Transmission and Distribution Infrastructure Management Must Enter a New Age

Stephen Chapel

The current electric delivery system evolved and was a direct result of the rapid growth of the post-World War II economy. This beginning, combined with the fact that electric utilities are extremely capital intensive, has resulted in an extensive transmission and distribution (T&D) infrastructure that is necessarily long-lived and aging.

The management of this infrastructure is critical for insuring the service that customers demand at a cost that is reasonable.

RAPIDLY AGING, RAPIDLY GROWING ASSET BASE

Electric transmission and distribution fixed assets expanded rapidly following World War II. In current dollars, net capital stock increased from $1.3 billion in 1947 to $149 billion in 2006. During the same period, an index of net capital stock adjusted for inflation increased from 5.59 in 1947 to 118.28, a 21-fold increase. The index of net investment increased from 13.42 to 86.65 and has been above 80 since 1999.[1]

In November 1992, *Electric World* reported net investment for electric utilities as $26.7 billion with $13.5 billion in distribution and $4.5 billion in transmission. The magazine projected net investment to grow from $26 billion in 1992 to $34 billion by 2000, with T&D growing to $22 billion. The Edison Electric Institute reports construction expenditures for investor-owned utilities (IOUs). These are shown in **Exhibit 1** for 1975–2004.

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Finally, while investment has been extensive, so have annual maintenance costs. Annual maintenance costs for IOUs (generation plus T&D) have been $11 billion to $12 billion for the period 1991–2004.[2]

The statistics demonstrate that a lot of T&D equipment has been put in place, and the stock continues to grow. The criticality of the asset management problem is made greater by the fact that that this stock is necessarily long-lived. Electric utilities are extremely asset-intensive, requiring about four dollars of capital in place for every dollar of annual revenue.[3] This high ratio translates into extra-long periods for capital recovery.

- The market will not allow quick capital recovery. While many industries can recoup billion-dollar investments in three or four years, the recovery period for electric utilities is four to five times as long.
- Long-period capital recovery requires necessarily long economic lives and significant maintenance requirements.

Given this large and aging capital stock, the emerging issue is how to maintain and replace the existing stock of equipment so as to wring as much economic value out of the system as possible. To me, this is life-cycle asset management focused on minimizing the costs of the delivery system subject to meeting customer needs for reliable electric service.

THE NEW CHALLENGES

The implication of the growth and capital intensity is that companies find themselves with large inventories of assets (transformers, poles, switches, breakers, 4kV distribution circuits, and other devices) some of which are over 50 years in age. In many (perhaps most) cases, companies do

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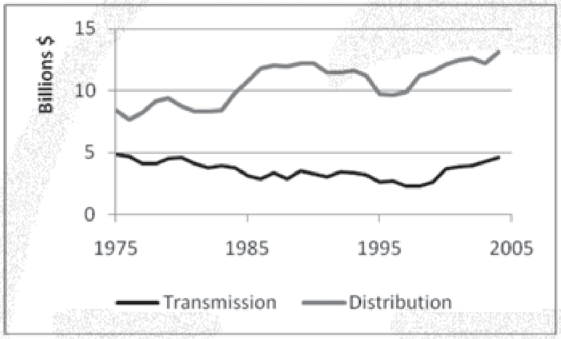
Exhibit 1. Construction Expenditures for Transmission and Distribution Shareholder-Owned Electric Utilities ($2004)



Source: Edison Electric Institute, Industry Statistics.

not have the detailed data necessary for managing this collection of assets. For important delivery assets such as underground cables, many times they do not know exactly how many, where, or the performance history of the assets.

The reasons for this situation are several. In the past, asset management was largely reactive and decentralized. The systems were growing rapidly, and there was constant need to extend the delivery systems and hook up new customers. Also, during the period up to the mid-1970s to early 1980s, the systems were young to middle-aged. Maintenance and replacement was yet to emerge as an important consumer of time and money.

Moreover, during the early growth period, reactive planning and decision making worked very well. Asset management, especially for distribution, was centered on local area planners who had detailed knowledge of both the area assets and area customers. When equipment or systems needed maintenance, the area planners knew it and the assets got fixed—for example, if a transformer was getting old and tests indicated possible problems, it got rebuilt or replaced. Asset decision making was largely decentralized—funds were provided by the corporation, and the area planners made sure that customers were kept happy.

