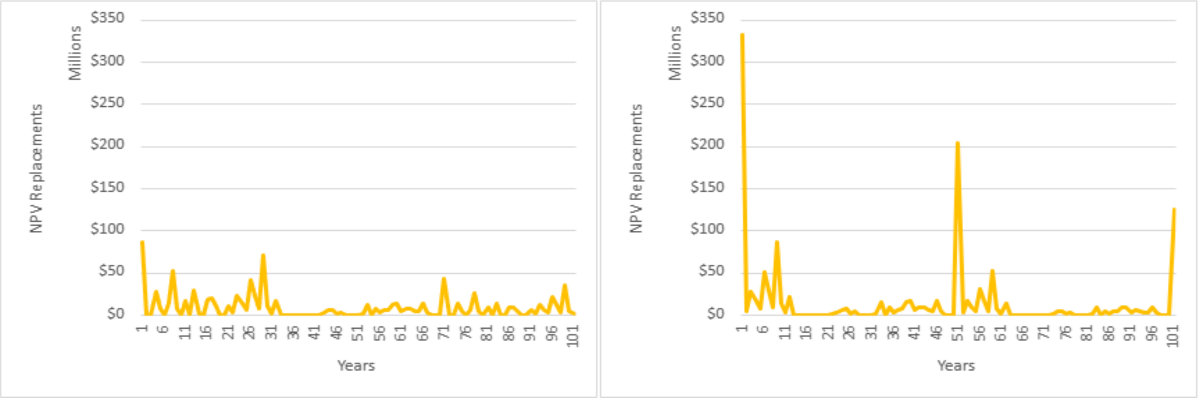

Figure 8: Left graph is the replacement costs with a replacement age of 70 years and right graph is the replacement costs with a replacement age of 50 years over the planning horizon.

The quartiles of the age of the transmission grid are shown below to depict how the replacement age impacts the median, third quartile, and first quartile ages. With a replacement age of 70 years, the median remains roughly between 30 to 40 years for the entire planning horizon. With a replacement age of 50 years, the median starts to follow the age of the poles that were immediately replaced at the start of the planning horizon since such a large portion of the grid is over 50 years of age. Overall, the median is still lower at around 20 years representing a much younger grid than if the replacement age is at 70.

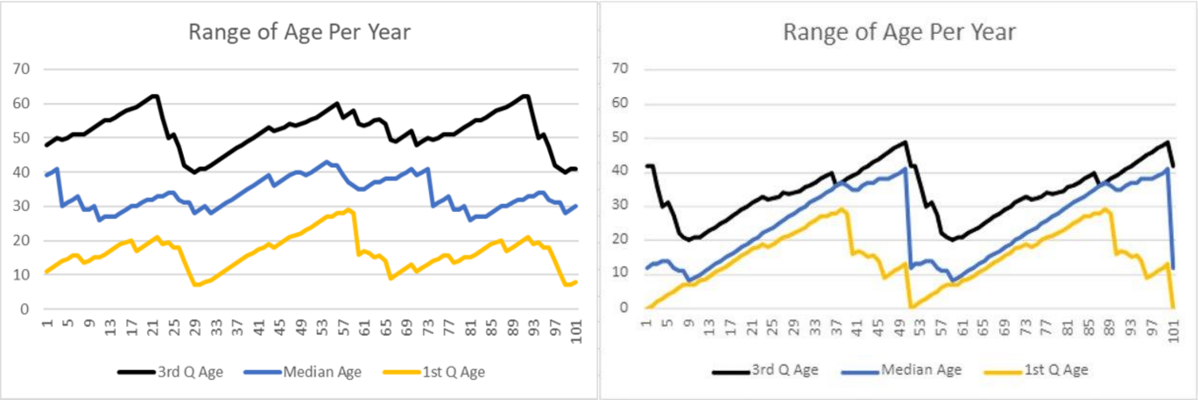

Figure 9: Left graph is the range of age over planning horizon at a replacement frequency of 70 years and right graph is the range of age over the planning horizon at a replacement frequency of 50 years.

Some studies have associated residual strength with age for wood poles. According to standards by the NESC, a pole must be retired when only 2/3's of its strength remains [19]. To analyze the strength of the pole, Abdollah Shafieezadeh, et al. used a rate of decay that coincides with the pole's age to determine the residual strength. The power model below is used to describe the decay of poles with an emphasis on the percentage of residual strength remaining, *Per(t)*, occurring throughout older poles.

$$Per(t) = b_1 * t^{b_2} \tag{3.17}$$

Shafieezadeh realized that while a linear model accurately described the state of poles below the age of around 50 years, performance in the model decreased as it aged beyond this.

The power model was generated as a way to overcome this obstacle. The values of b_1 and b_2 were reassigned the values of 0.00013 and 1.846 respectively. As the poles age the residual strength trends following this power model, however the variance in the rate of decay also increases. This variance is expressed at two standard deviations in the graph below with error bars for the two separate replacement ages of 70 and 50.

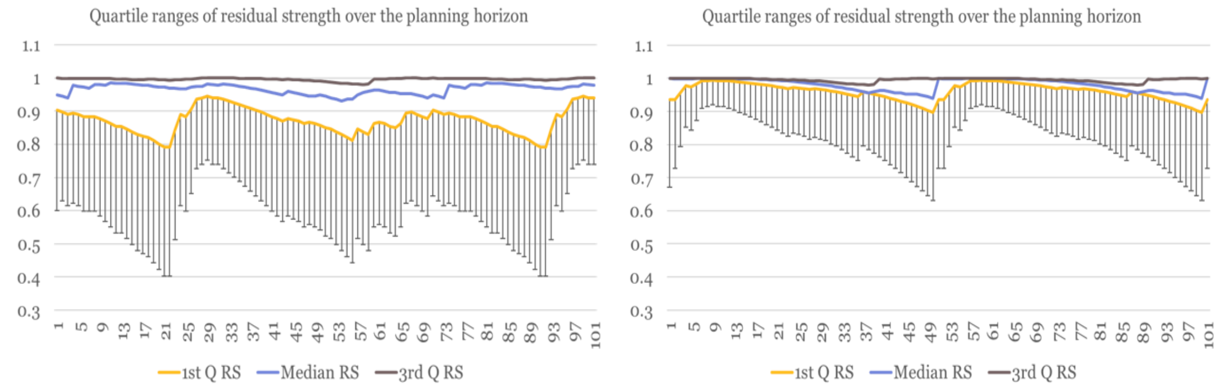

Figure 10: Left graph is the range of expected residual strength over planning horizon at a replacement frequency of 70 years and right graph is the range of expected residual strength over the planning horizon at a replacement frequency of 50 years.

The main purpose of this analysis is to provide a high-level understanding of the current condition of the transmission grid. The next section will focus on how to account for annual budgetary restrictions in maintenance planning of wood poles.

REPLACEMENT ABOVE TARGET AGE WITH BUDGET

As poles age into the next phase of treatments or need replaced, the capacity of the utility c’mpany's budget will determine how many poles can undergo these actions. Replacing a number of poles above the replacement age, up to the allotted budget is the most basic solution to maintaining the grid. Since there are over 18,000 poles in the transmission grid data provided by Sunflower Electric Power Corporation, it is necessary to carry some poles past the replacement age since they will not fit into that year's budget. Similarly with the treatment frequency, some poles will be at the time of treatment but will need to wait until a later date. This heuristic approach provides a baseline for understanding the annual needs of the grid under various restrictions and parameters. It has been designed with separate budgets for replacement and treatment costs, however they could be separated if it is beneficial.

The flowchart below is an outline of the coded solution in MATLAB which finds the poles that need to be treated and replaced each year of the planning horizon. The first portion of the flowchart finds the poles above the target replacement age and separates them based on their indices in a matrix. The second half of the code does a similar process for the poles above their treatment age. It is important to distinguish which poles to be replaced first so costs are not incurred for a pole treated and replaced in the same year.

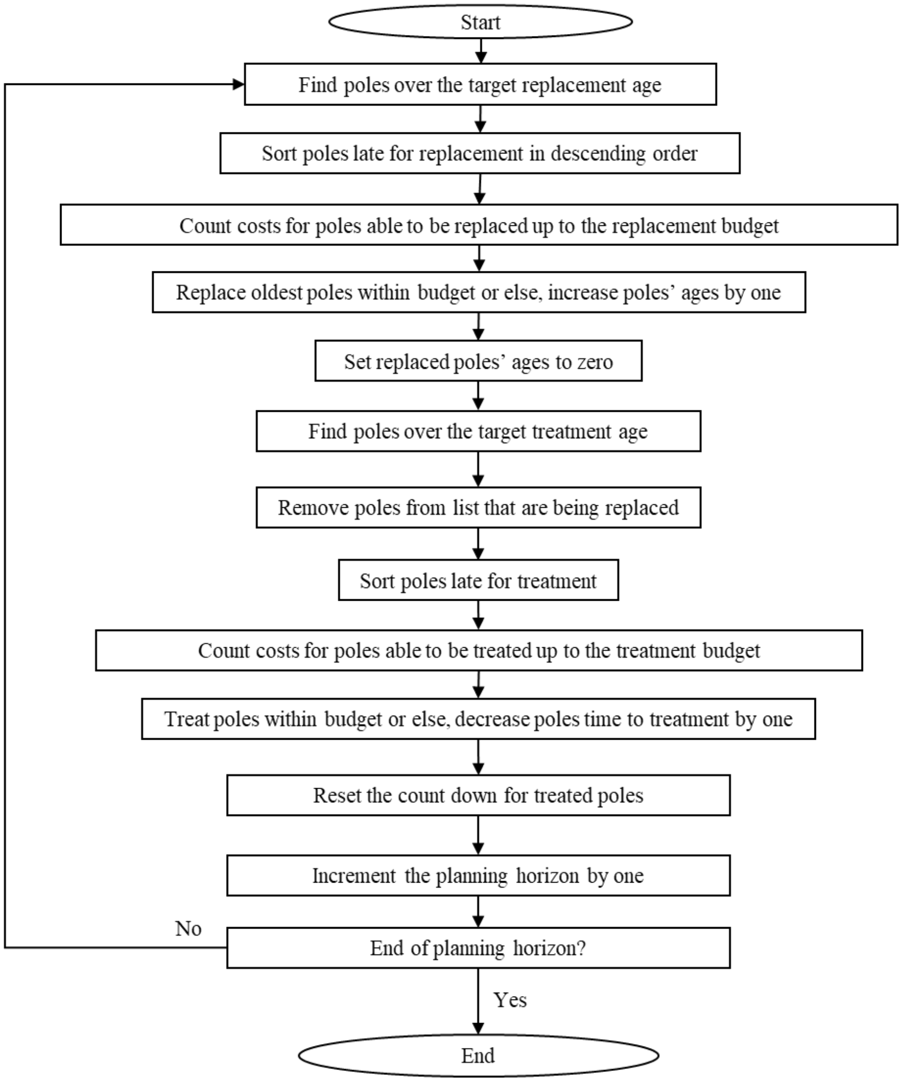

Figure 11: Flowchart of heuristic solution for budgeting treatment and replacement costs over planning horizon.

For the results shown below, it is assumed that the initial remaining time until another treatment is needed is the remainder when the pole's age is divided by 10. The targeted treatment age, T_i will remain at 10. While the targeted replacement ages, W_i will be included in the sensitivity analysis.

The graphs below show the pole age distributions over the planning horizon for 70 and 50 years for the targeted replacement age. Operating the grid at older targeted replacement ages allows the utility company to incur less costs per year. The budget for this figure below is $20 million and $5 million, for replacement and treatment, respectively. This budget translates to replacing a maximum of 435 poles annually. Therefore, the solution replaces the top 435 poles above the target age each year, unless there are not that many that require replacement. This budget is sufficient to keep the age of the grid consistently below 80 years in age, however neither trial of target replacement ages can be met initially. Since there are more poles that will need to be replaced in the first few decades, there are spikes in replacement frequency in the beginning of the planning horizon as shown in figure three for the annual replacement. Toward the end of the planning horizon for the right figure, the grid was able to achieve stability. The target replacement age of 70 allows for more bandwidth in the ages of the poles and therefore will have a wider distribution than that of a lower replacement age.

