ECONOMIC RELIABILITY FORECASTING IN AN UNCERTAIN WORLD

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Abstract Substantial work has applied stochastic techniques to network reliability models. These techniques can estimate *risk*, *variance* and *uncertainty* values. Unfortunately, these models do not address the issues of revenues, return on investment, or the time-value of money. To address these issues, we have developed an Economic Reliability Analysis [*ERA*] framework at the University of Virginia that fuses reliability engineering methods with economic analysis. We combine the *ERA* framework with stochastic techniques to evaluate a simple network and a proposed network upgrade. We simulate key availability and financial elements of both networks and apply the *ERA* framework to these elements. These results are compared with full path enumeration results of the same networks. This analysis provides a richer, more complete method to apply stochastic network techniques to operational network upgrades.

Index Terms Stochastic network models, Reliability and maintenance models, Stochastic simulation.

I. INTRODUCTION

Consider the following scenario. A company has a network that provides the basis for its revenue. The company must choose whether to maintain the status quo or modify the network to gain a new revenue stream. The company only has resources to choose one of these projects. The question is, *which project should be implemented*. The general problem, simply stated is: *"How do you profitably operate, maintain and evolve a dependable operational network?"* This general problem can be addressed by a set of smaller, more directed questions. These questions are:

1) What is the economic effect of developing and implementing a network change?
2) What is the economic improvement associated with improving network reliability?
3) When do the costs of improving network availability exceed its expected benefits?
4) How reliable must a new network be before it becomes operational?

These questions can be difficult to answer. Most organizations have several different types of network components in a network, each with different associated reliability and repair cost data. In addition, different *user-oriented* measurements for availability and their economic impact must be understood. As such, these two costs associated with a network failure (*network component repair cost* and, *lost revenue associated with a network failure*) must be considered when modeling the economic impact of network repairs.

This article aims to extend the network reliability model techniques with an Economic Reliability Analysis (*ERA*) framework developed at the University of Virginia [7] and apply it to an operational network system.

The motivation for writing this paper is threefold. First, we want to address the dilemma of picking a project that will affect the reliability and economics of an *operational* network system. We also want to extend the framework to provide some estimates of *risk* and *confidence* that can be provided from the inclusion of stochastic modeling techniques. Finally, we want to illustrate the power and usefulness that simulation techniques can provide to practical business and engineering decisions.

II. RELATED WORK

Several research groups have investigated the relationship between reliability and economic value. Current literature indicates this relationship has taken several directions.

Research at British Telecom, [8], [1], [9] focused on modeling repair costs of their own telecommunications network. This directed research aimed at predicting expected costs without providing any structural insight into controlling these costs. Their system was a very large, distributed network, where the principal issue was the rapid detection, identification and restoral of telephone service outages. Network design or new service offerings were not considered.

Economic models have been proposed to deal with the production and distribution of electrical power in which the reliability of the power grid, electrical production and distribution costs along with macroeconomic models are considered [10], [11], [12]. Yoon and Iliè treat electrical power as a commodity and propose a new business model for this industry. Their research aims to improve delivery of electrical power to consumers with greater economic efficiency.

Mitchell and Gelles [4] describe a framework for risk-value models. Research in Markov reward models [3], Petri net models [2], advanced Monte-Carlo simulation procedures [5],

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and rare event simulation [6] provide insights into the use of stochastic techniques to estimate network reliability.

Current approaches do not adequately describe the monetary benefits (i.e. *revenues*) associated with *operational* networks or the *time-value of money*. Inclusion of these concepts can produce a better understanding of the economic *worth* of a reliable *operational* network.

In [7], Stoker and Dugan define an Economic Reliability Analysis methodology to evaluate the economic worth of a reliable network. The general strategy behind the *ERA* framework is to collect and use *availability* and *financial* data about a system from within an organization rather than build *"yet another reliability/financial model."* The *ERA* framework provides a means to determine how *changes* in component reliability, service pricing, and component/task dependencies influence system *availability, return on investments*, and *design*.