One story illustrates past practice. In the late 1980s, the financial manager of a large IOU told me that the IOU had little control over or knowledge of how money was being spent in its distribution system. He stated, "We back up a large truck of money to the distribution department and unload it, but we have no idea what the money is used for." At the time, distribution was in sharp contrast to generation and transmission where the projects were larger and there was strong corporate and regulatory involvement in the planning and execution of capital and maintenance projects.

With restructuring and the resulting budget pressures and with the aging of the system, T&D asset management has changed. First, there has been a large downsizing of the workforce. As a result, in many companies, there are many fewer area planners. As a result, the knowledge base of local customer needs and infrastructure problems has been largely lost. This is a major reason why many companies find that they do not have the detailed data necessary for managing their collection of infrastructure assets—past practices were built on a system where the information base was based on planners' experience and knowledge and not on formal recorded information stored in company computer files.

Second, there are less funds being made available to the T&D system for the maintenance and replacement of equipment. Engineers and planners must now determine which systems need immediate attention and which can be deferred without incurring unacceptable risks of outage, safety, and environmental impacts.

Third, as part of the corporate budgeting process, planners are now being asked to justify their project spending decisions. They are being asked to build a business case for many of their project decisions. However, this places the existing T&D planners in a very difficult position.

- They are shorthanded because of the downsizing.
- They have limited or no training in how to formally build a business case for a specific decision.
- In many cases, they have very limited information about the condition of specific assets.
- Additionally, they lack the analytic tools to properly address the question of which problems can be ignored and which must be addressed immediately in order to avoid potential high-cost reliability, safety, and environmental impacts. These same tools are also needed to demonstrate the prudence of existing budget and project funding allocations.

The new dimension that T&D planners are being asked to formally address is economics—how to provide the service that customers demand as efficiently as possible. Planners have always had to focus on the engineering and design question. They now must expand their skill set to include economic analysis with explicit consideration of the risk of project deferral.

ANALYTIC TOOLS FOR MANAGING AGING T&D ASSETS

The fundamental decision problems in managing existing infrastructure assets are how much to spend in the current year, where to spend the money, and what problems and projects can be reasonably deferred to the future. To solve these problems, two related topics must be addressed. First, every company needs to create management information systems that support the decisions that must be made. Second, analytical decision frameworks must be constructed that allow companies to quantify the costs and risks of various repair/replace polices and, in the process, to identify strategies that are consistent with company goals.

Analytic Tools—The Early Evolution

Adoption of Reliability Centered Maintenance (RCM), a product of the airline industry, was part of the initial effort to formally incorporate economic analysis into T&D planning. The notion and application of a hazard function was also part of the early adoption.

The RCM approach and tasks are summarized in **Exhibit 2.**

A 1999 Electric Power Research Institute PowerPoint presentation by Harry Ng[4] addressed the RPM approach. Ng characterized RCM as an approach that

- is a systematic development of a preventive maintenance strategy,
- documents preventive maintenance decisions,
- allows noncritical equipment to operate until failure, and
- builds a reasonable defensive strategy against failure.

Ng reported increased efficiencies in maintenance operations following the implementation of RCM. Specifically, it was reported that following adoption of RCM, companies experienced lower overall resource usage, more use of predictive tasks, greatly reduced corrective maintenance costs, and better-focused failure-finding tasks. One company participating in the EPRI RCM work reported that it was using RCM to manage reliability and doing so with approximately 16 percent estimated cost savings. The company also reported that the approach provided further benefit because it documented the company's maintenance decision-making process.

The notion of a hazard function has been around for a long time. Typically, the curve is the functional relationship between age and likelihood of failure—the curve characterizes the fact that failure rates are very low until a system reaches old age or the "burnout" period. **Exhibit 3** illustrates a generic age–probability of failure relationship.

One of my colleagues likes to point out that a lot of ink has been spilled over exactly what kind of mathematical function best character-

Exhibit 2. Summary of RCM Approach and Tasks

RCM Approach	RCM Tasks
Do the cheap and easy tasks	Identify the system and decompose into subsystems
Prevent failure modes that have catastrophic consequences	Identify failure modes of subsystems Identify maintenance tasks related to failure modes Identify consequences of failure modes
Wait for squeaks	Select maintenance tasks based on risk assessment and cost of maintenance

Source: S. Chapel Associates & VMN Group LLC.

