EQUIPMENT
TESTING DECISION MODEL

Version 1.0
June 2005

USER'S MANUAL

S.CHAPEL ASSOCIATES
ANALYTIC SOLUTIONS TO ASSET MANAGEMENT

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Requests for copies of this User Manual should be directed to S.Chapel Associates, 325 El Carmelo Avenue, Palo Alto, CA 94306, (650) 856-2675.

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I am pleased to acknowledge the contributions of a number of individual that made the creation of this method and software possible. I owe a thanks to Peter Morris and Charles Feinstein (VMN Group LLC). They suggested and demonstrated the approach of using probability updating and a decision model for developing equipment testing strategies.

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Finally I owe a debt to colleagues at MidAmerican Energy, United Illuminating, ESKOM, Southern Company, and Alliant Energy, who provided the essential information necessary for me to begin to understand the nature of the repair/replace problems confronting their companies.

As usual any errors are my responsibility.

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USER SUPPORT

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CHAPTER 1
INTRODUCTION

This User's Manual provides instructions for using the Equipment Testing Model (ETM) Version 1.0 software. Chapter 2, describes running the model and presents the details of the Window's interface. Chapter 3, is a step-by-step tutorial that demonstrates how to use the model to develop an equipment testing strategy.

The Equipment Testing Model is a computer program for evaluation of diagnostic testing in the context of making repair/replace decisions. The system is designed to help utilities develop repair/replace strategies for any equipment category but especially transmission and distribution equipment and systems. The tool is designed for a wide variety of equipment applications including but not limited to substation breakers, transformers, distribution circuit equipment and underground conductors.

Installing the Model

The ETM program is written in Java and will run on all machines that have the Java Runtime Environment installed including Windows XP, NT and 2000, UNIX, Mac and Linux. The system requirements for the model are:

- 1 mb of RAM,
- 1 mb of free space on a hard drive,
- Acrobat Reader 4.0 and the Java Runtime Environment installed on the host machine.

Because the model is written in Java it requires that the Java Runtime Environment (JRE) be installed on the host machine. The steps required to install JRE are described below. Viewing the User's Manual also requires that *Acrobat Reader* be installed. If the user does not have *Reader* it can be downloaded for free from Adobe's website (www.adobe.com).

To install the model two steps are required:

1. Obtain the install file, *ETMinstall.zip* from the S-Chapel Associates. Unzipping this file will create the folder *EquipTestModel*. This folder contains three files: *ETM.jar, jhall.jar* and *ETMUserManual.pdf.* You can place the *EquipTestModel* folder in any folder on your computer. The *.jar files contain the compiled software and associated software necessary to run the model. Execution of the model is described in the Chapter 2, MODEL USER'S GUIDE.
2. Install the Java Runtime Environment (*JRE*) . Before the model can be run the JRE must be installed on the host computer. *JRE* is available free of charge from Sun Microsystems' website. Installation of *JRE* is straightforward and takes only a few minutes. Installation has the additional advantage of allowing you to run

other Java applications currently available. To install JRE go to the following web site link and click “Get It Now.”

http://java.com/en/index.jsp

The webpage for this link is shown in Figure 1.

Learn how Java technology fits into your life

Trick out your Java technology-powered phone | Buy Now»

The console action-classic is here!

Buy Snoop Dogg tones and 1000s more | Buy Now»

See what Java technology can do for your business

Java technology resources for developers of all levels

Figure 1
Java Web Page for Downloading JRE

Clicking “*Get It Now*” will download the *JRE* install to your computer. Simply run the install program and you will be ready to run ETM.

In the next Chapter, Model User’s Guide, the details of running the model are explained, including entering data, running the model and reviewing output reports.

Error Traps

Data inconsistencies are trapped at the user interface level. Input error traps are explained in the next Chapter.

Getting Help

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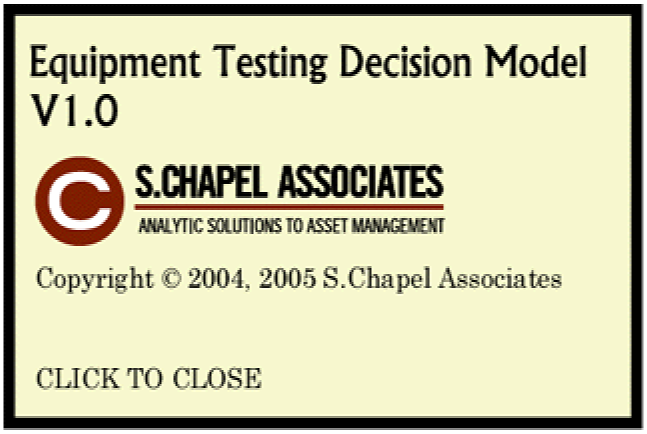
CHAPTER 2
MODEL USER’S GUIDE

Introduction

This User's Guide for the Equipment Decision Model describes the user interface and the way inputs and outputs are handled by the interface. The user interface is a standard Windows implementation. It was written in Java and will run on all machines that have the Java Runtime Environment installed including Windows XP, NT and 2000, UNIX, Mac and Linux. Because of the standard Windows implementation, users should be able to edit data sets, run the model and view results with little or no reference to this User Guide.

Running the Model

To run the model double click the executable jar file, *ETM.jar*. When the model starts a start-up screen will be shown for approximately 5 seconds and the program window will be displayed. The startup screen is shown in Figure 2 and the main program window in Figure 3.



Equipment Testing Decision Model
V1.0

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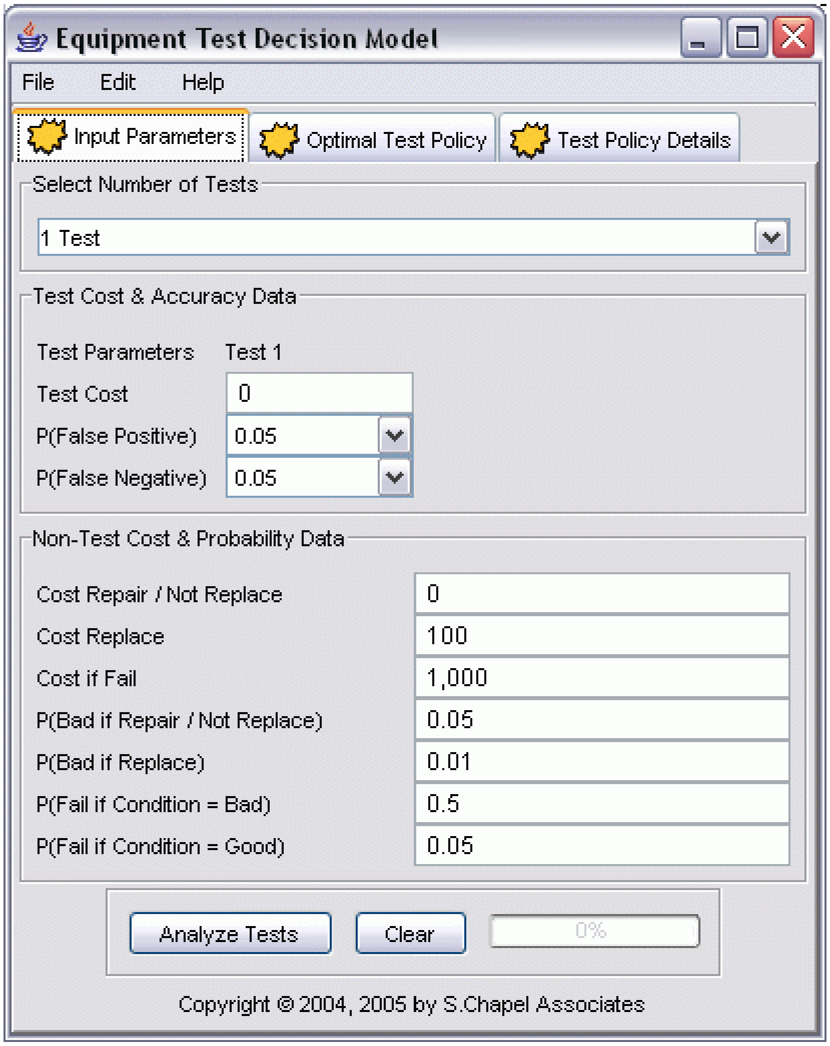
CLICK TO CLOSE

Figure 2
Start-Up Screen

Note that the main window has three tabs, (1) Input Parameters, (2) Optimal Test Policy, and (3) Test Policy Details. Each of these screens is described in the next three sections. At start-up the Input Parameters Tab is displayed with default data.



