Strategies and Techniques for Ensuring Network Reliability for Enterprise Customers

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1. Introduction

Contemporary networks are playing a critical role in sustaining business continuity in every vertical of the industry. The customers are becoming more sensitive to outage or degradation in service performance. In simple language, customers rely on networks for their day to day business. That brings an opportunity and responsibility on operators to assure that customers can rely on them. This assurance shall be reinforced with a tangible estimate and measure of the reliability metric.

Reliability heavily depends on the knowledge of Statistics, Physics, and Engineering. However, in order to systematically implement Reliability Engineering, the service operators have to evolve a mindset of viewing every aspect of the organization as contributor to the improvement of reliability.

This paper will discuss strategies and techniques to enhance network reliability for enterprise customers in the present state of network design and performance. This paper highlights one approach to reliability and many additional factors are involved in ensuring overall system reliability. These models can then be utilized to evaluate the impact of hardware, software, and machine learning components on reliability of network to the end customer. This paper will delve into the factors that drive optimized reliability goals such as cost, complexity, maturity, redundancy, and operational efficiency, and will illustrate the reliability of networks from conceptual, architectural, monitoring, and cost optimization perspectives.

2. General Terms and Concepts about Reliability

While reliability has been understood and interpreted from varying perspectives, the most widely accepted definition of reliability is stated by Electronics Industries Association (EIA) as follows:

The Reliability of an item (a component, a complex system, a computer program or a human being) is defined as the probability of performing its purpose adequately for the period of time intended under the operating and environmental conditions encountered.[1]

Study and analysis of reliability presents an opportunity to integrate Reliability, Availability, Maintainability and Safety (RAMS) at every stage in the product lifecycle to achieve excellent quality, optimal product reliability, and customer delight.

Reliability engineering is a mindset homogeneously internalized within an entire organization. It requires a collaborative team effort where contributors of diverse perspectives, skillsets, backgrounds, and functional departments synergize to produce superior reliability for the product.

It is accepted industry-wide that reliability of the product or services shall be examined and analyzed at the earliest stage of development. Every missed opportunity translates into a cost increase of a multiple of 10. If a team misses the opportunity to identify a reliability issue during the design stage, then it will cost 10 times more to remediate in the development stage. In essence, reliability shall be applied at every stage in the lifecycle of product.

2.1. Common Terms

2.1.1. Failure:

Failure is an event when the element/service is no longer available to perform as per SLO/SLA.

2.1.2. SLA (Service Level Agreement):

SLA is an agreement written between service provider and customer. This agreement clearly determines the measurable metrics of service quality, penalties, and remedies, along with the roles and responsibilities of both parties in maintaining the mentioned quality of service.

2.1.3. SLO (Service Level Objective):

SLO is a commitment where the service provider declares its intention of maintaining certain level of measurable metrics.

2.1.4. Failure Rate:

The frequency at which failures occur.

2.1.5. MTBF (Mean Time Between Failures):

Average time between the occurrence of failures. This can be calculated as following:

$$MTBF = N_s(t_i)\ [t_{i+1}\text{-}t_i]/(N_s(t_i)\text{-}N_s(t_{i+1}));\ \ t_i < t \leq t_{i+1}$$

$N_s(t_i)$: Number of Survivors at time t_i

2.1.6. MTTF (Mean Time To Failure):

This metric is similar to MTBF, measuring the average amount of time a non-repairable element operates before it fails.

2.1.7. Risk:

The estimate of likely loss due to failure influenced by the reliability of one or more components of the system

2.1.8. Maintainability:

The probability that an element/service can be retained in, or restored to, a specified operable condition within a specified interval of time when maintenance is performed in accordance with the prescribed procedure. Maintainability is the characteristic of design, installation, and operation.

2.1.9. Observability:

It is a capability of measuring/estimating the internal state of the system by measuring/ monitoring the external outputs of the system.

2.1.10. MTTR (Mean Time To Repair / Restore):

This metric is applicable only to repairable element/service. It measures the average time it takes to repair/restore a failure. This metric is an indicator of operational efficiencies and maintainability of the element/service.

2.1.11. *Availability:*

A measure of time that a system is operating versus the time that the system is targeted to operate

2.1.12. *Supportability:*

The capability of provider to maintain inbuilt reliability and to perform scheduled and unscheduled maintenance according to the Network maintainability with minimum cost.

2.1.13. *Minimal Path Set:*

Minimal Path Set is a set whose elements are paths. The System is available if all components of any element (path) are available. Refer to Figure1.

2.1.14. *Minimal Cut Set:*

Minimal Cut Set is a set of set of nodes. The System is unavailable if all nodes within an element of the Cut Set are unavailable. Refer to Figure 1.

