RELIABILITY ENHANCEMENT OF DATA CENTER

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NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

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ISLAMABAD, PAKISTAN

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Dedicated to my Parents and Family

CERTIFICATE OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

Date	Muhammad Usman

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"In the name of Allah, the Most Gracious and the Most Merciful"

All praises to Allah, it is because of his blessings that I have completed my thesis.

I am grateful to my current supervisor Dr. Adnan Maqsood for his keen interest in this work. Completion of this thesis would have not been possible without his support and motivation. Moreover, I am also thankful to my previous supervisor Dr. Ahmed Ejaz Nadeem for his guidance.

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List of Abbreviations

ANSI	**American National Standards Institute**
CCTV	**Closed Circuit Television**
COTS	**Commercial off the Shelf**
FAM	**Failure Analysis Matrix**
FMEA	**Failure Mode and Effect Analysis**
FMECA	**Failures Mode Effect and Criticality Analysis**
IEEE	**Institute of Electrical and Electronic Engineers**
MTBF	**Mean Time Between Failure**
MTBM	**Mean Time Between Maintenance**
MTTR	**Mean Time To Repair**
NUST	**National University of Sciences and Technology**
QFD	**Quality Function Deployment**
RBD	**Reliability Block Diagram**
RCM	**Reliability Centered Maintenance**
RCMS	**Research Center for Modeling and Simulation**
RPN	**Risk Priority Number**
SAN	**Storage Area Network**
ScREC	**Super Computing Research and Education Center**
SPOF	**Single Point of Failure**
TIA	**Telecommunication Industry Association**
UPS	**Uninterrupted Power Supply**
RPN	**Risk Priority Number**

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Abstract

The data center should remain operational round the clock to support critical applications and services hosted on the servers. The data center downtime not only means expenses on recovery but also results in loss of reputation. This research focuses on reliability analysis of RCMS Data Center. Statistical data is analyzed and failure mechanisms are discussed in this research. In order to perform the maintainability and reliability assessment of data centers, several techniques are used. The research mainly focuses on four System Engineering techniques including Quality Function Deployment (QFD), Calculation of Reliabilities using Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) parameters, Reliability Block Diagrams (RBDs) and Failure Mode and Effect Analysis (FMEA). QFD and RBD techniques are used in reliability assessment while calculation of reliabilities using MTBF and MTTR parameters and FMEA techniques are used for maintainability assessment. Components of data center are prioritized according to their importance determined on the basis of QFD. Those having more weightage/importance value must be acquired earlier. The head nodes are the most stable and most available component of data center whereas Storage Area Network (SAN) is the most unstable component. Therefore, special attention must be paid to increase the availability of SAN storage. The main reason behind its non-availability is frequent shutdown and restart of data center. Hence, the practice of daily turning off data center must be stopped. Failures having high severity and high occurrence rating should be addressed earlier and must be accorded priority. Risk Priority Number (RPN) and occurrence rating significantly reduces if a recommended action is taken. All components of RCMS data center are connected in series so there is no redundancy except the compute nodes, which are connected in parallel. A reliable data center must have critical components connected in parallel to provide redundancy and ensure round the clock availability.

CHAPTER 1

Introduction

Round the clock availability of services hosted on servers of data centers is of utmost importance. Downtime results in loss of business, revenue and reputation. A typical data center comprises of sub-systems listed in Table 1.

No	Sub-system	Critical	Non-critical
1	IT Equipment	Yes	
2	Precision AC	Yes	
3	Temperature Alarm		Yes
4	Uninterrupted Power Supply	Yes	
5	Fire Suppression System	Yes	
6	Trained Human Resource	Yes	
7	Power Alarm		Yes
8	Functional Display		Yes
9	Backup Power Generators	Yes	
10	CCTV Monitoring	Yes	
11	Sound Proof Enclosure		Yes
12	Preventive Maintenance Plan	Yes	
13	Network Management System		Yes
14	Access Control System	Yes	
15	Optimal Usage Plan		Yes
16	Business Plan		Yes

Table 1: Major Components of a Data Center

The facilities that result in downtime or affect the operations are deemed critical whereas others with no impact on operations regardless of the fact whether they are available or not are termed non-critical. Three fundamental and significant attributes of data center that are discussed in this research work are Reliability, Maintainability and Availability.

The definitions of reliability, maintainability and availability taken from, Moubray, John. (1) are given below:

- **Reliability** is an ability of a system or component to perform its required functions under stated conditions for a specified time

- **Maintainability** is the probability of performing a successful repair action within a given time
- **Availability** is a property of the system or a component to remain available or operable, when required to perform its intended or desired function. It is the aggregate of the resource's reliability and maintainability

Thus, if we increase the reliability and maintainability of a data center, its availability will automatically increase. If a data center is reliable and maintainable, its facilities, applications and services will remain available.

1.1. Research Problem

RCMS established its data center comprising of Supercomputer in 2012. At that time, no eventual upgrade was identified. This study focuses on the criticality of operations and identifies areas of up gradation for its future operations.

1.2. Purpose of the Study

The main purpose of the study is to enhance the reliability of data center by identifying critical deficiencies and areas that require up gradation for its future operations. There are four critical aspects that need to be addressed.

(a) Which components of data center are essentially required to ensure reliability?
(b) Calculate the reliabilities of individual systems, sub-systems and components to identify the unreliable systems, sub-systems and components.
(c) Draw the reliability block diagrams to identify which components are connected in series and which ones are in parallel. It will help in identifying redundant components.
(d) Perform Failure Mode and Effect Analysis to identify critical failure modes, causes and effects of all failures, severity of each failure and associated preventive action.

1.3. Objectives of the Study

The main objective of research is to increase the availability of RCMS data center by using four different techniques including Quality Function Deployment, Reliability Block Diagram, Failure Mode and Effect Analysis and Calculation of reliabilities using MTBF and MTTR parameters. Based on results of these techniques, reliability and maintainability of data center is enhanced which in turn results in improved availability of data center.

1.4. Potential Contributions

The first study of its kind is carried out where reliability, maintainability and availability studies are performed based on actual downtime data and futuristic expansion forecast is developed based on quantitative analysis. Additionally, reliability block diagrams of different components, sub-systems and complete data center are prepared which depicts complete state of redundancy available in the data center. Software "RC Tool" capable of calculating different parameters related to reliability including MTBF, MTTR, MTBM and operational / inherent / achieved availability is also developed. This software provides one interface for calculations of a number of parameters. The usage manual of software is available at Appendix 'A'.

