Cable Reliability Management Strategies

Technical Report

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PRODUCT DESCRIPTION

In previous collaborative research with several utilities, EPRI developed methods for forecasting the failures and cash flows associated with managing a population of underground cable. This study builds on that research and provides a method for developing least-cost repair and replacement policies for such a population. The policies specify when to replace a cable section or an entire circuit, depending on the age of the section and the number of failures the section has experienced.

Results & Findings

The optimal strategy for cable replacement depends critically on what information is available about the existing cable inventory. This report considers various levels of information that may range from knowing the type of cable, its age and failure history to essentially nothing except the approximate vintage. The algorithm and Strategic Decision Policy Model developed determine an optimal strategy for the level of information provided. The report also provides a method to quantify the benefits associated with various levels of information. Finally, the report examines two levels of cable repair/replace strategy. Information here will help utilities determine a cable replacement policy for individual sections in a circuit. It will also help them analyze whether to replace the entire circuit all at once, thereby realizing advantages of economies of scale.

Challenges & Objectives

The project's primary objective is to develop an algorithm and Strategic Decision Policy Model that utilities can use to optimize the replacement strategy for underground cable in distribution systems. Together, this algorithm and policy model create a framework for comparing policies based on different levels of knowledge on cable age and failure history. Example results indicated that a policy based on age-only generates significantly less value than the more sophisticated age- and failure-based policy. However, there appears to be only incremental value for the age- and failure-based policy compared with a simpler failure-based policy. While these results are only illustrative, they demonstrate the ability of the framework to attach an economic value to improved information and indicate how to perform a failure-based analysis. A new decision introduced into the analysis concerns whether it is worthwhile to replace an entire circuit, even if a section-by-section analysis indicates that not all individual sections should be replaced.

Applications, Values & Use

It is natural to formulate the problem of managing aging assets as a cost minimization problem, assuming that the asset is constrained to provide a fixed level of service. Replacement and repair costs are particularly important in the management of aging cable. As technology changes, replacement and repair costs will change, although the direction of such changes may be uncertain. This study analyzes the repair vs. replace decision at both the section and circuit levels, specifically focusing on repair and replacement costs. Of particular value is an approach for the dealing with the impacts of total circuit failures on individual section failure rates. Further research can generalize the framework to consider other costs, including operating and maintenance costs, salvage value, and lost revenue due to deteriorating quality or derating.

EPRI Perspective

The Strategic Decision Policy Model appears to be quite promising for utility management of aging cable assets. It addresses both the section-by-section repair/replace policy problem as well as the circuit-level policy issues. A key advantage of an analytic framework is the ability to ask "What if?" questions, such as, "What if the replacement cost were higher?" or "What if the repair cost were lower?" Other questions in a particular study might include: "How would the results change with a lower discount rate?" "How would the policy change if the failure rate assumptions are too low?" All these questions and more are amenable to analysis with EPRI's Strategic Decision Policy Model, which allows the user to select a probabilistic hazard function (e.g., Weibull or piecewise linear hazard function) to describe the cable failure process.

Approach

The Strategic Decision Policy Model describes the economic effects of various policy alternatives on an inventory of underground cable. Model developers first applied the Cable Failure Model from an EPRI companion report, Medium Voltage Cable Failure Trends: Research Status Report (1002256), to describe the behavior of cable. Using this model, they overlaid a specification of policy alternatives and costs to help determine the optimal (least-cost) policy. Developers contrasted a repair/replace strategy based on the age and failure history of a section of cable with strategies based solely on age or failure history. By quantifying these differences, they attached an economic value to collecting data that can be used to formulate more sophisticated policies. The policy alternatives examined in this report are "repair" or "replace." However, the decision structure is designed so that it can be later generalized with further research. This could lead to "rejuvenation" being added as an option. Finally, they created a decision framework that addresses whether the analysis should be performed at the individual single-section level or at the circuit level.

Keywords

Cable reliability
Cable asset management
Underground distribution cable
Cable replacement
Cable repair

ABSTRACT

The primary objective of this project is to develop a model and algorithm that can be used to optimize the replacement strategy for underground cable in distribution systems.

The optimal strategy for cable replacement depends critically on what information is available about the existing cable inventory. We consider various levels of information that may range from knowing the type of cable, its age and failure history to essentially nothing except the approximate vintage. The algorithm determines an optimal strategy for the level of information that is provided.

We provide a method to quantify the benefits associated with various levels of information. The main idea is that as information about the cable inventory increases, the optimal strategy becomes more responsive to differences among the cables in inventory and therefore yields a superior solution.

There is clearly a tradeoff between the cost of additional information and the benefit, based on the change in strategy, that such information provides. A consequence of quantifying the value of information is that we will be able to suggest to utilities what information to maintain about cable inventory.

We examine two levels of cable Repair/Replace strategy. We determine a cable replacement policy for individual sections in a circuit and also analyze the decision of whether to replace the entire circuit all at once, thereby taking advantages of economies of scale.

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INTRODUCTION

This report builds on work previously performed for EPRI as part of tailored collaborations with several utilities. In those collaborations, we developed methods for forecasting the failures and cash flows associated with managing a population of underground cable. This report provides a methodology for developing least cost repair and replacement policies for such a population.

The policies specify when to replace a cable section depending on the age of the section and the number of failures the section has experienced. We also develop a policy for when to replace an entire circuit.

1.1 Theory and Methods

The problem of specifying methods for managing aging assets requires consideration of three distinct phenomena. The first consideration is how best to represent the dynamic processes of failure and repair of equipment. The second consideration is how to modify the failure and repair processes to account for aging of equipment. The third consideration is how to combine the economics of failure and repair of equipment with decision alternatives available to the utility to come up with the least-cost cable repair/replace strategy. The first two considerations are addressed in an EPRI companion report, *Medium Voltage Cable Failure Trends: Research Status Report*, EPRI, Palo Alto, CA: 2003 (1002256). This report addresses the policy issue of how to make decisions about repairing and replacing cable sections and circuits.

1.2 The State of an Asset

The dynamic process of equipment failure can be represented mathematically and that representation provides a forecast of the behavior of the equipment. Clearly, the knowledge of the present condition of an aging cable section is essential for forecasting the future behavior of that section. The mathematical description that summarizes that present condition is known as the *state* of the asset. The specification of an asset's state, similar to that used in thermodynamics, is specific to an asset or class of assets. Now, as the past history of the asset varies, the present state varies. It is this variation that our methods investigate in order to determine a policy for an aging asset. The policies we develop for controlling aging assets are *state-dependent* policies; the policy varies by state. In principle, if the state of an asset were known with precision, then the policy would be known as well. However, three facts about the state of an aging asset make the problem of determining the best policy, and forming guidelines for treating aging assets, a challenging one.

First, there is no single description of asset state that is valid for all classes of aging assets. Nor is there a single description of a given asset's state that is necessarily uniformly applicable by all utilities (or asset managers). That is, the information that one person chooses to use to describe an asset (age, manufacturer, past peak loading, etc.) may be different from the information another person might use; and there is no single correct answer. Much of the description of state depends on what is known. Clearly, it is of limited value to base an aging asset policy on the variable *manufacturer* if the manufacturer of the particular piece of equipment is unknown.

Second, even if, at one time, all the information that comprises the state of an asset were known for a single piece of equipment, over time the knowledge of the true state of an asset becomes uncertain. This is because the process of aging has consequences that are themselves uncertain.

Third, some important components of the state description are unobservable. Important components are those the values of which can cause the policy to change. Unobservable states can be inferred based on the outcome of diagnostic tests or other observations. This process of inference adds to the uncertainty in the state.

Therefore, the problem of specifying the state of an asset is itself an interesting problem. The methods we have created require specification of the state before any analysis can be done. This study focuses on two key state variables for underground cable, age and failure history. However, conceptually the methods permit virtually any description of a state for any asset.

1.3 Cable Aging

The burnout period associated with aging indicates that as cable ages, it is not appropriate to apply stationary failure probabilities to represent failure dynamics. As equipment ages, it is important to determine whether the older equipment can perform the function for which it was originally installed.

Specific considerations come into play for underground cables. Such problems as corroded conductor, water trees, partial discharges, corroded neutral system, and failed jacket all can lead to cable failure. Unfortunately, these problems are not directly observable until the cable is removed from the ground, so absent test information, the best we can do is base decisions on the failure history of cable sections and circuits.

1.4 Economic Considerations

It is natural to formulate the problem of managing aging assets as a cost minimization problem, assuming that the asset is constrained to provide a fixed level of service. Replacement and Repair costs are particularly important in management of aging cable. As technology changes, replacement and repair costs will change, although the direction of such changes may be uncertain. In this study, we analyze the repair vs. replace decision at both the section and circuit levels, and thus we focus on repair and replacement costs. Further research can generalize the framework to consider other costs, including (a) operating and maintenance costs, (b) salvage value, and (c) lost revenue due to deteriorating quality or derating.

1.5 Description of Report

This report contains six additional chapters. In Chapter 2, we characterize the Strategic Decision Model and specify what information is sufficient to describe the state of the inventory of underground cable. We begin with a simplified “Toy Model” formulation for clarity. In Chapter 3, we show how the model is sensitive to the cost assumptions and to the level of detail of our state of information about the cable. In Chapter 4, we extend the Toy Model by introducing real hazard functions and a more realistic array of cable states. In Chapter 5, we generalize the analysis to encompass both optimal section and optimal circuit replacement strategy. Chapter 6 summarizes the work and suggests directions for further research. Chapter 7 provides a list of references.

2

STRATEGIC DECISION MODEL

The model describes the economic effects of various policy alternatives on an inventory of underground cable. We use the Cable Failure Model from the EPRI companion report, *Medium Voltage Cable Failure Trends: Research Status Report*, EPRI, Palo Alto, CA: 2003 (1002256) to describe the behavior of cable. We overlay on this model a specification of policy alternatives and costs. By adding control and economic considerations, we can determine the optimal (least cost) policy.

We will also demonstrate how the optimal policy and the overall cost can be determined as a function of level of information. We contrast a Repair/Replace strategy based on both the age and failure history of a section of cable with strategies based solely on age or solely on failure history. By quantifying these differences, we can place an economic value on collecting data that can be used to formulate more sophisticated policies.

The policy alternatives examined in this report are "Repair" or "Replace." However, the model logic does not depend on the existence of only two alternatives. The decision structure is designed so that it can be later generalized with further research. This could lead to "Rejuvenation" being added as an option.