Select Number of Tests

1 Test

Test Cost & Accuracy Data

Test Parameters	Test 1
Test Cost	0
P(False Positive)	0.05
P(False Negative)	0.05

Non-Test Cost & Probability Data

Cost Repair / Not Replace	0
Cost Replace	100
Cost if Fail	1,000
P(Bad if Repair / Not Replace)	0.05
P(Bad if Replace)	0.01
P(Fail if Condition = Bad)	0.5
P(Fail if Condition = Good)	0.05

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Figure 3
Program Main Window

Input Data

The Input Parameters Tab has four sections.

- The user must select the numbers of tests to be considered,
- For each test, the costs and accuracy parameters must be specified.
- The non-test costs and probability information must be specified.
- The final panel has two buttons, *Analyze Tests* and *Clear*. Clicking the *Analyze Tests* button causes the model to be run. After the calculations are complete the second tab, *Optimal Test Policy* is shown. Pressing the *Clear* button clears the output data in Tabs 2 and 3 and sets all input data, Tab 1, to the default values.

These inputs are explained in Table 1 below.

Table 1
Input Data

Input	*Explanation*
Number of Tests	The number of tests to be considered in the test strategy (1 to 3). Select from the drop-down menu.
Test Cost	The cost of each test (zero or greater). Formatting on all costs restricts inputs to be zero or greater. Only whole numbers are allowed. If you enter an invalid cost the model will not allow you to go to another field until the invalid cost is corrected.
P(False Positive)	This is one of the two required test accuracy parameters. These parameters must be specified for each test. This indicates the probability that, for the test, a good piece of equipment will test positive as being faulty. Select from the options in the drop-down menu
P(False Negative)	This indicates the probability that, for the test, a faulty piece of equipment will test negative as being faulty. Select from the options in the drop-down menu.
Cost Repair / Not Replace	The cost must be entered for the case where the piece of equipment is either repaired or ignored but not replaced (enter values of zero or greater).
Cost Replace	The cost must be entered for the case where the piece of equipment is replaced (enter values of zero or greater).
Cost if Fail	Enter the cost if the piece of equipment or system fails (zero or greater).
P(Bad if Repair / Not Replace	Enter the probability that the equipment or system is faulty if the option to not replace is chosen (between 0 and 1.0). Note that if an invalid probability is entered, the model will not allow you to go to another field until the invalid probability is corrected.
P(Bad if Replace).	Enter the probability that the equipment or system is faulty if the option to replace is chosen (between 0 and 1.0).
P(Fail if Condition = Bad)	Enter the probability that the equipment or system fails if the condition is faulty (between 0 and 1.0).
P(Fail if Condition = Good)	Enter the probability that the equipment or system fails if the condition is not faulty (between 0 and 1.0).

Viewing Model Outputs

Introduction

The *Optimal Test Policy* and *Test Policy Details* tabs contain the outputs for the model. The first tab summarizes the optimal policy and the second tab shows the detailed calculations. The outputs are described here for a model run using the default inputs (Figure 3 shows the input screen with default values). The default values are an evaluation of a single test strategy. In the next chapter a more detailed set of inputs and results is explained.

ETM creates a decision tree and identifies the least cost testing policy. An example tree is shown below, Figure 4 Three decision are evaluated at each node in the tree – (1) Repair/Replace – Do Nothing (RR-DN), (2) Repair/Replace – Replace (RR-REP), and (3) Test.

The nodes are numbered. Node 0 is the start of the tree. If a test is the best option that node generates two additional nodes, nodes 1 and 2. Node 1 represents the state that the test outcome is 'Positive' meaning that the equipment tested positive as being faulty. Node 2 is the state where the test outcome is 'Negative" meaning that the equipment tested negative as being faulty. Note that all odd numbered nodes represent Positive test outcomes and all even numbered nodes represent Negative test outcomes.

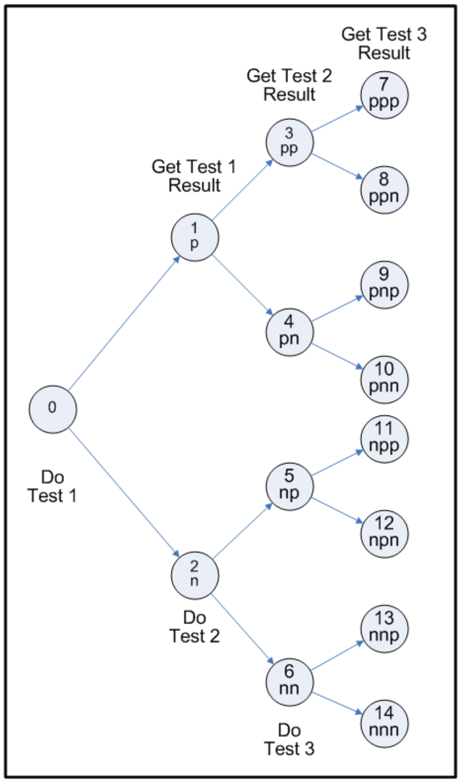


Figure 4
Tree Nodes & Test Outcomes

The tree above illustrates the case where three testes are evaluated. With three tests the model creates and evaluates 15 nodes (0 through 14). This tree is used to find the optimal testing strategy – essentially all possible decision and out comes are considered.

Figure 5 below shows the tree for an evaluation of a single test. At node 0 the test is performed. Then for both test outcome (*Positive* and *Negative*) the two repair/replace options (*RR-DN* and *RR-REP*) are evaluated and the least cost option is chosen. The expected cost of the test option is then compared to the expected cost of the best repair/replace decision without testing.