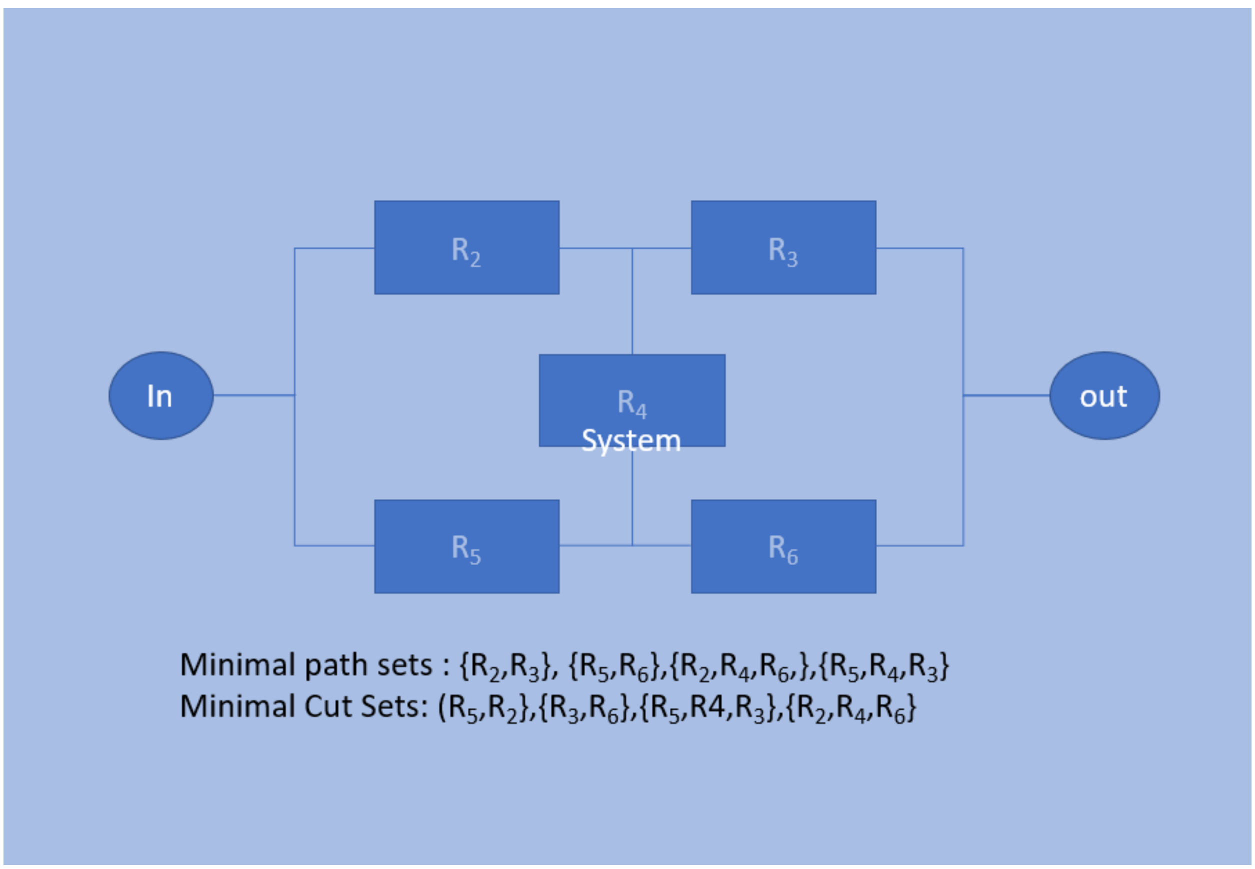

Figure 1: Minimal Pathset and Minimal CutSet

2.1.15. SDP (Sum of Disjoint Product):

The Joint Probability formula

Pr(E1 U E2 U E3 …..U En) = Pr(E1) + Pr(E2) + Pr(E3) + …..+ Pr(En)

is easy to calculate and valid only when Events E1, E2, E3,…En are mutually exclusive.

Referring to Figure 1, let P1 = R_2R_3 , P2 = R_5R_6 , P3 = $R_2R_4R_6$, P4 = $R_5R_4R_6$ be the Path Sets between Input and Output. Where R_2, R_3, R_4, R_5, R_6 are the components of the network (System).

In order to calculate the probability of success of the network a Boolean expression can be written such that all the terms of that expression are disjoint. This method of evaluating reliability is called Sum of Disjoint product. This disjoint form has one to one mapping with the probability expression.[7]

2.1.16. MVI (Multiple Variable Inversion):

MVI is a technique based on Boolean algebra used to generate a compact expression of SDP terms. In this technique a group of variables are inverted simultaneously. This results in generating a compact Boolean expression at very efficient processing time. The mentioned Lemmas in the illustrated table are used by MVI techniques to extract compact and disjoint form of Boolean expression.[8]

S. No	Lemma	Explanation
1.	$\overline{U}V.U \equiv \boxtimes$	
2.	$\overline{UV}$	$\overline{UV} = \overline{U} + U.\overline{V}$
3.	$\overline{UV}.\overline{U} \equiv \overline{U}$	$(\overline{U} + U\overline{V})\ \overline{U} = \overline{U}$
4.	$\overline{UV}.U \equiv U\overline{V}$	$(\overline{U} + U.\overline{V})\ U = U.\overline{V}$
5.	$\overline{UV}.\overline{UW} = \overline{U} + U.\overline{V}.\overline{W}$	$(\overline{U} + U.\overline{V})(\overline{U} + U.\overline{W}) = \overline{U} + \overline{U}.U.\overline{W} + U.\overline{V}.\overline{U}. + U.\overline{V}.\overline{W}$
6.	$UV + UW = U.(\overline{U} + (V + W))$	$U.\overline{U} + U.\ (V + W) = U.\ (\overline{U} + (V + W))$

Figure 2: Boolean Lemmas

3. Reliability As A Mindset

It is common knowledge that Reliability is synergy of Statistics, Physics and Engineering. This concept of Reliability is absolutely true. However, besides the pure objective part of Reliability Engineering, there is also a subjective aspect. That subjectivity is associated with the mindset that any reliability-aware organization should have intentionally evolved. This mindset involves viewing every part of the organization as contributor to reliability.

This vision of reliability not only enhances the customer experience but also provides enormous cost savings. The following chart will give an idea:

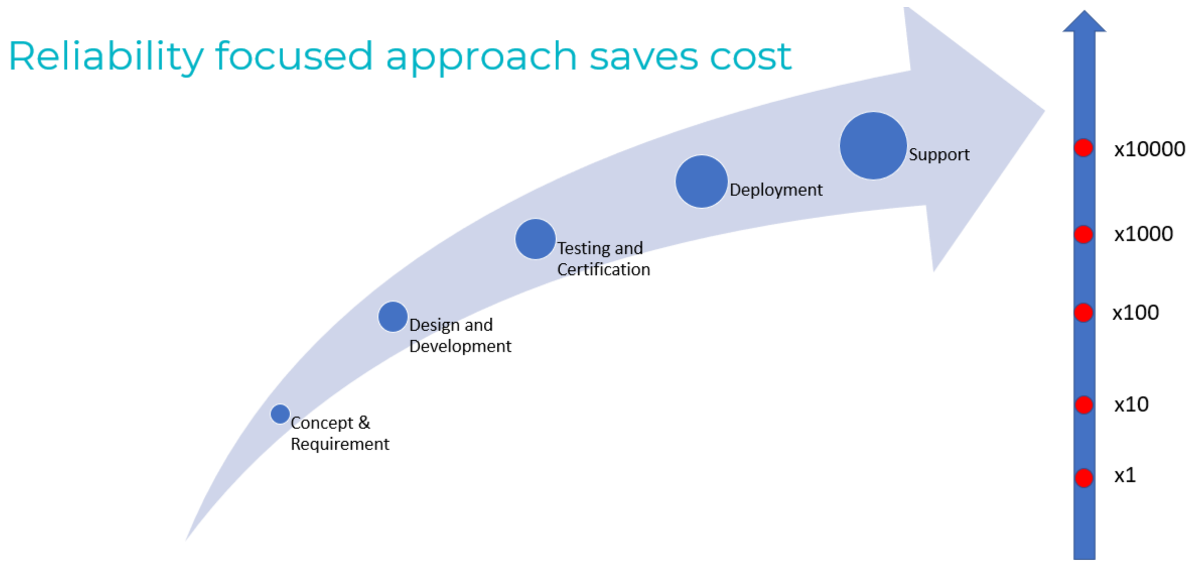

Figure 3: Reliability Cost Savings

4. Useful Life Of Components

There is a usual failure pattern in the lifetime of components when they are placed in service. These patterns are resultant of weaknesses in the components resulting in early-stage failures , normal random failures due to natural phenomenon of physics, and failures due to aging of the component. The following graph shows the three types of failures with their distributions and also the combined failure:

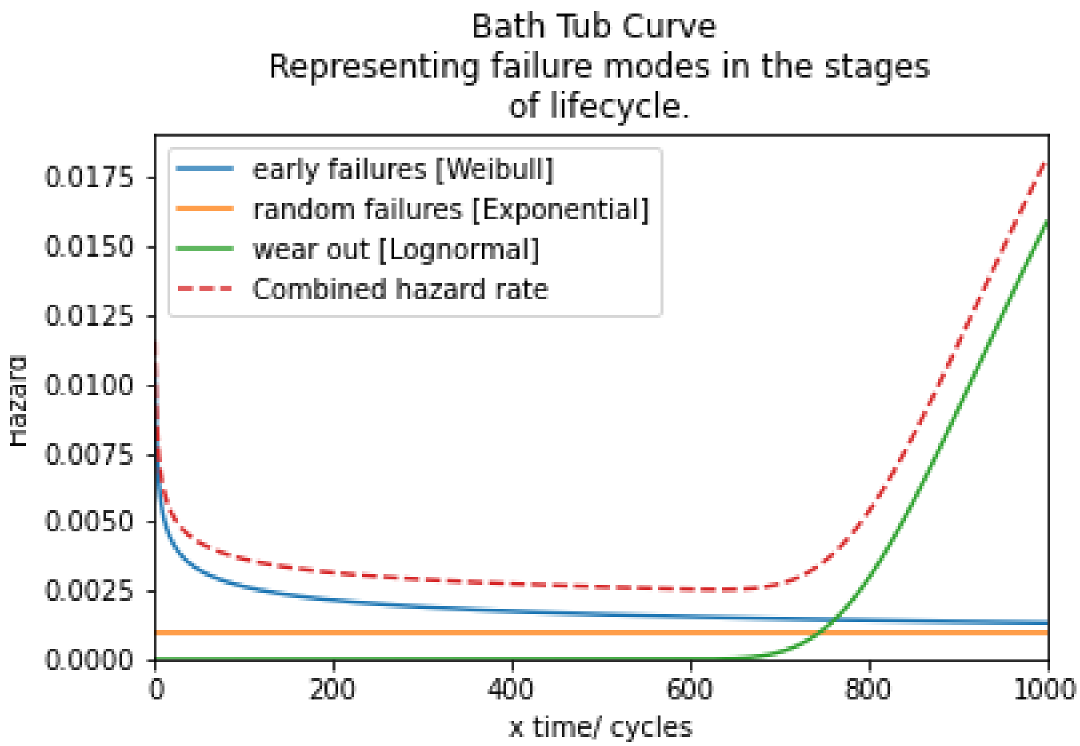

Figure 4: Example of Bathtub curve created by different life stages

If we take a large sample of components and operate them under constant conditions, a statistical pattern emerges with three regions. Each region providing its own interesting failure/ hazard behavior.

4.1.1. Early Failures:

This pattern of failures is also called burn-in, or debugging period. These failures are related to weakness in hardware, software, or design. Issues that arise during this period can be stabilized. These failures fit in a Weibull distribution. The **failure rate** in this region **decreases very rapidly**.

4.1.2. Chance Failures:

The useful life of the component starts after the burn-in period. This is the period where failure rates are at the minimum level. During this period the failure rate is constant which tells us that chance failures cannot be prevented by any replacement policy. Also, due to **constant failure rate**, these failures fit into exponential distribution.

4.1.3. Wear-out Failures:

The wear-out begins when the element has lived its life in terms of age, stress, or cycles of operation. **Failure rate starts increasing very rapidly** with the start of wear-out time. The simple indicator of wear-out time is a period during which approximately one-half of the total population will fail. These failures fit in Lognormal distribution.

The golden rule of reliability is to replace the component as it fails during the useful life and proactively replace them before the end of their useful life. The actual algorithms and optimization techniques of proactively replacing the component are not in the scope of this discussion but plenty of literature is available in this regard.