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izes the relationship. We agree that for the purpose of improving T&D asset management, this debate over the precise shape of the curve is not useful. In fact, as I will argue below, the curve by itself is not useful.

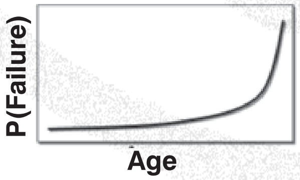
Analytic Tools—A New Perspective

What is wrong or incomplete in the early analytic perspective? First, with regard to RCM, this old standby is useful—as stated above, its application can produce increased efficiencies. RCM is aimed at preserving function. Underlying this objective is an implicit long-term economic evaluation. However, there is no explicit analysis of the long-term consequences of a policy in terms of system performance, costs, and cash flows. Clearly, one would expect that explicit quantification of system performance, costs, and cash flows would provide further improvements in spending decisions.

Second, let us consider the usefulness of the hazard function. The aging asset management problem (the repair/replace decision problem) is about forecasting when a specific system will fail. Hazard functions tell you the average failure rate for a population of an asset of a given age.

Hazard functions are rarely good predictors of the health of specific components or systems in the population. To illustrate, suppose we have a very good estimate of the hazard function for a particular asset class. Further suppose that for the asset class you have 100 systems of a particular age and you expect on average one will fail in the next year—the average failure rate is 1:100, or 1 percent. If the hazard function is used for screening, you are faced with fixing or replacing all 100 systems or ignoring the problem. The average failure rate is not much help in determining which systems will fail and which will not.

Exhibit 3. Example Hazard Function



The hazard function by itself can be a very blunt instrument. The question is, can you do better? Is there something that you can observe that gives you more information about the condition of specific systems that will improve the degree of failure predictability? The answer in general is yes.

You need both data and analysis tools (models) to develop sensible repair/replace policies. The data provide at least part of the basis for the analysis inputs. Models are required because the detailed probabilistic and economic computations are too complex to be done on the back of an envelope or in your head. Models provide the necessary structure and logic for performing the detailed calculations.

The interplay between data and models is that models dictate the kinds of data that are needed, while the quality of the data drives the nature of both the models and the types of policies that make sense. There is a very strong relationship between the kinds of models that are needed for solving a particular problem and the data needed to support the analysis.

Building a Better Predictor of Asset Performance

Managing existing T&D delivery systems requires monitoring the systems and performing maintenance and replacement over the life of the systems. The objective should be to minimize the life-cycle cost of the systems subject to meeting customer needs for service. Achieving the objective requires a policy that is specific to each asset class. Formally, the policy problem is the following: Given (1) an asset type (transformer, cable, poles, and other assets), (2) the asset characteristics (age, condition, and failure modes), and (3) a set of decision options (inspect, test, repair, replace, do nothing), what should we do, when, and under what conditions?

Developing a policy for a specific set of assets requires a *state-based* policy model. States are what we need to know to describe the condition of an asset. States can be observed through inspection or inferred from diagnostic tests. The advantage of a state-based methodology is that it prescribes when to inspect and/or test and what to do for different inspect/test results. The specific implementation of a state-based policy model varies by asset class, but the model structure is invariant and generally applicable.

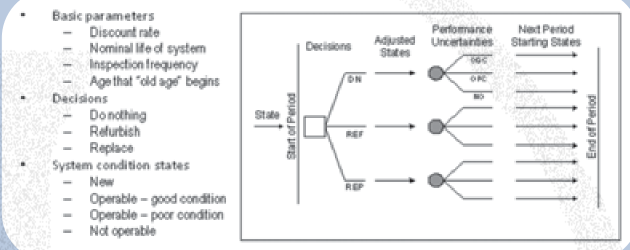
I am arguing that a state-based policy model be superimposed on the tradition hazard function. The hazard function tells us the average failure rate for a class of assets of a particular age. Through inspection and testing, we are building a better predictor of asset condition and, thus, potential system performance. We are extending the hazard function in order to better distinguish among assets in good condition and those in deteriorating condition.[5]

An Example Analysis

Thus far, this article has been mostly words and a few statistics. Let us look at an example. The elements of this asset management decision model are system performance and costs (failure costs, repair costs, replace costs, maintenance costs, etc.). **Exhibit 4** summarizes the problem and model structure. The exhibit lists the basic parameters, decisions, and system condition states.