Step	***Function***
1.	Determine the duration, size and scope of the analysis.
2.	Build network reliability models for all design choices.
3.	Map network reliability information into **component** and **task** failure data.
4.	Calculate revenue vectors for all design choices.
5.	Calculate lost revenue vectors for all design choices.
6.	Calculate recurring cost vectors for all design choices.
7.	Calculate other cost vectors for all design choices.
8.	Calculate capital cost vectors for all design choices.
9.	Calculate [**ERV**] for all design choices.
10.	Analyze and interpret results of evaluation.

TABLE I
ERA FRAMEWORK ALGORITHM

Table I provides a summary of the operational set of processes performed by the *ERA* framework. These processes will be illustrated in the following example.

III. STOCHASTIC RELIABILITY EXAMPLE

Economic and reliability processes will be simulated using *stochastic* methods, sampled and evaluated with the *ERA* framework. The results of this simulation will be compared to results using *deterministic* methods. See [7] for a complete description of the Economic Framework, network solutions and exact results. These simple simulations will allow us to easily compare the impact of *uncertainty* on expected system *reliability* and *economic worth*. In addition, these simulations will provide an expected range of parametric values for both networks. Finally, comparisons that account for normal variances between networks can be made.
Figure 1 shows a current network (**Network A**) and a proposed network (**Network B**). The proposed change will be to add a node and move two links (A_3 and A_6) to connect between Nodes s and t. **Network B** is more *reliable* than **Network A**,

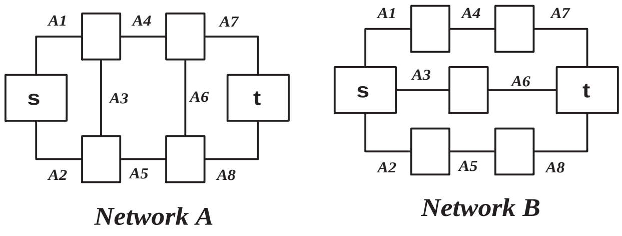

Fig. 1. Example Networks

assuming that only edges fail and that edge reliability metrics are identical in both Networks.

IV. QUESTIONS TO ANSWER

Stochastic network reliability models can provide *confidence intervals* on reliability parameters by simulating when components components fail and repair rates. These models also allow one to examine the impact of *uncertainty* on network availability. Both of these elements can significantly alter network design choices. Below are a set of questions that can be answered using a stochastic network model.

1) What is the range of expected availability for a given network?
2) What is the range of expected *Economic Reliability Values* for a given network?
3) What is the impact of *uncertainty* on expected network availability?
4) What is the impact of *uncertainty* on network *Economic Reliability Value*?
5) How does component reliability *variances* affect network availability?
6) How does component reliability *variances* affect network *Economic Reliability Value*?

A. Model Assumptions

1) $A_{Net_A} = \$1500$ and $A_{Net_B} = \$1550$.
2) Network failure cost is \$100 per failure. Network failure duration is 2 hours.
3) Edge MTTR is 2 hours, edge availability is .99, average edge repair cost is \$10/repair and the average edge repair rate is \$0/hour for all edge repairs and applies to both networks.
4) $F_{Net_A} = \$0$ and $F_{Net_B} = \$10$.
5) $G_{Net_B} = \$1000$ for the initial time period else, $G_{Net_B} = \$0$. $G_{Net_A} = \$0$.
6) Discount rate process (DR) is 1% per month for the duration of the analysis.
7) *Investment period is 24 months.* This is used to limit the size of the economic *vectors*.
8) *All revenues and expenses are estimated on a monthly basis.*
9) *Only edges fail.* Nodes do not fail.

10) *All edges fail identically and independently in all time periods.*
11) *The analysis only deals with the two-terminal (s - t) network availability.*
12) *Performance failures and costs are ignored in this analysis.* This limits the size and complexity of the analysis.