5. Failure Distribution

For an operating network it is important to understand the distribution of categories of failures. An example of a distribution is illustrated as follows:

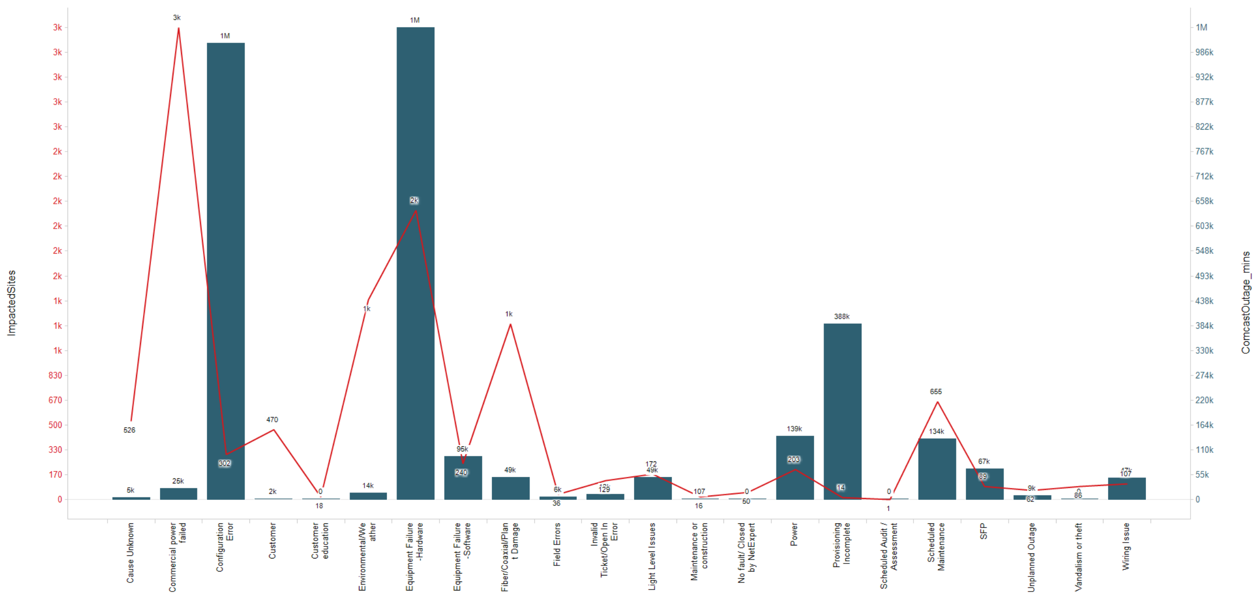

Figure 5:Example distribution of categories of events causing outages

This distribution allows us to identify the opportunities to enhance the reliability of the network. This will provide a very good data point to teams to start with their Failure Mode and Effect Analysis, and Fault Tree analysis.

Few examples from above illustration produces these observations:

- Failure cause code 1531 – Power. This indicates that the failures are attributed to the failure of electrical power managed by the service provider. This opens the opportunity to prevent power failures either by providing redundancy, back up, or in some cases, simple routine preventive maintenance of a backup power generator.
- Failure cause code 150 – Scheduled Maintenance. This failure cause code is attributed to failures that occur during scheduled maintenance. The opportunities for improvement are multiple including the potential for enhancement of method of procedures, network impact analysis, customer impact analysis, and data integrity of the network inventory management systems to name a few.
- Provisioning Incomplete 119 – This failure cause code can be attributed to the process of provisioning all service attributes in the system. It opens a number of systemic and

communication opportunities. Many times, these scenarios bring into light the issues like flexibility of product or need for automation.

6. Reliability Evaluation of the Network

Reliability of the system is the sum of reliabilities of its components. The components themselves are dependent on the reliabilities of their elements. There are numerous techniques and algorithms to determine overall reliabilities of the system.

A system can be a small system with very few components in it, or the components may be connected in a simple manner such as a series. Any component failure will cause system failure.

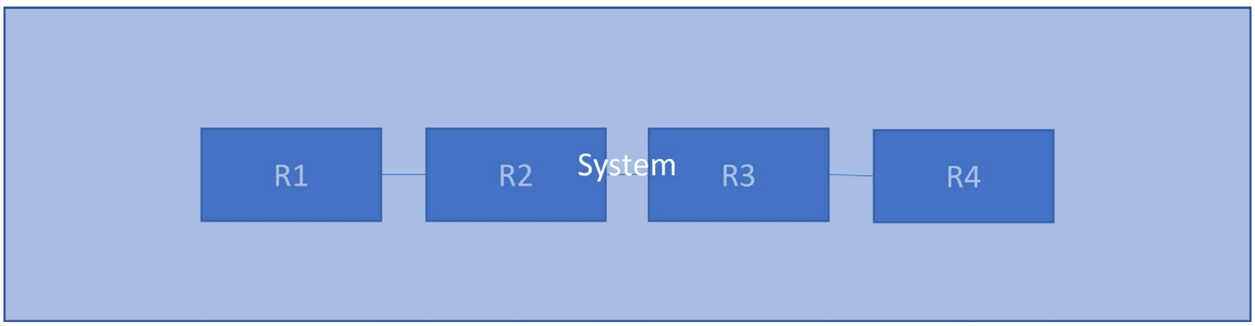

Figure 6:Series System

Another configuration could be that a few components are connected in parallel for the sake of redundancy. This system is termed as Series Parallel System.

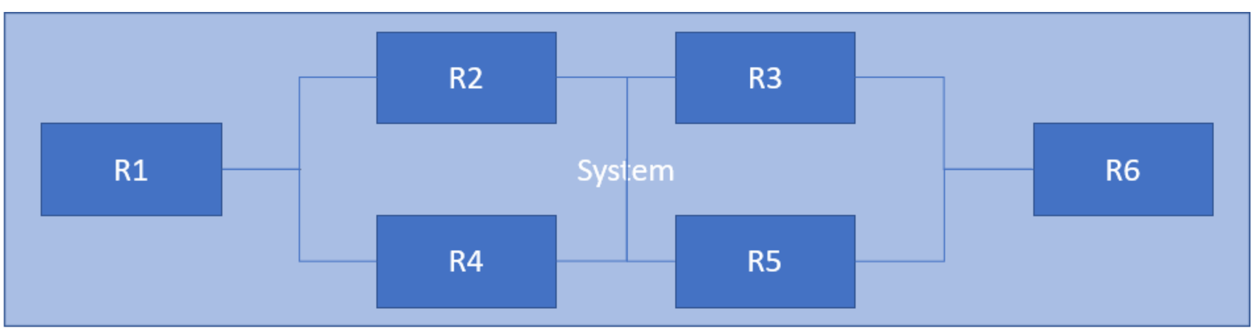

Figure 7:Series Parallel System

The next configuration is a Non-Series Parallel system (NSP). This is the configuration that presents us a reliability evaluation problem in most of our scenarios. The example is illustrated in the following picture.