A circuit is defined to be a collection of individual cable sections. A key model-design decision was whether the analysis should be performed at the individual single-section level, or whether it should be performed at the circuit level. We created a decision framework that addresses both levels. The decision model has two stages:

> Section Strategy – Determine the optimal strategy for individual sections. The optimal strategy is a complete specification for whether to replace a section for every possible combination of age and number of failures.
>
> Circuit Strategy – Given the optimal section strategy, the model then evaluates whether to replace the entire circuit all at once to take advantage of economies of scale in replacement cost.

2.1 Section Analysis – The Basic Model

We begin by addressing the section-level policy problem: How to decide when and under what conditions to replace individual sections. Chapter 4 discusses how this section-level analysis is integrated into a decision analysis framework for analyzing overall circuit strategy.

We proceed in two steps. In the first step we present a “Toy Model” which is useful for explaining the basic decision model. For insight and clarity, the Toy Model uses intentionally simplified failure probabilities and age states. In the second step, discussed in Chapter 4, we incorporate the detail of “real” hazard functions to show how hazard functions are woven into the policy model and to determine how sensitive the model is to them.

2.1.1 Section Interactions in a Circuit

It is important to note that, even for determining individual section strategy, the remainder of the circuit cannot be ignored. This is because section failures may be correlated in a given circuit. Indeed, total circuit failures may be more important than an individual section’s failure history in determining the hazard rate for that section.

A key source of correlation in section hazard rates is common-cause events. Simply put, several sections may fail together in a circuit for the same reason. For example, a cluster of failures in different sections of a circuit may indicate a more severe environment in the ground, a more severe loading history, or effects of cable fault locating techniques on nearby sections. Or, perhaps, a cluster of failures could indicate a common flaw in the cable buried in the circuit or a common problem with how it was installed.

Consequently, even in the optimal section strategy analysis, we must pay attention to the impacts of circuit failures on individual section hazard rates. This is a very difficult analytic problem. We will later describe an approximate model for quantifying cross-section interactions.

The Toy Model assumes that the circuit impacts on individual section failures have somehow been taken into account. In Chapter 4 we will model the circuit impacts explicitly in the context of real hazard functions.

2.1.2 Cable Failure Process

The basic cable failure process is described by a Markov process. The Markov process is a probabilistic model useful in analyzing complex systems. It is very general and allows us to describe a cable section as evolving through a dynamically changing sequence of states. The state transitions may be modeled quite generally as following whichever probabilistic process that we wish to specify. For example, we will model cable failures as following the well-known Weibull hazard function and also a Piecewise-linear hazard function.

Central to the theory of Markov process models are the concepts of state and state transition. Our general description of the Markov model quotes liberally from Ronald Howard who invented the policy iteration algorithm we shall utilize [1].

2.1.3 The State Concept

To understand the notion of "state," let us first realize that the present situation in a physical system can usually be specified by giving the values of a number of variables that describe the system. For example, a chemical system can often be specified by the values of temperature, pressure, and volume; the instantaneous description of a spacecraft would include its position in spatial coordinates, its mass, and its velocity. Such critical variables of a system are called "state" variables. For the chemical process the state variables are temperature, pressure, and volume; for the spacecraft they are position, mass, and velocity. When the values of all state variables of a system are known, we can say that its state has been specified. The state of a system thus represents all we need to know to describe the system at any instant.

In designing dynamic, state-based models, we focus on the variables that change over time using the other variables as background descriptors. For example, consider a system of underground cable. A set of descriptors for a particular section or circuit might include such things as:

CABLE CHARACTERISTIC	POSSIBLE LEVELS
Cable Type	– EPR, PILC, XLPE, TR-XLPE ...
Conductor Size	– 1/0, 2/0, 750 kcmil, ...
Voltage Class	– 15kV, 25kV, 35kV, ...
Insulation Thickness	– 175 mils, 220 mils,
Age	– new, 5 years, 10 years, ...
Failure History	– 0 failures, 1 failure, 2 failures, …

While all these factors may influence decisions made about the cable, only two change over time — age and failure history. The other variables may be just as important, but they are fixed quantities and may thus be treated as model inputs rather than state variables. Therefore our model focuses on age and failure history as state variables. Later we will discuss additional potential state variables.

2.1.4 The Transition Concept

In the course of time a system passes from state to state and thus exhibits dynamic behavior. In the chemical system such changes are caused by the application of heat, an increase in volume, etc. The spacecraft would experience a change of state if it burned fuel or even when it simply coasted under the earth's gravitational influence. Such changes of state are called "state transitions" or simply, "transitions." The most general "state transition" model would allow states described by continuous variables and transitions that could occur at any time. For tractability, we shall assume that a section of cable may occupy only a finite number of age and failure states, for example (age 15, 1 failure) or (age 25, 2 failures).

State transitions are modeled with a state transition matrix like the example below.

DATA INPUTS--BASE CASE

Section Failure Rates*

		Failures		
		0	**1**	**2+**
Age	**0**	0.1	x	x
	5	0.2	0.2	x
	10	0.3	0.4	0.5
	15	0.4	0.6	0.7
	20+	0.5	0.8	0.9

*Assumes circuit impacts built in failure rates

Replacement Cost	100
Repair Cost	50
Annual Discount Rate	0.11

Figure 2-1
Data Inputs for the Base Case

The rows in the matrix correspond to the cable's age and the columns correspond to the number of failures that cable has experienced. Each entry in the table is the probability that a cable in the given state defined by an (age, failures) pair will fail, assuming that the cable is not replaced. For example, in the simplified example, the failure probability for a cable section of age 15 that has experienced exactly one previous failure is 0.6. That is, there is a 60% chance that a cable in the (age = 15, failures = 1) state will fail.

To extend the example, with probability 0.6 the cable will fail and the next state will be (age = 20, failures = 2). With probability 0.4 the cable will not fail and the next state will be (age = 20, failures = 1).

We presume that if a cable section is replaced, then the next state will be (age = 0, failures = 0). That is, replacement means replacing with new cable.

Note that, given a specific state and time period, the state transition matrix allows us to describe the full range of possible future states in the next time period, and the probabilities of all these future states.

2.1.5 The Decision Structure

The most interesting problems in the treatment of dynamic probabilistic system models arise when we have the opportunity to control the system. In such problems we want to select from among the alternatives available for the operation of the system those alternatives that are in some sense most rewarding. We then augment the state description by saying that whenever the system enters a state the probability and reward functions governing departure from it are not fixed, but rather may be selected from among a finite set of alternatives. Associated with each alternative in a state will be the transition probability to the next state and a cost or reward for making this transition.

Note that we can only select an alternative when the system enters a state; when the selection is made, we have determined both the probabilistic and economic rules for the system until it makes its next transition. In general, the number of alternatives may differ from one state to another. In the Toy Model, we will assume that each state has exactly two alternatives: Replace or Not Replace.

The costs of the alternatives are specified in Figure 2-1. In the Toy Model, we assume that if a cable segment is replaced, it has a fixed cost of 100 (the cost units are arbitrary, but it may be helpful to think of them in $1000). However, if a cable unit is not replaced, as we have seen there is some probability that it will fail. We assume that if it does fail, it must be immediately repaired. In the example of Figure 2-1, the Repair cost is 50.

2.2 Policy Iteration

We want to solve the problem of how to select the alternatives that will make operation of the system most rewarding. The selection of an alternative for operation when the system enters a given state is called a decision, and the set of decisions for all states constitutes a policy. Then the problem is to find the most rewarding or least cost policy.

To solve the problem we must specify more clearly what we mean by "least cost." If the system is to operate for an indefinite interval of time, a reasonable criterion is to minimize the present value of the expected total cost. Thus we must specify an annual discount rate (0.11 in the Figure 2-1 example).

Policy Iteration is a mathematical programming algorithm that starts with a trial policy (a specific alternative for every state) and then iteratively selects alternative policies that have lower and lower total costs until it finds the overall best or optimal least cost policy. Unlike most other mathematical programming algorithms, Policy Iteration has the following two extremely desirable features: (1) each alternative policy it suggests is guaranteed to be at least as good as the previous policy and (2) it is guaranteed to converge to the optimal policy.

The need for a mathematical programming algorithm is apparent if we consider how many policies we would have to check if we needed to cost-out every possible policy. Since there are 12 states and two failures per state, there are 2 to the twelfth power or 4,096 possible policies. In the more realistic 24-state model we shall present in Chapter 4 there are 16,000,000 possible policies. Evaluating each one would be tedious and unenlightening. Thus, even in very simple cases, an algorithm is absolutely essential.

We will not present the details of the algorithm here, but we will provide a verbal overview. The interested reader can get a complete description in the R. A. Howard book cited above. The basic steps of the algorithm are as follows:

> Step 1. Begin with an arbitrary policy, i.e., a decision for each state. Given a decision for each state, it is possible using matrix theory and linear algebra to calculate the future expected present value of being in each state.
>
> Step 2. For each state, test each decision, Replace/No Replace, to see if changing the decision would reduce the total cost, assuming that the future values of the other states are fixed at the levels calculated in Step 1. This is a simple calculation because it assumes that changing the decision in each state does not affect the value of being in other states. This is an approximation because, in fact, all decisions affect all state values.
>
> Step 3. If no decision in Step 2 improves the future expected present value, the current policy is optimal. If at least one decision improves the future expected present value, modify the current policy with these decisions and go to Step 1.

A very useful benefit of applying the Policy Iteration algorithm is that the results may be used to compute the steady state frequencies of state occupancies. These are the fractions of times the segment will be in each (age, failures) state. For our application, we can use this result to forecast the long term inventory as a function of age and number of failures of a set of cable sections in a circuit. The example below will illustrate this.

2.3 Base Case Analysis

We now illustrate how Policy Analysis may be applied to the example in Figure 2-1 to derive the optimal strategy and costs. We shall call this case the Base Case and when we are finished analyzing it, we will compare it to other cases with different costs and characteristics.

Figure 2-2, "Iteration 0," shows the result of Step 1. While we might have selected any policy to begin, it is advantageous to make an educated guess about what the optimal policy might be. Often, a good starting point is to choose as the initial decision in each state the alternative that minimizes the cost for that state alone, ignoring the future consequences. For the current set of failure probabilities and costs, this "myopic policy" results in choosing "No Replace" no matter what age and failure state that cable might be in.