1.5. Organization of the Thesis

This thesis comprises of five chapters. The brief outline of each chapter is given below:

Chapter 1: Introduction

This chapter provides an insight into the scope of this research. The research problem, purpose, objectives and potential contributions are described. An orderly outline depicting organization of thesis is given at the end of the chapter.

Chapter 2: Literature Review

A comprehensive summary of the literature review is described in this chapter. This chapter shows the reliability, maintainability and availability studies already conducted and their importance.

Chapter 3: Problem Formulation and Description

In this chapter, the research problem is explained. It also gives insight into the anticipated goals and the means to achieve them. All the analyses, tools and techniques being used are explained here.

Chapter 4: Results and Discussions

The results obtained from application of techniques explained in section 3.3 and analyses performed on the results are discussed in this chapter.

Chapter 5: Conclusions and Future Work

The conclusions drawn from the results are compiled and presented in this chapter. Recommendations for the future work and possible extensions in the work are provided.

CHAPTER 2

Literature Review

2.1 Overview

Significant work has been done in Reliability, Maintainability and Availability analysis of data centers. In this section, different methods and techniques adopted by different scholars for increasing reliabilities of the systems and facilities including data centers are discussed.

RBD is also known as dependence diagram. It shows the contribution of component reliability in success or failure of the system. Wang, W., et al.(2) discussed the application of simulation approach through Reliability Block Diagrams. It was identified that the design and behavior affect the reliability of the system. Moreover, maintainability and reliability of different components of system also had a major effect on the reliability of system as a whole.

FMECA is used to identify, examine and record the conditions that led to failure. Becker, J.C., et al. (3) described the failures concepts and terminologies, benefits of using FMECA and classification of failure modes. Furthermore, the FMECA process augments the fault tolerance and verifies the accuracy of the recovery procedures. It also helps in performing tradeoff analysis for changes in requirements. FMECA describe the following:-

1) Failure Modes
2) Causes of failure modes
3) Detection and recovery mechanism
4) Impact on operations of the system

With the help of FMECA, it can be easily visualized that the lower level failure modes in the system hierarchy may cause higher order failure modes. Becker, J.C., et al. (3) illustrated the failures modes and effects hierarchy.

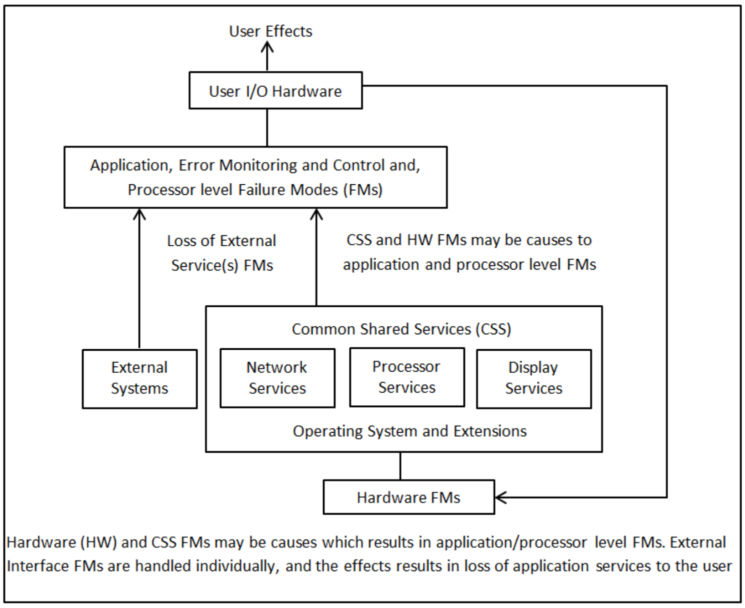


Figure 1: Failure Mode and Effects Hierarchy (3)

In order to perform the reliability assessment of data centers, Wiboonrat, M. (4) used Failure Mode Effects and Criticality Analysis and Reliability Block Diagram Techniques. The reliability assessment can be done using two important factors:

1) Mean Time Between Failures (MTBF)
2) Mean Time To Repair (MTTR)

Reliability Block Diagrams can be used to visualize the logical connection between components of the system. Simulation method can be applied to reliability block diagrams by using software called Blocksim 7. Wiboonrat, M. (4) integrated the FMECA and RBD models into one model to improve the availability.

The same concept of MTTR and MTBF is also discussed by Wiboonrat, M.(5). This study also discussed single point of failure (SPOF) in the systems as it effects system reliability. Data Center Engineers can design a reliable data center using the simulation results from the reliability block diagrams, which is not possible using the actual data center operations, as it will costs much more and will require more time. However, simulations can help to save time and costs by avoiding trial and error method.

The data center downtime not only means expenses on recovery but also results in loss of reputation as well. Wiboonrat, M.(6) discussed the advantages and disadvantages of series-parallel design. If components of system are connected in series, reliability of system will decrease. However, if the system components are connected in parallel, reliability will increase.

Computerized methods for predicting and utilizing the maintainability parameters, manpower requirements and availability was presented by Reinhart, H., et al.(7). The paper contained the study of software that applies statistical methods. Hierarchical model of system enables calculation of parameters for components, sub-systems and whole systems.

Azagury, A., et al. (8) provided the design for highly available computing cluster. A computing cluster usually consists of multiple interconnected nodes. The highly available cluster ensures the data integrity, if one copy of data fails, backup replica of that data can be used.

Monaghan, T.P.(9) described the techniques used for management and procurement of cost effective and mission critical systems. The study emphasized the fact that fault tolerant system architecture should be implemented early in the system design phase. Dependability hypothesis, that involves the interaction between failure data, analytical and functional modeling was discussed in this paper.

In order to increase the probability of system to perform its intended function, the failure rates should be reduced and causes of failures should be identified before putting the system in production or operation. The reliability and maintainability parameters have been evaluated and sensitivity analysis has been performed on different parameters to study their impact on systems success by Widawsky, W.H.,(10). Kuehn, R.E., (11) described the following aspects of redundancy techniques in the digital systems:-

1) Design Problems
2) Reliability Predictions
3) Field Performance
4) Future Applications

The engineering process of Reliability Centered Maintenance (RCM) has been discussed by Rausand, M.,(12). RCM is an engineering method used by maintenance, reliability and safety engineers for the following:-

1) Development of Maintenance Plans
2) Identification of tasks needed for achieving and maintaining the operational capability.