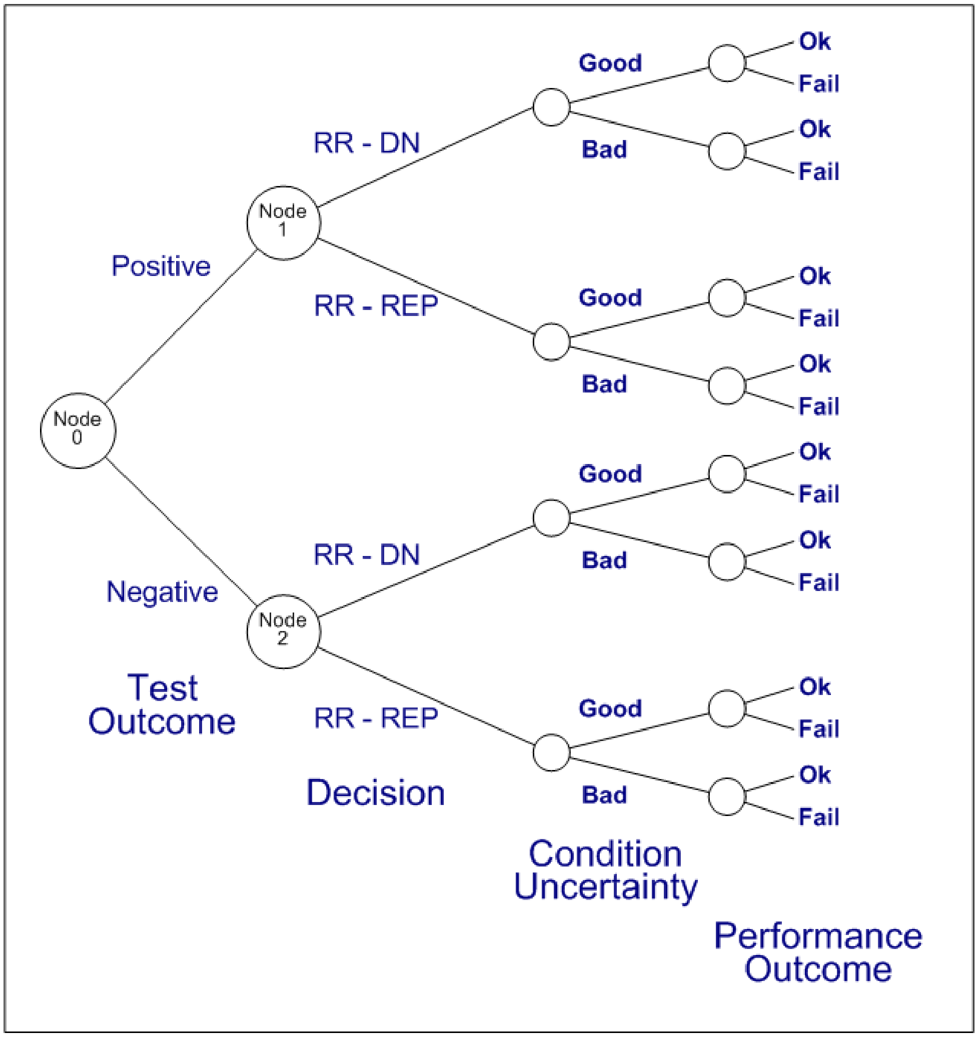
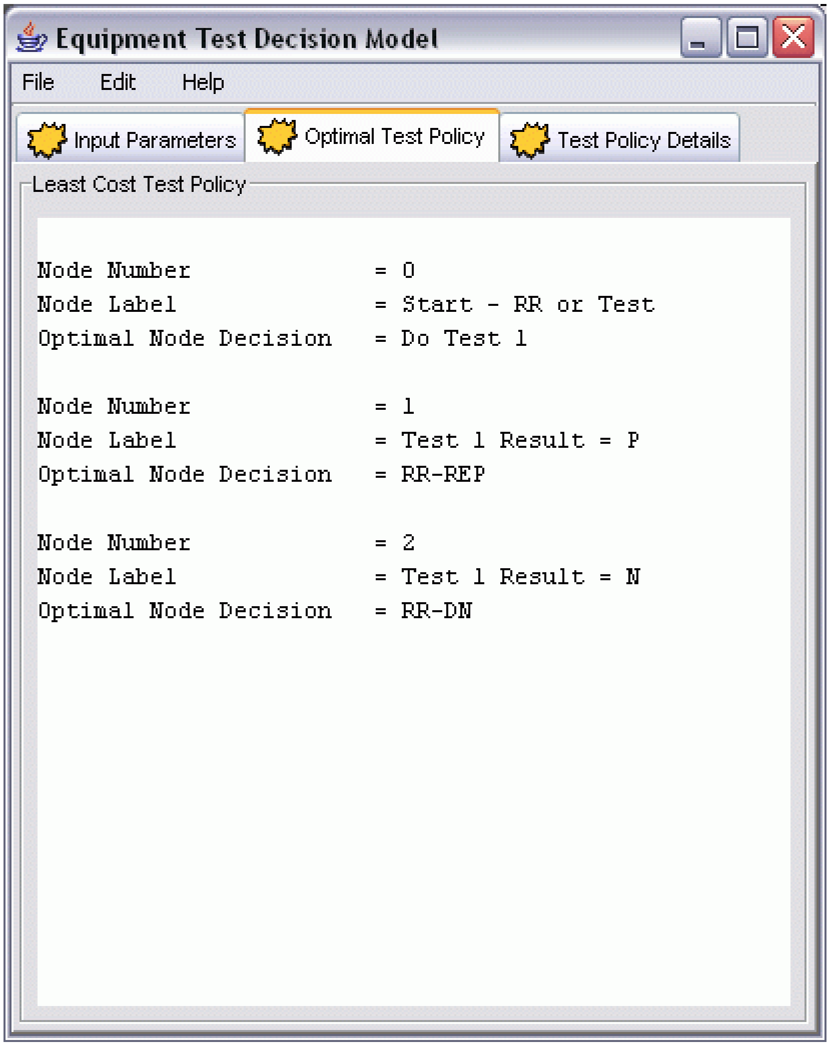


Figure 5
Decision Tree – One Test Evaluation

Optimal Test Policy

The optimal strategy is summarized for the default data set in Figure 6 below.



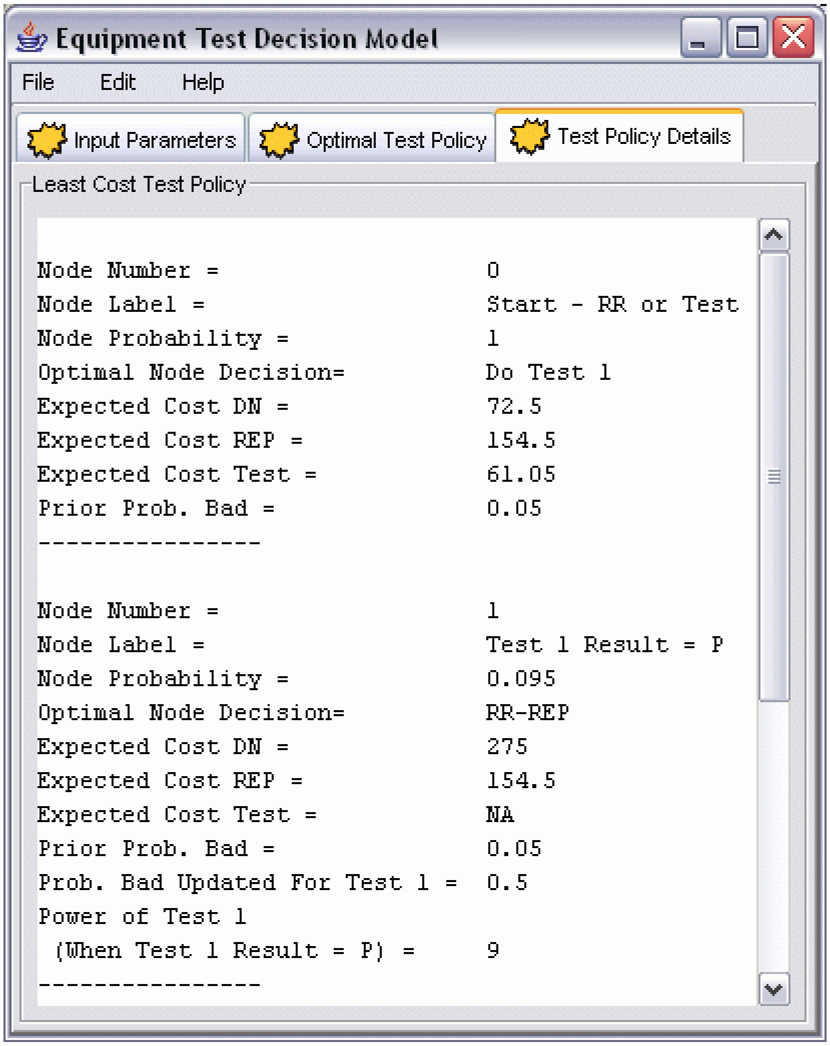
```
Node Number              = 0
Node Label               = Start - RR or Test
Optimal Node Decision    = Do Test 1

Node Number              = 1
Node Label               = Test 1 Result = P
Optimal Node Decision    = RR-REP

Node Number              = 2
Node Label               = Test 1 Result = N
Optimal Node Decision    = RR-DN
```

Figure 6
Optimal Test Policy – For Default Data Set

This shows that the best policy is to perform the test. If the test is positive you replace the piece of equipment. If the test is negative you do not replace the equipment or system.

Test Policy Details

The third tab, Test Policy Details, provides the information necessary to understand the economics of the optimal strategy. Figure 7 shows the details for nodes 0 and 1.



```
Node Number =                   0
Node Label =                    Start - RR or Test
Node Probability =              1
Optimal Node Decision=          Do Test 1
Expected Cost DN =              72.5
Expected Cost REP =             154.5
Expected Cost Test =            61.05
Prior Prob. Bad =               0.05
----------------

Node Number =                   1
Node Label =                    Test 1 Result = P
Node Probability =              0.095
Optimal Node Decision=          RR-REP
Expected Cost DN =              275
Expected Cost REP =             154.5
Expected Cost Test =            NA
Prior Prob. Bad =               0.05
Prob. Bad Updated For Test 1 =  0.5
Power of Test 1
 (When Test 1 Result = P) =     9
----------------
```

Figure 7
Test Policy Details – Default Data

For node 0 three decisions are considered, the test option and the repair/replace options. The test option has the lowest expected costs and thus performing the test is a part of the optimal strategy. Node 1 show the details for the case where the test outcome is positive (P). Because no further tests are being considered, just the repair/replace options are evaluated. Given a positive test outcome, the Replace option has the lowest expected cost. If you run the model and scroll down so that you can see the results for node 2, you will find that if the test outcome is negative, the best option is to Do Nothing.