An optimization model is required to solve real state-based policy problems. Such models essentially consider all possible decisions over all years and find the set of repair/replace decisions that are optimal given the state of the system (age and condition). To illustrate state-based model solutions, I use such a model that was formulated and implemented in Excel using Visual Basic for Applications. The inputs for an example run are given in **Exhibit 5** and results in **Exhibit 6.**

Exhibit 4. Problem and Model Structure

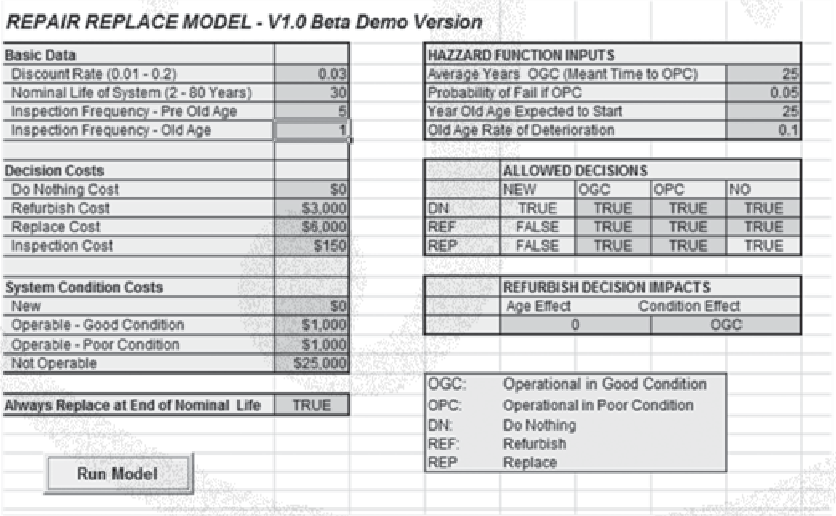


- Basic parameters
  - Discount rate
  - Nominal life of system
  - Inspection frequency
  - Age that "old age" begins
- Decisions
  - Do nothing
  - Refurbish
  - Replace
- System condition states
  - New
  - Operable – good condition
  - Operable – poor condition
  - Not operable

Most of the inputs are straightforward. For this example, the life of the system is nominally 30 years with old age or the burnout period starting at 25 years. There are costs associated with each decision and system condition. Note the hazard function inputs. The mean time to poor condition is 25 years; thus, the likelihood of being in good condition in any given year prior to old age is 24/25, or .96. After the system reaches old age, the likelihood of good condition decreases by 10 percent a year.

Exhibit 6 gives the model results. The model uses policy iteration to find the least-cost long-term repair/replace strategy. In this run, the system is inspected every five years prior to reaching old age and every year during old age. It is as-

Exhibit 5. Model Inputs



REPAIR REPLACE MODEL - V1.0 Beta Demo Version

Basic Data	
Discount Rate (0.01 - 0.2)	0.03
Nominal Life of System (2 - 80 Years)	30
Inspection Frequency - Pre Old Age	5
Inspection Frequency - Old Age	1

Decision Costs	
Do Nothing Cost	$0
Refurbish Cost	$3,000
Replace Cost	$6,000
Inspection Cost	$150

System Condition Costs	
New	$0
Operable - Good Condition	$1,000
Operable - Poor Condition	$1,000
Not Operable	$25,000

Always Replace at End of Nominal Life	TRUE

HAZZARD FUNCTION INPUTS	
Average Years OGC (Meant Time to OPC)	25
Probability of Fail if OPC	0.05
Year Old Age Expected to Start	25
Old Age Rate of Deterioration	0.1

	ALLOWED DECISIONS			
	NEW	OGC	OPC	NO
DN	TRUE	TRUE	TRUE	TRUE
REF	FALSE	TRUE	TRUE	TRUE
REP	FALSE	TRUE	TRUE	TRUE

	REFURBISH DECISION IMPACTS	
	Age Effect	Condition Effect
	0	OGC

OGC:	Operational in Good Condition
OPC:	Operational in Poor Condition
DN:	Do Nothing
REF:	Refurbish
REP	Replace