Wiboonrat, M.,(13) discussed the effect of unplanned downtimes on the critical operations of the data center. The study emphasized that the faults errors are different from failures of the system and both must be examined carefully. A comprehensive strategy must be prepared in order to avoid unplanned downtimes due to fault errors or system failures.

Several techniques and methods exist for determination and analysis of reliabilities of the system. Different analytical techniques identified by Wang, W., et al.(2) include:

- Reliability Block Diagram
- Event Tree
- Monte Carlo Simulations
- Boolean Algebra
- FMECA
- Cut Set
- Path Set
- Fault Tree
- Markov Model

Wang, W., et al. (2) suggests that two of the important and reliable data sources are IEEE Gold Book and PREP Database. There are two major steps for finding the reliability of the system

1) Construction of reliability model for a system
2) Analysis of the model

The methods for analyzing the reliability block diagrams for complex repairable systems have also been discussed. The paper also discusses a case study for applying the RBD and simulations method to IEEE network. One of the main advantages of simulations using RDB is that large and repairable systems can be modeled easily.

Failure Mode Effect Analysis (FMEA) is an important technique for studying the effects of different types of failures on the reliability of the system. Kara-Zaitri, C., et al. (14) discussed an improved FMEA Methodology. This technique was based on the Risk Priority Numbers (RPN's). RPN's are observed and recorded for every cause of failure that occurs in the system. RPN's can be calculated by multiplying the occurrence, detection and severity values. The RPN methodology use probability theory to determine cause of all failures. All observations are presented in a pictorial way and a new concept of Ordered Matrix FMEA has been introduced. This methodology uses hierarchical approach for FMEA. Firstly, the functional block diagrams are drawn and then level is identified from which analysis should be started.

Signor, M.C.(15) discussed Failure Analysis Matrix (FAM) model as an alternative to FMEA technique for determining the effects of failures on a system. With the help of FAM method, failures can be identified. FAM is developed using Excel®. Using FAM failures can be identified and solutions can be found. The FMEA method is mostly used in the automotive industries and has not been on software. Even in industry it has gained little success as it is not easy to comprehend. FMEA was only used by software engineers in specialized area of embedded systems.

Failure Analysis Matrix (FAM) technique has been designed especially for the people related to information systems. However, it is not alternative to Failure Mode Effect Analysis (FMEA), because FMEA gives more details. FMEA provides all the possible failures while FAM only provides information about very important failures. The major differences between FMEA and FAM are summarized below:

FAM	FMEA
Easy to use and learn	Difficult to use and Learn
Uses failures only	Uses failure modes, causes and effects
Uses expected costs	Uses severity, detection and occurrence
Gives result in 1 or 2 pages	May give result in thousands of pages

Table 2: Comparison of FAM and FMEA

FAM is user friendly and it has the provision of specifying the project name and number as well. Moreover, failures and solutions can also be added manually.

One of the most important method is FMECA for the computing systems by Becker, J.C., et al. (3). It presents the methodology used for failure mode, effects and critical analysis of computing systems. It detects the system failures, examines the recovery process and records the effects of those failures along with classification of criticality of each failure. FMECA can identify the following problems:

1) Common mode failures
2) Performance problems
3) Operational Issues

Reliability assessment method by Denson, W.K., et al. (16) modifies a base reliability estimate with process grading factors for the following causes of system failures:-

1) Parts
2) Design
3) Manufacturing
4) System Management

Bayesian techniques have been used to modify the base reliability estimates by using appropriate weights for the different data components. Benefits of this new methodology are given below:

1) It uses all available information to form a base reliability estimate
2) It can be tailored
3) Confidence bounds can be quantified
4) It has sensitivity to system reliability drivers.

On the basis of numerous studies conducted on reliability of systems, the reliability can now be quantified. In addition to this, several techniques have also been developed for performing reliability analysis of systems and processes by Krohn, C.A., (17). Using these techniques, low reliability areas can be identified very early in the system development, thus minimizing the chance of disastrous failures.

Reliability of system is the probability that a system will successfully perform its intended function. Many studies have been conducted on the reliability, maintainability and availability of the systems. Krohn, C.A., (17) discussed the impact of human factors on the reliability, maintainability, availability and safety of systems.

Thus, all above techniques including Reliability Block Diagrams, Failure Mode Effect Analysis (FMEA), Failure Analysis Matrix (FAM), Failure Modes Effects and Critically Analysis (FMECA), Reliability Assessment Procedures, Reliability Analysis Methods, Monte Carlo Simulations and Markov Model are used.

CHAPTER 3

Problem Formulation and Description

This chapter discusses the sources and description of data. The techniques and methodology used in the research is explained and various aspects of RCMS data center are studied in this chapter.

Availability of data center can be increased by enhancing its reliability and maintainability. The problem of reliability enhancement is addressed by using techniques of "Quality Function Deployment" and "Reliability Block Diagrams" while maintainability is addressed by techniques of "Calculation of MTBF, MTTR and Reliabilities" and "Failure Mode and Effect Analysis".

3.1. Data Sources

The factual data of three years operations of RCMS data center has been used to carry out all calculations and analyses.

3.2. Data Description

The complete log of RCMS data center contains all events of morning, evening and night shifts of RCMS data center. Data consists of following information:-

(a) Date of Event

(b) Shift (Morning, Evening or Night)

(c) Fault Type

(d) Recovery Time

(e) Severity of Fault

(f) Effected Component, Sub-system or System

3.3. Proposed Methodology

Several Techniques exists that are used to enhance Reliability and Maintainability. Most of these techniques have been used individually. However, the following four techniques have not been used collectively to enhance reliability of data center.

1. Quality Function Deployment
2. Calculation of System and Sub-System level reliabilities using MTBF and MTTR Parameters
3. Reliability Block Diagrams
4. Failure Mode and Effect Analysis

The proposed research will use above four techniques collectively to enhance reliability of data center. "Quality Function Deployment" and "Calculation of System and Sub-System level reliabilities using MTBF and MTTR Parameters" will enhance reliability whereas; "Reliability Block Diagrams" and "Failure Mode and Effect Analysis" will enhance maintainability. Increase in reliability and maintainability will result in increased Availability as Availability is aggregate of Reliability and Maintainability.