ITERATION	**0**			
		Initial Policy	**Steady State Frequencies**	**Policy Evaluation Values**
Age 0	**0 Failures**	No Replace	0%	298.87
Age 5	**0 Failures**	No Replace	0%	325.08
Age 5	**1 Failures**	No Replace	0%	344.65
Age 10	**0 Failures**	No Replace	0%	346.13
Age 10	**1 Failures**	No Replace	0%	371.30
Age 10	**2 Failures**	No Replace	0%	379.30
Age 15	**0 Failures**	No Replace	0%	360.82
Age 15	**1 Failures**	No Replace	0%	389.93
Age 15	**2 Failures**	No Replace	0%	396.40
Age 20	**0 Failures**	No Replace	0%	368.18
Age 20	**1 Failures**	No Replace	0%	399.92
Age 20	**2 Failures**	No Replace	100%	405.41
			Expected Value	405.41

Figure 2-2
Beginning of Policy Iteration

Given the No Replace policy, we calculate the future expected present value of being in each state. This is shown in the Policy Evaluation Values Column. We also can compute the steady state (long term) frequency of occupying each state, shown in the Steady State Frequency column. Notice that the steady state frequency is 100% in the final state, (Age 20, 2 Failures). This is the natural consequence of the fact that if you never replace the cable, over time the cable inventory will gravitate to the maximum number of age and failures. The Expected Value of 405.41 shown at the bottom of the column is a weighted average of the steady state frequencies and the policy values; this is a single number that is a useful numeraire for summarizing the worth of the overall policy.

Figure 2-3 shows the result of the first iteration of the Policy Iteration algorithm.

ITERATION 1

		Updated Policy	Steady State Frequencies	Iteration 1 State Values
Age 0	**0 Failures**	No Replace	27%	272.72
Age 5	**0 Failures**	No Replace	24%	296.55
Age 5	**1 Failures**	No Replace	3%	310.97
Age 10	**0 Failures**	No Replace	19%	315.47
Age 10	**1 Failures**	Replace	7%	335.48
Age 10	**2 Failures**	Replace	1%	335.48
Age 15	**0 Failures**	Replace	14%	335.48
Age 15	**1 Failures**	Replace	6%	335.48
Age 15	**2 Failures**	Replace	0%	335.48
Age 20	**0 Failures**	Replace	0%	335.48
Age 20	**1 Failures**	Replace	0%	335.48
Age 20	**2 Failures**	Replace	0%	335.48
			Expected Value	304.66

Figure 2-3
Results of First Iteration

Note that the algorithm results in a different policy – the new policy is to replace if the section is Age 10 and has at least one failure, and to replace at age 15 or higher regardless of the number of failures. Also note that the Policy Evaluation Values are lower in every state. This uniform improvement is a feature of the Policy Iteration algorithm. Finally, observe that the overall Expected Value is lower by about 75%, even after only one iteration.

The policy improvements for intermediate iterations are not particularly meaningful. Thus, for brevity, we simply summarize the results of Iterations 2 and 3. In Iteration 2, the policy changed and the Expected Value went to 276.79. In Iteration 3, the policy once again changed and the Expected Value was lowered to 275.92.

In Iteration 4 the policy did not change, which implies that the Iteration 3 policy is the overall cost-minimizing optimal policy. Figure 2-4 shows the final policy (Iteration 4) and the consequences of following that policy. Figure 2-5 shows the final policy in the form of a policy diagram. The policy diagram's left-hand region (light shading) indicates the states in which the optimal policy is No Replace and the upper-right region (dark shading) indicates the states in which the optimal policy is Replace. Reading the policy table, we see that the optimal policy is not to replace a cable segment unless it has reached Age 15 and experienced 2 or more failures, or if it has reached Age 20 and experienced 1 or more failures.

ITERATION 4

		Updated Policy	Steady State Frequencies	Iteration 4 State Values
Age 0	**0 Failures**	No Replace	18%	238.37
Age 5	**0 Failures**	No Replace	16%	258.54
Age 5	**1 Failures**	No Replace	2%	271.43
Age 10	**0 Failures**	No Replace	13%	273.98
Age 10	**1 Failures**	No Replace	5%	290.29
Age 10	**2 Failures**	No Replace	0%	296.64
Age 15	**0 Failures**	No Replace	9%	284.35
Age 15	**1 Failures**	No Replace	7%	301.14
Age 15	**2 Failures**	Replace	2%	304.56
Age 20	**0 Failures**	No Replace	11%	290.15
Age 20	**1 Failures**	Replace	12%	304.56
Age 20	**2 Failures**	Replace	4%	304.56
			Expected Value	275.92

Figure 2-4
Optimal Policy

Replacement Cost	100	**Repair Cost**	50

Failures	**Optimal Policy**				
2	x	X	No Replace	Replace	Replace
1	x	No Replace	No Replace	No Replace	Replace
0	No Replace	No Replace	No Replace	No Replace	No Replace
Age	**0**	**5**	**10**	**15**	**20**

Optimal Cable Policy by Age and Failure History
Base Case

Figure 2-5
Optimal Cable Policy for the Base Case

Consider the steady state frequencies associated with the optimal policy in Figure 2-5. There are 18% new cable sections in steady state, which means that 18% of the sections are replaced each period. Note that 18% is also the total contribution from the three states in which the optimal strategy is to replace: 2% from (age 15, 2 failures), 12% from (age 20, 1 failure) and 4% from (age 20,2 failures). One way to think about these results is that if there are 1000 sections of cable, multiplying the percentages by 1000 indicates in the long run how many sections will be in each state. The result is shown in Figure 2-6. A bar chart showing the composition of the steady state inventory in graphical terms is shown in Figure 2-7. For example, in the long run, following the optimal policy would result, on average, in 182 sections at age 0 with 0 failures; 164 sections at age 5 with 0 failures; 18 at age 5 with 1 failure, and so on. Thus, in this example, the long term inventory would include a fairly even distribution of sections across ages and numbers of failures.

Replacement Cost	100	**Repair Cost**	50

Failures	**Cable Inventory**				
2	x	X	4	23	41
1	x	18	47	68	119
0	182	164	131	92	110
Age	**0**	**5**	**10**	**15**	**20**

Cable Inventory by Age and Failure History
Base Case

Figure 2-6
Steady State Cable Inventory

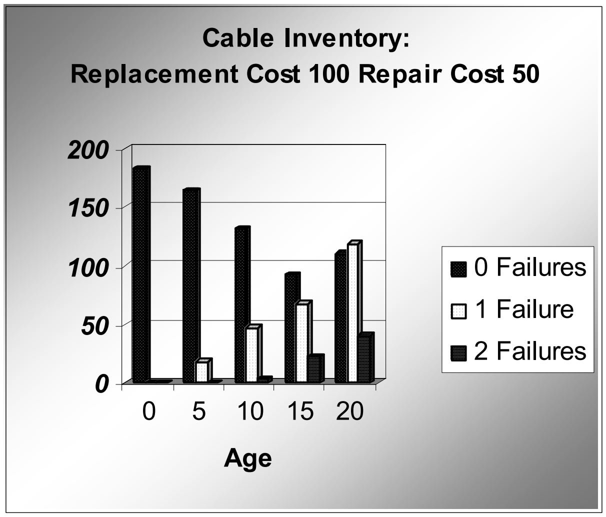


Figure 2-7
Cable Inventory by Age and Failure History

We observe that the optimal Expected Value is 276 compared to the starting value of 405, a cost reduction of close to 33%. It is not surprising that the Policy Iteration algorithm converged so rapidly. While it could theoretically take many more iterations, in practice it is quite rare to observe more than 4 or 5 iterations before optimality, even for much more complicated models. Compare this to the 4,096 evaluations that would have been necessary to enumerate all the policies.

2.4 Sensitivity Analysis

A key advantage of an analytic framework is the ability to ask “What if?” questions, such as, What if the replacement cost were higher, or What if the repair cost were lower? Other questions in a particular study might include: How would the results change with a lower discount rate? How would the policy change if the failure rate assumptions are too low? Are the results sensitive to the type of Hazard Function used to generate the failure rates? All these questions and more are amenable to analysis with the model. For brevity, we will not show every possible sensitivity result, but rather we present a range of cost sensitivities that illustrate the power of the model even in this over-simplified context. The sensitivity of the results to failure rates is addressed in Chapter 4.

The Toy Model is currently programmed in Excel. We hope to extend it to a more general Visual Basic program, but even in Excel we are able to automate many analyses. For example, for the Toy Model, the user can input a set of up to five pairs of replacement and repair costs, and the model will automatically compute the optimal policy for each of the five cases. That is, every time the user changes a cost, five versions of policy iteration run simultaneously so that we can compare the results. The software for these simultaneous optimizations takes only fractions of a second to run.

We briefly discuss each sensitivity case below, followed by a summary comparison of all cases.

Figures 2-8, 2-9 and 2-10 show the results of doubling the replacement cost (everything else being equal). Note that the optimal policy is never to replace, which results in the oldest possible steady state inventory – 100% of the cable sections are the maximum age with maximum failures.

Replacement Cost	200	**Repair Cost**	50

Failures	**Optimal Policy**				
2	x	x	No Replace	No Replace	No Replace
1	x	No Replace	No Replace	No Replace	No Replace
0	No Replace	No Replace	No Replace	No Replace	No Replace
Age	**0**	**5**	**10**	**15**	**20**

Optimal Cable Policy by Age and Failure History
Sensitivity Case 1

Figure 2-8
Optimal Cable Policy by Age and Failure History

Replacement Cost	200	**Repair Cost**	50

Failures	**Cable Inventory**				
2	x	X	0	0	1000
1	x	0	0	0	0
0	0	0	0	0	0
Age	**0**	**5**	**10**	**15**	**20**

Cable Inventory by Age and Failure History
Sensitivity Case 1

Figure 2-9
Cable Inventory by Age and Failure History

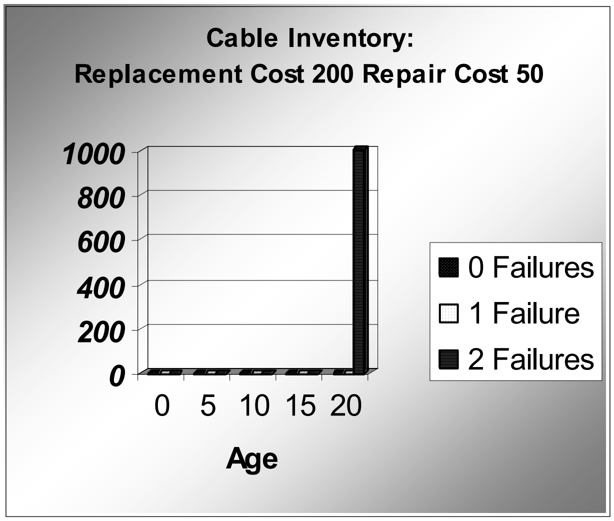


Figure 2-10
Cable Inventory by Age and Failure History

Figures 2-11, 2-12 and 2-13 show the results of halving the replacement cost (everything else being equal). Note that the Replace policy region is bigger than the Replace region of the base case. In other words, with lowered replacement costs provides an inducement to replace earlier and more often. Notice also that the steady state inventory becomes younger and "healthier." Counting the 1 and 2 failure cells in Figure 2-12 reveals that 320 cable sections have one or more failures in the base case, compared to 236 in the reduced-replacement-cost case.