The test changes the least-cost decision (when you think about it it becomes obvious that for a test to have positive value it must change the least cost decision). Without a test the best option is to do nothing and the expected cost is 72.5 (Figure 7). With the test the best decision depends on the test outcome and the expected cost is 61.05. In the default data set the cost of the test is zero. The value of the test (and maximum amount that you should be willing to pay for the test) is the difference between the expected cost if the test is not done and the expected cost if the test is done (72.5 – 61.05).

Other details provided in the tab are:

- *Node Probability:* For node 1 this is the probability of a positive test outcome. This is calculated by the model and is the sum of the probabilities of a positive test given the equipment is faulty and given the equipment is not faulty.
- *Prior Probability Bad*: This is the probability that the equipment is faulty prior to being tested. For this case, because there is a single test, the prior probability is the probability of faulty equipment reported for node 0.
- *Probability Bad Updated for Test 1*: This is the updated probability that the equipment condition is faulty. This is calculated using Bayes' Law. Inputs to the calculation are (1) prior probability of being faulty, (2) test outcome and (3) test accuracy. The formula for Bayes' Law is given in the appendix. For node 1, a positive test outcome, the updated probability that the equipment is faulty is 0.5.
- *Power of Test:* The power of the test is calculated by the model. This is defined as the ratio of the change in the assessment that the equipment is faulty divided by the prior probability that it is faulty. For node 1 this is 9.0.

Menus

Most of the functionality of ETM does not require the use of the menus. However, three menus are provided, *File, Edit* and *Help*.

The *File* menu has *Open, Save, Save As* and *Exit* items. Only the *Exit* item is functional at this time. In a future version of the model the ability to Open and Save data sets will be added.

The *Edit* menu has the standard *Cut, Copy, Paste* and *Select All* items. These allow the user to edit the data in the output data tabs. For example if the user wants to save or print results, they can copy and paste to a text file or a word processing file.

The *Help* menu has two items, *Help contents* and *About*.

- *Help contents*: Selecting this item opens the ETM help system.
- *About*: Clicking this item gives information about the model including Model Name, Version and Copyright information.

CHAPTER 3
TUTORIAL

Background

Many electric power companies have a large inventory of existing assets including perhaps hundreds of power transformers, thousands of miles of underground cable, thousands of distribution poles and hundreds of substation breakers. Many of these systems were installed 20 to 50 years ago and over the next five to twenty years will be candidates for replacement.

The cost of replacement is potentially enormous and thus utilities would like to get as much use out of the assets a s possible. At the same time it is critical to have a planned approach to replacement that avoids extra ordinarily large cash outflows in any given year. Predicting the useful life of assets is central for companies to control outage and replacement costs and manage the cash flows associated with repair/replace.

The problem faced by utility managers is how to predict the useful life of a specific system or piece of equipment and use this information to make repair/replace decisions. For some systems such as wood poles the process of testing, maintaining and replacing is reasonably straightforward – establishing the condition of a pole is not expensive and is reasonably accurate. For other systems, power transformers and underground cable are examples, the problem of establishing system condition is more expensive and imprecise. For such systems diagnostic tests and the integration of these tests into decision models have great promise for the improving repair/replace management decisions. The Equipment Testing Decagon Model (ETM) is specifically designed for this purpose. This tutorial illustrates some of the key aspects of the use of ETM.

Diagnostic testing has potential high value when the consequences of failure are significant and the underlying condition of the asset is uncertain and not directly observable. ETM is designed to help you evaluate tests when the consequences of failure are significant.

Example Problem

This example draws upon experience helping companies solve the repair/replace problem for underground residential cable distribution systems (URD). Company X has about 10,000 miles of URD cable. Some of their inventory of cable has been in the ground for over 40 years. The company would like to use diagnostics to help refine their policies for replacing cables as the cables reach end of life. Currently the company replaces cable segments when they are 20 years old or older and have failed twice.[1] This policy is developed using a simple forecasting model for predicting failure probabilities. The forecasting model is imbedded in an engineering economic calculation of the present value of costs conditional on alternative replace policies. The replace policies are defined by age and number of prior failures.

The forecasting model is a hazard function that predicts the average failure rate for cables as a function of age. Figure 8 shows form of the hazard function.[2]

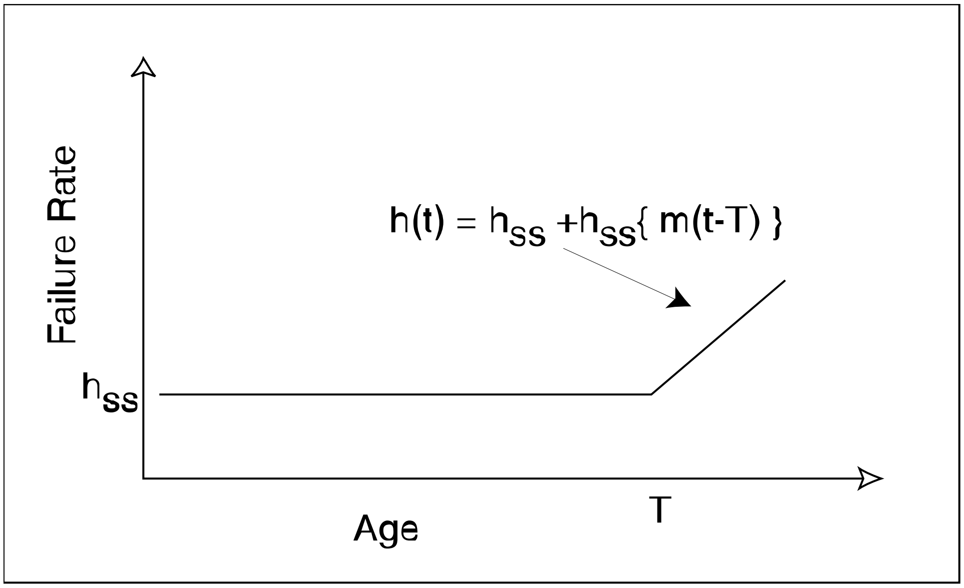


Figure 8
Hazard Function

The hazard function is a failure rate forecasting model where the independent variable is t, the age of the cable, and the dependent variable is h(t), the failure rate for a cable t years old. The failure rate in this formulation is the expected number of failures per mile of installed cable per year. The hazard function is a piecewise linear function that is constant at the steady-state rate h_{ss} until the onset of the burnout period, which begins at age T. After the onset of burnout, the hazard function grows linearly with slope m.

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[1] This policy is purely hypothetical and is not based on any specific company replace policy. However it is similar to policies that exist at many companies.

[2] This functional form was suggested by Charles Feinstein, VMN Group LLC. It has been used in several applications to develop replace policies.

For further reading see Guidelines for Intelligent Asset Replacement, Volume I, Feinstein C.D., Morris P.A., 2003, EPRI Report 1002086. Also see the publications page of my web site www.s-chapel.com.

The purpose of this sidebar is to add perspective to the problem. There is much literature devoted to the debate of the appropriate mathematical form for hazard functions. However, from a practical perspective this debate is not helpful. The debate suggests that there is a precision associated with these predictive models.

In fact the models are not precise predictors of the likelihood of failure. For any given age of cable or other systems there can be subpopulations with widely differing average failure rates. Thus while the hazard rate model may give a reasonable prediction of the average failure rate for specific equipment of a given type and age, it may not be a good indicator of the likelihood of failure for specific equipment or systems. We can do better if we can further subdivide the type and age categories. This subdividing is precisely the reason for diagnostic testing.

Figure 9 is graphical representation of the fact that you should expect variation in the failure rates for the sub-groups

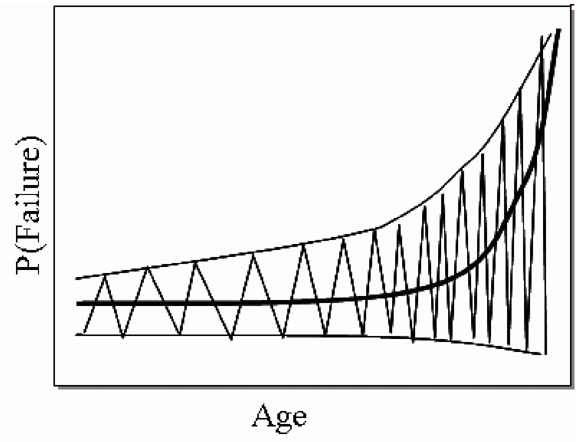


Figure 9
Hazard Functions (Average Rate by Year) may not be a good predictor for specific equipment

For the purposes of this example the onset of burnout period, *T*, is 20 years and the slope of burnout, *m*, is 0.2. This means that the average failure rate will double every five years after age 20. The steady-state failure rate (the average failure rate for cables younger than 20 is 0.02 – on average 2 percent of these cables segments will failure each year. For cables that reach 25 years old the failure rate is 4% and for those reaching 30 years the rate is 6%. In addition the company assumed that once burn-out is reached (year *T*), for each time a cable fails and is repaired the probability of failing doubles.