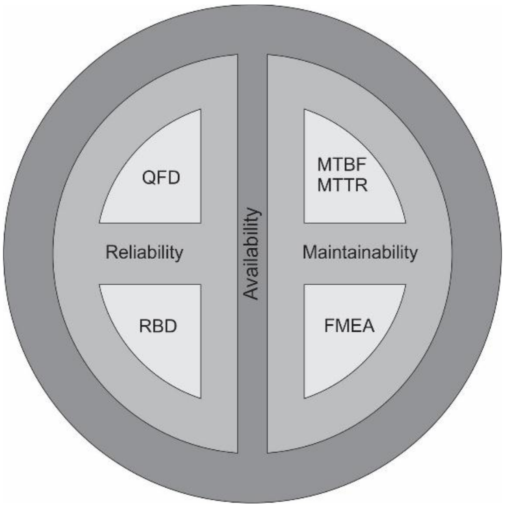


Figure 2: Adopted Methodology

3.4 Study of RCMS Data Center

In the last decade, Pakistan lagged behind in the establishment of high-end computing facilities. Such facilities were essentially required for solving large-scale & complex modeling and simulation problems. The requirement of supercomputer for solving high complexity problems always existed.

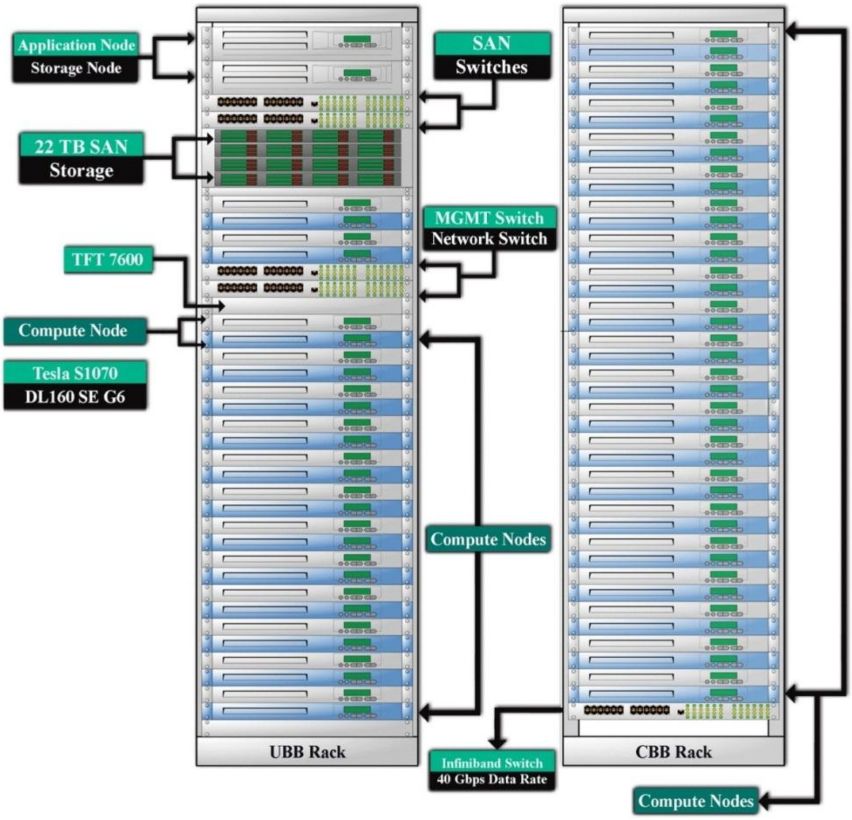


Figure 3: Study of RCMS Data Center

In the past, building a data center involved state of the art design, manufacturing & integration technologies, which were strictly guarded to restrict any technology transfer. With the rapid growth in the processor technologies, the implementation of a supercomputer through parallel processing became feasible. This breakthrough made it possible for developing nations to build their own supercomputer by using commercial of the shelf (COTS) systems. NUST used this opportunity & proceeded with integrating a supercomputer on the concept of a parallel processing cluster. This not only elevated us among selected few nations having their own supercomputer but also provided us the capability of solving crucially important complex problems indigenously. Due to the limited financial resources and lack of planning, many essential components of Data Center were ignored and not included in the project plan.

3.4.1 Comparison of RCMS with Standard Facilities

On comparing facilities available at RCMS data center with facilities of a standard data center, it is observed that many essential facilities are missing or insufficient. Figure 7 shows all standard facilities of data center. Only 44% of the standard facilities are available in RCMS Data Center.

No	Sub-system	Available
1	IT Equipment	Yes
2	Precision AC	Yes
3	Temperature Alarm	No
4	Uninterrupted Power Supply	Yes
5	Fire Suppression System	Yes
6	Trained Human Resource	Yes
7	Power Alarm	No
8	Functional Display	No
9	Backup Power Generators	Yes
10	CCTV Monitoring	No
11	Sound Proof Enclosure	No
12	Preventive Maintenance Plan	Yes
13	Network Management System	No
14	Access Control System	No
15	Optimal Usage Plan	Yes
16	Business Plan	No

Table 3: Comparison of RCMS with Standard Facilities

3.4.2 Mapping of RCMS Data Center and Standard Tiers

American National Standards Institute (ANSI) published ANSI/TIA-942, Telecommunications Infrastructure Standard for Data Centers in 2005, which defined four levels called tiers of data centers in a thorough and quantifiable manner. The comparison of RCMS data center with the standard tiers is given in Table 2.

Tier requirements	TIER I	TIER II	TIER III	TIER IV	RCMS
Distribution paths power and cooling	1	1	1 active / 1 alternate	2 active	1
Redundancy active components	N	N+1	N+1	2 (N+1)	N
Redundancy backbone	no	No	yes	yes	yes
Redundancy horizontal cabling	no	No	no	optional	no
Raised floors	12"	18"	30" -36"	30" -36"	19.5”
UPS / generator	optional	Yes	yes	dual	yes
Concurrently maintainable	no	No	yes	yes	no
Fault tolerant	no	No	no	yes	no
Availability	99.67%	99.75%	99.98%	100.00%	95.86%

Table 4: Comparison of RCMS Data Center with Standard Tiers

The four tiers represent the standard method to determine the uptime of data center. These tiers are helpful in measuring the performance of data center, investment and return on investment. In "Distribution paths power and cooling", RCMS data center successfully competes with tier 2 data centers. In "Redundancy active components", RCMS data center conforms to tier 1. In "Redundancy backbone" RCMS conforms to tier 3 & 4. In "Raised floors" and "UPS / generator" RCMS conforms to tier 3, whereas in "Concurrently maintainable" and "Fault tolerant" areas, RCMS conforms to tier 2 and 3 respectively. However, availability of RCMS data center is far below the tier 1 standard. It is the area of concern and main reason behind this meaningful research.