Replacement Cost 50

Repair Cost 50

Failures	**Optimal Policy**				
2	x	x	Replace	Replace	Replace
1	x	No Replace	No Replace	Replace	Replace
0	No Replace	No Replace	No Replace	No Replace	Replace
Age	**0**	**5**	**10**	**15**	**20**

Optimal Cable Policy by Age and Failure History
Sensitivity Case 2

Figure 2-11
Optimal Cable Policy by Age and Failure History

Replacement Cost 50

Repair Cost 50

Failures	**Cable Inventory**				
2	x	x	4	23	0
1	x	22	58	83	45
0	223	201	161	112	67
Age	**0**	**5**	**10**	**15**	**20**

Cable Inventory by Age and Failure History
Sensitivity Case 2

Figure 2-12
Cable Inventory by Age and Failure History

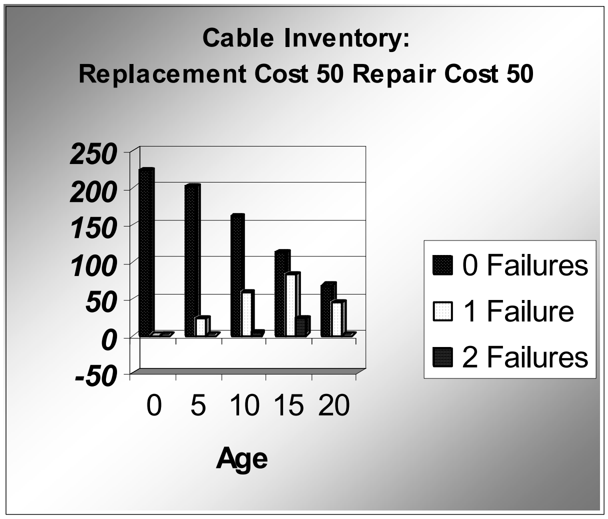


Figure 2-13
Cable Inventory by Age and Failure History

Figures 2-14, 2-15 and 2-16 show the results of reducing the replacement cost by a factor of 4 and Figures 2-17, 2-18 and 2-19 show the results of reducing the replacement cost by a factor of 10 (everything else being equal). Not surprisingly, the Replace policy region increases as the replacement cost diminishes. Also, as before, the steady state inventory continues to become even younger and "healthier" to the point at which in the Replacement Cost 10 case, 95% (950 out of 1000) of the cable sections have experienced no failures at all.

Replacement Cost 25

Repair Cost 50

Failures	**Optimal Policy**				
2	x	x	Replace	Replace	Replace
1	x	No Replace	Replace	Replace	Replace
0	No Replace	No Replace	Replace	Replace	Replace
Age	**0**	**5**	**10**	**15**	**20**

Optimal Cable Policy by Age and Failure History
Sensitivity Case 3

Figure 2-14
Optimal Cable Policy by Age and Failure History

Replacement Cost 25

Repair Cost 50

Failures	**Cable Inventory**				
2	x	x	7	0	0
1	x	33	87	0	0
0	333	300	240	0	0
Age	**0**	**5**	**10**	**15**	**20**

Cable Inventory by Age and Failure History
Sensitivity Case 3

Figure 2-15
Cable Inventory by Age and Failure History

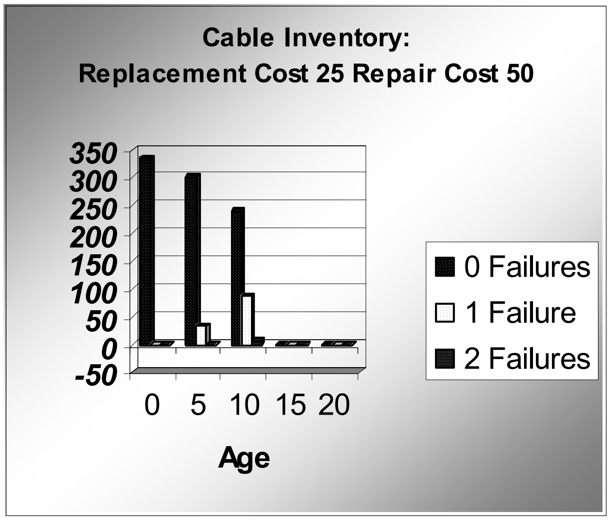


Figure 2-16
Cable Inventory by Age and Failure History

Replacement Cost 10

Repair Cost 50

Failures	**Optimal Policy**				
2	x	x	Replace	Replace	Replace
1	x	Replace	Replace	Replace	Replace
0	No Replace	Replace	Replace	Replace	Replace
Age					

Optimal Cable Policy by Age and Failure History
Sensitivity Case 4

Figure 2-17
Optimal Cable Policy by Age and Failure History

Replacement Cost	10	**Repair Cost**	50

Failures	**Optimal Policy**				
2	x	x	0	0	0
1	x	50	0	0	0
0	500	450	0	0	0
Age	**0**	**5**	**10**	**15**	**20**

Cable Inventory by Age and Failure History
Sensitivity Case 4

Figure 2-18
Cable Inventory by Age and Failure History

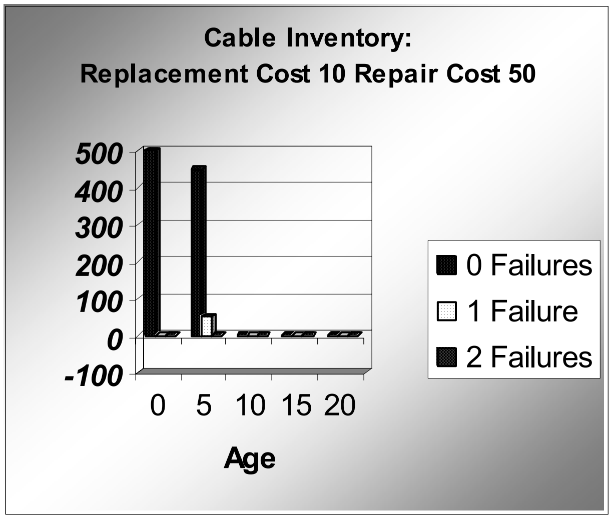


Figure 2-19
Cable Inventory by Age and Failure History

Two other ways to summarize the results are shown in Figures 2-20 and 2-21, which show the number of replacements and the expected cost as a function of the Replacement/Repair cost ratio. The number of replacements is easily calculated in each case as the sum of the numbers in the steady state inventory table across the cells in which replace is the optimal strategy. Note that if the Replacement/Repair cost ratio is the neighborhood of 1 to 2, the number of replacements is just about constant at 200. If the cost ratio is believed to be in this range, then we may not need to estimate costs very carefully because the policy may not be sensitive. However, if the ratio is lower than 1 or higher than 2, the number of replacements is quite sensitive to the exact ratio. In contrast, the Expected Value is a fairly smooth function of the ratio over all values in the range.

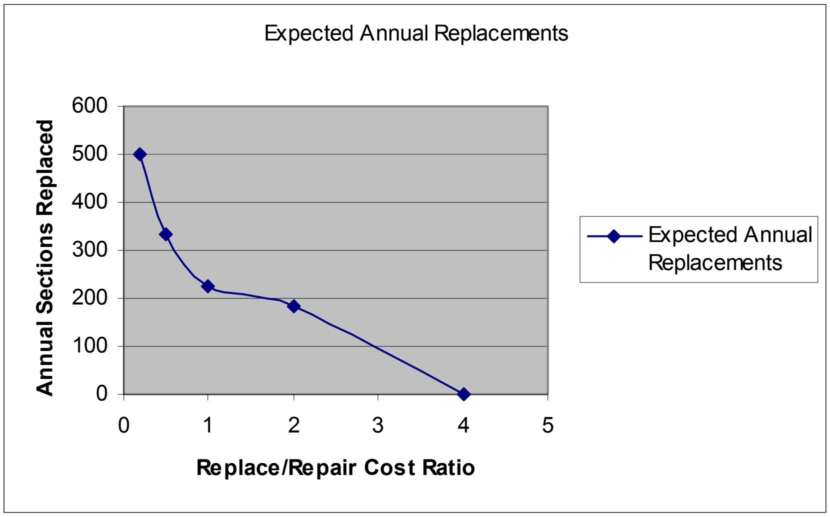


Figure 2-20
Replacements as Function of Cost Ratio

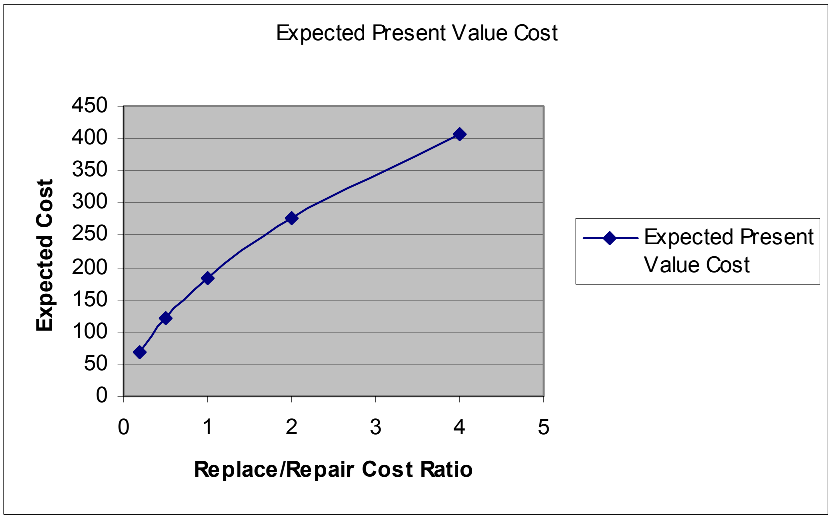


Figure 2-21
Total Cost as Function of Cost Ratio

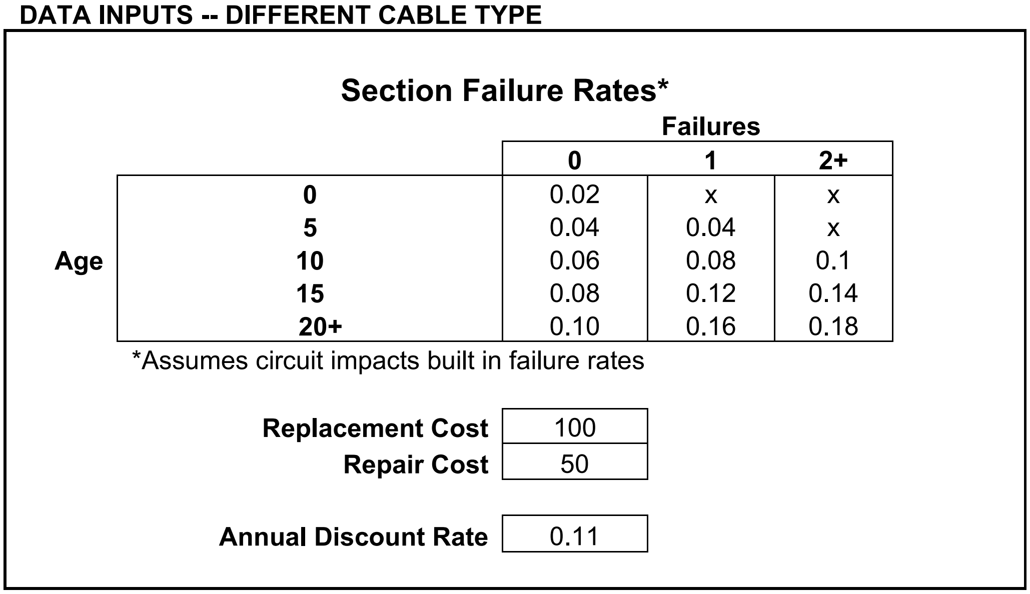
These results are intended only to be illustrative of what can done with a policy-oriented model. The absolute numbers not important here. Since the inputs were fictitious, the actual numerical results should not be applied to other situations. The objective here is to illustrate how the model can illuminate tradeoffs.