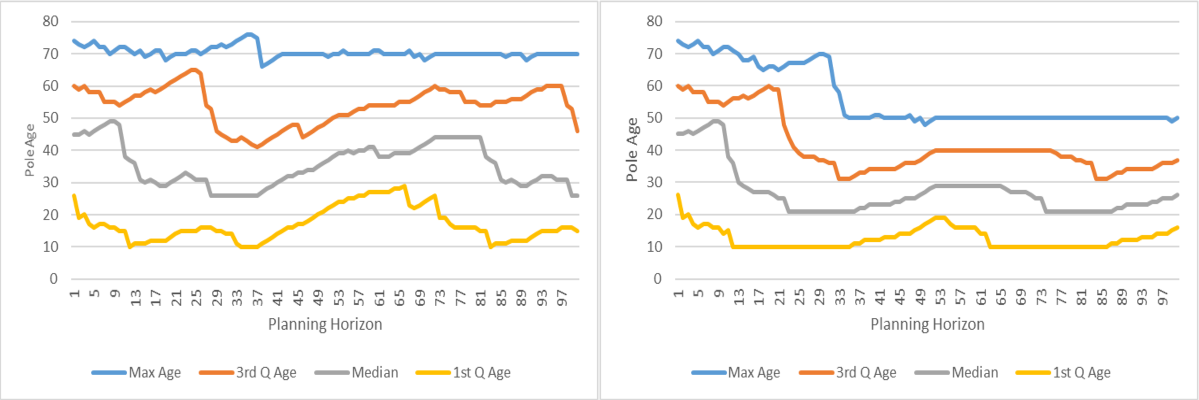

Figure 12: Left graph is the range of age over planning horizon at a replacement target of 70 years and right graph is the range of age over the planning horizon at a replacement target age of 50 years.

Since both figures below show that the target is far exceeded, the budget is insufficient for operating treatments under these conditions. The same data was used for the treatment ages here as was used in calculating the replacement graph data above. However, a negative value represents an overdue time between treatments. The target treatment age is the time between treatments, which for the graphs below is every ten years. For the value of zero on the vertical axis, this means the pole is due for treatment in that year.

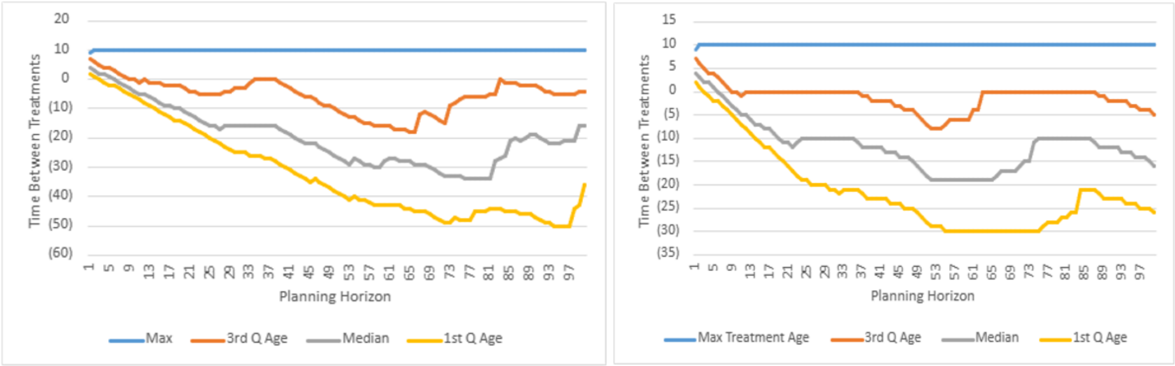

Figure 13: Left graph is the range of treatment ages over planning horizon at a replacement target of 70 years and right graph is the range of treatment age over the planning horizon at a replacement target age of 50 years.

In this next scenario, the replacement budget is $5 million smaller, where now the budget is $15 million. The same distribution occurs for each of the different target ages of replacement when the budget is too low to allow for a difference in the number of poles that get changed. This budget is enough for the age of the poles to level out and keep the grid relatively young. The upper quartile for both target replacement ages are higher than what was shown in the figures with a larger budget.

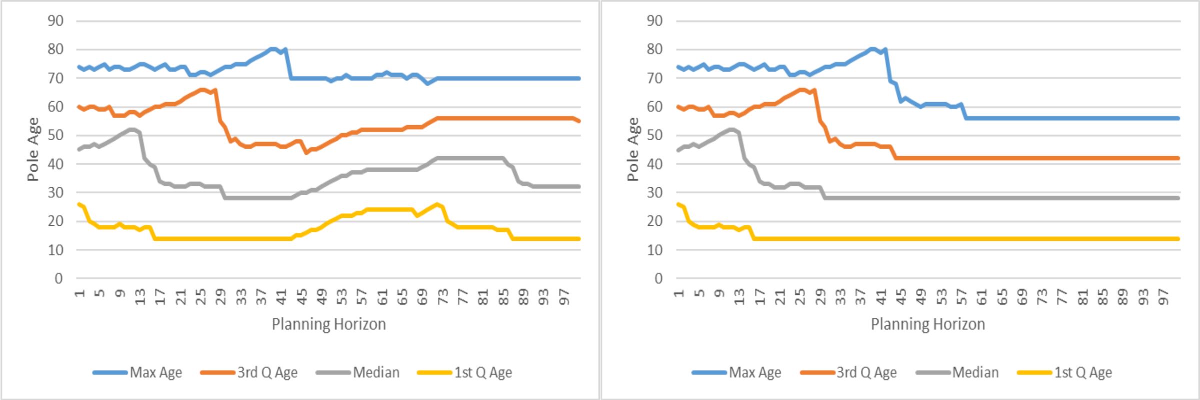

Figure 14: Left and right graphs show the range of age over the planning horizon on a replacement budget of $15 million and target replacement ages of 70 and 50, left to right.

There is a significant limitation with this heuristic method that solidifies the need for an improved strategy. The graph below shows the maximum and upper quartile ages over several replacement budgets. The end of the replacement budget is where the maximum age finally reaches the target replacement age of 50 years. The large budget is just the cost of the year where the most poles need to be replaced. That means that whichever year has the most poles to be replaced will eventually set the required budget. The graph also shows that there is a substantial pole age initially until around $20 million before the pole age hits a steady decline. The initial steep slope is due to the budget being so small that the age of the poles is actually growing within the planning horizon. More specifically, when the budget is too small, the oldest poles are not all able to be replaced, hence, the maximum age is governed by the age of those poles at the end of the planning horizon.

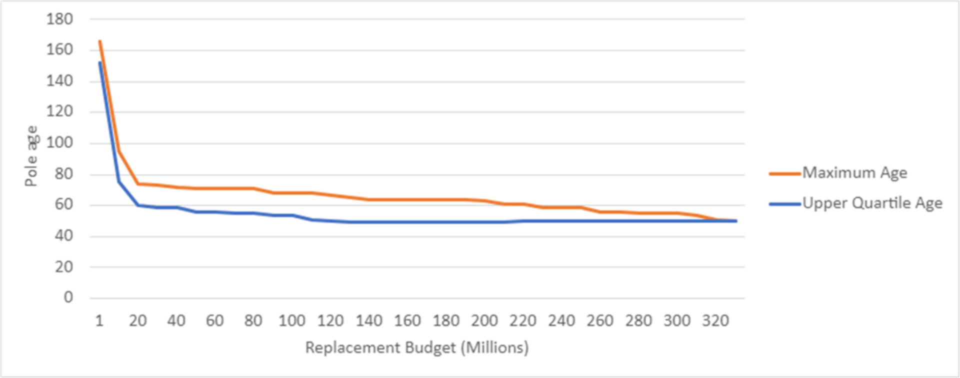

Figure 15: Graph shows maximum and upper quartile age with a replacement target of 50 years over varying replacement budgets.

These results can inform utility companies what effects different budgets will have on their grid if replacement and treatment is constrained by the pole age or time since the last treatment. These heuristic solutions are a good tool to account for the simple budget and target age constraints, but an optimized solution is still to be desired.

Due to the nature of the heuristic, it can only replace or treat a pole when the pole reaches its target age or timeline. The recommended budget then becomes whatever year in the planning horizon that has the most lines needing to be maintained. While the heuristic provides information as to how the wood poles cyclic nature of replacement interacts with the budget and target replacement age, there needs to be a way to take action on poles earlier and later than the target age to level out the budget.

UNRESTRICTED REPLACEMENT AGE WITH BUDGET

With the intention to keep poles in operation as long as possible and thus reduce costs, it becomes difficult to even out the budget year-to-year. If poles could be replaced early and age was not considered, then even though poles are in service for less time it could have monetary advantages to help create a budget that is even throughout the planning horizon. To balance the age of the poles according to how many poles can be replaced in a given year and the initial age of the grid the budget must be able to capture enough poles yearly to deter the maximum age from increasing. If the budget is too low, there will be poles continually to growing in age past the target because the funds are insufficient to keep the average age of the grid below its target. In this section, a heuristic solution is built that selects wood poles for replacement and treatment while considering the annual budget limitation.

The model operates by updating the age of the poles yearly as they are replaced or treated. Poles cannot be replaced and treated in the same year. The poles are sorted in descending order of their age so that the oldest poles are replaced first. The same number of poles will be replaced every year because the number of poles replaced is only dependent on the budget. The scenario below has the budget of $20 million for replacements and $5 million for treatments which translates to 435 poles replaced and 2,000 poles treated annually. The treatments occur every ten years, with a maximum time between treatments, τ_i at 20 years. Under the assumption that treatments should occur every ten years, the counter for time between treatments is reset to ten after every treatment or replacement. Otherwise, it continues to count down, being represented as a negative value, which represents an overdue treatment on that pole. The maximum lifespan, L_i, is 100 years, and the target replacement age W_i, is set to 70 and 50 years for comparison.

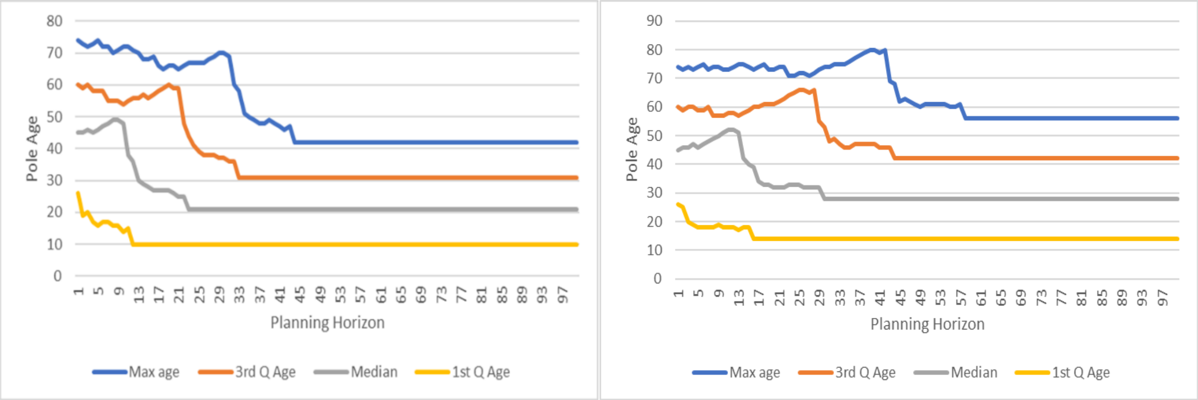

Figure 16: Left graph is the range of age over planning horizon for a budget of $20 million and right graph is the range of age over the planning horizon for a budget of $15 million.

By expressing the quartiles, the overall grid age can be tracked. There are large peaks in this graph showing how the grid ages significantly before those older poles are replaced. This has a lot to do with the initial age of the grid and how many poles share the same age. Since the initial oldest pole is 74, the first year will always begin at above 70 but those poles should be the first to replace.