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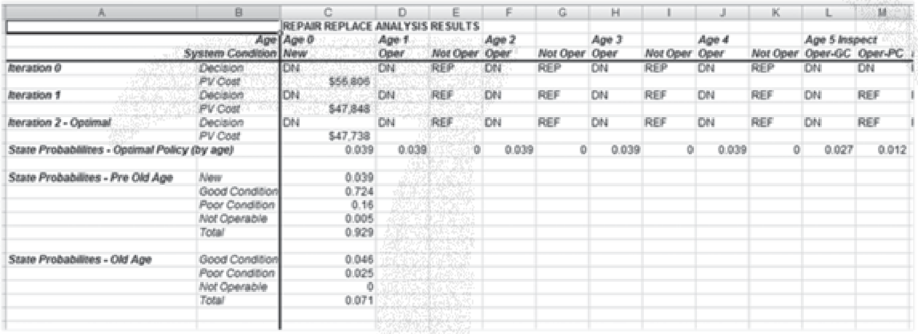
Exhibit 6. Model Results



A	B	C	D	E	F	G	H	I	J	K	L	M
		REPAIR REPLACE ANALYSIS RESULTS										
	Age	Age 0	Age 1		Age 2		Age 3		Age 4		Age 5 Inspect	
	System Condition	New	Oper	Not Oper	Oper	Not Oper	Oper	Not Oper	Oper	Not Oper	Oper-GC	Oper-PC
Iteration 0	Decision	DN	DN	REP	DN	REP	DN	REP	DN	REP	DN	DN
	PV Cost	$56,806										
Iteration 1	Decision	DN	DN	REF	DN	REF	DN	REF	DN	REF	DN	REF
	PV Cost	$47,848										
Iteration 2 - Optimal	Decision	DN	DN	REF	DN	REF	DN	REF	DN	REF	DN	REF
	PV Cost	$47,738										
State Probabilites - Optimal Policy (by age)		0.039	0.039	0	0.039	0	0.039	0	0.039	0	0.027	0.012
State Probabilites - Pre Old Age	New	0.039										
	Good Condition	0.724										
	Poor Condition	0.16										
	Not Operable	0.005										
	Total	0.929										
State Probabilites - Old Age	Good Condition	0.046										
	Poor Condition	0.025										
	Not Operable	0										
	Total	0.071										

sumed that at the end of 30 years the system is replaced. Without inspection, the system is observed as either operable or inoperable. In periods when inspection is done, the observed system is in operable good condition, operable poor condition, or not operable. The least-cost policy is to do nothing unless the system is in poor condition or not operable. If either not operable or in poor condition, the policy is to refurbish through age 17 and replace after that.

In addition to providing the least-cost policy, the model shows the system state probabilities by age and by pre-old age and old age. This example analysis shows that it is feasible and straightforward to perform analysis and identify repair/replace policies that in fact minimize life-cycle costs.

RECOMMENDATIONS FOR T&D ASSET MANAGERS

It is a sign of the times that almost every company I have worked with has assigned someone formal responsibility for "asset management." These managers might consider the following:

First, define the classes of assets that are to be included in asset management programs and develop a story for each asset class. The story should include the size of the inventory of the assets (e.g., number of poles by type, miles of cable by type, and number of power transformers by size and type), the money invested in the class, the potential importance of the class to customer satisfaction and company reputation, and a rough estimate of the cash flow requirements for maintenance and replacement over the next 10 to 20 years.

Second, put in place a plan of action for one important asset class (e.g., power transformers) and give yourself six months to develop the plan and sell it to your management. The plan should include elements that cover monitoring and testing, repair/replace decision making, and longer-term cash flow planning. This plan will set the stage for what you want to do for all classes of assets, provide a clear example of what you can accomplish, and develop expertise on repair/replace planning, including the role of various analysis tools and the role of data.

Third, set a goal to create an in-house capability for using state-of-the-art analysis tools to aid asset management decision making. This would involve obtaining and/or developing a couple of tools, understanding decisions that must be made, deriving the data requirements to support the decisions, and developing in-house expertise to use the tools.

NOTES

1. Bureau of Economic Analysis. *Investment in private nonresidential fixed assets,* http://www.bea.gov/bea/dn/FA2004/Details/Index.html.
2. US Census Bureau. (2007). *2007 statistical abstract of the United States,* Table 915, http://www.census.gov/prod/www/statistical-abstract.html.
3. Electric Power Research Institute. (1982, June). The electric utility industries financial condition: an update, EPRI EA-2446-ls.
4. (1999, June). EPRI Workshop: Reliability centered maintenance for distribution.
5. The comments in this section are the result of work done in collaboration with the VMN Group LLC.