3

SENSITIVITY OF POLICY TO STATE OF INFORMATION

3.1 Sensitivity to Cable Type

It is straightforward to use the model to compare policies and costs for different cable types. One has only to enter the appropriate failure rates and costs. For example, consider Figure 3-1 in which we assume a different type of more reliable cable. For illustrative purpose, we lowered all the failure rates by 20% across the board. We assumed the same costs as for the base case, a Replacement cost of 100 and a Repair cost of 50.



DATA INPUTS -- DIFFERENT CABLE TYPE

Section Failure Rates*

		Failures		
		0	**1**	**2+**
	0	0.02	x	x
	5	0.04	0.04	x
Age	**10**	0.06	0.08	0.1
	15	0.08	0.12	0.14
	20+	0.10	0.16	0.18

*Assumes circuit impacts built in failure rates

Replacement Cost	100
Repair Cost	50
Annual Discount Rate	0.11

Figure 3-1
A Different Cable Type

The results for the new cable type are shown in Figures 3-2, 3-3 and 3-4. Note that for the original cable type with the same costs, the optimal policy was not to replace a cable segment unless it has reached Age 15 and experienced 2 or more failures, or reached Age 20 and experienced 1 or more failures. Now, the optimal policy is never to replace, with the intuitive consequence that all cable segments will in the long run wind up in the oldest possible steady state inventory state.

Replacement Cost 100

Repair Cost 50

Failures	Optimal Policy				
2	x	x	No Replace	No Replace	No Replace
1	x	No Replace	No Replace	No Replace	No Replace
0	No Replace	No Replace	No Replace	No Replace	No Replace
Age	**0**	**5**	**10**	**15**	**20**

Optimal Cable Policy by Age and Failure History
Base Case

Figure 3-2
Optimal Cable Policy by Age and Failure History

Replacement Cost 100

Repair Cost 50

Failures	Cable Inventory				
2	x	x	0	0	1000
1	x	0	0	0	0
0	0	0	0	0	0
Age	**0**	**5**	**10**	**15**	**20**

Cable Inventory by Age and Failure History
Base Case

Figure 3-3
Cable Inventory by Age and Failure History

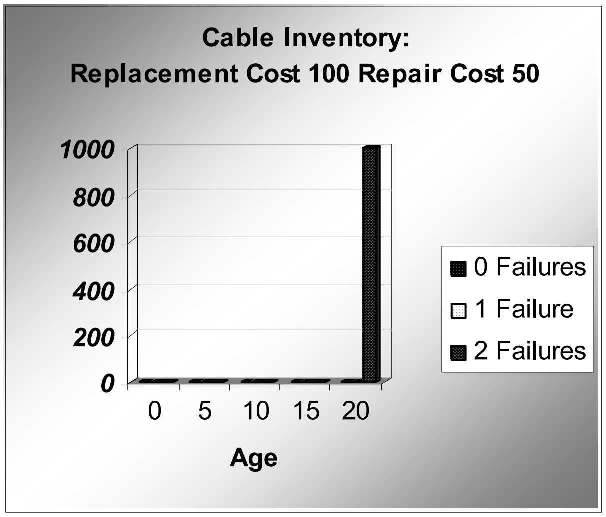


Figure 3-4
Cable Inventory by Age and Failure History

Not surprisingly, the overall costs for the new cable type are significantly lower. Using the same cost inputs, the expected value for the new cable is 81 compared to 276 for the original cable, a cost reduction directly attributable to the significantly lower failure rates.

3.2 Age-Based Policy

One of the primary objectives of this research was to be able to compare policies based on different levels of knowledge. We can use the Policy Model to determine how much difference it makes to have detailed data and records on which to make decisions. This is important for two reasons. First, many utilities simply don't have detailed data. We would like to know how this impacts the utility's cable strategy and what can we do about it. Second, we would like to quantify what it would be worth to collect and maintain more detailed data. The model puts an economic value on better information.

First, we consider what would be the best policy if the utility could make decisions conditional on cable age only. To achieve this, we set up the model to run based on a user-input policy. In this mode, the user provides a decision for each state and the model evaluates the results.

Figure 3-5 shows how this works for evaluating the policy, Replace after Age 10. By running similar cases for each possible age, we were able to compare different age-based policies. The results are shown in Figure 3-6. The Inventory Turnover interval is simply a measure of how long on average it takes for the entire inventory to be completely replenished.

Replace at Age

10

		User-Input Policy	Steady State Frequencies	State Values
Age 0	**0 Failures**	No Replace	33%	585.12
Age 5	**0 Failures**	No Replace	30%	645.06
Age 5	**1 Failures**	No Replace	3%	645.06
Age 10	**0 Failures**	Replace	24%	616.67
Age 10	**1 Failures**	Replace	9%	616.67
Age 10	**2 Failures**	Replace	1%	616.67
Age 15	**0 Failures**	Replace	0%	616.67
Age 15	**1 Failures**	Replace	0%	616.67
Age 15	**2 Failures**	Replace	0%	616.67
Age 20	**0 Failures**	Replace	0%	616.67
Age 20	**1 Failures**	Replace	0%	616.67
Age 20	**1 Failures**	Replace	0%	616.67

Figure 3-5
Age-Based Policy

	AGE-BASED STRATEGY			
	Replace Age 5	Replace Age 10	Replace Age 15	Replace Age 20
Replacement Cost	100	100	100	100
Repair Cost	50	50	50	50
Annual Replacements	500	333	250	200
Inventory Turnover Interval	10	15	20	25
Annualized Value	473	616	687	730

Figure 3-6
Age-Based Strategy Comparison

First note that the Age-Based policies get more expensive as the age threshold increases. The least-cost Age-Based policy is to replace at Age 5. This has a expected cost of 473. Replacing at Age 10 has an expected cost of 616 and the costs go even higher for higher ages.

To understand the implications of the Age-Based policies, recall that the Expected Value for the Optimal Policy based on exactly same costs and failure statistics was 276. In other words, a policy based only on age compared to one based both on age and failures results in a 42% increase in total expected costs. Put another way, for the electric utility that does not retain failure history data, this type of analysis, when added up across all cable sections and circuits, could estimate the potential worth of creating and maintaining a failure database.

We should also point out the dependence of these results on the replacement and repair cost assumptions. For different sets of costs, the relative worth of a policy based on age compared to one based both on age and failures will be different. For example, if both replacement and repair costs are 50, the best Age-Based policy has a cost of 248, a 35% increase over 183, which is the cost of an Age and Failure-Based policy.

3.3 Failure-Based Policy

Next, we consider what would be the best policy if decisions must be made conditional on failure history only. To achieve this, we set up the model to run based on a user-input policy in which the Replace decision is made following a specified number of failures. Figure 3-7 shows the results for three policy levels: Replace after 1, 2 or 3 failures. For the purposes of this model, Replacing after 3 failures means never replacing.

	FAILURE-BASED STRATEGY		
	Replace Failure 1	Replace Failure 2	Replace Failure 3
Replacement Cost	100	100	100
Repair Cost	50	50	50
Annual Replacements	211	159	0
Inventory Turnover Interval	24	31	NA
Annualized Value	286	437	901

Figure 3-7
Failure-Based Strategy Comparison

Interestingly, the results are similar to the Age-Based results in that the least cost policy is to Replace after 1 failure. This has an expected value of 286. The policies associated with replacing after two or three failures have much higher costs. In contrast with the Age-Based results, the expected cost associated with the best Failure-Based policy (286) is only slightly higher than the results from the more sophisticated age/failure history policy (276), a difference of about 4%.

If this were a real case, the result would be that there is not much value to the more sophisticated Age/Failure-Based policy over a simpler Failure-Based policy. However, we must once again mention that these results are illustrative only, so the actual conclusions may be completely different in real applications.

4

REALISTIC HAZARD FUNCTIONS

This chapter describes the impacts of more realistic models of the dynamics of failure of underground cable. In particular, we examine the impact of real hazard functions on the Policy Model. To begin, we analyze the Weibull model. This is perhaps the most popular statistical model for reliability analysis. The conceptual foundations for the Weibull model and the mechanics of estimating a Weibull distribution from empirical data are described in detail in the companion report.

4. 1 Converting Hazard Functions into Failure Transition Rates

Before proceeding, we must address three practical issues and one conceptual issue that arise in translating hazard functions into failure transition matrix. The practical issues are how to deal with variable section length, multi-year intervals and failure history. The conceptual issue is how to deal with impacts of total circuit failures on individual section failure rates. We begin by addressing the three practical issues.