As suggested above, the problem with this predictive model is that for any age of cable there can be many cable segments in good condition. Thus applying a policy to replace cables that have reached a certain age or even age and two failures can result in many good cables being replaced. The application of *ETM* can reduce this problem and lower repair/replace costs.

Application of ETM

Input Data

The company has the option to apply two different diagnostic tests in order to better predict the condition of URD cable. These tests use two entirely different mechanisms for detecting the presence of water trees in the cable (water trees are essentially the breakdown of the insulating material). If water trees are present the likelihood of failure in the next year is estimated to be about 0.50. If water trees are not present the failure rate is assessed as 0.01 or less.[3]

The two tests are <u>not</u> 100 percent accurate. Test 1 is cheap but will only detect bad cable segments about 70% of the time (test 1 has about a 0.3 probability of a false negative). In addition Test 1 will identify good cable segments as bad about 30% of the time (false positives). Test 2 is much more accurate (the chance of false positives and negatives are only about 5%) but is more expensive.

The question that the company wants to address is which of the tests should it used and what age cables should be tested.

The inputs for all cases are shown in the table below. This table has the test cost and accuracy data as well as the non-test cost and probability information.

Table 2
Input Parameters – all cases

TEST COST AND ACCURACY DATA	
Test 1 Cost (per cable segment)	$100
Test 2 Cost (per cable segment)	$1000
Test 1 P(false positive)	0.30
P(false egative)	0.30
Test 2 P(false positive)	0.05
P(false negative)	0.05
NON-TEST COST AND PROBABILITY DATA	
Cost of Not Replace	$0
Cost of Replace	$50,000
Cost if Fail	$200,000
Probability of Bad if No Replace	Case Dependent
Probability Bad if Replace	0.01
Probability Fail if Bad	0.50
Probability Fail if Good	0.01

The test cost and accuracy data were obtained from test vendors. The cost of *Replace* and the cost of *Not Replace* are one-time costs estimated by the company.

---

[3] Again these assumption are purely hypothetical and for illustrative purposes only.

The cost of failed cables include the cost to the utility to repair the circuit and the outage costs of customers. This cable failure cost required some side calculations. If the company decides to not replace a piece of cable, the failure costs were calculated as the present value of the number of failures over a ten year period.

Analysis

Case 1: Testing Cable Younger than 20 Years (using accurate but expensive test)

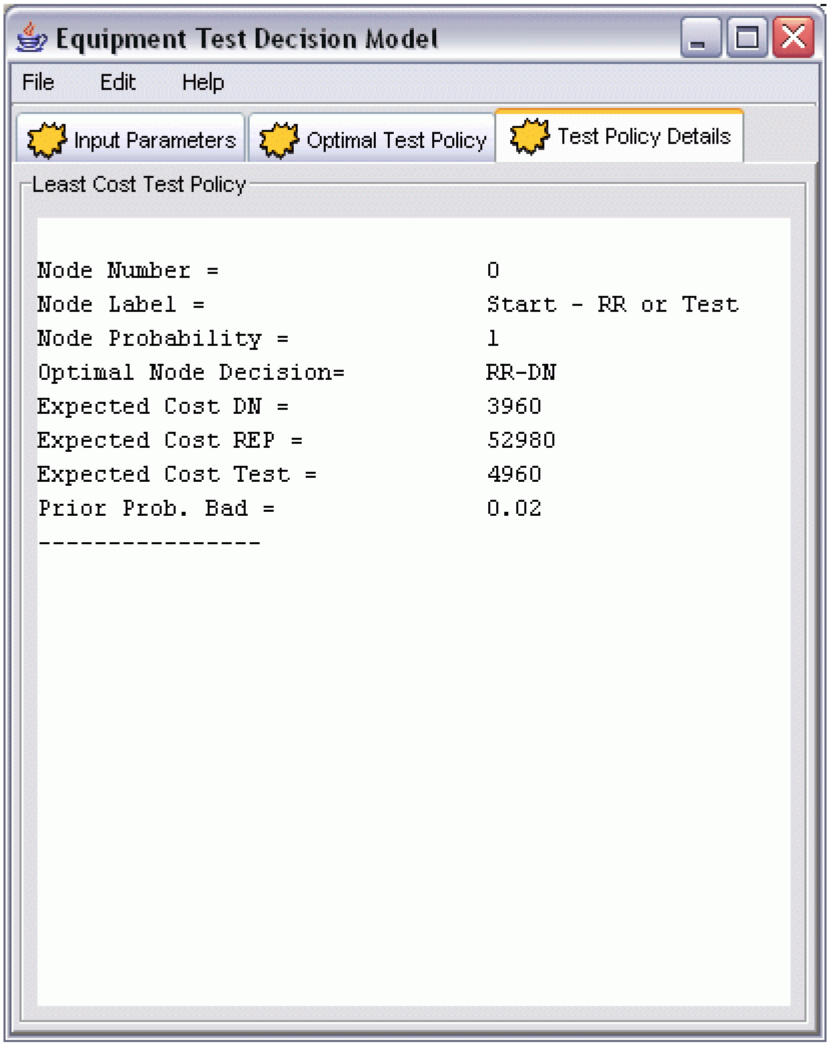
For cable 20 years old or younger examination of the inputs would seem to indicate that it is not cost effective to test. Analysis using ETM demonstrates this fact.

Prior to burnout there is a very low likelihood of failure (2%) in any given year. However, in order to perform an analysis of the value of testing we need an assessment of cable condition prior to testing (the average failure rate is not enough – we need to know what the average failure rate implies for the likelihood of condition being bad)). This assessment was made by recognizing the relationship between the average failure rate and the probabilities of failing given the underlying conditions of good and bad. The probability of the presence of water trees, p(bad) ,is obtained by solving the following equation:

$$p(fail) = p(fail \mid bad)\,p(bad) + p(fail \mid good)\left\{1 - p(bad)\right\}$$

Applying this equation indicates that approximately 2% of these cable segments have water trees or some other condition that could lead to failure.

The results for this analysis using the more accurate but more expensive test is shown in Figure 10. The cost of failure must be almost doubled to $300,000 before it becomes cost effective to test cables prior to the onset of the burnout period. Analysis of the inexpensive test indicate that it is not cost effective either.



```
Node Number =                   0
Node Label =                    Start - RR or Test
Node Probability =              1
Optimal Node Decision=          RR-DN
Expected Cost DN =              3960
Expected Cost REP =             52980
Expected Cost Test =            4960
Prior Prob. Bad =               0.02
----------------
```

Figure 10
Case 1 Policy Details (Pretest Probability of Bad Condition = .02)

Case 2 Testing 30 Year Old Cable (using accurate but expensive test)