The following graphs are the treatments for the same input data for the graphs as shown above. The nature of the constraints effects on the treatments shows that the budget of $5 million was covering most of the grid's treatments, however some poles suffered greatly by not being treated for over 50 years. The code was written to reset the counter to ten if a replacement or treatment occurred, so these poles did not get replaced or treated. This will likely have detrimental consequences to the strength of this pole since the preferred method is to be treating every ten years. Maximum treatment age and the third quartile overlap for the majority of the planning horizon.

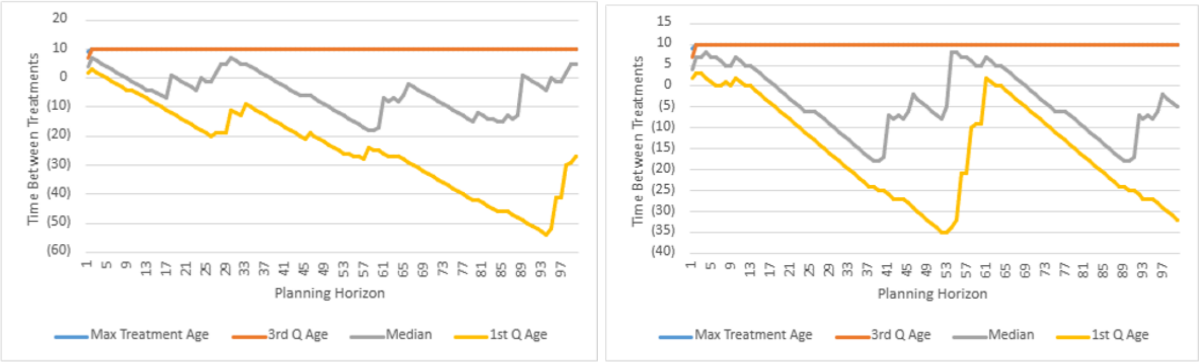

Figure 17: Left graph is the range of treatment ages over planning horizon at a replacement target of 70 years and right graph is the range of treatment age over the planning horizon at a replacement target age of 50 years.

With a tighter budget for replacement from $20 million seen earlier to $15 million, there will only be 326 poles now able to be replaced. The expectation of this scenario is that the quartile ranges will be raised and possibly exceed the target age of the grid because there are insufficient funds. Both target replacement ages of 50 and 70 were once again tested to find how both would manage the age of the grid. While both stayed under their respected target ages, the peaks of the third quartile and median ranges in the graph with a target age of 50 years nearly reached 50. This shows that the large majority of the grid was aged near 50 years, while the replacement age of 70 years does a slightly better job to manage poles below its target.

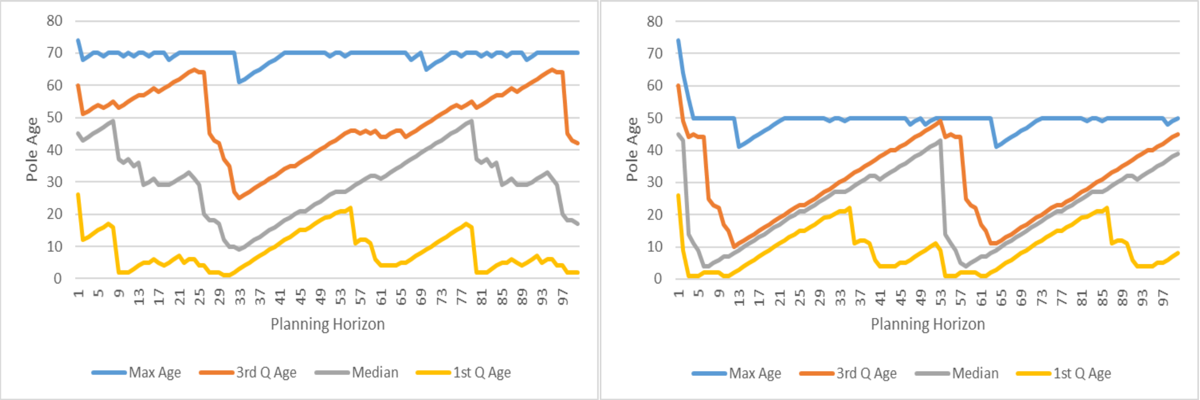

Figure 18: Left and right graphs show the range of age over the planning horizon on a replacement budget of $15 million and target replacement ages of 70 and 50, left to right.

OPTIMIZATION MODEL

With the age-target heuristic solution, it is not possible to plan ahead to replace or treat poles early if there will be a large portion of the grid due for maintenance in the same year. With the intention to level out the budget annually, maintenance can be done ahead of time when there is flexibility in the budget to dampen the effects of years that would have had costs above budgetary restrictions. A mixed-integer program has been optimized to maintain the grid while having a consistent budget that can make it easier for utility companies to plan for the years ahead. This will flatten out peak costs and keep the grid functional at the target replacement and treatment ages. The results shown below have been run on the same scenarios as the heuristic solution above to see how the recommendations differ. Additional metrics such as the optimality gap was set to 10% with a run timeout of 15 minutes. In most cases, the model either got within the gap or did not find a feasible solution.

The first scenario as in the heuristic solution has been recreated, with the parameters of the budget as \$20 million for replacements and \$5 million for treatments annually. However, most of the models would not converge under this budget. The model started from that budget and was increased until the problem was able to be solved in each scenario in the results below. The treatments are set to occur every ten years, but have a maximum time between treatments, τ_i at 20 years. A maximum lifespan, L_i before forced replacement, is 100 years, and the target replacement ages, W_i will be compared in the two scenarios with one being W_i set to 70 years and the other being set to 50 years. The structure of the input data was transformed from each individual wood pole to transmission lines to run the model in a timely manner. With a grid size over 18,000 poles, by consolidating the input data to transmission lines instead, there were 204 inputs instead. Each transmission line had a replacement cost that coincided with the number of poles in it.

The graphed ages were able to stay under the target age when using the optimization framework at a replacement budget of $24 million and a treatment budget of $5 million. The target replacement age returns an infeasible solution below this budget. The optimization tool had a gap of 97.9% when it timed out for the 50-year replacement age, while the 70 year replacement age graph had a gap of 0.0% within 20 seconds and thus, converged successfully.

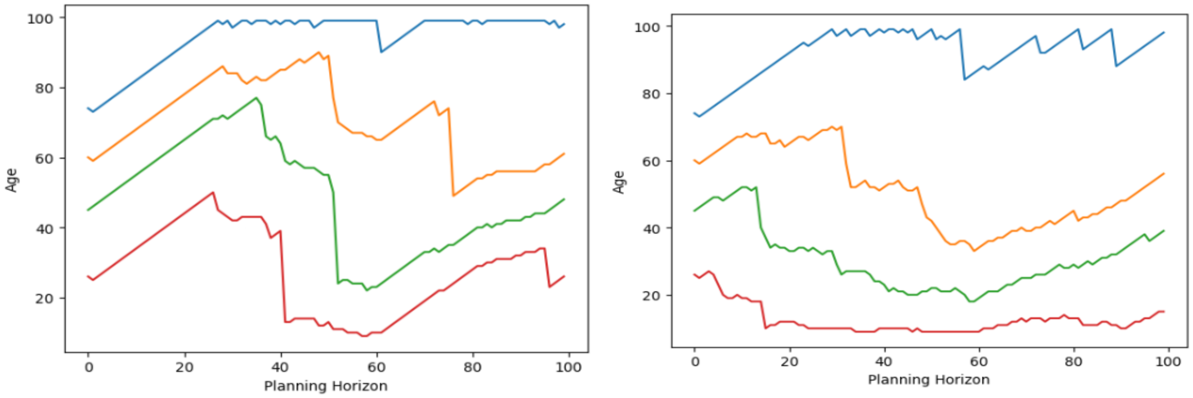

Figure 19: Left graph is the quartile ranges of age over planning horizon at a replacement target of 70 years and right graph is the range of age over the planning horizon at a replacement target age of 50 years with a replacement budget of $24 million.

The following graphs are the same scenario as the above figures but showing the dynamics and distribution of the treatment age. In the heuristic solution, it is shown that the budget of $5 million is sufficient to cover all treatment costs because the treatment times are kept at the optimal value of every 10 years with a maximum time between treatment of 20 years. With the only thing being changed is the replacement age, there are minimal effects on treatment, but still noticeable. There seems to be a median of higher treatment age for a target age of 70 years. This would likely be due to the fact that poles are aging further, so naturally the treatment age follows the trend and treatment is restarted less frequently due to replacements occurring.

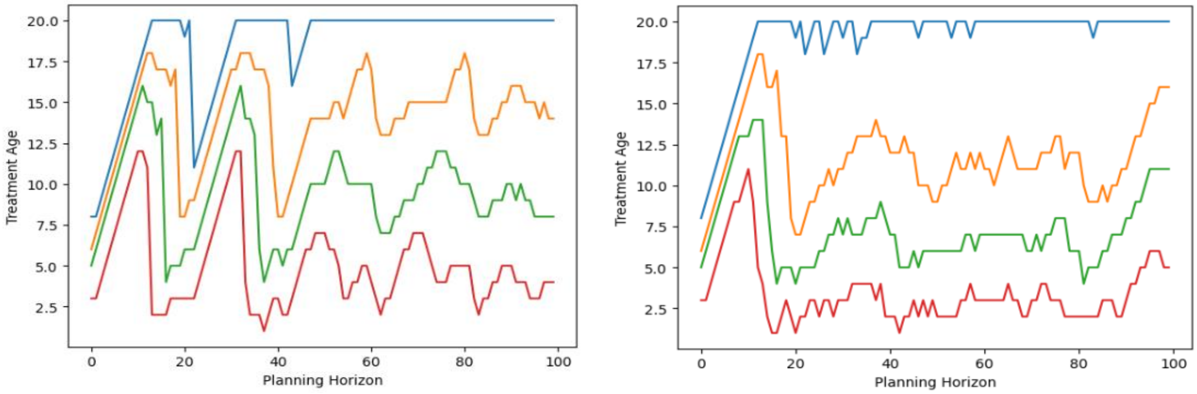

Figure 20: Left graph is the quartile ranges of treatment ages over planning horizon at a replacement target of 70 years and right graph is the range of treatment age over the planning horizon at a replacement target age of 50 years.

To show how the age of a single pole changes in the model, the graph below shows the evolution of a pole that started with an initial age of 74. Since the budget was not enough to cover every pole at the age of 74, this pole actually aged further before finally being replaced around year three or four in the planning horizon. The age of the pole grows steadily until it is replaced again around age 63. Because the optimization model is allowed to replace poles before the target replacement age, the optimal solution does not wait until the target age is reached to take action.

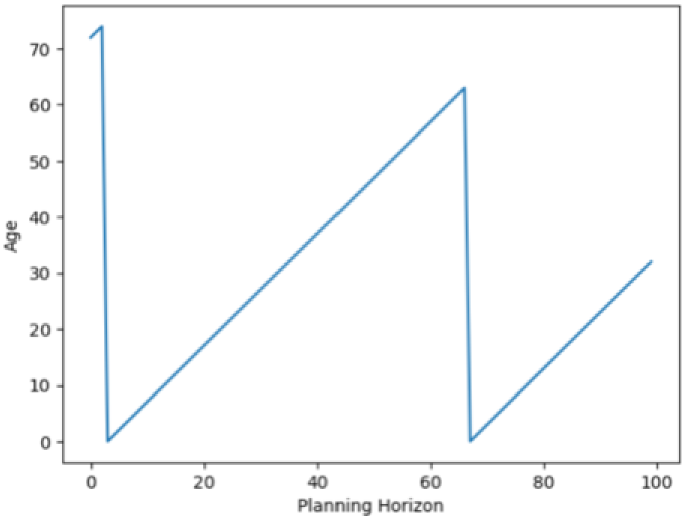

Figure 21: Graph shows the age of a single pole over the planning horizon.

In addition to the correction for having replacements not constrained to the year they are due, but to whenever the budget best allows in the preceding or proceeding years, the model can also account for varying needs of the poles. The climate in the area where the pole is located can influence when the replacements for that type of region need to be completed. In areas where there is significant moisture, wood poles can decay at a much faster rate than in a dry area. Generic models have been created that separate regions into three categories. Three categories of low, moderate, and severe risks make up the United States' climate [19].