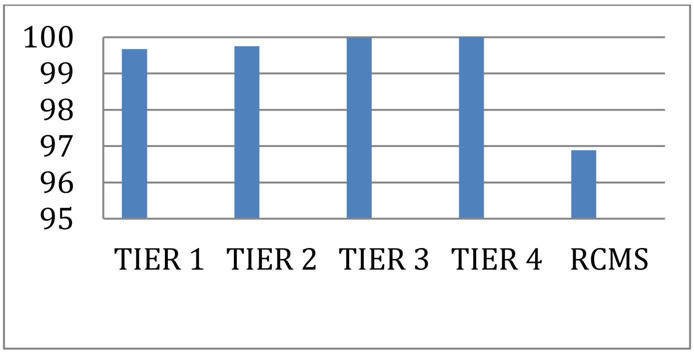


Figure 4: Comparison of Data Centre Availability with Standard Tiers

3.4.3 Downtime Percentage of RCMS Data Center

Factual data of 3 years was used for calculation of downtime percentage of RCMS Data Center.

Total No. of Days	= 962
Total No. of Holidays	= 275
Total No. of Hours	= 12,366 Hours
Total Downtime	= 512 Hours
% Downtime	= $\frac{512 \text{ Hours}}{12{,}366 \text{ Hours}} \times 100$
	= 4.14%

Figure 5: Downtime Percentage of RCMS Data Center

Total numbers of days were 962, out of which 275 were holidays. So, total operational days were 687. From these 687 days, hours were calculated. Total recorded downtime hours were 512. Hence, dividing total downtime hours with total operational hours and multiplying by 100 gives downtime percentage of 4.14%. So, the availability of RCMS data center is 95.86%, which is far less than the availability of tier 1 standard.

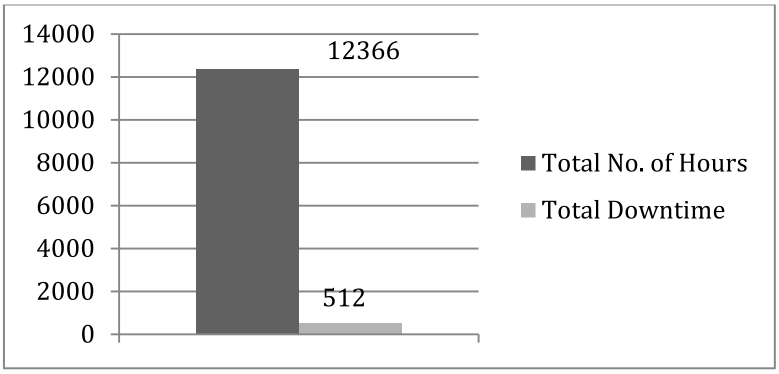


Figure 6: Downtime of RCMS Data Center

3.4.4 Comparison of RCMS Data Center and Standard Tiers

In section 3.4.2, we compared RCMS data center with standard tiers relative to following areas:

(a) Distribution paths power and cooling
(a) Redundancy active components
(b) Redundancy backbone
(c) Redundancy horizontal cabling
(d) Raised floors
(e) UPS / generator
(f) Concurrently maintainable
(g) Fault tolerant
(h) Availability

RCMS data center can also be compared with standard tiers in terms of Implementation Time, Relative investment costs and Costs per square meter. Cost of RCMS data center is $ 3,814 per square meter and has been calculated as follows:-

Area of Data Center:	$= 94.34\ m^2$
Total Cost of Data Center	= Cost of Supercomputer + Cost of Precision AC + Cost of Electrical Infrastructure + Cost of Fire Suppression System
Total Cost of Data Center	= 33.39M + 3.3M + 0.05M + 0.9M = 37.64 M
Total Cost per m^2	$= \frac{37.64}{94.34}$ $= 0.3989\ M / m^2$ ~ **$ 3,814**

Figure 7: Calculation of cost per square meter

Tier requirements	TIER I	TIER II	TIER III	TIER IV	RCMS
Implementation Time	3 months	3 - 6 months	15 - 20 months	15 - 20 months	13 months
Relative investment costs	100%	150%	200%	250%	80%
Costs per square meter	~ $ 4,800	~ $ 7,200	~ $ 9,600	~ $ 12,000	~ $ 3,814

Table 5: Comparison of RCMS Data Center and Standard Tiers

From Table 3, it can be inferred that implementation time of RCMS data center is almost similar to tier 3 data centers. However, the main reason for it taking more time is not its facilities of tier 3 standard but in fact it was due to lack of experience and prior knowledge. The relative investment costs and costs per square meters are less than the tier 1 data centers. These lower costs are not due to efficient planning but because many of the essential components of data center have been left out, resulting in reduced costs.

3.4.5 Power consumption and Costs

There are three main components of RCMS data center which include Supercomputer, Precision AC and Supercomputing Lab. The phase loads of these three components have been calculated and tabulated below:

Phase Load	Supercomputer	Precision AC	SC Lab
Red	42 A	21.5 A	2 A
Blue	36 A	19 A	5 A
Yellow	34 A	21 A	4 A
Total Load	112 A	61.5 A	11 A

Table 6: Loads on three phases of RCMS Data Center

Power load has been calculated for Supercomputer using the following equation:

$$P(w) = V \times I \times Cos\theta \times \sqrt{3}\ watts \quad (1)$$

$$P(w) = 400 \times 112 \times 1.732 \times 0.85\, watts \quad (2)$$

$$P(w) = 65{,}955\, watts \quad (3)$$

Similarly, load has been calculated for remaining two components of data center and tabulated below:-

Component	Load
Super Computer	65,955
Precision AC	36,216
SC Lab	6,478
Total Cost	**108,649**

Table 7: Total Loads of Components RCMS Data Center

Based on loads tabulated above, cost has been calculated using the following equation:-

$$Cost\ (Rs.) = \frac{Watts \times Hours \times Days \times Unit\ Cost}{1000} \quad (4)$$

The costs of individual components of data center and complete data center are tabulated below:-

	Load	Hours	Days	Unit Cost	Total Cost
Super Computer	65,955	24	30	14	6,64,826
Precision AC	36,216	24	30	14	3,65,057
SC Lab	6,478	24	30	14	65,298
Total Cost	**108,649**				**10,95,182**

Table 8: Power Load and Power Costs of RCMS Data Center

Total Units Consumed per Month = 78227.28 Units

3.4.6 Data Center Downtime Summary

Factual data of three years has been used to do analysis on RCMS data center. Downtime has been categorized into Partially Down, Fully Down and Fault without Downtime. It has been further categorized into planned downtime and unplanned downtime as well. Faults that occurred in three shifts and total number of faults of all shifts have also been documented and analyzed. The summary of downtime data is given in Table 7.