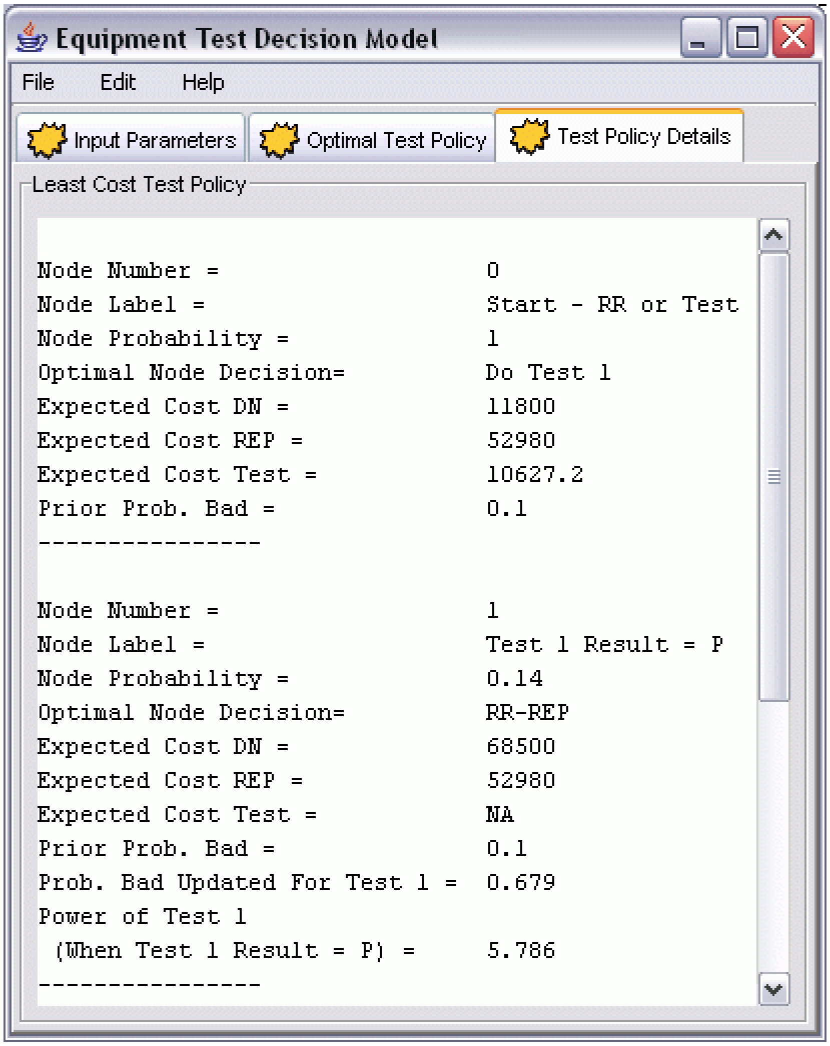
According to the hazard function and no additional information, this cable category has a 6% chance of failure in any given year. This implies that the likelihood of observing water trees is 10%. Thus the input for *P(Bad if Repair / Not Replace)* is changed to 0.10 and the model rerun.

The results for the accurate but expensive test now indicates that it is cost effective to test. The results are shown in Figure 11Figure 11. If the test is positive the best option is to replace. If it is negative it is best to not replace.

.

There is a 14% chance that the test will be positive. In this case the probability that the cable condition = bad is updated to 0.68 from 0.1 (the power of the test is 5.786). While it is not shown in Figure 11, there is a 86% chance that the test will be negative and in this case the probability of the cable condition being bad is reduced from 0.1 to 0.006 (the power of the test is -.942). These results indicate that the test significantly improves the ability to discriminate between cables that are in good and bad condition.

The value of the expensive test is the difference between the costs when the test is done and the cost of not doing the test. This is $1,173 = $11,800 - $10,627. While this is a hypothetical example, it illustrates that there are potentially significant savings for every cable segment tested. If this is for longer cable segments, say 0.25 miles each and a company has hundreds or thousands of miles of old cable, there is real potential to improve the identification of bad cable segments and save money.



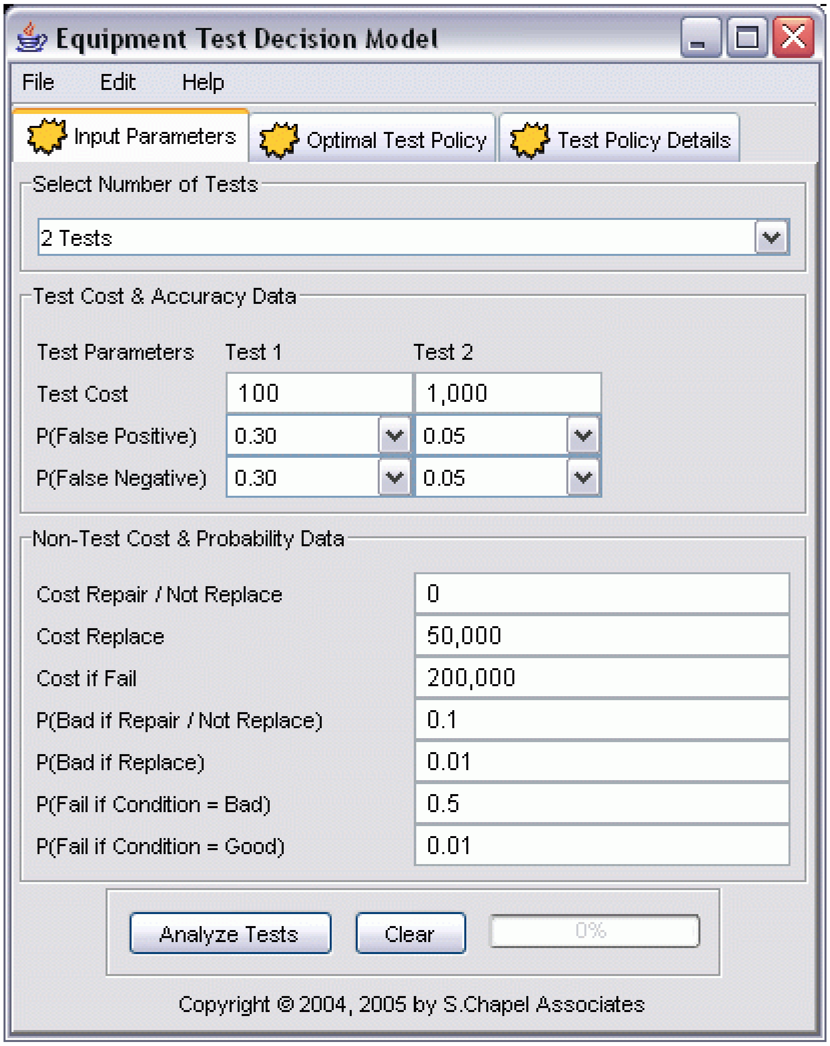
```
Node Number =                      0
Node Label =                       Start - RR or Test
Node Probability =                 1
Optimal Node Decision=             Do Test 1
Expected Cost DN =                 11800
Expected Cost REP =                52980
Expected Cost Test =               10627.2
Prior Prob. Bad =                  0.1
----------------

Node Number =                      1
Node Label =                       Test 1 Result = P
Node Probability =                 0.14
Optimal Node Decision=             RR-REP
Expected Cost DN =                 68500
Expected Cost REP =                52980
Expected Cost Test =               NA
Prior Prob. Bad =                  0.1
Prob. Bad Updated For Test 1 =     0.679
Power of Test 1
 (When Test 1 Result = P) =        5.786
----------------
```

Figure 11
Case 2 (Pretest Probability of Bad Condition = .10)

Case 3 Use of Multiple Tests on 30 Year Old Cable

Does it make sense to use multiple tests – say a cheap test followed by an expensive test or perhaps two cheap tests. Addressing these questions is demonstrated here. In the first multiple test run we examine the sequence of a cheap test followed by an expensive test. The inputs for this analysis are shown below, Figure 12.



Select Number of Tests

2 Tests

Test Cost & Accuracy Data

Test Parameters	Test 1	Test 2
Test Cost	100	1,000
P(False Positive)	0.30	0.05
P(False Negative)	0.30	0.05

Non-Test Cost & Probability Data

Cost Repair / Not Replace	0
Cost Replace	50,000
Cost if Fail	200,000
P(Bad if Repair / Not Replace)	0.1
P(Bad if Replace)	0.01
P(Fail if Condition = Bad)	0.5
P(Fail if Condition = Good)	0.01