For the purpose of testing the effects of various climate risks on the model, each region has been included in the optimization model. Since locational and climate data was not provided about the poles, the input data was split into three categories evenly and the regions were allocated to each category. To distinguish between regions, there are a few factors that need to be adjusted. Treatment and replacements need to occur more frequently in areas of severe risk and moderate risk. Low risk areas will be left at the originally used parameters of replacement and treatment. For the higher risk areas, treatment frequency will increase since decay is occurring faster. The treatment costs will also increase to account for using a higher quality treatment chemical on the wood poles. Replacement costs remain the same since it is still the same type of pole being used.

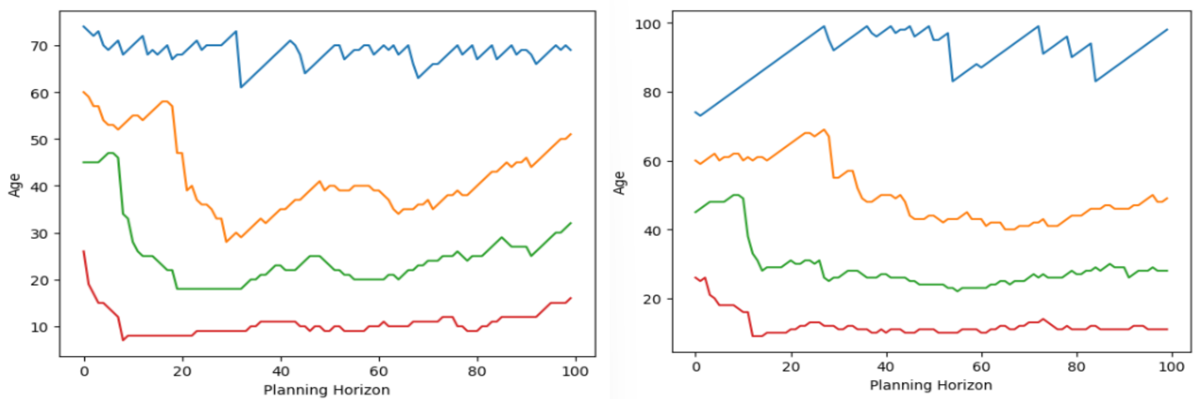

Figure 22: Left and right graphs show the quartile ranges of age over the planning horizon on a replacement budget of $29 million and target replacement ages of 70 on the left and 50 on the right with regionally dependent costs.

When testing the optimization model for the entire grid with a budget of $20 million dollars, the solution space was unfeasible for the replacement age of 50. Since the calculation time was only a few minutes for each run, the budget was incremented by $1 million dollars until a feasible solution was found. The results shown above are thus a replacement age of 50 and 70, both with the larger budget for comparison purposes. At a replacement budget of $29 million and a treatment budget of $5 million, the optimization model was able to converge and keep the maximum age of all poles below 100 years of age. The median age is around 30 for the right graph and 25 for the left so it is a strong solution. The higher costs associated with regional poles caused the age of the grid to be higher. This is in line with what is expected because the budgetary restrictions would not allow as many poles to be replaced in a year.

Older wood does not necessarily always mean weaker wood and thus further investigation is required into the condition of the pole to know what course of action the utility company should take on the aging pole. Chapter IV will discuss a condition-based maintenance strategies to decide on treatment or replacement actions based on the poles' degradation condition.

DISCUSSION AND CONCLUSION

The transmission grid has aged with now almost three quarters of the grid over 25 years in age. With budget restrictions, utility companies must prioritize the lines most at risk for failure to attend to first. This usually occurs in the form of replacements or treatments. Utility companies typically maintain their grid on a rotational timeline every few years to check on poles. This section focuses on a time-based maintenance approach for transmission grids with budget allocation in the form of the net present value. Two methods of time-based maintenance were presented, one without budget constrictions and one with. The database of wood poles tested comes from a local Kansas transmission utility company, Sunflower Electric Power Corporation. The results show how different variations of the budget affect the quartile ranges of all the pole's age. Testing for replacement frequencies also shows how to keep the median age of the grid within satisfactory ranges.

FUTURE WORK

There are several extensions to the proposed ideas to optimize maintenance of wood poles. Financial scenarios not considered here would involve several different interest rates. A different annual budget limitation for replacement and treatment costs could provide a better suited solution since a utility company likely does not have the same amount of money available each year. If a better loan can be obtained in a few years, then the timing of financing can be included as another decision variable. By considering the remaining lifetime as a factor of degradation instead of the calendar age, there can be models that include different climate zones. The method to expressing this would be to extend $Z_{i,t+1} = Z_{i,t} + \xi_i$, where ξ_i is the rate of aging of pole i due to environmental factors in the climate zone it is located at. There are three climate zones that could each have a separate model for this relative age to the environment it is exposed to. Continuing sensitivity analysis and further computational experimentation will also be more robust in future work.

CHAPTER IV

CONDITION-BASED MAINTENANCE OF WOOD POLES

ABSTRACT

As the need for more energy increases, the transmission grid is expected to keep up with generation and consumer demand. A large portion of transmission lines have been in service for decades and require more attention through treatment, repairs, and replacements. Wood poles support the transmission grid up to 345kV making them a widely used structure to hold conductors and the voltage they carry for hundreds of miles [20]. Degradation factors vary widely for wood poles based on the environment, climate, fungi, and animal species inhabiting the region. This research presents a Markov Decision Process (MDP) to obtain an optimal policy for replacement and treatment of wood poles based on their condition. The actions considered are waiting, treating, or replacing each wood pole in the transmission grid. The optimal policy ensures that the recommended actions at each decision epoch meet the budget constraints. Transition probabilities portray the states of no decay, decay, or failure and their likelihood to switch to the other states. By finding the expected total discounted costs for a particular state and conducting a sensitivity analysis on the costs and transition probabilities, utility companies can take the appropriate action that considers the state of all wood poles and their budget restrictions.

INTRODUCTION

Overhead transmission lines have to provide large amounts of energy across hundreds of miles to ensure energy is delivered to consumers from the location of generation. A transmission line is exposed to damaging conditions all year round from storms, wildlife, car crashes, gunshots, moisture, and fungi. Over decades of service in the grid, these factors begin to show on the wood poles either internally or externally. Inspections by experts in the field typically are responsible for measuring and locating poles that will need further attention in the form of repairs, chemical treatments, or replacement.

With an aging infrastructure, it is imperative that utility companies fortify the integrity of wood poles in the grid, to reduce heavy expenses caused by a failure. Additional responsibility and costs are incurred due to the constant growth of the energy grid and the call for renewable energy resources to increase the variation in energy generation resources. Each new resource requires the transmission system to be installed and carry the energy from generation to the consumer. In the midst of the growth, the Department of Energy reports around “70% of transmission lines are 25 years or older” [24] and will be needing further attention for maintenance while utility companies leverage a limited budget and workforce.

With a grid size of 19,000 wood poles, Sunflower Electric Power Corporation has to be replacing wood poles every year as they reach the end of service. 13,000 poles in the transmission grid are above the age of 40 and may need replaced. However, due to the varying factors that can degrade wood poles it is necessary to manage the replacement and treatment of each pole due to the cost that incurs. Based on the condition of a pole, the MDP interprets the poles’ conditions and assigns the optimal action to be taken. This works addresses the need for knowledge about the condition of the pole and its likelihood to failure as well as the budgetary restriction set forth by the utility company to be able to address the replacement and treatment of wood poles in the grid.

By employing an MDP with transition probabilities that consider the factors of degradation, utility companies can follow a recommended policy to reduce costs while keeping the wood poles in operations for the many years to come. The optimal policy is solved for by the value improvement algorithm and costs are calculated over an infinite horizon for the expected total discounted costs. For proof-of-concept illustration, the proposed method is run for multiple poles under various scenarios of costs and transition probabilities.

PROBLEM DESCRIPTION

Wood poles see an array of forces that cause decay over the several decades they are expected to be in service. Utility companies may struggle to maintain the hundreds of miles of transmission lines due to the variation in rates of decay for the wood poles. A failure of a transmission line structure puts the grid at risk and in some cases may cause a loss of power, especially at the distribution level. There are many potential hardware failures that risk the line’s demise, but the wood pole is the main structural component allowing the conductor to hang suspended in various climates. Since frequent transmission line replacement and treatments are costly, it is important that each maintenance task is done in a timely and economical manner. The NESC requires that wood poles be replaced after the loss of 33% of their original strength [19]. By knowing the condition of the wood pole, it becomes easier to know when the pole will need replaced, however constraints such as budget or labor must be considered as well.

One method of asset management and asset deterioration is to model processes using Markov processes. Many equipment failures can occur without dependency on the age of the equipment, and instead the environment and operating conditions determine failure. Deciding when to invest in new equipment and make repairs is done optimally when condition-based maintenance procedures are followed. This method identifies critical stages of degradation and enables preventative action planning. Condition-based maintenance (CBM) is heavily reliant upon accurate deterioration conditions and thus requires significant data collection prior to mapping the probability between state transitions.

RELATED RESEARCH

Several methods have been used to find the degradation of wood poles in transmission and distribution lines. Due to the complexity of various degradation factors such as fungi, wildlife, moisture, and age, studies typically focus on the effects of one of these factors. Several different probabilistic and risk determining techniques have been used to find the solutions for condition-based maintenance for asset management. CBM is largely based on the quality of data collected about the degradation of an asset, so that it might be properly represented. Numerous types of degradation to an asset are typical for any equipment such as physical properties represented as corrosion, wear, or other natural processes [56]. Degradation is also heavily impacted by the operational conditions it is exposed to which can be controlled. Some factors include time in operation, atmosphere, intensity of load [57]. Mainly, asset managers want to predict when an unexpected event will happen such as failure or performance drops to cushion the economic blow of the event [58]. For these purposes, models require either current state condition monitoring or detailed historical data. Some authors advocate against the use of CBM in large scale problems, saying that the complexity of an effective implementation is too great of a deterrent to allow for a successful approach [59]. In support or not of CBM models, it is crucial to have properly informed degradation rates.

CBM strategies are focused on predicting when a failure modality will occur and should consider all possible ways of failure possible to be a comprehensive model [59]. By finding the optimal time that maintenance should be performed on equipment, CBM can assign the best action to take and reduce the costs associated with maintenance. Thus, preventative maintenance is a component of CBM because the asset is desired to be replaced at the end of its remaining useful life, prior to a failure. A standard of CBM has been defined by ISO 13374 which categorizes the framework of any CBM into data acquisition and handling, state identification, assessment of health and prognostics, and policy recommendation [60]. Various architectures and applications of condition-based maintenance strategies have been applied to industry and are discussed in the following paragraphs.

Niu et al., describes a CBM application combined with reliability centered maintenance to optimize maintenance costs [61]. They use a data fusion strategy to track the equipment's condition and run diagnostics. RCM is used to find vital equipment conditions first. Then the cost analysis is done considering the possible actions. The fusion of degradation predictors is proposed to improve the accuracy and determine a precise remaining useful life. Application was done to indicate motor faults with decision-level fusion and compressor conditions with featurelevel fusion. Guillén et al., proposed a structure of CBM that uses reliability centered maintenance analysis to inform each failure mode [59]. They present five separate technical areas that should be considered when forming a CBM strategy. To define the elements and their relationships a unified modeling language was used on power transformers data.

Star et al., recommends using the fault tree analysis and the failure mode and effect criticality analysis to identify the condition of a piece of equipment [62]. The research also shows a way of categorizing which equipment should be selected for monitoring. Rastegari and Bengtsson give a similar solution as Star et al., however they implement a particular focus on organizational aspects like cultural needs and competences with the company [63]. Al-Najjar developed a model that compared CBM to vibration-based maintenance to act as the surrogate for health assessment and worked with three companies to implement the vibration technique to which the companies found cost-effective [64].

MDPs are a well-known tool for maintenance in aging devices. Abeygunawardane, et al., propose a MDP for local transformers with inspection and maintenance actions [66]. Probabilistic failure in components is an important piece to estimate the maintenance requirements of wood poles in hazardous environments. Shafieezadeh, et al. propose an age-dependent fragility model for wood poles under extreme winds by calculating the moment capacity of the poles [67]. Using a power model this report finds the expected residual strength of wood poles as a function of its age.