4.1.1 Dealing with Time Period, Section Length, and Failure History

Typically, failure rate data comes by year, but we wish to analyze failures over arbitrarily longer time periods. In this study, we wish to address policies covering periods of 5-year intervals so we must make an assumption about the process governing failures over the period. For simplicity, we assume a constant failure rate over each one-year period. With this assumption, it is possible to think of the Weibull distribution as a time-varying Poisson process. A Poisson process is characterized by an exponential interarrival time distribution with a failure rate λ that governs the time between failures in the interval. Let a be a given cable segment age. The Weibull hazard function specifies $\lambda(a)$ as a function of age. Thus, for a given age a, if we denote t as the arrival time of the next failure, the probability density on t is exponential with a time-varying rate, as follows,

$$\text{Interarrival Time Density } f(a,t) = \lambda(a)\, e^{-t\lambda(a)}$$

Within each age interval, given the Poisson model, the impacts of section length, multi-year intervals and failure history are straightforward to model:

<u>Section length</u> – typically, empirical data measures failures by foot of cable. However, for our policy analysis, we wish to analyze failure rates of an entire section of cable, which can range from a few hundred to a few thousand feet. We need to multiply by the number of

feet in a section to get hazard rates for a section. Suppose that the failure rate for a given age as measured from the raw data is equal to $\lambda(a)$. Let the number of feet in a section be equal to n. Then the section failure rate is easily computed,

$$\text{Section Failure Rate} = n * \lambda(a)$$

The resulting updated Interarrival Time Distribution is then,

$$\text{Interarrival Time Density } f(t) = n\lambda(a)\, e^{-nt\lambda(a)}$$

Multiple years — For multiple-year periods of length T, we can calculate the probability of failure to be equal to one minus the probability of no failure over the period. The probability of no failures is equal to the integral of the Interarrival Time Density from T to infinity, where, since the failure rate depends on age, we must sum over the Weibull failure rate for each age, $\lambda(a_i)$, where a_i is the age in the i^{th} period, i = 1 to T. We omit the mathematical details for brevity and summarize the result for the probability of at least one failure in T years,

$$\text{Probability of no failures in T years} = e^{-n(\lambda(a_1) + \ldots + \lambda(a_T))}$$

Failure history — Finally, we must overlay the impacts of failure history. As discussed in the companion report, most engineers agree that failure history is an important determinant of future reliability; however, there is not much empirical data to support a detailed statistical analysis. Therefore, we have chosen a very simple model for the phenomenon. Let m be a measure of the impact of multiple failures. This may be estimated if data is available or assessed based on engineering judgment. If the number of historical failures is f, our simple model is that the failure rate multiplier is m raised to the f^{th} power, or,

$$\text{Failure Rate Multiplier} = m^f$$

Adding the Failure Rate Multiplier into the expression for failure probability, we get,

$$\text{Probability of no failures in T years} = 1 - e^{-n(\lambda(a_1) + \ldots + \lambda(a_T))\, m^f \lambda}$$

In the examples to come, we assumed a failure rate multiplier of 2^f based on engineering judgments elicited in two recent EPRI cable studies.

4.1.2 Circuit Impacts

As mentioned in the introduction, even for determining individual section strategy, the other sections in the circuit cannot be ignored because section failures may be correlated in a given circuit. Recall that a source of correlation in section hazard rates may be common cause events, i.e., several sections may fail together in a circuit for the same underlying reason. For example, a cluster of failures in different sections of a circuit may indicate a more severe environment or more severe loading conditions. Or, perhaps, a cluster of failures could indicate a common flaw in the particular cable in the circuit or how it was installed.

Consequently, even in section strategy analysis, we must pay attention to the impacts of circuit failures on individual section hazard rates. This is a very challenging analytic problem.

It is instructive to illustrate how we would solve the problem exactly, even though that will be ultimately impractical. Suppose that we define a state that included the ages and failure history of the entire set of N sections in a circuit. It is most convenient to work with the probability of No Failure and then later translate this into the probability of Failure. Thus, let us consider how to calculate the probability of No Failure for a given section, assuming perfect correlation, that is, assuming that if any of the sections fails, the current section will fail. With this assumption, the probability that no section fails is

$$\text{Probability of No Failure} = (1 - h[a_i, f_i]) * \prod_{j \neq i} (1 - h[a_j, f_j]) \quad j = 1, \ldots, N$$

This is not approximate, but to calculate it would be an impossible computational burden. Our example below involves an analysis with 27 possible age/failure states for each section in a circuit with 10 sections. Creating a joint state for every possible combination of age/failure states for all of the 10 sections would require 27^{10} states, or approximately 200 trillion states, which is clearly intractable.

Calculational difficulties are not the only issue with the multi-section model. Notice that with perfect failure correlation among the sections, the probability of No Failures is the same for all sections. This is counterintuitive since one would presumably want the policy model to be sensitive not only to the entire circuit, but also to an individual section's failure history. For example, it is reasonable to assume that a cable engineer faced with two sections of equal age would want to replace the one with more failures.

An approximate model for quantifying correlation effects among the sections is to assume that the hazard rates for the other sections are approximately constant and equal to the average rate in the flat part of the hazard curve. With this assumption, the probability that no section fails is,

$$\text{Probability of No Failure} = (1 - h[a_i, f_i]) * \prod_{j \neq i} (1 - h_{avg}) \quad j = 1, \ldots, N$$

Note that this model deals with both issues. The first term ensures that the failure probabilities for each section are proportional to the individual hazard rates. The second term ensures that the impacts of all the sections in the circuit are taken into account. Further research may yield a richer model.

Each segment's failure rates will be used as in the current model to reflect individual section characteristics (age and failures); simultaneously, we incorporate impacts of other section failures on by multiplying the independent section failure rate by the other n-1 section failure rates assuming other sections fail at the average hazard rate. This is a first order approximation that avoids the need to have other section characteristics in the state. Thus, the model will operate at a section-level for decision purposes, but the failure rates will be driven by the circuit-failure mechanism. (The total circuit replacement decision still works exactly as before, so we still have a section-level and circuit-level decision.)

4.2 Weibull Analysis

Figure 4-1 shows independent failure rates based on a Weibull hazard function that was estimated from real utility data (the two Weibull parameters are denoted a and b). The details of the estimation are discussed in the companion report. The raw data, which came in units of failures per foot per year, were transformed as discussed above into rates per 500 foot section per 5 year period.

DATA INPUTS WEIBULL ANALYSIS

Independent Section Failure Rates

	Failures		
Age	**0**	**1**	**2+**
0	0.0001	x	x
5	0.0048	0.0096	x
10	0.0356	0.0700	0.1352
15	0.1311	0.2450	0.4300
20	0.3215	0.5396	0.7880
25	0.5822	0.8254	0.9695
30	0.8198	0.9675	0.9989
35	0.9528	0.9978	1.0000
40+	0.9528	0.9978	1.0000

Average Hazard Rate	0.18703	
No. Sections in Circuit	10	
Feet per Section	500	
Years per Period	5	
Weibull Hazard	**a**	**b**
Function Parameters	5	95

Replacement Cost	1200
Repair Cost	1000
Annual Discount Rate	0.11

Figure 4-1
Weibull Failure Rates

For those familiar with the Weibull function parameters, a is the slope or shape parameter and b is the characteristic life or scale parameter.

Figure 4-2 shows how the failure rates change when the impacts of the circuit are factored in. Note that the failure rates are significantly higher, especially for lower age states. This is not surprising, given that the failure rates now represent the probability of one or more of 10 sections failing rather than the probability of just one section failing. In the future, we may wish to investigate methods for attenuating the circuit impact if this model is too extreme.

Section Failure Rates with Circuit Impacts

	Failures		
Age	**0**	**1**	**2+**
0	0.8449	X	x
5	0.8456	0.8464	x
10	0.8504	0.8557	0.8659
15	0.8652	0.8829	0.9116
20	0.8948	0.9286	0.9671
25	0.9352	0.9729	0.9953
30	0.9721	0.9950	0.9998
35	0.9927	0.9997	1.0000
40+	0.9927	0.9997	1.0000

Figure 4-2
Section Failure Rates with Circuit Impacts

The remainder of the analysis applies precisely the same model used for the Toy Model cases; the only difference is the number of states and the data inputs. To establish a base case, we chose a Replacement cost of 1200 per section and a Repair cost of 1000 per section failure.

Figures 4-3 and 4-4 show the results of running the model with these costs based on the Section Failure Rates with Circuit Impacts of Figure 4-1. Note that the least cost policy is to Replace after 2 failures at 20 years, Replace after 1 failures at 25 years, and Replace after 0 failures at 30 years or older. The steady state inventory consists of cable sections all under 25 years old since sections are replaced when they get older than this. Note that the annualized expected value is 933. The annualized value is simply the overall expected value multiplied by the discount rate to amortize it to a yearly equivalent.

Weibull Policy Analysis

Segments of Cable	1000
Replacement Cost	1200
Repair Cost	1000

Optimal Policy

Failures									
2+	No Replace	No Replace	No Replace	No Replace	Replace	Replace	Replace	Replace	Replace
1	No Replace	No Replace	No Replace	No Replace	No Replace	Replace	Replace	Replace	Replace
0	No Replace	No Replace	No Replace	No Replace	No Replace	No Replace	Replace	Replace	Replace
Age	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40+**

Figure 4-3
Weibull Policy Analysis

Weibull Inventory Analysis

Steady State Population

Failures									
2+	x	X	142.72	187.29	197.51	1.83	0.00	0.00	0.00
1	x	168.63	52.08	11.58	1.97	0.23	0.01	0.00	0.00
0	199.58	30.95	4.78	0.71	0.10	0.01	0.00	0.00	0.00
Age	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40+**

Annual Replacements	200
Avg Replacement Interval	25.1
Annualized Total Cost	933

Figure 4-4
Weibull Inventory Analysis

4.3 Piecewise-linear Analysis

It is interesting to compare the results to the exact same case, except with a piecewise-linear hazard function instead of a Weibull hazard function. Figure 4-5 shows independent failure rates based on a piecewise-linear hazard function that was estimated from the same real utility data. Figure 4-6 shows how the failure rates change when the impacts of the circuit are factored in. The details of the estimation are discussed in the companion report. As with the Weibull model, the raw data which came in units of failures per foot per year were transformed into rates per 500 foot section per 5 year period.