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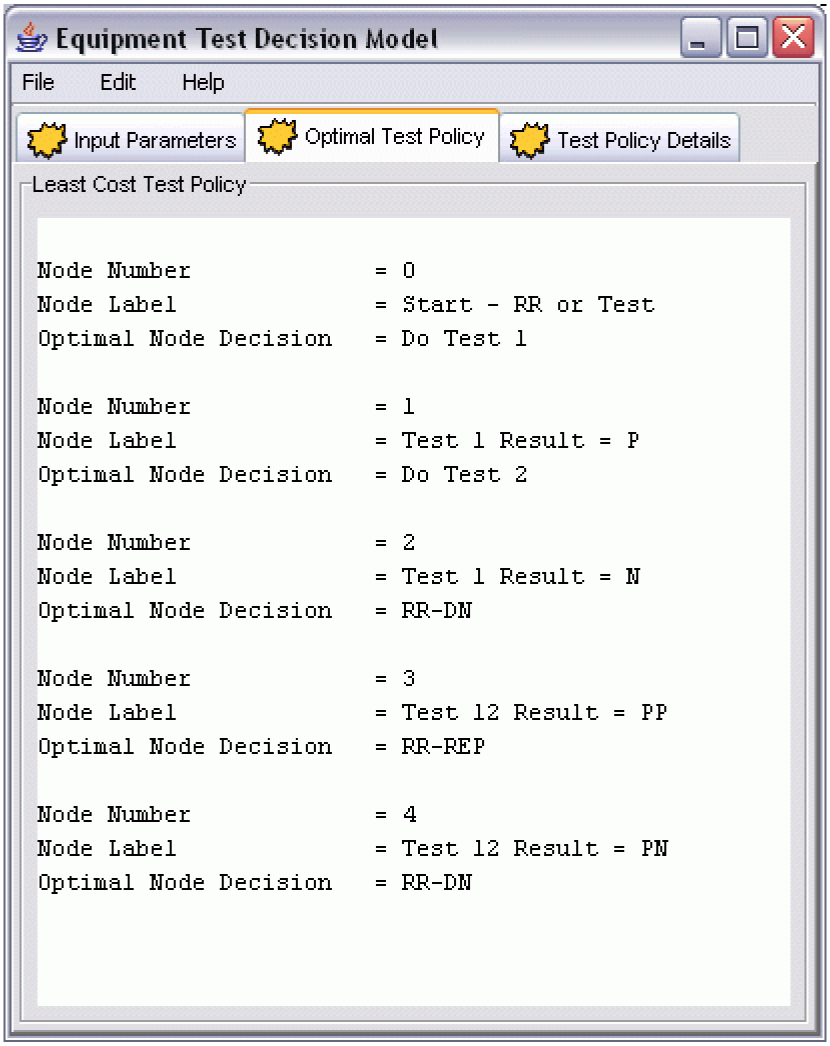
Figure 12
Inputs for Multiple Test Analysis (Cheap followed by Expensive)

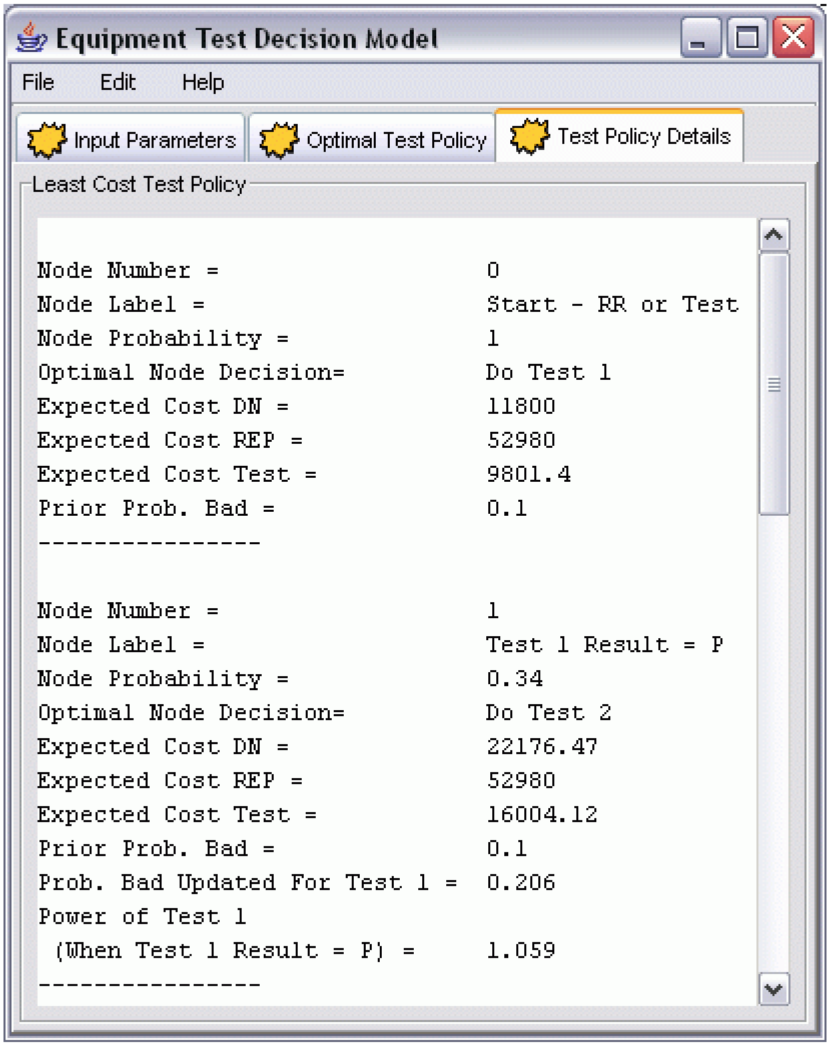
Results indicate that this "Cheap followed by Expensive" strategy is a cost effect. The policy is summarized in Figure 13. This result indicates that the best policy is to do the cheap test. If the test is negative forego the second test and do not replace. If the test is positive, the more expensive and accurate test should be done. If the second test is positive the cable segment should be replaced.



```
Node Number              = 0
Node Label               = Start - RR or Test
Optimal Node Decision    = Do Test 1

Node Number              = 1
Node Label               = Test 1 Result = P
Optimal Node Decision    = Do Test 2

Node Number              = 2
Node Label               = Test 1 Result = N
Optimal Node Decision    = RR-DN

Node Number              = 3
Node Label               = Test 12 Result = PP
Optimal Node Decision    = RR-REP

Node Number              = 4
Node Label               = Test 12 Result = PN
Optimal Node Decision    = RR-DN
```

Figure 13
Multiple Test Analysis – Policy Summary

The value of this multi test strategy is almost twice as great as the best single test strategy, $1,999 versus $1,173 ($1,999 = $11,800 - $9,801). The detailed results are shown in Figure 14 below.

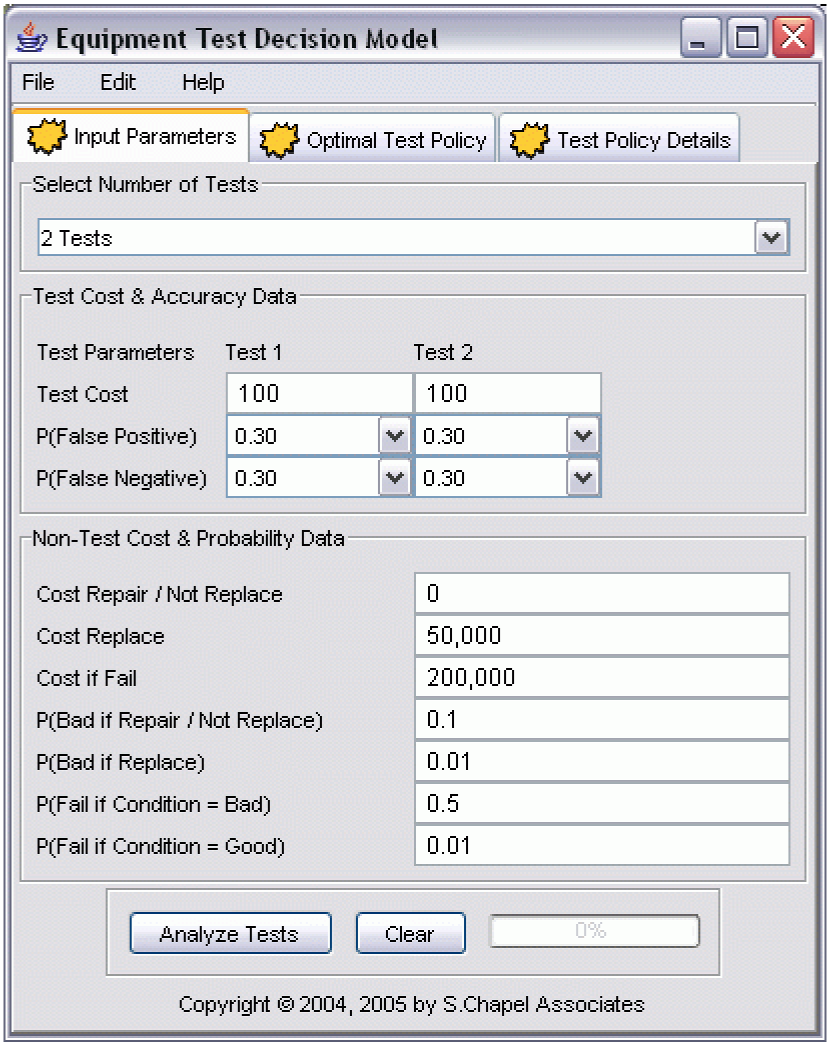


```
Node Number =                   0
Node Label =                    Start - RR or Test
Node Probability =              1
Optimal Node Decision=          Do Test 1
Expected Cost DN =              11800
Expected Cost REP =             52980
Expected Cost Test =            9801.4
Prior Prob. Bad =               0.1
----------------

Node Number =                   1
Node Label =                    Test 1 Result = P
Node Probability =              0.34
Optimal Node Decision=          Do Test 2
Expected Cost DN =              22176.47
Expected Cost REP =             52980
Expected Cost Test =            16004.12
Prior Prob. Bad =               0.1
Prob. Bad Updated For Test 1 =  0.206
Power of Test 1
 (When Test 1 Result = P) =     1.059
----------------
```

Figure 14
Multiple Test Analysis – Test Policy Details

If we have two completely independent but cheap tests, would this be better than one expensive test or an expensive and cheap test combination? To evaluate this it is assumed that there are two such tests and the costs and accuracy are the same as for the cheap test we have been working with. The inputs for this case are shown in Figure 15.