Suprasad V. Amaari, et al. provide a generalized condition-based maintenance model for various industry applications which includes a stochastic deterioration model, maintenance actions, and inspection policies to detect the equipment's condition [68]. They formulate this problem with discrete maintenance actions and a continuous interval for inspection which is then converted into a semi-MDP. Another attempt was taken at using semi-MDP to portray the deterioration of assets with a focus on infrastructural decay. Most papers had focused on the theoretical solutions for finding the optimal time for replacement due to time spent in a given state. The paper by Black, et al., looks at the practical aspects for infrastructure maintenance [69]. With datasets for a transformer and the condition of the switchgear oil, a Weibull distribution was used to determine the transition probabilities between states.

Tian, et al., explains the various ways for currently existing tools for asset management of power generations systems that focus on one component of windmill systems. Their methods entail creating an artificial neural network informed by probabilistic failures for the main components of a windmill. At the time of this research, the only current CBM models for wind generation had been done on individual components. By including multiple components like the main bearing, gearbox, etc. the economical dependencies can be included for the asset to its entirety [48]. A simulation calculates the cost of CBM policies.

To capture the aging process of devices using MDP as an adaptive maintenance policy, Abeygunawardane, et al., describes a flexible model of conducting inspection and maintenance [66]. Their device of choice was also in transformers, similar to Black, however their focus was to capture the long-term aging process with short-term variations in the equipment's condition.

The researchers proposed an optimization model for the inspection and maintenance of aging equipment so that deterioration processes differed with the age of the equipment. This sets a unique way to decide upon maintenance policies by understanding the equipment's condition, operational age, and time delays. Other reports specify life cycle costs for infrastructure like bridges [70] and wind turbines [71] for maintenance optimization using MDP. The work presented in this document is unique in its approach because the entirety of a system of parts is looked at under budgetary limitation instead of individual components for the application domain of utility pole networks.

METHODOLOGY

This research discusses how to employ a MDP framework to inform the maintenance planning for a transmission grid in southwest Kansas. MDPs differ from Markov chains because MDP's future states depend not only on the current state, but on the decisions made in conjunction. The MDP framework is a common tool to address asset replacement and maintenance decisions, however no application has been into the domain of wooden poles within transmission grids. The discussion that follows includes the characteristics of a MDP for wooden poles including the observable states, actions, costs, transition probabilities and optimal policies. The initial model will optimize the decisions made at each transitioned state of a single wooden pole over an infinite horizon. This will then be expanded to include a large sample of the transmission grid of wooden poles with the constraint of utility company resources like funding and labor. The time steps in which actions will be performed is dependent on the time between consecutive inspections as well as the timeline of decay and failure processes.

The literature has many different maintenance degradation models in an effort to simplify and predict the degradation of the equipment. This is done via reliability analysis, condition-based probability modeling, historical data, sensors, and other means. The deterioration rate of the pole is the most critical question to answer for the MDP because it will determine how the framework operates. Since the poles are wood, they are at great risk for climate, operational, wildlife, and vandal attacks. Since some of these can be unpredictable, the emergency replacement considers the outlier situation of unprecedented failures. Woodpeckers, insect infestation, fungal growth, and moisture are all also factors for decay. These factors are region based and vary by the type of wooden pole used. The most common is Southern Pine, but many others can be used as well. The type of chemical used in the treatments is also a determinant of what decay factors will be more prevalent. These degradation factors can inform the transition probability matrices of the MDP for each state to action relationship.

To create an MDP, we identify the stochastic processes for the wooden poles' description and the decision process. Let X be the wood pole description process with a state space S. For the decisions to be made about the wood pole, we denote D as the decision process with the action space A. We must also define a cost function f(s,k) that describes the cost incurred when choosing action k in state s. The probability matrices will show the possible and likely transitions from state s to s' such that $\Pr(X_{t+1} = s' \mid X_t = s, D_t = k)$. A stationary policy, denoted by $d(.)$, is one where an action d(s) is taken when $X_t = s$, regardless of any other factors such as the time or previous actions and states [72].

The MDP aims to find the policy that minimizes the expected total discounted cost. Let α be the discount factor such that α = 1/(1+r) where r is the rate of return [72]. When using this method, it should be observed that the expected total discounted cost will be dependent on the initial state and the stationary policy chosen as shown in the following equation:

$$C_d(s_0) = E\ [\sum_{t=0}^{\infty} \alpha^t * f(X_t, d(X_t))|\ X_0 = s_0] \tag{4.1}$$

The objective is to sustain a functioning grid while minimizing the costs and operating under model constraints.

The probability of transitions are outlined below. Future collection of additional field data will calibrate those probabilities by utilizing information about the environment, location, and residual strength. However currently, these values were derived through intuitive assumptions on how the poles might decay.

TABLE 3: SHOWS THE TRANSITION PROBABILITIES MATRICES IN THE ACTION ORDER OF WAITING (DOING NOTHING), TREATING, AND REPLACING.

Transition Probability Action N (Nothing)					Transition Probability Action T (Treat)				Transition Probability Action R (Replace)			
From	States	0	1	2	States	0	1	2	States	0	1	2
	0	0.9	0.1	0	0	0.9	0.1	0	0	1	0	0
	1	0	0.95	0.05	1	0	0.99	0.01	1	1	0	0
	2	0	0	1	2	0	0	1	2	1	0	0

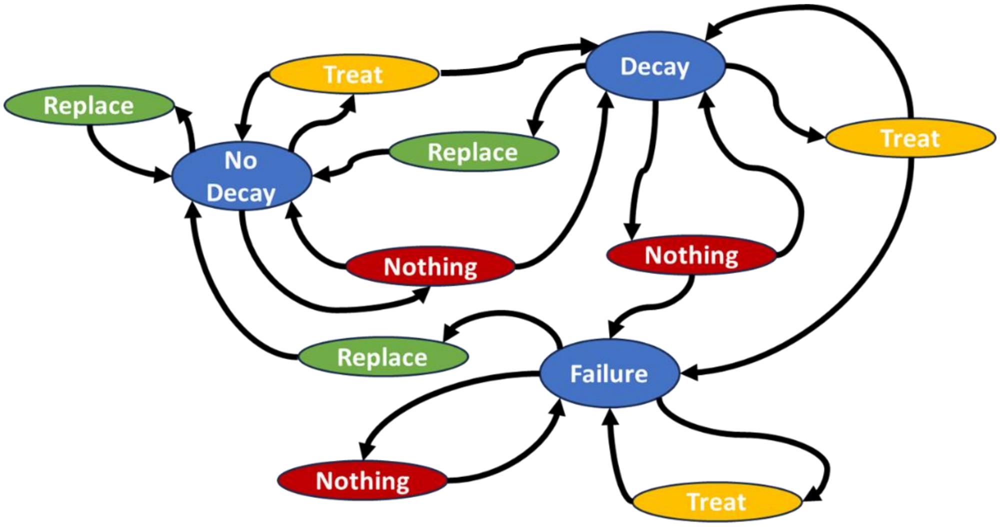

Figure 23: State and Action diagram and transition probabilities.

The diagram above is a representation of the MDP states and actions possible. For each wooden pole replacement and treatment, a standard cost is incurred of $45,894.34 and $2,500, respectively. Assuming that transmission lines are 115kV single circuit tangent structures with 160-meter Hawk conductor spans, the cost of replacing a pole is derived from the table below. Treatment for labor and materials is found in literature [55].

TABLE 2: MISO TRANSMISSION COST ESTIMATES FOR WOOD POLE REPLACEMENT

Item	Price
Retirement/Removal	$14,691
Shield Wire	$1.35 /foot
Optical Ground Wire (OPGW)	$6.09 /foot
Conductor	$2.60 /foot
Wood Pole	$25,933

Due to the repercussion of an emergency replacement, we incur a cost of replacement 10x that of a standard replacement to deter the model from allowing failures to take place via pole negligence. By opting to do nothing, the pole will not incur expenses unless the pole is in the failed state. There are three states of the pole and three actions possible at each state. The states, s, of the pole are defined as no decay (s=0), decayed (s=1), or failed (s=2) which makes up the state space S. The actions, k, in space A include treating the pole, replacing the pole, or waiting (doing nothing). At each time step an action will be taken, but the state does not have to change. If the action taken when the pole has failed is to do nothing or to treat, there can be severe consequences for the transmission grid. This can be avoided by coding a cost of an arbitrarily large number in as the cost incurred for actions "nothing" and "treat" when X = 2. The matrix for costs F is shown below.

TABLE 4: COST FUNCTION F.

	State 0	State 1	State 2
Action N	\$0	\$0	\$M
Action T	\$2,500	\$2,500	\$M
Action R	\$45,894.34	\$45,894.34	\$458,940.34

The expected total discounted cost is an equivalent operation to using a present worth calculation as a foundation for decision making. The value improvement algorithm can be used to solve for the optimal policy that minimizes the expected total discounted costs because there are finite state and action spaces. The minimum cost value function v is thus solved for in the value improvement algorithm to find the optimal policy. This means that each pole in the grid will be mapped within the state space S and undergo a recommended action to alter the state or remain the same with the intention to minimize the total discounted costs over an infinite horizon. With α, the discount rate, between zero and one, the iterative procedure will procure an approximation of the solution, being the optimal policy. If each stationary policy yields an irreducible Markov chain, then there is a stationary policy that does solve the problem [72]. The optimal policy may depend on the discount factor or change based on the definition of the vector, v. Where d is the policy from all possible policies, D and the objective is to find $v_d(s) = v\ (s)\ for\ s\ \epsilon\ S$. This work defines vector v as:

$$v(s) = \min_{d\ \epsilon\ D} v_d(s) \tag{4.2}$$

Based on this definition, there is a straightforward iteration procedure based on the Fixed-Point Theorem for MDPs [72]. The theorem limits the optimal value function by beginning with an initial guess of the value, then recursively iterating the objective value, $v(s)$ closer to the solution until $v_{n+1}(s)$ is the same or the difference in $v_{n+1}(s)$ is negligible. This work begins with an initial value function (e.g., $v_0(s) = 0$). The level of acceptable difference is determined by the user and referred to as ε. This stopping criterion in equation form is written as

$$\delta = \max_{\mathrm{s}\ \epsilon\ \mathrm{S}}\{|v_{n+1}(s) - v_n(s)|\} \tag{4.3}$$

If $\delta < \varepsilon$, let the value of v take on the value of v_{n+1}. Otherwise, increment the value of n by one and search for the optimal value function again. The following equation yields the optimal value function from the value improvement equation:

$$v_{n+1}(s) = \min_{k \in A}\{f(s,k) + \alpha \textstyle\sum_{s' \in S} P_k(s,s')v_n(s')\} \tag{4.4}$$

The maximum change for all values of the solution vector between v_n and v_{n+1}, or δ is then compared to ε. We stop the iteration process once δ falls below the user-specified parameter ε. The process can be slow to converge to a solution depending upon the dimensionality of the action space and the state space. In addition, there is not a clear rule on what is considered a relevant amount of difference between iterative values. In practice, appropriate values of ε can be determined empirically.

Each policy of the MDP recommends an action that needs to be taken according to every possible state space. Each individual pole can be in a no decayed, decayed, or failed state. Out of these states, the actions that can be taken are to wait (do nothing), treat it, or replace it. Thus, there exists three states with each of their own individual action, creating nine total possible combinations of states and actions per pole. There are three possible states that each pole can inhabit and that make up the entirety of the state spaces. A policy is strategy of mapping the set of states to the set of actions. A policy is dependent on the number of poles, the costs of each action at each state, and the probability of transitioning from one state to another under different actions.

RESULTS AND ANALYSIS

We implement the value iteration algorithm within MATLAB and solve for the optimal policy based on the value improvement algorithm described in the previous section. The states are defined as 0 – no decay, 1 – decay, 2 – failed and the actions are defined as N – nothing, T – treat, and R – replace. In the absence of any binding constraints, the optimal policy for the single pole case can be applied to individual poles in a grid. Therefore, additional tests on MDP framework were run for various constraints on the multiple pole scenarios to view the policy's adaptations.

