Planning and Managing Copper Cable Maintenance through Cost-Benefit Modeling

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SUMMARY AND CONCLUSIONS

This paper describes our work to reduce the cost, and improve the reliability of our outside plant. Lacking adequate information, we cannot apply traditional life-cycle cost models. In this paper, we will focus on the process and modeling portions of our work. We describe the rehabilitation process first, then the dominant failure modes associated with outside plant equipment. This knowledge leads us into the strategic model we use to plan long term rehabilitation, and the tactical models we use to support immediate rehabilitation decisions.

Although our work continues, we have already improved our use of rehabilitation funding in the following ways:

- In applying cost-benefit modeling to the rehabilitation process, we have simplified the engineering analysis, and will continue to save money by guiding engineering decisions.
- Our models have helped finance managers with long-term rehabilitation budget planning, and have provided them with better control of the rehabilitation budget.
- By applying science to this problem, we have given visibility to maintenance and reliability planning.

1. INTRODUCTION

Regional Bell Operating Companies (RBOC) maintain the outside plant portion of the network through rehabilitation. These copper cable facilities are costly, mission critical, and subject to degradation. Due to the amount and diversity of the equipment, we cannot apply simple life cycle cost models. However, we can still apply reliability and operations models to improve the cost-effectiveness of our rehabilitation.

1.1 *Notation*

T	age of a given unit of plant, in years
R	region of the territory where the plant serves: 1 = south, 2 = central, 3 = north
I	regression intercept term
β	regression coefficient
P(T,R)	probability that the cable is cracked, given T and R
Z(T,R)	expected hazard rate for a twisted wire pair/loop, given T and R
C	constant, > 1
FR	failure rate, or hazard rate, for a unit of plant
IFR(t)	hazard rate at time unit t
λ	failure rate, or hazard rate, for a twisted wire pair in a wet section
N	total number of twisted wire pairs in the wet section, excluding failed pairs
$Pn(t\|N,\lambda)$	probability that n pairs have failed by time t, given N and λ
$E(n\|t)$	expected number of failures experienced by time t
E(t)	expected time when the cable exhausts its supply of spare wire pairs
A	number of assigned pairs in the wet section, the number of pairs in use

1.2 *Nomenclature*

Defective Pair Recovery – the act of locating a fault in a defective line, and then repairing the fault, usually through rehabilitation. The defective line is a failed twisted copper pair that a technician could not repair.
Defective Fill – the proportion of copper pairs in a unit of plant, or section of cable, that are not available for use because they are already serving a customer, or they are faulted.
Dispatch – the act of sending a repair technician out to the field to restore service or to change outside plant facilities in order to provide service.
Facility Modification – the act of changing the outside plant in order to install service.
Legacy System – a source of data and information internal to the corporation, often a large database holding information collected from management and control systems.
Outside Plant – the portion of the telecommunications network that connects the customer to the central offices; this is often twisted pairs of copper wire, bundled into cables, and connected through splices and exposed access points.
Proactive Rehabilitation – the act of performing maintenance replacement prior to non-repairable failure.
Rehabilitation – replacing and redesigning old portions of the outside plant to reduce maintenance expense, and improve customer service.

1.3 *Acronyms and Abbreviations*

PIC	Plastic Insulated Cable

RBOC		Regional Bell Operating Company

Because we lack sufficient information to apply traditional life-cycle cost models, we made some assumptions that allow us to construct cost-benefit decision support models.

1.4 *Model Assumptions*

1. The hazard function for degraded outside plant at time t is of the form

$$IFR(t) = IFR(t-1) * C \quad (1)$$

2. Copper cable does not crack within its first year of life.
3. Any portion of the outside plant that engineers consider for rehabilitation has degraded and is experiencing an increasing hazard rate. If this assumption were not true, the rehabilitation job would not be cost-effective, so we would not complete the work.
4. Copper pairs in a wet section each have a constant hazard rate.

2. REHABILITATION PROCESS

Cost-benefit models enable us to change the traditional rehabilitation process into a more cost-effective one. Generally, the process requires engineers to collect information from legacy systems and field technicians. They have available a known amount of cash to allocate to rehabilitation jobs. Their goal is to gain the best benefit from this rehabilitation budget. Where the process was once informal, we have added structure to the current process.