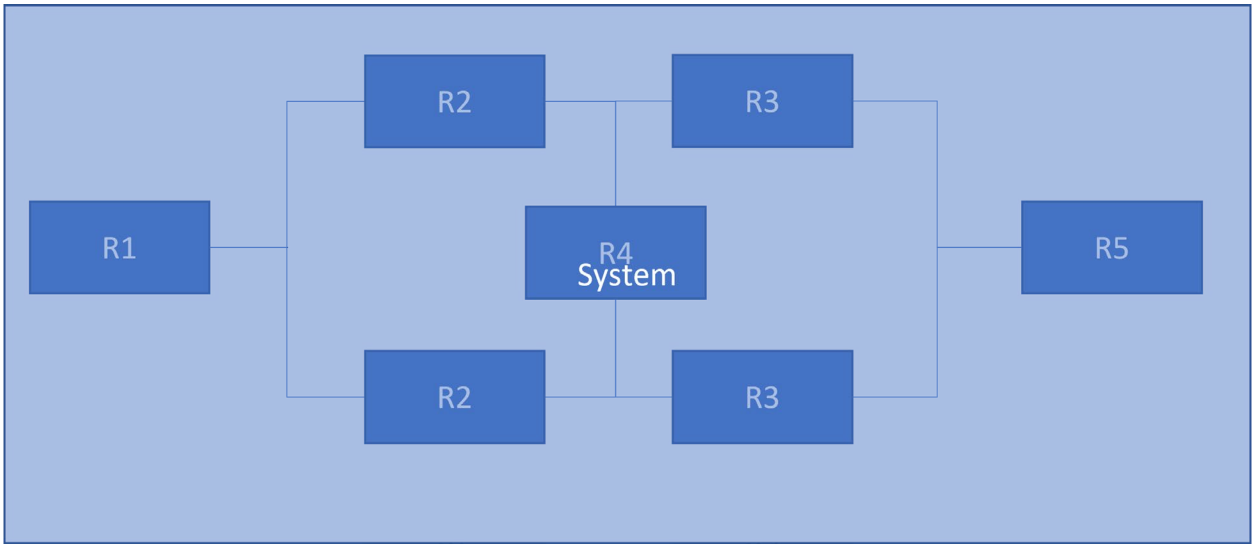

Figure 8:Non-Series Parallel System

6.1. Reliability Evaluation of a large Network

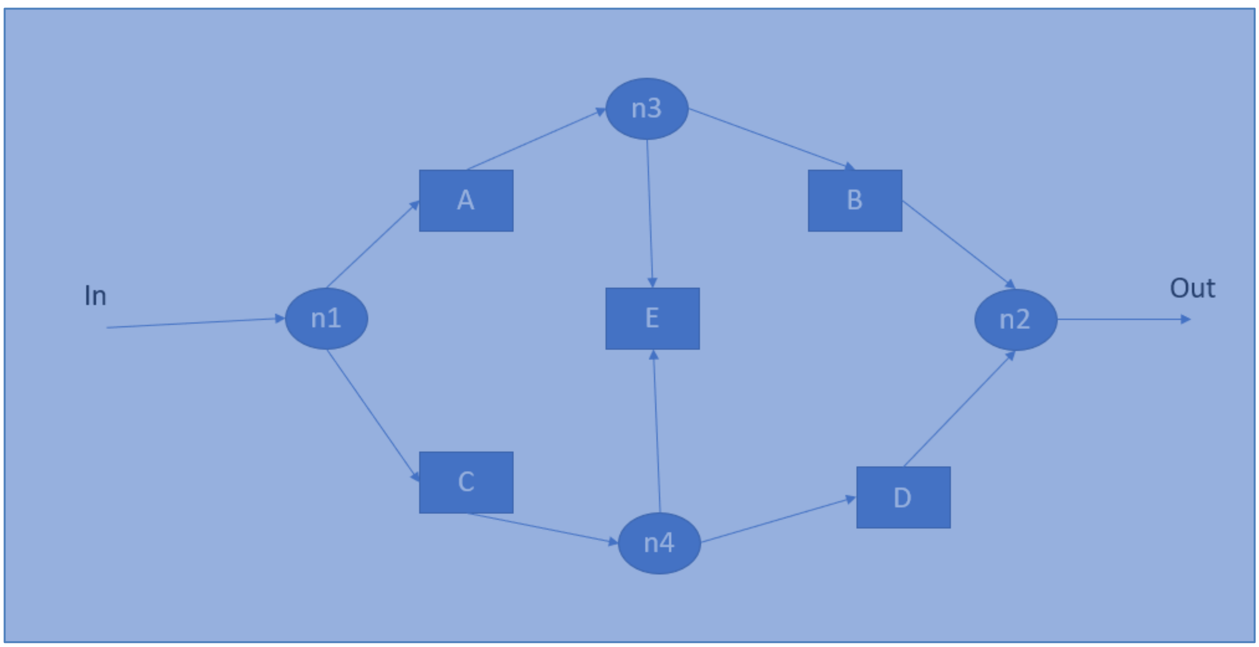

Figure 9: Small Sample NSP Network for Reliability evaluation

The above picture shows a network with n1, n2 as input and output nodes respectively. Nodes n3, n4 are intermediate nodes. A, B, C, D, and E are edges.

In order to evaluate the reliability of the above network following two assumptions are made in order to simplify the mathematics:

1. Edges failure (success) are statistically independent
2. Nodes are perfectly reliable

Let p_a, p_b, p_c, p_d, p_e be success Probabilities of Edges A, B, C, D, E respectively.