In the case of two poles, the possible states of the system grow to nine since each pole can inhabit three states and be in any combination of states with the other pole. Consequently, there are also nine actions possible in the action space. While some impossible or improbable, the combination of possible actions to states becomes a nine-by-nine or 81 separate outcomes. From these outcomes, each state will be assigned a value correlating to an action that is optimal in that scenario. The results show that the optimal policy for a singular pole in the state of no decay is to do nothing, in decay to treat, and failed to replace. This policy is followed for two poles under the same costs and transition probabilities. Each state of a pole will be assigned the action as shown below:

TABLE 5: OPTIMAL POLICY FOR STATES OF A SINGLE POLE WITH THE COST OF EACH ACTION

State	0	1	2
Action	N	T	R
Cost	$0	$2,500	$45,894.34

The method of comparison for choosing which policy is chosen is to minimize the costs associated with the actions taken of each policy. Under varying circumstances, the MDP will choose the policy and associated actions that minimize the total expected discounted costs.

SENSITIVITY ANALYSIS

Initially, it is important to test for one-way sensitivity to find how each element of the model changes the outcome. Several alterations can be made to either the probabilistic transition matrices for each action, or the cost function associated with each action. In order to compare alterations, one state was chosen, and the results were recorded as it changes across different policies and according to the dependent variable increments. The expected total discounted cost for a given policy d when starting from state s_0 is given as:

$$E\left[\sum_{n=0}^{\infty} \alpha^n * f(X_t, d(X_t)) \middle| X_0 = s_0\right] = ((\mathrm{I} - \alpha \mathrm{P}_d)^{-1} \mathrm{F}_d)(s_0) \tag{4.5}$$

where P_d and F_d are the transition probability matrix and the vector of cost values under policy d, respectively. Therefore, to obtain P_d, a row from each of the different action’s probability matrices are combined into one matrix. The cost vector, F_d is built similarly to then match the cost of the actions taken for each of the given states according to the policy.

The intention behind the experimentation is to see the tipping points that cause a different policy to be more economical than the previously recommended policy. With one pole it is unnecessary to require a budget constraint since the results are straightforward, however with two or more poles a budget has a significant impact on the policy recommendations.

Every utility company faces monetary constraints otherwise they could replace poles at will. It is necessary to have a budget constraint implemented into the MDP. As the number of poles in the vector space increases, there will be a cap on how many poles can take the action of being treated or replaced. This constraint will dictate how many poles will undergo these actions and will act as a budget limitation. A pole in the failed state must be replaced or there is more harm than that will come to the system. Thus, we enforce the model to replace all poles in the failed state, regardless of the budget limitations. In the case the budget is exceeded via replacements of failed poles, the model will opt to take no action on poles in the other two states to not incur any further costs. However, if there is sufficient budget, a pole that is not decayed or decayed will be subject to budget constraints in the form of removing treatment or replacement and in consequence their associated costs. The way the MDP is deterred from assigning an unwanted action is to increase the corresponding cost to infinity. Practically, this is set as a value sufficiently large to discourage the solution to include that state-action combination. The budget constraints were tested on a two-pole scenario to exemplify the behavioral changes for the policy. The graphs below are all the policies that were suggested throughout 20 increments of a single variable. Since this is an economic analysis, the lowest expected total discounted cost in the graph is the policy that is recommended.

The graph on the left below is the results of the MDP's policy recommendations under a $48,500 budget constraint and the increments of the treatment cost. The reasoning behind this budget is to allow for one pole to be replaced and one to be treated outside of the failed state. The policy cannot include two replacements unless the poles are already in the failed state. In the graph, treatment costs begin at $0 and increase by $500 to $9,500 for two poles. This is reflected in the graph as the percentage of change to the original treatment cost of $2,500. The framework provided four policies in the span of the 20 increments. These policies were then extended for the entirety of the treatment costs to see how they compared with the other policies. Policy A refers to the policy that recommends taking the action to do nothing in a state of no decay, to treat when there's decay, and to replace in the state of failure. As the treatment costs increase, the MDP's policy changes to a lower costing policy, which instates less frequent treatments. Policies E and C represent cases that treatment has been excluded so poles are either replaced or left alone. This causes there to be no change in the expected total discounted costs.

Figure 24: Left graph is the expected total discounted costs of the recommended policies with varying treatment costs under a budget constraint of $48,500 and the right graph is the expected total discounted costs of the recommended policies with varying treatment.

The graph to the right above is tested under the same circumstances, but with a budget of $46,000. This budget was chosen because it is just above the costs of a regular replacement cost without including a treatment cost. So, each state is limited to either treating or replacing, but can only afford one of the two actions. The results provided additional separate policies, but Policy A was recommended first under both budgets. The policies are shown in detail in the table below.

TABLE 6: POLICIES RECOMMENDED BY THE MDP UNDER BUDGETARY CONSTRAINTS AND INCREMENTAL TREATMENT COSTS.

State	1	2	3	4	5	6	7	8	9
	(0, 0)	(0, 1)	(0, 2)	(1, 0)	(1, 1)	(1, 2)	(2, 0)	(2, 1)	(2, 2)
Policy A	N, N	N, T	N, R	T, N	T, T	N, R	R, N	R, N	R, R
Policy B	N, N	N, T	N, R	T, N	T, R	N, R	R, N	R, N	R, R
Policy C	N, N	N, R	N, R	R, N	R, R	N, R	R, N	R, N	R, R
Policy D	N, N	N, R	N, R	R, N	T, T	N, R	R, N	R, N	R, R
Policy E	N, N	N, R	N, R	R, N	N, R	N, R	R, N	R, N	R, R
Policy F	N, N	N, R	N, R	R, N	R, R	N, R	R, N	R, N	R, R

For all policies A-E, the actions are the same for any state that has a falied pole. States six through nine and the third state all require the replacement cost with increased expense because at least one pole is in the failed state. The only possible action left is to do nothing to the other pole. With an unlimited budget, the optimal policy remains as the conventional solution until the cost of treament is high enough that Policy F arises where no treatments occur and instead every pole in the decayed state will be replaced. Thus the flat line represents the lack of sensitivty to the increasing costs of treatment. This is seen in Figure 26.

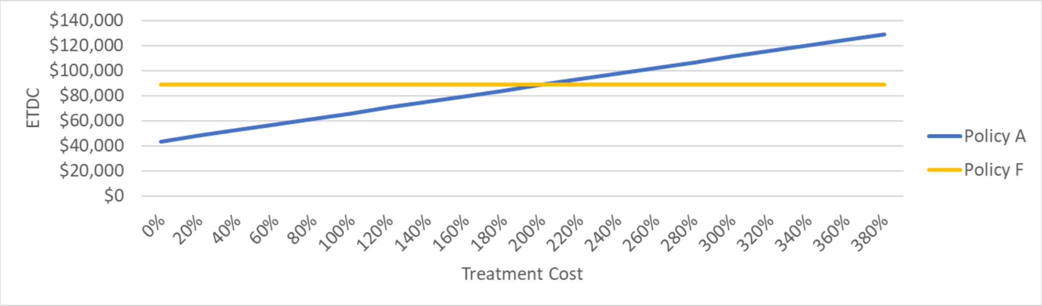

Figure 25: Graph is the expected total discounted costs of the recommended policies with varying treatment costs ($2500) under no budget constraints.

Figure 26: Left graph is the total discounted cost as the transition probability under action "N" from states 0 to 1 increases with any budget below $49,000 and right graph is the total discounted cost as the transition probability under action "N" from states 0.

The graphs from Figure 27 show where the policies change between the probability of transitioning from state 0 to state 1, when taking the action to do nothing with and without a budget limitation. As the probability increases from 0.1 to 0.29 by increments of 0.01, the policy changes to include treatment more often. Table 7 shows the policies from Figure 27. Without a budget, the policy for the right graph in Figure 27 after the probability to decay from no decay becomes too high recommends treating poles in both states of no decay and decay. Policy H and Policy I vary only by its action in the first state. Policy H recommends doing nothing, while Policy I takes the action to treat both poles in the state of no decay. These both are suggested by the change in the transition probability analysis because for a short amount of time as each of the policies cross Policy H has a lower expected total discounted cost for one increment, but ultimately it becomes better to treat decayed and no decayed poles and shown by Policy I.

TABLE 7: POLICIES RECOMMENDED BY THE MDP FOR INCREMENTAL TRANSITION PROBABILITY INCREASES FROM STATE 0 TO STATE 1 WHEN ACTION “N” IS TAKEN.

	1	2	3	4	5	6	7	8	9
	(0, 0)	(0, 1)	(0, 2)	(1, 0)	(1, 1)	(1, 2)	(2, 0)	(2, 1)	(2, 2)
A	N, N	N, T	N, R	T, N	T, T	N, R	R, N	R, N	R, R
G	T, T	T, T	T, R	T, T	T, T	T, R	R, T	R, T	R, R
H	N, N	T, T	N, R	T, T	T, T	N, R	R, N	R, N	R, R
I	T, T	T, T	N, R	T, T	T, T	N, R	R, N	R, N	R, R

When these two scenarios are combined in a two-way sensitivity analysis, they cancel one another out. The optimal policy remains as the conventional policy when the treatment cost and the probability of transitioning under action “N” from state 0 to state 1 are incrementally increasing. While this solution serves as an adequate representation of the transmission grid for small-scale problems, it is extremely time consuming to find a solution for larger problems due to the curse of dimensionality. With the current makeup of states and actions, the hardware capacity is reached with a system of eight poles. In order to account for the hundreds of transmission lines in a system, the states and actions must be redefined.

STATE-AGGREGATED MDP

With the current framework and the hardware capabilities at the group's disposal, there is a limitation of how many poles can be included in the MDP framework. The number of states and actions, as well as the size of the transition probabilities grows exponentially for every additional pole in the system. This is because the original state definition had three states such that $\{0,1,2\} \times \{0,1,2\} \times \cdots \times \{0,1,2\}$ represented the number of states and poles which accrued the number of states for n poles by 3^n. When the number of states becomes more than the memory can store, there is a physical limitation of how many poles can be included in the MDP. To work around this issue, a new way to define the states of the system was created. The MDP model was reformed to incorporate state aggregation which reduces the number of states and actions in the system.

Instead of each individual pole having its own three states and then being combined with every other state of every pole in the system, the states can be defined as the total number of poles within the three states making up the state space. Each pole can occupy one of the three categories of no decay, decay, or failed. We define the state of the system as the distribution of poles across those three categories. In particular, the state of the system is denoted by (N, D, F) where N, D, and F represent the number of no-decay, decayed, and failed poles, respectively. This reduces the number of states for n poles from 3^n in the previous state definition to $\binom{n+2}{2} = \frac{(n+2)(n+1)}{2}$.

Instead of having the action to either replace or treat each individual pole, actions are characterized as the number of poles that are treated and replaced within each category of (N, D, F). More specifically, actions are denoted by a five-parameter vector of the form $(X_1, X_2, X_3, Y_1, Y_2)$ in which X_1 represents the replacements in the no decay state, X_2 is the replacements in the decayed state, and X_3 is the number of replacements in the failed category. Similarly, Y_1 and Y_2 represent the number of poles treated from the no-decay and decayed categories, respectively.

To calculate the transition probabilities between aggregated states under a given action, we need to consider all possible trajectories from the origin state to the destination state. Specifically, consider the pair of origin and destination states (N, D, F) and (N', D', F') under the action (X_1,X_2,X_3,Y_1,Y_2). To find the desired transition probability, we first enumerate all possible trajectories that lead from (N, D, F) to (N', D', F') under (X_1,X_2,X_3,Y_1,Y_2). We then calculate the probability of the occurrence of each trajectory and sum up the corresponding probability values. Possible trajectories can be expressed as non-negative integer solutions to a system of linear equations. To derive this system of equations, we start by considering all possible transitions under each action for an individual pole as follows:

TABLE 8: SHOWS THE ACTIONS AND TRANSITIONS ASSOCIATED WITH INDIVIDUAL POLES.