B. Uncertainty

We will now add *uncertainty* to stochastic model assumptions (1,2 and 3) by incorporating *stochastic* rather than *deterministic* revenue, cost, and component failure functions. We will also assume that all network failures in both networks are detected and solved. Revenue *uncertainty* is usually treated as receiving *less* than expected (or contracted) payments for services. Typically, accountants will assign a 'reserve' for bad credit extended to customers. It is important to model revenue stochastically rather than as a weighted average to account for the *time value* of the revenue vector. The same reasoning applies to modeling network and component costs.

1) $A_{Net_A} = \$1500$ occurs with a probability of 0.95; $A_{Net_A} = \$1300$ occurs with a probability of 0.05 of the time when one or more customers do not pay. This amounts to a \$200 loss of revenue in the month that it occurs. $A_{Net_B} = \$1550$ occurs with a probability of 0.95; $A_{Net_B} = \$1300$ occurs with a probability of 0.05 of the time when one or more customers do not pay. This amounts to a \$250 loss of revenue in the month that it occurs.
2) The network failure cost function for Net_A and Net_B exhibits a *uniform pdf* between \$75 per failure and \$125 per failure with an average of \$100 per failure. The network *MTBF* function has a *uniform pdf* between 5667 hours per failure and 7667 hours per failure with an average of 6667 hours per failure.
3) The component failure cost function for Net_A exhibits a *uniform pdf* between \$5 per failure and \$15 per failure with an average of \$10 per failure. The component *MTBF* function has a *uniform pdf* between 168 hours per failure and 228 hours per failure with an average of 198 hours per failure.

V. QUESTIONS ANSWERED

A simulation was run on both networks using the assumptions described above. The simulation consisted of 10,000 runs for each month for both networks. Minimum, mean, median, and maximum along with the 5^{th} and 95^{th} quantile values for *revenues*, *lost revenues* and *component repair costs* were captured. The *ERV*s for both networks were also solved using *full path enumeration* to get a *deterministic* set of values. This analysis is used to answer the questions raised earlier.

1. What is the range of expected availability for a given network?

Monthly availability for Network_A ranges from a minimum of 0.9962 in month_3 to a maximum of 0.9983 in month_4 with an average of 0.9970 over the 24 month duration. These values compare with the exact monthly availability value for Network_A of 0.9997. The monthly availability for Network_B ranges from a minimum of 0.9996 in $\text{months}_{0,11,21}$ to a maximum of 1.0 in $\text{months}_{15,17,22}$ with an average of 0.9998 over the 24 month duration. These values compare with the exact monthly availability value for Network_B of 0.99998.

2. What is the range of expected Economic Reliability Values *for a given network?*

Table II compares the exact and stochastic *ERV*s for both networks over a 24 month period. The first observation to note is that, for the duration of the analysis, the stochastic *Network A* model always has a greater *ERV* than stochastic *Network B* model. This is a different result than is obtained from solving an *analytic* model. The *analytic* choice over a 24 month period is *Network B*.

Time	**Analytic** Net_A	**Analytic** Net_B	**Stochastic** Net_A	**Stochastic** Net_B
0	1196.91	247.36	1184.58	221.13
1	2381.97	1482.37	2357.69	1430.95
2	3555.29	2705.15	3518.68	2627.69
3	4717.00	3915.82	4668.45	3812.46
4	5867.20	5114.51	5806.76	4986.87
5	7006.02	6301.33	6932.82	6149.30
6	8133.56	7476.40	8049.11	7300.59
7	9249.94	8639.83	9153.63	8440.15
8	10355.26	9791.75	10247.23	9569.16
9	11449.64	10932.26	11330.45	10686.28
10	12533.19	12061.48	12402.32	11791.63
11	13606.01	13179.52	13463.29	12886.36
12	14668.20	14286.48	14514.58	13970.91
13	15719.88	15382.49	15555.11	15043.87
14	16761.14	16467.65	16585.21	16106.32
15	17792.10	17542.06	17605.11	17158.98
16	18812.85	18605.84	18615.53	18200.40
17	19823.49	19659.08	19615.43	19232.11
18	20824.13	20701.89	20606.20	20254.02
19	21814.86	21734.38	21587.05	21264.86
20	22795.77	22756.65	22557.30	22265.48
21	23766.98	23768.79	23518.55	23256.84
22	24728.57	24770.92	24470.17	24238.40
23	25680.64	25763.12	25411.69	25210.39