	Partially Down	Fully Down	Fault without Downtime	Unplanned Downtime	Planned Downtime	Total Faults
Morning Shift						
Instances	15	16	2	28	5	33
Downtime (h)	84	104	0	148	40	188
Downtime (m)	5040	6240	0	8880	2400	11280
Evening Shift						
Instances	8	16	3	22	5	27
Downtime (h)	30	54	0	68	16	84
Downtime (m)	1800	3240	0	4080	960	5040
Night Shift						
Instances	9	13	3	21	4	25
Downtime (h)	108	132	0	192	48	240
Downtime (m)	6480	7920	0	11520	2880	14400

Table 9: Downtime Summary of RCMS Data Center

The bar graph showing the comparison of number of fault instances and downtime in each shift is given below:-

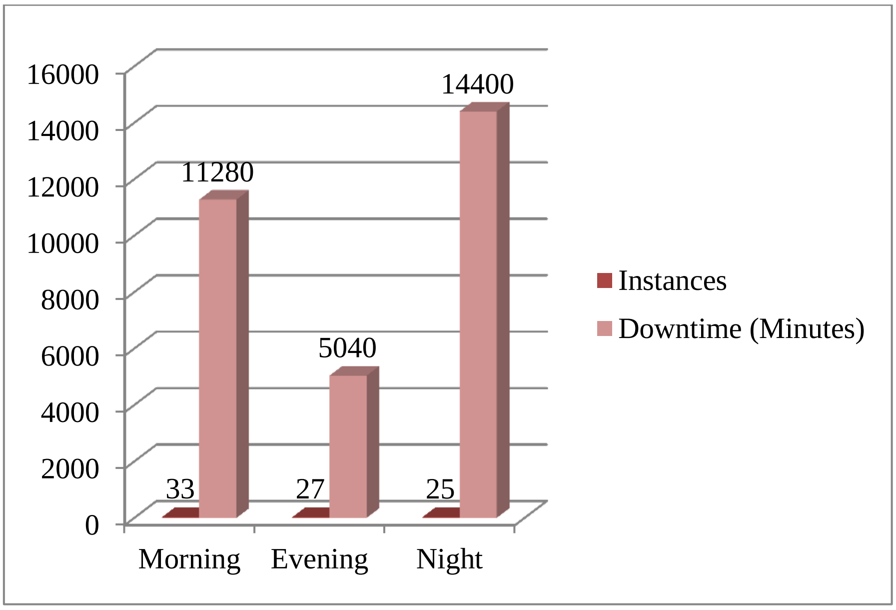


Figure 8: Comparison of Fault Instances and Downtime in Each Shift

3.5 Techniques

3.5.1 Quality Function Deployment

Quality Function Deployment is an orderly process which provides a mean to companies and organizations to focus on requirements of their clienteles. It focuses on customer requirements and helps in converting customer requirements into functional requirements.

Requirement analysis is an important part of QFD. In requirement analysis, customer needs are identified. Requirement analysis is a continuous process as products and services keep on changing due to changing requirements and technological advancements.

QFD resembles the structure of House and is often called house of quality. The main components of House of Quality are listed below:

(a) Customer requirements
(b) Functional Requirements
(c) Correlation between different functional requirements
(d) Relationships between customer and functional requirements
(e) Weightages and Importance of all customer and functional requirements

3.5.2 Calculation of MTBF, MTTR and Reliabilities

Basic parameters have been calculated in this section and analysis is performed on them. List of parameters is given below:-

(a) MTBF
(b) MTTR
(c) MTBM
(d) $\overline{M}$
(e) Inherent Reliability
(f) Achieved Reliability
(g) Operational Reliability
(h) Failure Rate
(i) Repair Rate
(j) Reliability

MTBF and MTTR are reliability parameters based on methods and techniques for lifecycle predictions for a product. The definitions of reliability parameters are given below:-

Mean Time Between Failure (MTBF)

Mean time between failures is defined as the time passed between different failures of the system. MTBF is calculated by dividing the total time of operation by total number of failures.

$$MTBF = \frac{\sum(Start\ of\ Downtime - Start\ of\ Uptime)}{Number\ of\ Failures} \tag{5}$$

$$MTBF = \frac{Total\ Time\ of\ Correct\ Operation\ in\ a\ period}{Number\ of\ Failures} \tag{6}$$

The MTBF can alternatively be defined in terms of function of time:-

$$MTBF = \int_0^\infty t f(t) dt \tag{7}$$

Mean Time To Repair (MTTR)

Mean Time To Repair is defined as an average time required to repair a failed component or system. Actually, it is calculated by dividing the total hours of downtime caused by the system failures by number of failures.

$$MTTR = \frac{Total\ Hours\ of\ Downtime\ caused\ by\ System\ Failures}{Number\ of\ Failures} \tag{8}$$

It is also expressed mathematically as:-

$$MTTR = \int_{-\infty}^{\infty} g(t) dt \tag{9}$$

Mean Time Between Maintenance (MTBM)

It is a measure that signifies the average time between both corrective and preventive maintenance actions.

$$MTBM = \frac{Total\ Uptime}{Total\ number\ of\ Downtime\ Instances} \tag{10}$$

Mean Active Maintenance Time ($\overline{M}$)

Mean Active Maintenance Time is calculated by dividing the total downtime by the total number of downtime instances.

$$\overline{M} = \frac{Total\ Downtime}{Total\ number\ of\ Downtime\ Instances} \tag{11}$$

Inherent Availability, A_I

Inherent availability is defined as the availability in which we consider only unplanned downtimes. Planned downtimes and other administrative delays are not included in this time.

As planned downtimes can be controlled, therefore, only unplanned downtimes are considered in calculation of inherent availability.

$$A_I = \frac{MTBF}{(MTBF+MTTR)} \tag{12}$$

Achieved Availability, A_A

Achieved availability is defined as the type of availability in which we consider both planned and unplanned downtimes with the exception of administrative delays. Achieved availability is calculated by dividing the MTBM by the sum of MTBF and mean maintenance downtime, $\overline{M}$.

$$A_A = \frac{MTBM}{(MTBM+\overline{M})} \tag{13}$$

Operational Availability, A_o

Operational availability is the actual time for which system remains in operation. It includes both planned and unplanned downtimes as well as the administrative delays.