Also, q_a, q_b, q_c, q_d, q_e be failure Probabilities of Edges A, B, C, D, E respectively.

Using available reliability evaluation methods, the reliability of the system is calculated as follows:

$$R(z) = p_a p_b + p_a p_c q_b p_d$$

There are several algorithms and techniques for evaluation of reliability of large networks. They had their own advantages and disadvantages in terms of efficiency, scalability, and accuracy.

With the recent contributions and advancements, Graph Theory has been playing a very important role in the field of reliability evaluations of large networks.

In this paper we will evaluate the reliability of a very large network using Sum of Disjoint Product (SDP) and Multi Variable Inversion (MVI) techniques. This is a three-step process.

1. Create reduced network topology
2. Extract minimal path set or minimal cut set from the topology
3. Evaluate reliability from the path set or cut set extracted from step 2 using SDP and MVI

Step1.

For the current networks spanning large distances, operators are using the model of access network delivering to a full or nearly fully meshed core network as illustrated below:

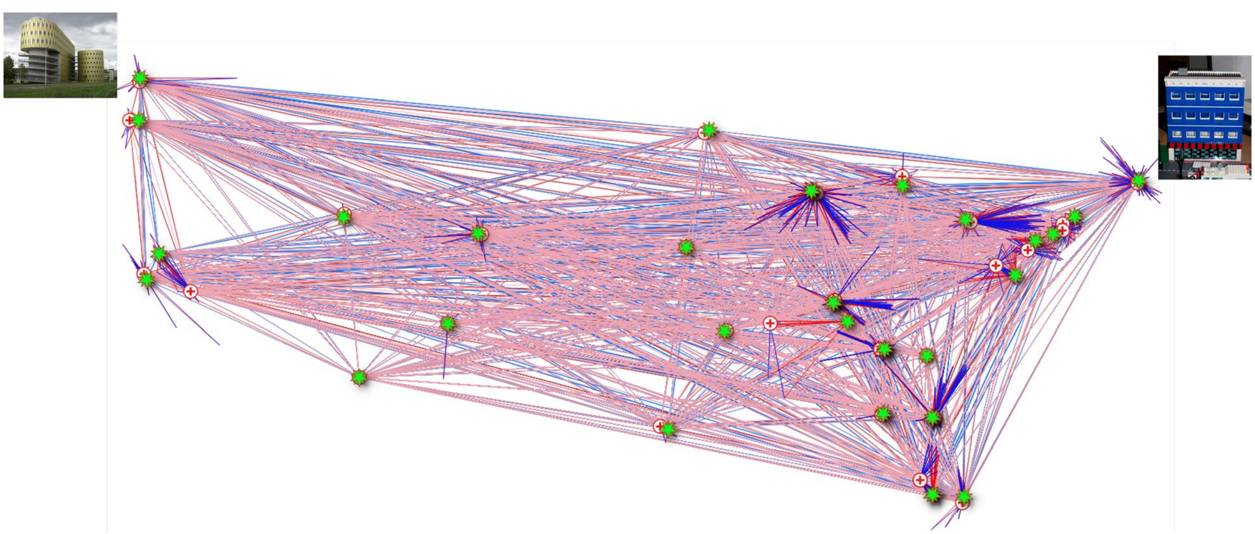

Figure 10: Example Point 2 Point link between customer locations

From this illustrated network it is evident that there are potentially hundreds of millions of paths sets or cut sets. This makes any reliability evaluation algorithm reach its processing limits and accuracy suffers due to roundup errors.

In this paper we address this problem by reducing the size of this network into a focused network. We are aware of the situation where network boundaries are limited by the latency introduced by the links. If the total latency introduced is beyond the service level objective, then that path is a failed path (infinite horizon). Based on this philosophy we have extracted path sets belonging to k-shortest paths. Following table list the 8 shortest paths between node 1 and node 2011:

Table 1: k-Shortest Paths

Path	Latency(ms)
[1, 25, 62, 2011]	12.20812742
[1, 53, 62, 2011]	12.20812742
[1, 25, 37, 62, 2011]	12.22414687
[1, 53, 65, 62, 2011]	12.22414687
[1, 25, 65, 62, 2011]	12.22414687
[1, 53, 37, 62, 2011]	12.22414687
[1, 25, 34, 2011]	12.40271075
[1, 53, 34, 2011]	12.40271075

These paths are then merged into a new reduced subgraph as illustrated below.

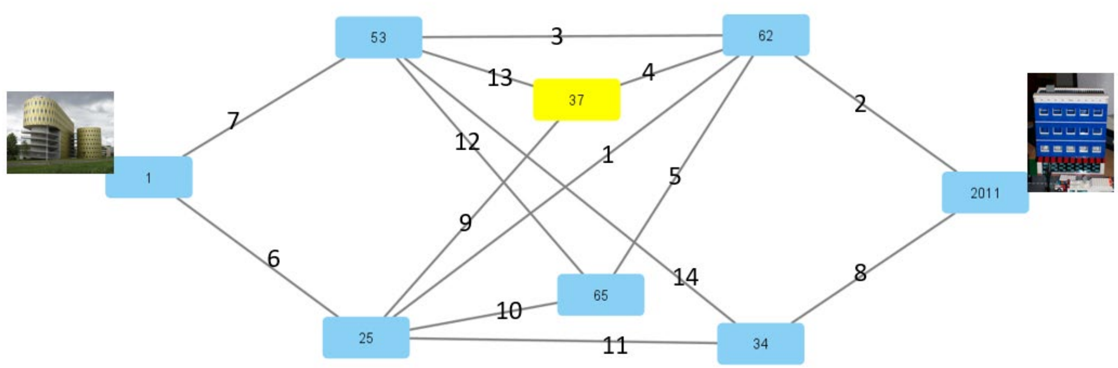

Figure 11:Simplified network topology

Step2.

At this stage we must decide whether we should utilize a cut set or path set approach. It has been suggested by Aggarwal, Chopra, & Wajwa, (1982) that for a network of n nodes and l links, the number of cut sets between any pair of nodes would be of the order of 2^{n-2}, whereas the number of path sets is of the order of 2^{l-n+2}. From this recommendation the estimated cut set = 64 and path set = 256.