TABLE II
ANALYTIC / STOCHASTIC ERV TABLE

The discrepancies between the *stochastic* and *analytic* models occur in the *revenues*. They are lower in the *stochastic* models and most notably in the network costs which are higher in the *stochastic* models. These differences disappear as one *narrows* the range of the costs and the *MTBF* values to the *average*. The net result shows the difference in the *analytic ERV*s decreases more quickly than the *stochastic ERV*s.

3. What is the impact of uncertainty *on expected network availability?*

Allowing *uncertainty* into availability calculations (in the form of a probablistic function for component MTBF), produced a slightly lower average network availability over the two year forecast for both networks (see Table III). The proportional error difference for the expected network availability of these networks is 0.27% for $Network_A$ and 0.019% for $Network_B$.

Network	Min. Avail.	Avg. Avail.	Exact Avail.	Max. Avail.
Net_A	0.9962	0.9970	0.9997	0.9983
Net_B	.9996	.9998	.99998	1.0

TABLE III

AVAILABILITY COMPARISON TABLE

4. What is the impact of uncertainty *on network* Economic Reliability Value*?*

Uncertainty has a slightly greater impact on the economic elements that form the *ERV* than it has on network availability. This is due in part to the asymmetric nature of *uncertainty* leading to *lower revenue* and *higher failure costs*. This impact can be seen in Table IV.

Month	Min. Annuity	5^{th} Q Annuity	Mean Annuity	Median Annuity	95^{th} Q Annuity	Max. Annuity
0	952.06	1111.67	1184.58	1190.69	1244.94	1301.74
1	930.11	1113.39	1184.84	1190.60	1245.50	1319.61
2	942.99	1113.84	1184.32	1190.07	1244.95	1305.40
3	949.17	1116.69	1184.60	1190.40	1245.31	1298.22
4	950.34	1113.21	1184.53	1190.67	1244.99	1299.44
5	962.09	1109.98	1183.50	1189.80	1244.26	1296.89
6	960.24	1119.12	1184.97	1190.05	1245.41	1299.84
7	966.44	1110.77	1184.19	1190.15	1246.20	1312.84
8	948.55	1107.64	1184.21	1190.02	1244.21	1301.29
9	946.44	1109.43	1184.70	1190.24	1244.93	1300.53
10	921.13	1108.02	1184.02	1190.19	1245.17	1296.77
11	943.77	1112.36	1183.69	1190.00	1245.15	1312.01
12	960.12	1111.44	1184.62	1191.04	1244.83	1323.03
13	944.08	1111.83	1184.22	1189.78	1244.07	1301.74
14	949.72	1106.15	1184.07	1190.03	1244.66	1308.01
15	949.22	1111.66	1184.07	1190.28	1245.47	1302.65
16	893.83	1114.04	1184.80	1190.36	1245.06	1300.81
17	949.10	1108.18	1184.18	1189.74	1245.72	1313.72
18	946.72	1110.85	1185.11	1191.04	1244.79	1302.16
19	929.60	1112.14	1184.97	1191.39	1245.68	1309.00
20	925.56	1103.78	1183.88	1190.40	1245.17	1310.42
21	940.28	1114.16	1184.64	1190.44	1244.48	1300.13
22	953.94	1114.66	1184.49	1189.93	1243.06	1299.00
23	948.04	1106.08	1183.64	1189.77	1243.49	1302.75
Average	944.31	1111.30	1184.37	1190.30	1244.90	1304.92

TABLE IV

NETWORK_A MONTHLY ANNUITY METRICS TABLE

The exact monthly *annuity* for Network_A is 1193.96. The percentage error for the median stochastic annuity and the exact annuity is 0.31%, which compares with the relative network availability error of 0.27%. The percentage error of the expected stochastic *ERV* from the expected closed form *ERV* is 0.32% for Network_A and 0.89% for Network_B. Figure 2 plots the relative *ERV* error for both networks over time. The comparatively large relative error in Network_B in the first month is caused by the small size of Network_B *ERV* in the first month.