Operational availability is calculated by dividing the uptime by operating cycle. Mathematical formula for operational availability is given by:-

$$A_O = \frac{Uptime}{Operating\ Cycle} \tag{14}$$

Operational availability is defined as:

$$Ao = \frac{MTBM}{(MTBM+MDT)} \tag{15}$$

Failure Rate (λ)

Failure rate is defined as the number of failures per unit time. Lambda denotes the failure rate in reliability engineering. Mathematically, failure rate is expressed as:-

$$\lambda = \frac{1}{MTBF} \tag{16}$$

Repair Rate (μ)

Repair Rate is the rate of happening of failure incidences for a system or component. It is expressed as:-

$$\mu = \frac{1}{MTTR} \tag{17}$$

Reliability

Reliability is a property of any component, sub-system or system that consistently performs according to its specifications. It is a capability of a component of system or a whole system to perform its intended functions for a specified time under specific conditions. Mathematically, it is expressed as:-

$$R(t) = e^{-(\lambda)t} \tag{18}$$

Bathtub curve is the best technique that describes the hardware failures. Lifecycle of a product or a system is divided into three periods:-

(a) Early life period

(b) Useful Life Period

(c) Wear-Out Period

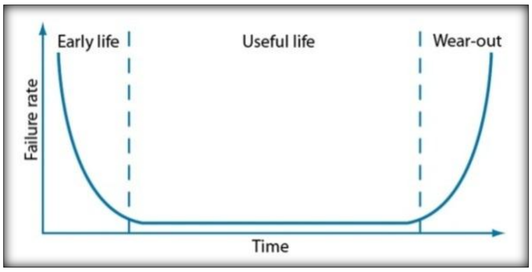


Figure 9: Bathtub Curve

In early life period, rate of failures is greater, during the useful life it becomes less and steady and then again start increasing in wear-out period due to wear and tear of machine, product or system.

3.5.3 Failure Mode and Effect Analysis

Failure Mode and Effects Analysis (FMEA) is the methodology designed to identify potential failure modes for a product or process, to assess the risk associated with those failure modes, to prioritize the problems in terms of significance and to ascertain and carry out corrective actions to address the most critical concerns.

Basic Process for FMEA

The Basic FMEA procedure is sequential in nature. It consists of following steps:-

- Learn about the design
- Set the level of the analysis
- Describe the desired functions
- Analyze and streamline desired functions
- List all possible modes of failure
- Again analyze and streamline failures against desired functions
- List the probable effects of each failure mode
- List probable causes of all failures
- Describe current control processes
- Assess criticality of each failure
- Take remedial or corrective action
- Normalize the corrective actions taken

Risk Evaluation Methods

Risk Analysis is an important component of Failure Mode and Effect Analysis. Risk Analysis can be performed using a variety of techniques. Two of the most used methods include Risk Priority Numbers (RPN) and second one is Criticality Analysis. In this Research, Risk Priority Numbers method has been used to prioritize the failures.

Risk Priority Numbers

The steps involved in calculating the RPNs are listed below:-

- Rank the severity of each failure on the scale of 1 -10
- Rank probability of occurrence for all causes of failures
- Rank probability of detection for all causes of failures

- Calculate RPN by multiplying severity, occurrence and detection rating.

$$RPN = Severity \times Occurence \times Detection \tag{19}$$

Applications and Benefits

The FMEA method is used to enhance the product and process designs. It results in greater reliability, improved quality and better safety. FMEA technique can also be used to optimize maintenance procedures for different systems or components. It provides a database of failures and corrective actions which will serve as a training tool for troubleshooting by future engineers.

3.5.4 Reliability Block Diagrams

A Reliability Block Diagram (RBD) is used to describe the network relationships between different components of the system. Reliability and Availability analysis can also be performed on the system using its RBDs. The RBD starts with an input node and ends at output node. In between input and output node all components are either connected in series or in parallel depending upon their utilization. A parallel RBD will have redundancy and will have multiple paths to reach end node from starting node. While series RBD will have no redundancy and there will be a single path from starting node to end node.

Series and Parallel Reliability

Reliability of the system is determined by connecting the parts or components of a system in series or parallel. The general rubrics used to decide parallel or series connectivity of parts are listed below:-

- If a system becomes inoperable due to a faulty part, it means that the parts are connected in series
- If a system remains operable even in presence of faulty part, it means that some alternate part has taken over the function of faulty part. In such a system parts are said to be connected in parallel.

Reliability in Series

Figure 10: Reliability in Series

In case, due to the failure of any one of the above mentioned two parts, whole system fails, we can say that the system was connected in series. Hence, the system will remain operational if and only if both parts remain functional. Therefore, reliability of components connected in series is the product of the reliability of the two components. Reliability in series can be expressed as:-

$$RS = R1.R2.R3 \dots\dots RN \quad (20)$$

It can be inferred from above that the availability of components connected in series is always less than the availability of individual components.

Reliability in Parallel

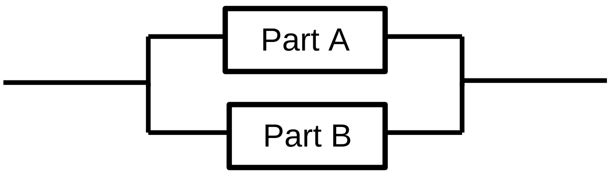


Figure 11: Reliability in Parallel

In case system fails due to failing of both the components A and B, then the components are connected in parallel. In case any one of A or B is operational, system will work. The reliability in parallel is defined as 1 - (both parts are unavailable). The mathematical expression for reliability in parallel is :-

$$RP = 1 - (1 - R1)(1 - R2)(1 - R3) \dots\dots (1 - RN) \quad (21)$$

It can be inferred from above that the availability of components connected in parallel is always greater than the availability of individual components.