2.1 *Informal Rehabilitation Process*

Until recently, the rehabilitation process was ad-hoc. Think of the process as having three portions:

1. *Budget* – Each year, engineers would write a business case that outlines the expected payback from a requested budget.
2. *Engineering* – After the annual funding cycle, engineers would begin collecting information from legacy systems. This information would indicate which portions of the outside plant cost the company most to maintain, and provided the poorest service to our customers. Engineers would then ask for information from the field technicians. Technicians would indicate to the engineers which units of plant they believe needed rehabilitation. Engineers would then decide which parts of the plant to rehabilitate, and they would design large, expensive rehabilitation jobs.
3. *Construction* – Finally, construction would complete the work.

In most cases the result was fewer dispatches for repairs and installations, and better service for our customers. But we couldn't be sure that we were doing the right amount of rehabilitation, or if we were applying our resources in the best way possible.

2.2 *Current Process*

Through modeling, we have improved the current rehabilitation process:

- *Strategic Models* have helped us estimate the rehabilitation budget we need to control outside plant failures. At a high level, the strategic model compares the cost of rehabilitation to the impact we expect on dispatched repairs, dispatched installation, and facility modifications. This helps finance managers understand the value of maintaining our outside plant, and guides them in their decision of funding rehabilitation. We use the strategic model to create rehabilitation scenarios, and then we compare the results.
- *Tactical Models* have provided engineers with ways to assess the cost of maintaining portions of the outside plant, and the cost-effectiveness of rehabilitation work on these portions of plant. We began with simple spreadsheet decision support tools, and are now integrating the decision support tools into a system that can gather information from legacy systems.

The engineering portion of the current process involves two phases:

1. *First Cut* – at the beginning of the year, we provide the engineers with a list of units of plant to consider rehabilitating.
2. *Second Cut* – after engineers design the work, they compare the cost and benefit expected from each proposed rehabilitation job.

In addition, we are closing the loop on rehabilitation work. We plan to measure the results from last year's engineering effort, then use this to improve the models, and to guide engineering and financial decisions.

3. DOMINATING OUTSIDE PLANT FAILURE MODES

There are two dominant outside plant failure modes: "cracked PIC", and "wet section". These are dominant because they are frequent, costly to maintenance, and service affecting. Both are the result of degradation, so they appear in older outside plant.

Through field studies of outside plant failures, we have found that the dominant failure mode for copper cable facilities is what we call "cracked PIC". Cracked PIC is a degradation phenomenon where stabilizers leach out of the plastic insulation over time. When cable is directly exposed to the air, such as in technician access points, these stabilizers leave the insulation faster. Over time, the insulation becomes brittle. With temperature cycling, and with technicians moving the wire, the brittle insulation cracks, and exposes the copper wire. The exposed wire circuit is more likely to short, ground, or cross with another circuit. This causes degradation, or complete loss of service.

An additional failure mode that we are concerned about is what we call a "wet section". This occurs when a cable sheathe is damaged, and allows water to enter the cable.

Manufacturing defects create pinholes in the insulation on twisted wire pairs. In a wet section, the water corrodes the copper through these pinholes, and eventually the quality of service degrades.

Wet sections, because they can result from damage, are not strong candidates for traditional life-cycle cost models.

These failure modes, because they result from degradation, are important drivers to the models we have developed. Ref. 1 provides more discussion on this subject.

4. STRATEGIC AND TACTICAL MODELS OF OUTSIDE PLANT RELIABILITY AND OPERATIONS

In this section, I discuss the models that support the rehabilitation process. Our constraints, common in many industries and applications, direct us to create unique models. I will explain the failure model we use as part of the strategic model. I will also explain the important failure and operational models we use within our tactical models.

4.1 *Constraints to Modeling and Implementation*

The available data presents some interesting constraints to our modeling, and therefore to implementation. We suspect these constraints, or similar ones, are common in other industries.

- *Plant Age* – Although our systems can tell us how much cable we have at each age, we cannot obtain the age of a given outside plant component without direct inspection. This would require excavation in some cases, and would still be inaccurate. Due to both growth and rehabilitation projects, a given copper pair may consist of various ages of cable.
- *Failure History and IFR* – At best, we have one to two years worth of repair records. Because plant hazard rate is strongly influenced by seasonal and annual weather patterns, we cannot accurately model the hazard function. Simple models with simple assumptions serve our needs best.
- *Failure Mode History* – Our reporting mechanisms do not collect component and failure mode information. However, we can combine narrative information, and other reported codes to estimate the type of component that is degraded the most in a unit of plant.