DATA INPUTS -- PIECEWISE-LINEAR ANALYSIS

Failure Probabilities for No Replace

Age	0	1	2+
0	0.1706	x	x
5	0.1706	0.3121	x
10	0.1706	0.3121	0.5268
15	0.2762	0.4761	0.7256
20	0.4851	0.7349	0.9297
25	0.6337	0.8658	0.9820
30	0.7394	0.9321	0.9954
35	0.8146	0.9656	0.9988
40+	0.8146	0.9656	0.9988

Average Hazard Rate	0.18703
No. Sections in Circuit	10
Feet per Section	500
Years per Period	5

	average	breakpoint	slope
Piecewise Linear Function Parameters	0.00007	15	0.00003

Replacement Cost	1200
Repair Cost	1000
Annual Discount Rate	0.11

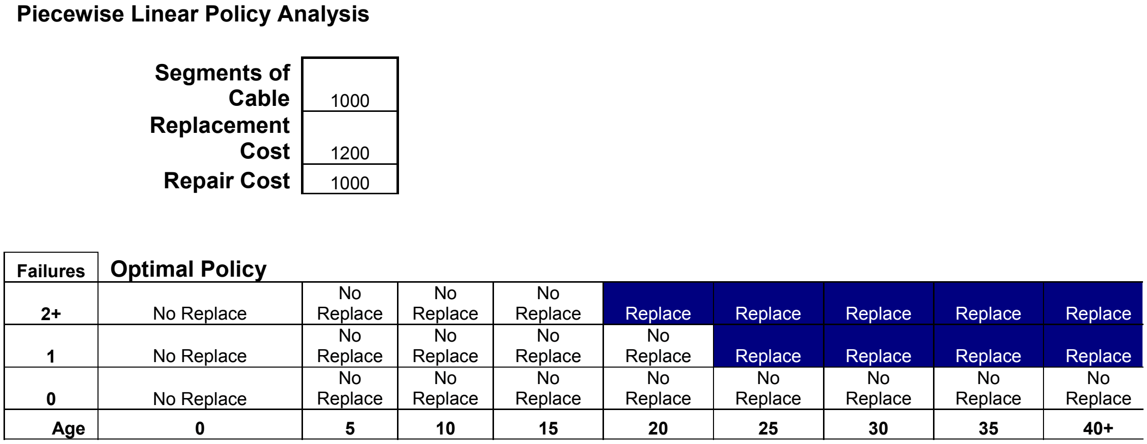
Figure 4-5
Piecewise-Linear Failure Rates

Circuit-Impacted Section Failure Rates

	Failures		
Age	**0**	**1**	**2+**
0	0.8714	X	x
5	0.8714	0.8933	x
10	0.8714	0.8933	0.9266
15	0.8877	0.9187	0.9574
20	0.9201	0.9589	0.9891
25	0.9432	0.9792	0.9972
30	0.9596	0.9895	0.9993
35	0.9712	0.9947	0.9998
40+	0.9712	0.9947	0.9998

Figure 4-6
Circuit-Impacted Piecewise-Linear Failure Rates

Figures 4-7 and 4-8 show the results of running the piecewise-linear model with the same Repair/Replace costs as in the Weibull model. Now the least cost policy is somewhat less aggressive in the sense that the optimal strategy is to never replace unless there has been at least one failure. The reason for this is intuitively clear. The piecewise-linear hazard function has higher failure probabilities for the lower ages, but the Weibull hazard function goes up non-linearly and reflects a far higher failure probability for higher ages. Note that the annualized expected value is 967, which is only about 4% different than the Weibull case. Also, the annual replacements and replacement interval are almost identical with the Weibull case.

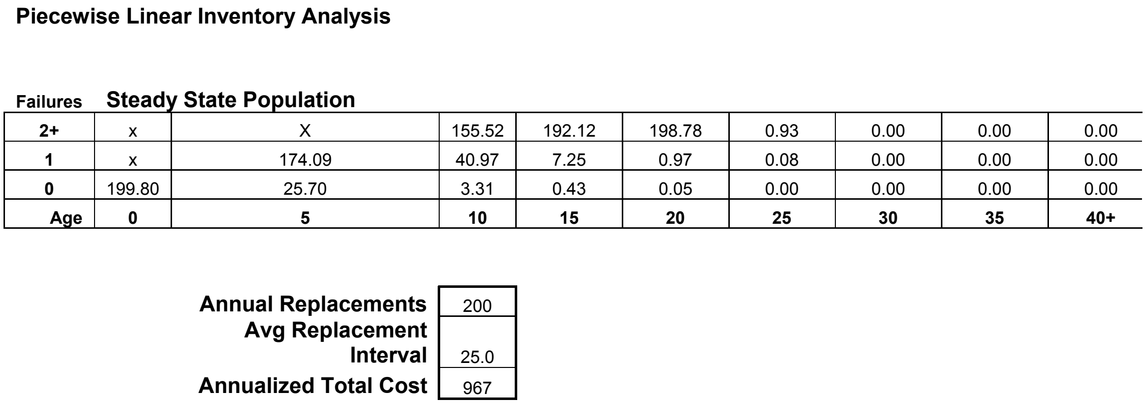


Piecewise Linear Policy Analysis

Segments of Cable	1000
Replacement Cost	1200
Repair Cost	1000

Failures	**Optimal Policy**								
2+	No Replace	No Replace	No Replace	No Replace	Replace	Replace	Replace	Replace	Replace
1	No Replace	No Replace	No Replace	No Replace	No Replace	Replace	Replace	Replace	Replace
0	No Replace	No Replace	No Replace	No Replace	No Replace	No Replace	No Replace	No Replace	No Replace
Age	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40+**

Figure 4-7
Piecewise Linear Policy Analysis



Piecewise Linear Inventory Analysis

Failures	Steady State Population								
2+	x	X	155.52	192.12	198.78	0.93	0.00	0.00	0.00
1	x	174.09	40.97	7.25	0.97	0.08	0.00	0.00	0.00
0	199.80	25.70	3.31	0.43	0.05	0.00	0.00	0.00	0.00
Age	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40+**

Annual Replacements	200
Avg Replacement Interval	25.0
Annualized Total Cost	967

Figure 4-8
Piecewise Linear Inventory Analysis

This raises the key issue of "Does it matter?" Without a policy model, we could not answer that question. We ran the analysis for the piecewise linear hazard function assuming the same policy as was optimal for Weibull. The resulting expected value was almost exactly the same. The intuitive reason is that even though the policy for the piecewise linear hazard function involves replacing at higher ages, in the long run very few sections will ever achieve that age. Thus, it makes almost no difference from a decision perspective on whether we use a Weibull or a piecewise-linear hazard function.

The conclusion we draw by comparing these two analyses is that the precise level of the steady state or average hazard rate – the region of relatively low and flat hazard – does not appear to have much impact on policy. However, a large difference between hazard functions in the high-age/greater-failure-risk range clearly can cause differences in optimal policy in the higher risk regions. However, because very few cable sections will ever become high risk (or high age), the choice of hazard function appears to make very little difference, so long as the steady-state values and the initial behavior of the burnout period are reasonably similar.

Thus, by performing a decision sensitivity, we can infer that for the case under analysis, it makes no sense to expend resources in attempting to make the hazard function more precise. Additional resources would better be spent on improving the accuracy of the cost estimates or possibly analyzing potential cable testing schemes. This is an important conclusion because the failure data is typically very sparse. If this type of conclusion generalizes across real utility applications, we will be able to make strong recommendations for the industry.

5

CIRCUIT REPLACEMENT STRATEGY

A circuit is defined to be a collection of multiple sections. The sections can interact in two different ways:

1. The failure history of Section i generally provides information about Section j if they are both in same circuit. The model of circuit failures presented in Chapter 4 dealt with this type of interdependency within a circuit.

2. There may be economies of scale when replacing a set of sections all at the same time. Such economies of scale may make it worthwhile to replace an entire circuit, even if a section-by section analysis indicates that not all individual sections should be replaced.

5.1 Economies of Scale

This chapter introduces a new alternative into the analysis: that is the decision of whether to replace or not replace the entire circuit. Let us assume that each section replacement has a fixed and variable cost component. Denote by v_i the variable cost of replacing section i. The variable cost must be paid for each section replaced regardless of how many other sections are replaced. Suppose that there is a fixed cost F for replacing a section. This fixed cost is a constant expenditure that is not a function of the number of sections to be replaced. If there are N sections in a circuit, the total cost of circuit replacement is,

$$\text{Cost of Circuit Replacement} = F + \Sigma_{i=1,N}\ v_i$$

Compare this to the cost of repairing each section independently without any economy of scale,

$$\text{Cost of Circuit Replacement without Economy of Scale} = N^*F + \Sigma_{i=1,N}\ v_i$$

We define the Economy of Scale Factor to be the reduction in cost due to economies of scale, which is the ratio of the costs above,

$$\text{Economy of Scale Factor} = (F + \Sigma_{i=1,N}\ v_i)/(N^*F + \Sigma_{i=1,N}\ v_i)$$

Figure 5-1 shows an example which we shall use in the remainder of the analysis. We take the same Toy Model base case as in Chapter 2, except that now we separate the Replacement Cost of 100 into two components, a variable cost of 50 and a fixed cost of 50. We presume there are ten sections in our example circuit, which means that the total circuit replacement cost is equal to

550, or 10 times the variable cost (500) plus the fixed cost (50). Compare this to the cost of replacing 10 sections with no economy of scale, which is 1000 (10 x 100). The Economy of Scale Factor is thus 550/1000 or 55%.

DATA INPUTS FOR CIRCUIT STRATEGY ANALYSIS

Failure Probabilities for No Replace			
	Circuit Failures		
Age	**0**	**1**	**2+**
0	0.1	x	x
5	0.2	0.2	x
10	0.3	0.4	0.5
15	0.4	0.6	0.7
20+	0.5	0.8	0.9
		Variable	**Fixed**
Replacement Cost	100	50	50
Repair Cost	50		
Sections in Circuit	10		
Economy of Scale Factor	55%		
Circuit Replacement Cost	550		
Annual Discount Rate	0.11		

Figure 5-1
Data for Circuit Strategy Analysis

5.2 Circuit Policy Implications of Economies of Scale

What are the policy implications of the economy of scale? To examine this question we break the decision problem into two stages. In Stage 1 we determine the optimal Section by Section policy as described in Chapter 2. A by-product of the optimal section policy was a set of expected values for each state. For convenience, we replicate the Toy Model base case run in Figure 5-2.

ITERATION 4

		Updated Policy	Steady State Frequencies	Iteration 4 State Values
Age 0	0 Failures	No Replace	18%	238.37
Age 5	0 Failures	No Replace	16%	258.54
Age 5	1 Failures	No Replace	2%	271.43
Age 10	0 Failures	No Replace	13%	273.98
Age 10	1 Failures	No Replace	5%	290.29
Age 10	2 Failures	No Replace	0%	296.64
Age 15	0 Failures	No Replace	9%	284.35
Age 15	1 Failures	No Replace	7%	301.14
Age 15	2 Failures	Replace	2%	304.56
Age 20	0 Failures	No Replace	11%	290.15
Age 20	1 Failures	Replace	12%	304.56
Age 20	1 Failures	Replace	4%	304.56
			Expected Value	275.92

Figure 5-2
Optimal Policy for Section-Level Analysis

Recall that the State Values are the future expected value of a section being in each of the 12 possible states. Fortunately, these values are just what we need to evaluate the optimal circuit policy.

Figure 5-3. shows a sample circuit with an inventory of 10 sections. Each section is described by its current age and number of failures, which defines its state. The fourth column of the table shows the expected future cost for following the optimal Section Strategy for each section. The numbers correspond to the expected future values for the corresponding states in Figure 5-2. We can interpret the total Expected Future Cost, which is the sum of the section costs, as the total cost for the entire circuit of independently following the optimal strategy for each section.