Hence, we have decided to use cut set approach.

The cut sets are enumerated as per algorithm described in Ahmad, (1990).

The following cut sets were returned by using the algorithm:

Table 2: Cut Sets for the reduced network graph

Cut Sets		
2 8	1 7 8 9 10 14	1 5 7 8 9 12 14
6 7	2 3 7 11 12 13	2 3 4 7 9 11 12
2 11 14	3 4 6 9 12 14	2 3 5 7 10 11 13
1 3 4 5 8	3 5 6 10 13 14	3 4 5 6 9 10 14
1 7 9 10 11	3 6 8 11 12 13	3 4 6 8 9 11 12
3 6 12 13 14	1 2 4 6 10 13 14	3 5 6 8 10 11 13
1 2 6 9 10 14	1 2 5 6 9 12 14	1 2 4 5 6 12 13 14
1 3 4 5 11 14	1 3 4 10 11 12 14	1 3 9 10 11 12 13 14
1 3 4 8 10 12	1 3 5 9 11 13 14	1 4 5 7 8 12 13 14
1 3 5 8 9 13	1 3 8 9 10 12 13	2 3 4 5 7 9 10 11
1 4 7 10 11 13	1 4 5 7 11 12 13	3 4 5 6 8 9 10 11
1 5 7 9 11 12	1 4 7 8 10 13 14	

We can visually verify that the links in each cut set is isolating network with node 1 (Source) with node 2001(Sink).

Step3.

Finally, we can now evaluate reliability of the network by using CAREL algorithm *(Soh, S. & Rai, S., 1991 [7]).* The input that mentioned algorithms needed are minimal cut sets and failure probability of the link. We assumed that all links fail with 0.1 probability.

After applying CAREL algorithm to the minimal cut sets derived in Step 2, the Reliability / Unreliability of the Mentioned P2P links is calculated as following:

System Unreliability = 0.02082693568

System Reliability = 0.979173064

With total disjoint paths = 76

7. Reliability Cost Optimization

Every organization aspires to achieve maximum profit while keeping customer satisfaction at an optimum level to sustain the profit margin. Reliability engineering is the scientific tool that management can use to keep balance between customer satisfaction and cost of the product or services.

The following picture is illustrated to enumerate important categories that contribute to the cost incurred by implementing Reliability enhancement methods.

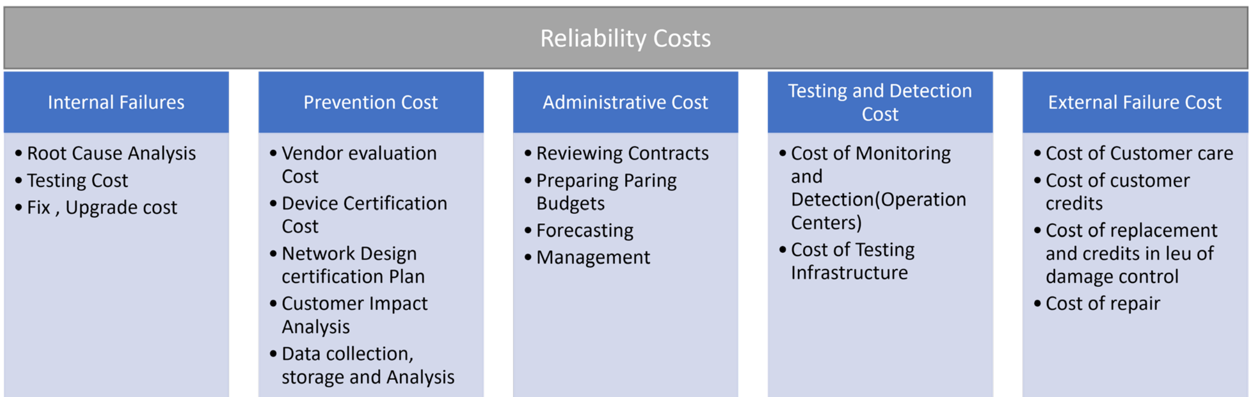

Figure 12 :Reliability cost categories [7]

It is not always profitable to increase reliability to achieve perfection. There is always an optimum point where a balance should be made. That decision of balance shall be dictated by the facts emerging from reliability analysis as shown in this diagram.

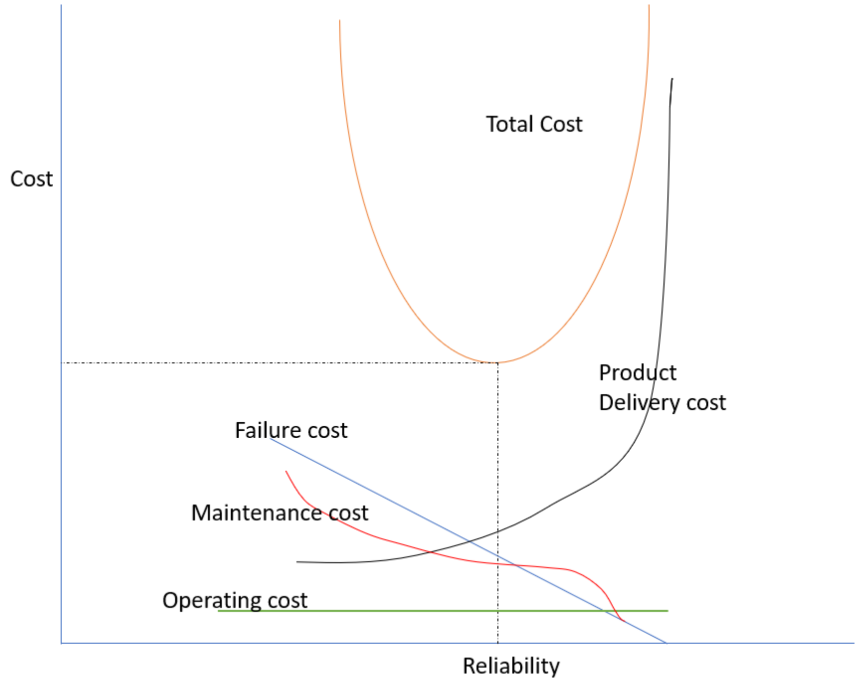

Figure 13: Cost curves for the service/product [7]