Transition (origin → destination)	# of Transitions	Action
0 → 0	m_1	Nothing
0 → 1	m_2	Nothing
0 → 2	m_3	Nothing
0 → 0	m_4	Treat
0 → 1	m_5	Treat
0 → 2	m_6	Treat
1 → 1	m_7	Nothing
1 → 2	m_8	Nothing
1 → 1	m_9	Treat
1 → 2	m_{10}	Treat
2 → 2	m_{11}	Nothing
0 → 0	X_1	Replace
1 → 0	X_2	Replace
2 → 0	X_3	Replace

By setting the total number of transitions that start from or end at a particular state, we obtain the following system of equations:

$$N = X_1 + m_1 + m_2 + m_3 + m_4 + m_5 + m_6 \tag{4.6}$$

$$D = X_2 + m_7 + m_8 + m_9 + m_{10} \tag{4.7}$$

$$F = m_{11} + X_3 \tag{4.8}$$

$$N' = m_1 + m_4 + X_1 + X_2 + X_3 \tag{4.9}$$

$$D' = m_2 + m_5 + m_7 + m_9 \tag{4.10}$$

$$F' = m_3 + m_6 + m_8 + m_{10} + m_{11} \tag{4.11}$$

$$Y_1 = m_4 + m_5 + m_6 \tag{4.11}$$

$$Y_2 = m_9 + m_{10} \tag{4.12}$$

We search for possible nonnegative integer solutions to the system of equations above by assigning values to the variables $m_4, m_5, m_6, m_9, m_{10}$ and then solving for the variables $m_1, m_2, m_3, m_7, m_8, m_{11}$. If the values are all non-negative integers, the set of variables is a possible solution. Before searching for possible solutions, we check the feasibility of transitioning from the origin to destination states under the given action by checking the following conditions, otherwise the probability is set to zero for that instance.

$$N + D + F = N' + D' + F' \tag{4.13}$$

$$X_3 \leq F \tag{4.14}$$

$$X_1 + X_2 + X_3 \leq N' \tag{4.14}$$

$$X_1 + Y_1 \leq N \tag{4.15}$$

$$X_2 + Y_2 \leq D \tag{4.16}$$

The final representation of finding $\Pr\{(N, D, F) \xrightarrow{(X_1, X_2, X_3, Y_1, Y_2)} (N', D'F')\}$ is determined by the sum of all the solutions for the number of possible transitions, m_1, $m_2, \ldots m_{11}$, with the transitions probabilities of no-decay poles with the action to treat, no-decay poles under action wait , decayed poles under treatment, and decayed poles with the action to wait. These terms are expressed in the following equation:

$$\sum\nolimits_{\boldsymbol{all\ solutions}\ (\boldsymbol{m_1},\boldsymbol{m_2},\ldots,\boldsymbol{m_{11}})} \binom{Y_1}{m_4,m_5,m_6} P_T^{m_4}(0,0) P_T^{m_5}(0,1) P_T^{m_6}(0,2)$$

$$\times \binom{N-(X_1+Y_1)}{m_1,m_2,m_3} P_N^{m_1}(0,0) P_N^{m_2}(0,1) P_N^{m_3}(0,2)$$

$$\times \binom{Y_2}{m_9,m_{10}} P_T^{m_9}(1,1) P_T^{m_{10}}(1,2) \tag{4.17}$$

$$\times \binom{D-(X_2+Y_2)}{m_7,m_8} P_N^{m_7}(1,1) P_N^{m_8}(1,2)$$

While the previous MDP solution improved the expected total discounted costs by updating the values iteratively assigned to each state, here we apply a policy improvement algorithm to iteratively update the policy based on the expected total discounted costs. The policy improvement algorithm works by first defining an initial policy d_0. At each iteration of the policy improvement algorithm, we first calculate the cost function, and in turn, the value function associated with the current policy d_n as

$$v_n = \left(I - \alpha P_{d_n}\right)^{-1} F_{d_n} \tag{4.18}$$

where the transition probability matrix P_{d_n} shows the probabilities of transitioning between different states under the current policy d_n. Using the calculated value function v_n, we then seek to find a new policy that minimizes the updated value function for each state s by solving the following optimization problem:

$$d_{n+1}(s) = \underset{k\in K}{\operatorname{argmin}}\{f(s,k) + \alpha \textstyle\sum_{s'\in S} P_k(s,s')v_n(s')\} \tag{4.19}$$

Finally, the termination condition is set as $d_{n+1} = d_n$, otherwise we increment n and reiterate the step.

A simple case of five poles was used to explain the framework of the solution space. The solution time for this size of problem only takes a few seconds to complete. The budget for replacement was set to $150,000 which should limit the policy to only making a maximum of three replacements since it costs $45,894.34 per replacement. The treatment budget was set to $8,000 which corresponds to treating 3 poles at a treatment fee of $2,500 per pole. The cost matrix remained the same as originally presented in the first MDP framework. The transition probability under the action of waiting when the pole is not decayed was changed to transition to no decay at 90%, to decay at 8%, and to failed at 2%. The reasoning behind this change was to allow the possibility of going from no decay to failed so the policy would have more variation to consider. With this increased complexity, the model gives nontrivial solutions. For every possible state in the solution space that five poles can inhabit, there is a mapped action recommended by the MDP. There are 21 states the system can enter when there are five poles. The table below shows the optimal policy recommended by the MDP.

TABLE 9: SHOWS THE POSSIBLE STATES FOR A FIVE-POLE SYSTEM.

State	N D F	Policy for State	X_1	X_2	X_3	Y_1	Y_2
1	0 0 5	1	0	0	5	0	0
2	0 1 4	2	0	1	4	0	0
3	0 2 3	3	0	2	3	0	0
4	0 3 2	4	0	3	2	0	0
5	0 4 1	5	0	3	1	0	1
6	0 5 0	6	0	3	0	0	2
7	1 0 4	7	0	0	4	0	0
8	1 1 3	8	0	1	3	0	0
9	1 2 2	9	0	2	2	0	0
10	1 3 1	10	0	3	1	0	0
11	1 4 0	11	0	3	0	0	1
12	2 0 3	12	0	0	3	0	0
13	2 1 2	13	0	1	2	0	0
14	2 2 1	14	0	2	1	0	0
15	2 3 0	15	0	3	0	0	0
16	3 0 2	16	0	0	2	0	0
17	3 1 1	17	0	1	1	0	0
18	3 2 0	18	0	2	0	0	0
19	4 0 1	19	0	0	1	0	0
20	4 1 0	20	0	1	0	0	0
21	5 0 0	21	0	0	0	0	0

Since the state of (N, D, F) is considered one state, State 2 (0, 1, 4) is a state where any one pole can be decayed, while all the other poles are failed. However, decayed and failed are not states themselves as in the previous MDP. For any poles that are failed, the MDP has been formulated to replace them whether there is enough budget or not. This is because there is a heavy penalty to doing nothing or treating a pole that has failed. While initially this solution seems intuitive, the model does not act as trivially as the previous MDP framework. For example, State 5 is shown to have four poles decayed and one failed. The recommended policy for this state is to treat three decayed poles, replace one decayed pole, and replace the failed pole. It is advised to take two separate actions on poles that are both decayed.

This leads to the question of how the MDP will decide upon an optimal policy for a much larger number of poles in the system. After running several iterations with 30-40 poles, the same structure emerged for any number of poles as the structure for a smaller poled system. The run time for a problem of 40 poles takes around seven hours. For the example above with the same parameters for a larger grid, the MDP recommends replacing poles up to the allotted budget whether that pole is failed or decayed. Any remainder of poles that were not replaced and are decayed will be treated until there is no remaining budget.

To incorporate more poles into the state-aggregated MDP and compare the policies recommended for a similar ratio of states for smaller and larger problems, a Monte Carlo sampling method was used. This allowed for the model to sample 100 different scenarios and find the transition probability of those random states. Due to the dimensionality of the systems with greater amounts of poles, a sampling technique is required to have reasonable run times for the code. A Bellman factor, ε of $1x10^{-2}$ was used for the stopping condition. Grids containing five to fifty poles have been outlined below. To allow for a similar number of actions to be placed on a larger grid, the budget was increased based on the multiple of the actions allowed for a five-pole system. Since the original state-aggregated MDP allows for three replacements with a budget of $150,000 and three treatments with a budget of $8,000 in a five-pole system, a 20-pole system then would include four times the budget since there are four times as many poles.

TABLE 10: SHOWS THE RESULTS OF LARGE-SCALE STATE-AGGREGATED MDP

Number of Poles	Possible States	CPU (sec)
5	21	~ 54
10	66	~236
20	231	~3610
30	496	~11395
40	861	~49999
50	1326	~102580

EFFICIENCY IMPROVEMENTS

Due to the calculation runtime, the problem shifted from a value improvement to a policy improvement algorithm for discounted costs. This means that the algorithm now focuses on policies so that the calculated value of $v(i)$ is associated with a particular policy. By making a few alterations to the previous value iteration, the value is now optimizing the policy cost as discussed above. The transition matrix is only saved for each iteration to find the policy, then it is rewritten in the next improvement step when the gap is less than the predetermined value of ε which was $1x10^{-3}$ for calculations. The difference between knowing if the value needs updated or not is set by the relative value of the change between the old value function and the new value function so that it is expressed as a relative value. If the policy was the optimal policy, then the next iteration will give the same policy, otherwise it will improve, and the next policy will have a better value associated to it [72].

To improve performance efficiency, we initialize the value of v instead of using the vector of zeros. Specifically, we initialize v using a naïve policy that would treat poles in the decayed state up to the treatment budget allowance. Any remaining treatment budget will be spent on treating poles in the no decay state. Additionally, any remaining decayed poles will be replaced up to the replacement budget allowance. Finally, the poles in no-decay state will not be replaced even if the remaining replacement budget allows.

The optimal policy is constructed as an approximate solution if the number of combinations of actions is too large. The adaptive grid completes a course grid search where a general idea of the solution values is identified, then a fine grid search tunes the values by checking nearby numbers to give a better objective value.

The value of 500 is used as the sample size to estimate transition probabilities. More specifically, if the number of possible trajectories for a pair of origin and destination states under an action exceeds 500, we sample those trajectories and compute the transition probability based on the sampled trajectories only. The estimated probability based on the sample is scaled by the number of all possible trajectories. This allows us to obtain an estimate of the transition probability between the two states for the given action.

SENSITIVTY ANALYSIS

To study the way the algorithm will react to changes in its parameters, one state was chosen to be compared to the same state of various scenarios with different input transition probabilities or treatment costs. The state will be from a five-pole system with one pole showing no decay, three poles decayed, and one pole failed. The metric of comparison will be the policy cost assigned to the State (N = 1, D = 3, F = 1). Because the policy improvement algorithm aims to minimize the policy cost, a lower policy cost means that the chosen state performed better under those circumstances.

There are two recommended policies with the increase of treatment costs over time for the state of (N = 1, D = 3, F = 1). The initial slope up to 60% recommends a policy to replace the failed pole and treat the three decayed poles. The plateaued discounted cost is for a policy that recommends replacing all the decayed and failed poles.

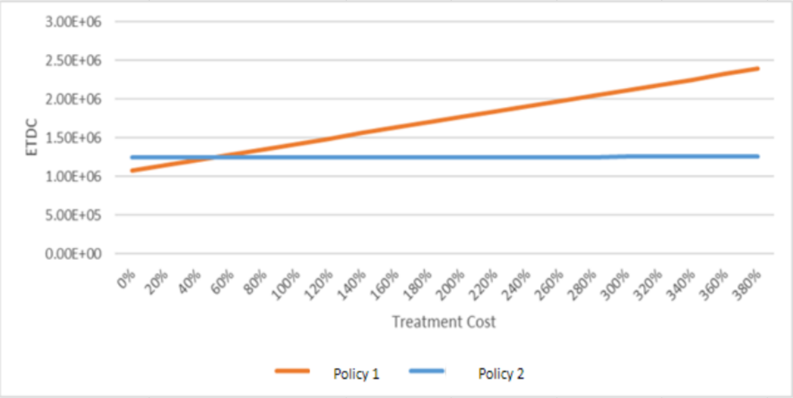

Figure 27: Graph of the policy transition as treatment costs are increased.