As a result of these constraints, traditional modeling techniques do not work well for us. For example, a proportional intensity model might work well for cable failures if we had the data to support this approach.

4.2 *Strategic Model*

The strategic model considers each of these cost factors:

- facility modifications,
- defective pair recovery,
- the cost of rehabilitation, and
- the impact from dispatch repairs.

These dispatched repairs result when customers experience trouble with their service; then we isolate the trouble beyond the central office, and send a technician to the field to repair the line.

In this subsection, I will explain the portion of the strategic model that predicts the number of dispatched repairs. Although the complete model accounts for the other costs, we use much simpler models for the other costs. In the future, we hope to improve our models for facility modifications, defective pair recovery, and the cost of rehabilitation.

The strategic model provides an expected cost for maintaining plant with a given profile. The profile is defined by the amount of plant in each combination of age and region. In this subsection, a loop will be the expected length of copper pair for a customer's line.

We fit a logistic regression model to a small data set. The data was manually collected as part of a separate, commissioned study on insulation cracking in copper cable. The logistic regression model is of the form

$$P(T,R) = \frac{e^{(T*\beta_T + R*\beta_R + I)}}{1 + e^{(T*\beta_T + R*\beta_R + I)}} \qquad (2)$$

Eq (2) provides the probability that a section of cable, or a loop, has cracked PIC problems, given its age and the region in which it serves. Using this probability function, and conditioning on assumption 2 that copper cable does not crack in the first year, we estimate the expected amount of plant that is cracked at each age and location combination.

We apply our hazard rate assumption 1 (eq (1)), sample degraded plant, and measure the change in hazard rate over the year to approximate the hazard function.

The rate of failure for an arbitrary loop depends on the age at which it began to crack. For an arbitrary loop defined by an age and location combination, the rate of failures is the convolution of (a) the distribution of the age it begins to crack, and (b) the distribution of the hazard rate for a loop. We approximate this with

$$Z(T,R) = \sum_{t=1}^{T} [P(t,R) - P(t-1,R)] * C^{(T-t)} * FR \qquad (3)$$

Through a Monte Carlo approach, we estimate the rate of dispatched failures that various rehabilitation scenarios yield. By making assumptions about the plant replaced through various rehabilitation scenarios, we build plant profiles for rehabilitation and apply these to eq (3).

After adding the costs from dispatched failures, facility modifications, recovered pairs, and rehabilitation; we have cost comparisons for the scenarios we considered.

4.3 *Tactical Model for Wet Sections*

Our model must compare the costs of replacing the wet section today, or waiting until we must replace it in an emergency. I will explain the concept of a wet section replacement, and then explain our simplified failure model.

We use this failure model to generate cost estimates, and then calculate financial measurements to support decisions.

A wet section replacement is a proactive rehabilitation of a wet section of cable. This is the concept: if we do not replace today, we will replace more cable in a future emergency to put customers back in service. Meanwhile, customers will experience trouble, and we must dispatch for repairs. Because the faults exist inside the cable, the technician cannot repair the troubles. Instead, she must give the customer another pair each time. Eventually, if not replaced proactively, this cable will run out of spare pairs. Then, we must replace this cable in an emergency.

Under assumption 4, that copper pairs in a wet section have a constant hazard rate, we have

$$P_n(t \mid N, \lambda) = \frac{N!}{n!(N-n)!} e^{-n*\lambda*t} (1 - e^{-\lambda*t})^{N-n} \quad (4)$$

This states that the probability of experiencing n troubles in this wet section over a given time interval t is a binomial function with exponentially distributed success/failure proportions.

From eq (4), we can easily calculate the probability distributions for the number of troubles in a given year, and the probability of exhausting the cable in a given year. However, the error introduced through assumption 4 does not justify this detail in our model. Instead, we use expected values.