Comparison of Section and Circuit Strategies

CIRCUIT DESCRIPTION			Section Strategy Expected Future Cost	Future Cost of Circuit Replacement
Section Number	Age	Failures		
1	0	0	238	214.6
2	0	0	238	214.6
3	5	0	259	214.6
4	5	1	271	214.6
5	10	1	290	214.6
6	10	2	297	214.6
7	15	1	301	214.6
8	15	1	301	214.6
9	20	2	305	214.6
10	20	2	305	214.6
		Total	2805	2146
			Immediate Circuit Replacement Cost	550
			Total Circuit Replacement Cost	2696

Figure 5-3
Circuit with Inventory of 10 Sections

But we can also use the expected future values to determine the circuit replacement cost. Note that if we replace the entire circuit, this brings each of the ten sections to the (Age 0, 0 Failures) state at the end of the time period. Ignoring for a moment the replacement cost, we know that in one time period each of the sections will be in the (0, 0) state, and the value for that has already been computed (238). Note that 214.6 is the state value 238, discounted by one period. Therefore, the present value of bringing all ten sections to the (0, 0) state is 2146, or ten times 214.6. If we add the total cost 550 of replacing the circuit including the economy of scale, we get a Total Circuit Replacement Cost of 2696.

The implications are summarized in Figure 5-4. The optimal section strategy cost, which involves replacing some but not all sections is 2805. The optimal circuit strategy cost, including the economy of scale is 2696. Thus, the best policy is to replace the entire circuit. The savings due to the circuit policy is 109 compared to the independent section strategy.

Optimal Section Strategy Cost	2805
Optimal Circuit Strategy Cost	2696
Difference	109
Optimal Strategy	**Replace Entire Circuit**

Figure 5-4
Summary of Circuit Replacement Evaluation

Before proceeding, we should mention that the above analysis relies on an underlying assumption that the optimal section strategy values are accurate estimates of the true future values for the states. But, in fact, these numbers did not include the possibility of replacing the entire circuit again at some future time. It seems reasonable, however, to assume that after a circuit is completely replaced, it will be many years before it will make sense to replace it again completely. Thus, the economic impact of having this option in the future will be heavily discounted. For example, suppose we have just replaced an entire circuit. Now suppose that we believe it will be at least 30 years before total circuit replacement will again be a serious option. In this case, the impacts of the future replace-circuit option will be only 4% of the value discounted to today's decision. Using the savings due to the circuit policy as a benchmark, the error introduced by the assumption would be about 4 cost units out of 2500, a negligible impact.

5.3 Sensitivity to Cable Inventory Characteristics

To understand the Circuit Strategy model and its implications, we investigated the sensitivity of the circuit-replace decision to the characteristics of the sections in the circuit. The results are shown in Figure 5-5. The Base case is the case described above. The Best State case assumes that the circuit has been completely replaced so that every section is new with no failures. In this case, as would be expected, the Optimal Section Strategy dominates and it is not economic to replace the entire circuit.

Base Case		**Best State**		**Worst State**		**Mixed State**		**Younger State**		**No Failures**	
Case 1		**Case 2**		**Case 3**		**Case 4**		**Case 5**		**Case 6**	
Age	Failures	Age	Failures	Age	Failures	Age	Failures	Age	Failures	Age	Failures
0	0	0	0	20	2	0	0	0	0	0	0
0	0	0	0	20	2	0	0	0	0	0	0
5	0	0	0	20	2	0	0	0	0	5	0
5	1	0	0	20	2	0	0	0	0	5	0
10	1	0	0	20	2	0	0	5	1	10	0
10	2	0	0	20	2	15	1	5	1	10	0
15	1	0	0	20	2	15	2	10	1	15	0
15	1	0	0	20	2	15	2	10	1	15	0
20	2	0	0	20	2	20	1	15	2	20	0
20	2	0	0	20	2	20	2	15	2	20	0

Optimal Section Strategy Cost	2805	2384	3046	2711	2686	2691
Optimal Circuit Strategy Cost	2696	2696	2696	2696	2696	2696
Optimal Strategy	**Circuit Strategy**	**Section Strategy**	**Circuit Strategy**	**Circuit Strategy**	**Section Strategy**	**Section Strategy**
Value of Circuit Strategy	109	-312	350	16	-10	-5

Figure 5-5
Summary of Circuit Replacement Evaluation

The Worst case assumes an inventory made up of the oldest possible sections, each with the maximum number of failures. Intuitively, the best strategy is the Replace Circuit Strategy, which is now 350 cost units lower than the Optimal Section Strategy.

In real applications, the situation will be mixed. An inventory that varies by age and failure history is postulated in Case 4, the Mixed State. In this case, the values of the Replace Circuit Strategy and the Optimal Section are quite close, with the Replace Circuit Strategy lower by 16 cost units.

Case 5 involves a younger inventory, and as one would expect, a younger inventory favors the Section Strategy. Similarly, Case 6 shows that an inventory with a more favorable failure history also favors the Section Strategy.

6
CONCLUSIONS

6.1 Summary

The algorithm we use to optimize the replacement strategy for underground cable is implemented in the form of a strategic decision model. We employ a dynamic probabilistic modeling approach to determine the contingent policy that minimizes the costs of operating an aging cable system under different levels of knowledge. The inputs to the model include the hazard function, the cable inventory, and the costs of failure, repair, and replacement. The outputs are a state-dependent optimal policy, a forecast of the costs associated with the policy, and a forecast of the steady state cable inventory that results from the optimal policy.

One of the primary objectives of this research is to create a framework for comparing policies based on different levels of knowledge. We use the Policy Model to determine how much difference it makes to have detailed data and records on cable age and failure history. The example results indicated that an Age-Only based policy generates significantly less value than the more sophisticated Age and Failure-Based policy . However, there appears not to be much incremental value for the Age and Failure-Based policy compared with a simpler Failure-Based policy. While these results are illustrative only, they demonstrate the ability of the framework to attach an economic value on improved information and indicate how to perform such an analysis in future real applications.

We examined the impacts of more realistic models of the dynamics of failure of underground cable. In particular, we tested the impact of hazard functions based on real data on the Policy Model. We compared the implications of a Weibull hazard model and a Piecewise-linear hazard model fitted to the same data. The interesting conclusion from comparing the analysis of the Weibull and piecewise-linear hazard functions is that the choice of hazard functions did not appear to have much impact on policy. This is true even though a difference between hazard functions in the high-age/greater-failure-risk range can cause differences in optimal policy in the higher risk regions. That policy difference may not matter because few cable sections will ever become high risk. In the cases we analyzed, that difference was of little consequence.

The analysis addressed a set of practical issues related to variable section length, multi-year intervals and failure history. We also created and applied an approximate approach for the dealing with impacts of total circuit failures on individual section failure rates.

Finally, we created a framework for examining circuit replacement strategy. Based on a mild approximation, we were able to introduce a new decision into the analysis: Whether it is worthwhile to replace an entire circuit, even if a section-by-section analysis indicates that not all individual sections should be replaced. The analysis demonstrated that because of economies of scale in repair costs, it sometimes make sense to replace the entire set of sections all at the same time. We performed a range of analyses to demonstrate the sensitivity of the circuit-replace decision to the characteristics of the sections in the circuit.

6.2 Further Research

The Cable Management Strategy model appears to be quite promising. It addresses both the section-by-section Repair/Replace policy problem as well as the circuit-level policy problem. Case studies would be extremely useful for several purposes: to validate the structure of the model; to verify that model addresses all the key elements of problem; to address data issues in more depth; to enrich the cost structure; and to expand the circuit analysis to make it more realistic.

Several technical issues require further investigation. We would like to investigate combining *Failure History* and *Age* states in some way, perhaps by using the concept of effective age. If we can simplify the state description, it would help enable an analysis of cable testing strategies, which might require a number of additional state dimensions.

Further research could enrich the set of decisions under evaluation. For example, we could add a *Rejuvenation* decision to supplement the Repair/Replace decision. Rejuvenation does not make a cable just like new, but could be modeled as decreasing the cable's effective age and perhaps eliminating some or all of its failure history.

A particularly interesting and relevant type of cable decision is the decision as to whether to test a cable section or circuit. By adding test results to the Policy Model, we would have an analytic framework for performing an economic evaluation of cable testing. Based on previous work we have done, we believe that an economic analysis of the value of the information provided by commercially available cable tests would be of some value to utilities.

We have done some preliminary thinking about how a cable testing model might function. First, we could assume a sequence of condition state changes, from less serious conditions to more serious conditions. For a given type of test, these conditions will likely be descriptors of the pervasiveness of some type of problem. For example, a cable might be in one of the following states:

C0 : No water trees

C1 : Cable has moderate density of water trees

C2 : Cable has significant water trees

C3: Water trees permeate the cable

We would need to build a probabilistic model of how the cable makes transitions from one state to the next. We presume that each test returns an assessment of the seriousness of the condition.

We envision a Learning Model that would quantify the reduction in the power of the test as a function of when the previous test was performed. In particular,

- The power of the test goes up as the probability of condition change since the previous test goes up
- The probability that the condition changes increases as a function of the time since the previous test.
- Hence, waiting longer between tests increases the effectiveness of each successive test.

The challenge in statistical terms is to specify a multi-dimensional likelihood function, which is which is the probability distribution over current test results given the true underlying condition, the most recent test result, and the number of periods in the past that the previous test was performed. The result of a testing model would be the ability to identify the optimal strategy conditional on the test outcome. We could also quantify the value of testing.

Another avenue of investigation is to investigate methods for automating the analysis of policies based on different levels of knowledge. In the analyses of Age-only and Failure History-only policies above, we ran the model multiple times by entering the more limited policies by hand. It would be valuable to have such comparisons be an automatic byproduct of the Policy Iteration.

The model should be automated using Visual Basic to make it more flexible, easier to generalize, and easier to use. The current model is implemented in Excel because of Excel’s convenience in writing research code. In order to add additional features and to make the model more user friendly, the software should be redesigned and reprogrammed in Visual Basic or another computer language designed for iterative algorithms. Such an endeavor should begin with a careful definition of the desirable user inputs and outputs. The model specifications should be developed in close cooperation with the EPRI project leader and perhaps a small group of utility advisors.

Finally, it is envisioned that this model could be incorporated into a broader electronic cable maintenance management system which could be linked to existing databases within a utility. Thus, real-time data could be used to generate accurate, utility-specific failure rates and hazard functions. These, combined with updated cost information and diagnostic test results could be used to create a continuous installed-cable inventory system, and also predict the current and future risk of failure and resulting costs.

7

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