There are several cost reliabilities functions in the literature. A few have been listed here:

- Misra et al Function
- TIllman et al Function
- Aggarwal et al Function
- Fratta et al's Function
- Majumdar et al's Function
- Llyod and Lipow's Function

A hypothetical study is illustrated here on a model trained on real failures from a very large network. Here the goal is to showcase an optimum time at which the preventive maintenance shall be done on the devices. In this example the cost of preventive maintenance is 5 and cost of corrective maintenance is 200.

```
Cost model assuming as good as new replacement (q=0):
The minimum cost per unit time is 0.0092
The optimal replacement time is 1095.22
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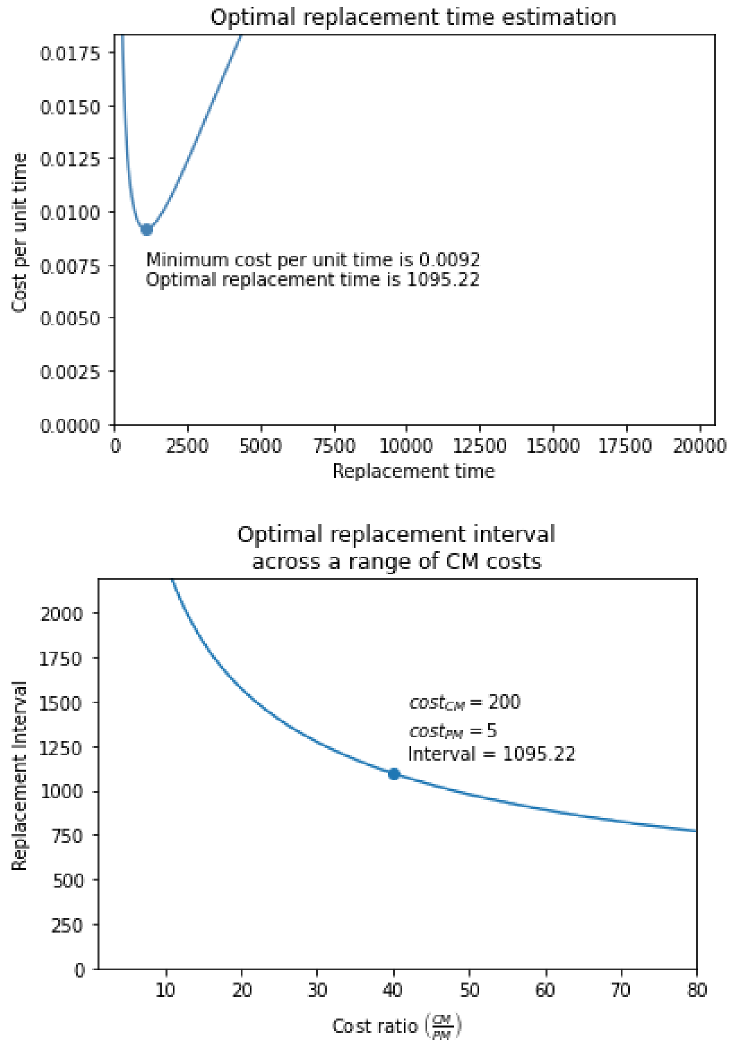

Figure 14: Optimal preventive maintenance time

8. Conclusion:

As we discussed in this paper reliability of the network needs to be measured, monitored, tested, and investigated continuously. The reliability should be investigated for each product right from its inception. We have talked about different life stages of components. Reliability evaluation technique is demonstrated with an optimized approach for large networks.

Referring to Figure 14, the reliability studies can optimize the opex and capex by making optimally calculated decisions.

There is an enormous opportunity for improvement, development, and enhancement for telecom networks' reliability and availability.

Abbreviations

MVI	Multiple Variable Inversion
NSP	Non-Series-Parallel systems
RAMS	Reliability Availability Maintainability and Safety
SCTE	Society of Cable Telecommunications Engineers
SDP	Sum of Disjoint Products
SLA	Service Level Agreement
SLO	Service Level Objective
SVI	Single Variable Inversion

Bibliography & References

Reliability Engineering: Theory and Practice 8th ed. 2017 Edition: Alessandro Birolini [1]

Quality And Reliability Engineering International. VOL. X. 349-354 (1992): Economical Design of Reliable Systems – Some Practical Situations: K.K. Aggarwal [2]

Shen, Y. (1995). A New Simple Algorithm for Enumerating all minimal Paths and Cuts of a Graph. Microelectronics Reliability, Vol. 35(6), 973–976. [3]

Mishra, R., Saifi, M. A. & Chaturvedi, S. K., 2016. Enumeration of Minimal Cutsets for Directed Networks with Comparative Reliability Study for Paths and Cuts. Quality and Reliability Engineering International, Vol.32(2), pp.555–65. DOI: 10.1002/qre.1772 [4]

Ahmad, S. H. (1988). Simple Enumeration of Minimal Cutsets of Acyclic Directed Graph. IEEE Transaction on Reliability, R-37, 484–487. [5]

Ahmad, S. H. (1990). Enumeration of Minimal Cutsets of an Undirected Graph. Microelectronics Reliability, Vol.30(1), 23–26 [6]

Soh, S. & Rai, S., 1991. CAREL: Computer Aided Reliability Evaluator for Distributed Computing Networks. IEEE Transaction on parallel and Distributed Systems, Vol.2(2), pp.199–213. [6]

Reliability Engineering: K.K. Aggarwal [7]

Network Reliability Measures and Evaluation: Sanjay K. Chaturvedi [8]

Irredundance Graphs: C.M. Mynhardt; A. Roux; arXiv:1812.03382v3 [math.CO] 7 Apr 2021 [9]