This next sensitivity analysis scenario focuses on changing the transition probability of an individual pole under the action of wait (do nothing). The state is specified as (N = 1, D = 3, F = 1) being a five-pole system. As the probability of a pole remaining without decay decreases by 1% and it transitioning to decay increases by 1% at each datapoint the suggested policy changes. The change of policy is nearly identical to that of the previous graph which makes sense because both are incentivizing replacement instead of treatment. The action in the policy says to replace the failed pole and treat all the decayed poles for the first four iterations. Thereafter the action in the policy says to replace all the poles decayed and failed.

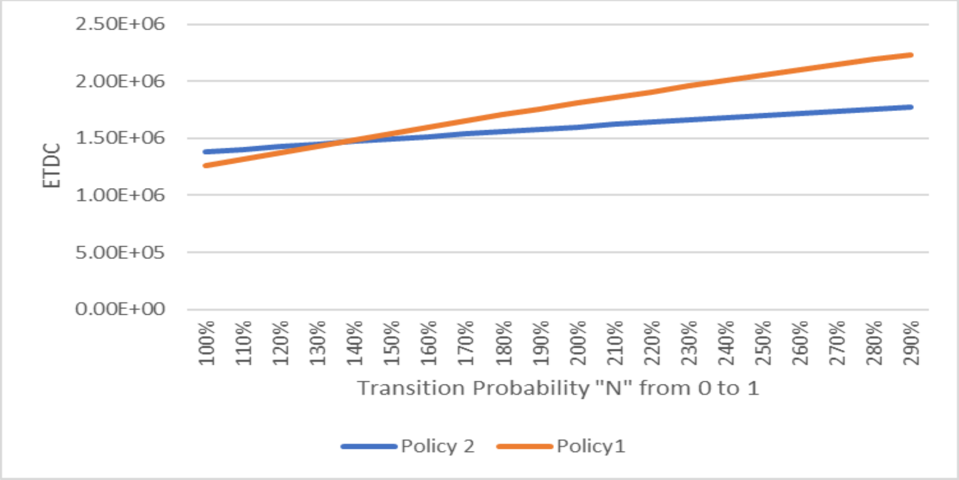

Figure 28: Graph of the policy transition as probability of transitioning from 0 to 1 under action “N” is increased.

The next analysis will focus on the structure of the budget as it relates to being a singular value for both treatment and replacement costs or a separate budgeting scheme. The importance of testing which scenario provides the best policy is based on how the decision makers prefer to operate the grid. If the operator wants to have a higher importance on treated poles, it may be beneficial to combine the budgets to use an extra from the replacements on the treatments. Otherwise, if there are specified number of poles budgeted to be treated and to be replaced, then it is best to separate the budgets so that the code always can optimize up to the maximum. To allow the budget structure to impact the recommended policy, the probability of transitioning from the no-decay to decay state under the do-nothing action was increased compared to the same transition probability under the treat action to a percentage that incentivized treatment more than replacement in the MDP. This increases the relative effectiveness of the treatment action in preventing pole decay.

In the graph, a separate budget of \$170,000 for replacement and \$8,000 for treatment provides the opportunity to replace three poles and treat two poles. The graph has a single budget of \$178,000, by combining these two separate budgets together. The expected total discounted costs of each are shown below. The single budget outperforms the separate budget across all iterations of the possible states. This is likely because poles that are considered at risk for failing can be treated with leftover budget, but that is not necessarily the case for the separate budgets.

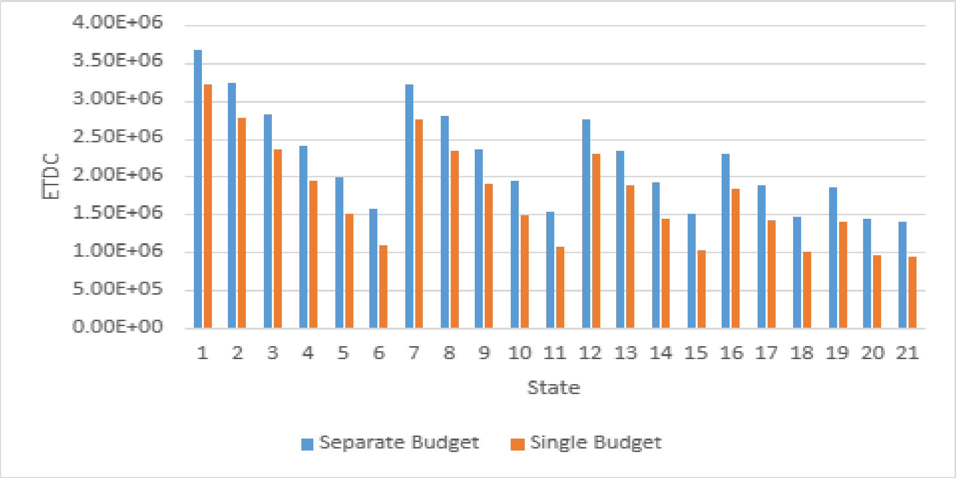

Figure 29: Graph of the optimal policy's expected total discounted costs for a single and separate budget.

Within the 21 mapped actions there are 10 states that have different actions for a separate and single budget. The bold numbers reference changes in the policies compared to the other budget. The number of treatments in the single budget trends higher than the separated budget, while the separated budget trends higher in replacements. Ultimately, the single budget seems like a better solution because it can address the states' needs in a more direct fashion and the optimal policy favors treatment of decayed poles over replacement.

TABLE 11: SHOWS THE OPTIMAL ACTIONS THAT DIFFER FOR STATES IN THE SYSTEM UNDER SEPARATE AND SINGLE BUDGETS.

	Separate Budget					Single Budget				
(N, D, F)	X_1	X_2	X_3	Y_1	Y_2	X_1	X_2	X_3	Y_1	Y_2
0 4 1	0	**1**	1	0	**3**	0	**0**	1	0	**4**
0 5 0	0	**2**	0	0	**3**	0	**0**	0	0	**5**
1 3 1	0	0	1	**0**	3	0	0	1	**1**	3
1 4 0	0	**1**	0	**0**	**3**	0	**0**	0	**1**	**4**
2 3 0	0	0	0	**0**	3	0	0	0	**2**	3
3 1 1	0	0	1	**2**	1	0	0	1	**3**	1
3 2 0	0	0	0	**1**	2	0	0	0	**3**	2
4 0 1	0	0	1	**3**	0	0	0	1	**4**	0
4 1 0	0	0	0	**2**	1	0	0	0	**4**	1
5 0 0	0	0	0	**3**	0	0	0	0	**5**	0

DISCUSSION AND CONCLUSION

With an increasing number of maintenance required to the transmission grid it is imperative that utility companies find a versatile solution to treating and replacing poles in the system. This section provides a condition-based maintenance methodology for utility companies to find the optimal maintenance policy under various constraints. By looking at the policies sensitivity to changes in the costs of treatment as well as changes in the likelihood of poles transitioning into other states when no action is taken, the policies can be compared against one another to see how sensitive the recommended policies are to input data. If the pole enters a state of failure, then there is immediate action required, which is why the MDP deters failure, while suggesting the lowest possible costs by association with the respective actions at various states.

By combining Chapter III and IV, this research provides a holistic approach to identify priority need of maintenance operations on wood poles in transmission grids. The condition-based maintenance solution through MDP can be used to inform the time-based maintenance solutions what the best policy is for when to suggest action on a given pole.

FUTURE WORK

While the MDP produced valuable results, there are many more additions to be made that can enhance the quality of the policy output. The results of the sensitivity analysis to find the optimal policy convey the importance and impact induced by slight changes of costs and transition probabilities. The calibration of the transition probabilities is a future step that will involve creating a climate dependent degradation database to develop probabilities for decomposition of the wood poles. The current transition matrices are based on intuitive assumptions, and therefore are fillers for the true transition likelihoods. In the scope of this thesis, the MDP will be expanded to solve a larger problem that includes more poles in the system.

State aggregation gives an approximated MDP by considering states of the same nature into one state instead of having each individual pole's state as a unique state. Other extensions to our proposed framework is to incorporate other asset health surrogates such as age into the state definition while ensuring the Markov property is met. A final step for the validation of the MDP will be to prove optimality in the presented policy. This can be determined through analytical proofs with set transition probabilities, state to action costs, and budget.

CHAPTER V

CONCLUSION AND FUTURE WORK

The energy grid is a versatile system constantly changing and adapting to future technological advancements. From generation to transmission to distribution, consumers expect a steady flow of electricity to be always at their disposal. When an interruption happens, it is maintenance personnel's number one focus to return electricity to restless consumers. The transmission grid's role in this system is to deliver high-voltage energy across many miles, which will then be stepped down and sent for individual usage. When a transmission line is disturbed, it puts many more people at risk of losing power. Hundreds of miles make up a single company's transmission network and it takes an incredible amount of labor and monetary investments to keep the transmission grid working flawlessly. With a majority of transmission lines being installed in the mid 1900's, there is a significant number of lines becoming due for replacement or intensive other intensive maintenance procedures. It is vital that companies plan economically and ensure the grid maintains its integrity to withstand operational and environmental stresses impacting it. Sunflower Electric Power Corporation has a grid size that would require over a half billion dollars to replace transmission lines that have been in service for over 40 years. This research provides data analytic solutions to maintain overhead transmission line's vital assets.

Chapter II focuses on how the conductor reacts to stress by creating a simulation of the sag it incurs over time. By knowing the hourly conditions, the line is exposed to, a degradation model was developed to show a way of measuring health in the conductor by knowing its permanent elongation. Sensitivity analysis provided a means of seeing how conditions like ice storms, at various energy loads, and wind will impact the permanent elongation of the conductor.

Chapter III proposes time-based maintenance strategies for managing wood poles within overhead transmission lines. The replacement age of a pole is the focal point of the chapter, and its effects on the costs. Economic analysis is performed on replacement and treatment strategies in order to examine various ages on the distribution of wood pole ages and reduce total treatment and replacement costs per year. Using an optimization framework, the maintenance of wood poles can be improved by replacing and treating at the optimal ages. Various scenarios were shown to portray the impact of a few chosen ages.

Chapter IV used Markov Decision Processes to develop a condition-based maintenance strategy to provide decision makers with a policy to follow at the state of the grid. The possible actions and states were aggregated to deter the curse of dimensionality and include more poles in the system. The proposed MDP framework provides the grid operators with pole maintenance policies that minimize the total discounted cost over an infinite horizon.

The next steps for the simulation of the conductor will be to gather field data to compare against the model. This requires field measurements which are not available to the team currently. Other inclusions to the conductor’s degradation simulation would be to find out the environmental conditions for more poles and have the simulation loop through an entire network instead of a single pole at a time. This way there can be a quickly updated framework that data analysts can give the model the current weather conditions and operational conditions and find out which lines are likely to have the most permanent elongation. By knowing this health index across the entire transmission line network, maintenance personnel can decide amongst the hundreds of transmission lines which to inspect first.

The optimization model for time-based maintenance can be improved in future work by changing the remaining life of the pole to include a factor of degradation instead of only operating by its calendar age. Other scenarios that would be beneficial for transmission company's usage would be how the model reacts to different budgets on a yearly basis. The financial state of the economy determines the type of loan companies can receive and if it is preferable to wait for a better loan to be obtained in the future, maintenance personnel will need to know how that decision will impact on the grid. This includes various interest rates or budget changes as well.

The framework of the Markov Decision Process presented in Chapter IV can be expanded upon by using field data to inform the transition probability matrices. Calibration is necessary to have reliable policy development. Current transition probabilities have been estimated by intuitively analyzing how wood poles decay over time; however, a database with the degradation of thousands of poles will be needed to have reliable probabilities. The main limitation of this model is the number of poles that can be in the MDP. Hardware capabilities limited the matrix storage size for the non-aggregated model. The state aggregated model gives an approximate solution and does not identify which poles to be replaced, only the number that require that action. Further research would include combining the MDP and other health asset surrogates, like age, into the state definitions.

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