VI. SUMMARY AND CONCLUSIONS

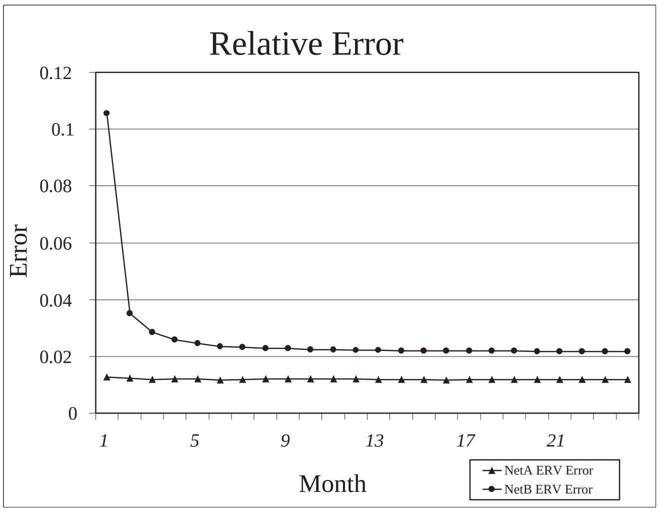

Fig. 2. Network_A & Network_B relative error over time

Stochastic reliability techniques have long been used to estimate network availability. Even simple stochastic models of networks can provide reasonable estimates of both economic efficiency and network availability with greater behavioral realism than comparable analytical methods. We have applied these techniques to estimate the expected economic impact of network and component availability and validated the results against a closed form solution.

The initial results are encouraging. We have taken our *Economic Reliability Analysis* framework and incorporated stochastic methods into it with satisfactory results. Further research and application is planned. Current plans are to apply the methods described in this paper to an operational network.

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APPENDIX

Symbol	**Definition**
BPR	Business Process Re-engineering
DCF	Discounted Cash Flow
ERA	Economic Reliability Analysis
ERV	Economic Reliability Value
NPV	Net Present Value
A	Revenue process as a function of network design and finance
$\vec{A}$	Revenue vector produced by A
B	Lost revenue process as a function of network failure
$\vec{B}$	Lost revenue vector produced by B
$\vec{TF}_n$	Task$_n$ failure vector
$\vec{TC}_n$	Task$_n$ repair cost per failure vector
$\vec{PF}_n$	Process$_n$ failure vector
$\vec{PC}_n$	Process$_n$ repair cost per failure vector
C	Lost revenue process as a function of QoS failure
$\vec{C}$	Lost revenue vector produced by C
LR	Lost revenue process: $B+C$
$\vec{LR}$	Lost revenue vector: $\vec{B}+\vec{C}$
D	Component repair cost process as a function of network failures
$\vec{D}$	Component repair cost produced by D
E	Component repair cost process as a function of QoS failures
$\vec{E}$	Component repair cost vector produced by E
F	Other recurring cost process based on normal network operations
$\vec{F}$	Other recurring cost vector produced by F
OC	Other recurring cost process unrelated to normal network operations
$\vec{OC}$	Other recurring cost vector produced by OC
RC	Recurring Cost process: $D+E+F+OC$
$\vec{RC}$	Recurring cost vector: $\vec{D}+\vec{E}+\vec{F}+\vec{OC}$
G	Capital cost process as a function of
G	network design and finance
$\vec{G}$	Capital cost vector produced by G
H	Annuity process as a function of reliability
$\vec{H}$	Annuity vector produced by H
DR	Discount rate process
$\vec{DR}$	Discount rate vector produced by DR
EC	ERV Contribution process
$\vec{EC}$	ERV Contribution vector produced by EC

TABLE V
NOTATION