The model indicates that two independent cheap tests are not a cost-effective. In fact it is not cost effective to perform even a single inexpensive test. Detailed results are shown in Figure 16. Note that the cost of doing nothing is $11,800 and the cost of a strategy involving an inexpensive test is 11, 900. For those interested an inexpensive test does not change the repair / replace decision and it costs $100. Thus the cost of a strategy with the test is $11,800 + $100.



Select Number of Tests

2 Tests

Test Cost & Accuracy Data

Test Parameters	Test 1	Test 2
Test Cost	100	100
P(False Positive)	0.30	0.30
P(False Negative)	0.30	0.30

Non-Test Cost & Probability Data

Cost Repair / Not Replace	0
Cost Replace	50,000
Cost if Fail	200,000
P(Bad if Repair / Not Replace)	0.1
P(Bad if Replace)	0.01
P(Fail if Condition = Bad)	0.5
P(Fail if Condition = Good)	0.01

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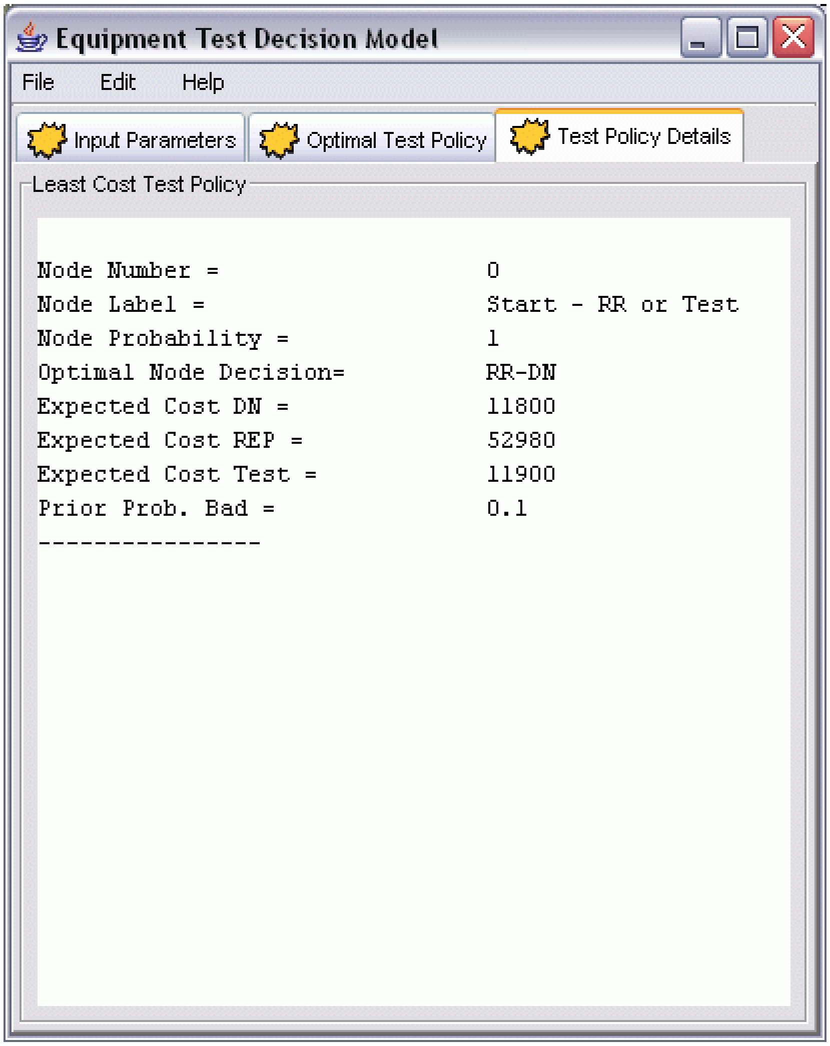
Figure 15
Multiple Test Analysis – Inputs for Two Inaccurate Cheap Tests



```
Node Number =                    0
Node Label =                     Start - RR or Test
Node Probability =               1
Optimal Node Decision=           RR-DN
Expected Cost DN =               11800
Expected Cost REP =              52980
Expected Cost Test =             11900
Prior Prob. Bad =                0.1
----------------
```

Figure 16
Detailed Results – Two Cheap Tests

Tutorial Summary

This tutorial has illustrated the key aspects of the use of ETM. The tutorial examined various testing policies – single, multiple, cheap, expensive, accurate, not accurate. The application of the model is straight-forward but requires some thought in preparing inputs and interpreting results.

- Specific data on test cost and accuracy is required. Diagnostic test experts (probably the test vendors) should be willing to provide the information.
- A model for forecasting failure rates, a hazard function, is required. This function will be different for different systems and equipment.

- Costs of repair and replace are likely to be easily obtained within the utility.
- Costs of failure are complicated by several factors. For systems like underground cable, it is likely that a segment may fail multiple times and be repaired before it is replaced. Failure costs must reflect this reality. Failure costs must include customer outage costs as well as direct company costs. Customer costs are “soft” but important numbers and must be included in any valid analysis.
- It is important for a testing analysis to differentiate between equipment condition and equipment failure. Tests help establish condition. Condition determines probability of failure.

Finally while this tutorial has focused on underground cables, the model, ETM, is a general methodology and has potential application to other systems and equipment. A natural application is to power transformers. Test results here might be defined as changes from prior test results.

APPENDIX ANALYTICAL METHOD

The Equipment Testing Decision Model uses stochastic dynamic programming to develop least cost testing strategies. Essentially a decision tree is developed that considers all possible test and repair/replace decisions. This tree is solved recursively to identify the least cost strategy. The only restriction to the solution is that multiple tests are only considered in the order specified in the inputs (test 1 precedes test 2 which precedes test 3).

Two equations underlie all probability calculations, Bayes' Law and an equation to calculate the branch probabilities for test outcomes – the probability of a positive test outcome and a negative test outcome.

Bayes' Law – Updating Probability of Equipment Condition

Bayes' Law provides the updated probabilities that a piece of equipment or system is faulty (bad) conditional on test outcome. Equation 1 gives the probability that the condition, *c* is bad, *b*, given that the test outcome is positive, *p*. Equation 2 gives the probability that the condition, *c* is bad, *b*, given that the test outcome is negative, *n*.

Equation 1

$$p(c=b\,|\,t=p)=\frac{p(t=p\,|\,c=b)\,p(b)}{p(t=p\,|\,c=b)\,p(b)+p(t=p\,|\,c=g)\,p(g)}$$

Equation 2

$$p(c=b\,|\,t=n)=\frac{p(t=n\,|\,c=b)\,p(b)}{p(t=n\,|\,c=b)\,p(b)+p(t=n\,|\,c=g)\,p(g)}$$

Calculating Branch Probabilites

The branch probabilities are calculated as follows. The probability of a positive test is given by $p(t=p)=p(t=p\cap g)+p(t=p\cap b)$. Equation 3 provides the calculation in terms of the probabilities of false positive and false negative.

Equation 3

$$p(t=p)=p(\mathit{false\ positive})\,p(g)+\left\{1-p(\mathit{false\ negative})\right\}p(b)$$

Test Independence

Multiple tests must be independent for this method to apply. This means that multiple test must be completely different approaches for testing the condition of equipment. For example test 2 cannot be a repeat application of test 1. Test 1 results (positive or negative) are used to update the assessment of the probability of condition being bad. This update is done by applying Equations 1 and 2. With independent tests, this updated assessment can be further updated through tests 2 and 3.