The number of failures we expect to experience by time t, and the amount of time we expect to pass before the cable exhausts are, respectively,

$$E(n \mid t) = N * e^{-\lambda*t} \quad (5)$$

$$E(t) = \frac{\ln(\frac{A}{N})}{-\lambda} \quad (6)$$

Using eqs (5) - (6), we can model all the cash flows in the model, and calculate financial measurements to help engineers decide whether to replace or wait. Here are the important cash flows to consider:

- Cost of dispatches for keeping customers in service.
- Costs of replacing the cable today, and when we expect it could exhaust in the future.
- Scrap value of the replaced cable.
- Depreciation value of the new cable replaced today, or in the future.

4.4 *Tactical Model for General Rehabilitation*

Much like the wet section model, our model for other rehabilitation work must compare the cost of completing a rehabilitation job now, versus waiting. In this subsection, I will explain our current state of knowledge for modeling the first cut in the engineering process, which I described in section 2.2. Next, I will explain how the models for the second cut differ. Finally, I will point out some ways we want to improve these models. Although we developed these models independently, we later found Ref. 2, which explains similar, but more complex models.

In this subsection, I refer to a unit of plant. This I define to be all the outside plant equipment serving customers through a given cross connection. The cross connection is the first point of access for a technician beyond the central office. Simply put, a unit of plant serves a large neighborhood of customers.

The first cut is a list of potential rehabilitation jobs, with present value costs for each major type of outside plant component. Each potential rehabilitation job is associated with a unit of plant. We calculate the present value, after-tax cost over a given horizon, separately for each major type of outside plant component. With the exception of the cost of rehabilitation, the cost categories we model in the first cut are the same as those we described for the strategic model: dispatch repairs, facility modifications, and defective pair recovery. Included in these costs are tax and depreciation effects.

- Dispatch Repairs – under assumption 3 regarding rehabilitation jobs, we apply the hazard function described in assumption 1, eq (1). We estimate the current hazard rate as the average dispatch repair rate over the past 12 months.
- Facility Modifications – through a regression model, we predict the future number of facility modifications based on the current level of facility modifications, the defective fill rate, and the growth in demand for that area.
- Defective Pair Recovery – we only estimate the missed opportunity cost for providing service through a recovered pair if we expect to use all existing pairs for growing demand in the area. From the growth rate, we estimate when we might need the recovered pair. We also estimate the number of defective pairs we might recover, and estimate the benefit we expect to receive from the recovered pair in the future. This is our lost opportunity cost.

We normalize these costs for each major type of outside plant equipment based on the number of customers affected, and the amount of that type of equipment we expect to impact. The first basis makes fair the comparisons between units of plant. The second basis makes fair the comparisons between the types of equipment in the plant.

The second cut in the engineering process differs from the first in two important ways:

- What is compared – in the second phase, engineers have examined the costs for the types of equipment in the unit of plant, and have engineered work. In the second cut, we compare the impact from the work proposed in each unit of plant.
- Basis for comparison – in the second phase, engineers have estimated the cost of the rehabilitation work, and improved the estimates of

the impact we expect. In the second cut, we compare the rehabilitation jobs based on the net present value, instead of net present cost, over an assumed horizon.

The decision support system we are constructing must facilitate the future changes we plan.

- Several parameters in these models need to be updated periodically. For example, we must update the cost of capital, corporate tax rate, and the hazard function. This is an advantage because it allows for a robust model.
- As we obtain better information about the impact on various plant components and cost categories, we can improve our cost estimates in the models, and provide more accurate comparisons.
- We hope to improve our models as we capture new information. For example, consider our model for facility modifications. We hope to compare stochastic process models to our regression model, and improve our prediction of future facility modifications.

Our desire to serve customers motivates us to tackle our given constraints, which are typical in many industries. While we work to relieve some of the data limitations, we have immediate needs to cost-effectively maintain our copper outside plant. Through understanding the failure mechanisms and creating models to support cost-benefit decisions, we have leveraged our maintenance dollars and created a framework for future improvements.

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Jason Rupe completed the *BS* and *MS* degrees from Iowa State University in Industrial Engineering. After transferring to Texas A&M University, he received the *PhD* in Industrial Engineering under an Operations Research program. In academia, he conducted research in command and control, communication and information network performance modeling, performability modeling of flexible systems, and tool changing problems. He now works at U S WEST Advanced Technologies as a member of the Mathematical and Statistical Modeling Group. He acts as in internal consultant to operations problems, focusing on reliability issues. He often applies the skills of reliability, stochastic processes, and statistics to U S WEST problems. He is a member of IEEE and IIE.