CHAPTER 4

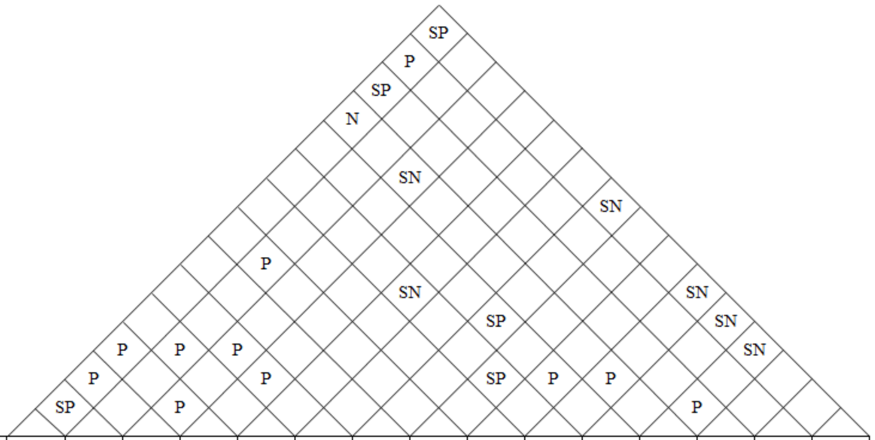
Results and Discussions

4.1 Quality Function Deployment

4.1.1 Analysis

The house of quality of RCMS data center has been prepared which contains customer requirements i.e. “Whats” and functional Requirements i.e. “Hows”. The relationships between functional requirements and customer requirements are defined in relationship matrix. Relationships may be strong, moderate or weak. Direction of improvement for each functional requirement is also indicated using a symbol. Direction of improvement is categorized as minimize, maximize or target. Relationship between each functional requirement is classified as strong positive correlation, positive correlation, negative correlation or strong negative correlation. Moreover, target or limit value and difficulty level of each functional requirement has also been specified. Maximum relationship values in columns and rows have also been calculated. On the basis of weight/ importance, relative weight of each functional and customer requirement has also been calculated.

Strong Relationship	9
Moderate Relationship	3
Weak Relationship	1
Strong Positive Correlation	SP
Positive Correlation	P
Negative Correlation	N
Strong Negative Correlation	SN
Yes	✓
No	×



Functional Requirements (Hows) / Customer Requirements (Whats)	IT Equipment	Precision Air Conditioner	Modular UPS	Backup Power Generator	Temperature Alarm	Power Alarm	Display Screen	Sound/ Dust Proof , Closed Enclosure	Access Control System	Fire Detection and Suppression	CCTV Monitoring System	Preventive Maintenance Plan	Business/ Financial Plan	Optimal Usage Plan	Trained Human Resource	Strongest Relationship	Individual Weight	Relative Weight
Enhancement Required	✓	×	×	×	×	×	×	×	×	×	✓	×	×	×	✓			
Computatioal Power	9	3														9	9.0	12.7
Cooling		9						9								9	9.0	12.7
Un-Interrupted Power Supply	9	9	9	9		1			3	3	3					9	9.0	12.7
Administration/ Maintenance / Operations															9	9	9.0	12.7
Fire Safety					3			3		9	1	1			3	9	8.0	11.3
More Profit/ Revenue/ Income												3	9	3		9	7.0	9.9
Less Failures												9				9	6.0	8.5
Round the clock Monitoring							9				9				3	9	5.0	7.0
No Un-authorized Access									9		3					9	4.0	5.6
Alert on Power Shutdown						9										9	2.0	2.8
Alert on rise in Temperature					9											9	1.0	1.4
Network Monitoring							9								3	9	1.0	1.4
Noise/ Dust Free Environment								9				3				9	1.0	1.4
Desired Value	32 Compute Nodes	1	1	2	1	1	1	1	1	1	4	1	1	1	11			
Strongest Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	3	9			
Relative Weight	12.7	14.8	6.3	6.3	2.6	2.1	3.5	8.9	4.9	7.7	7.2	6.7	4.9	1.6	9.6			
Overall Weightage	228.2	266.2	114.1	114.1	46.5	38.0	63.4	160.6	88.7	139.4	129.6	121.1	88.7	29.6	173.2			

Figure 12: House of Quality of RCMS Data Center

4.1.2 Results

Components of Data Center have been prioritized according to their importance based on QFD. Those having more Weightage/ Importance Value must be acquired earlier.

Components	Weightage
Precision Air Conditioner	266.2
IT Equipment	228.2
Trained Human Resource	173.2
Sound/ Dust Proof , Closed Enclosure	160.6
Fire Detection and Suppression	139.4
CCTV Monitoring System	129.6
Preventive Maintenance Plan	121.1
Modular UPS	114.1
Backup Power Generator	114.1
Business/ Financial Plan	88.7
Access Control System	88.7
Display Screen	76.1
Temperature Alarm	46.5
Power Alarm	38.0
Optimal Usage Plan	29.6

Table 10: Weight / Importance of Components of Data Center

4.2 Calculation of MTBF, MTTR and Reliabilities

4.2.1 Analysis

The factual data of shift operations of RCMS data center was available and same has been utilized to perform statistical analysis. For most of the time data center was operated from 9am to 9pm in two shifts i-e morning and evening. However, for approximately 4 months it was operated 24/7 (round the clock) in three shifts i-e morning, evening and night. Total Operational Time, Total Downtime and Total Uptime has been calculated and given in Table 9. The available data of three years operations of RCMS datacenter was sorted date wise. The data contains all the faults that occurred in morning, evening and night shifts. The downtime has been divided into planned downtime and unplanned downtime. It has been further divided into partially down, fully down or fault without downtime.

Description	Total Time	Total Operational	Total Downtime	Total Uptime
Days	962	687	21.333	665.667
Hours	23088	12366	512	11854
Minutes	1385280	741960	30720	711240

Table 11: Summary of Data Center Operations

Details of downtimes of individual components of data center are given in Table 12.

Component	Code	Morning	Evening	Night	Instances	Downtime (Hours)	Downtime (Minutes)
Head Nodes	H1	0	1	0	1	1	60
Compute Nodes	C1	3	0	0	3	9	540
SAN Storage	S1	18	15	15	48	363	21780
Power Issue in Super Comp Lab	S2	0	1	0	1	2	120
UPS of Super Computer	U1	3	2	2	7	23	1380
AC of UPS Room	A2	1	2	3	6	4	240
Precision AC	A1	3	0	0	3	2	120
Power in Data Center	P1	0	1	0	1	2	120
Power outside Data Center	P2	1	0	1	2	9	540
Generated Related Issue	G1	0	1	0	1	1	60
Software of Super Computer	E1	4	4	4	12	96	5760
Network Switches of Super Computer	N1	0	0	0	0	0	0

Table 12: Component Wise Downtime Details

On the basis of available data all basic parameters i-e MTBF, MTTR, MTBM and M have been calculated. The reliability, repair rate, failure rate and availability have been calculated using the basic parameters and available data. The details of all calculations are tabulated below:-

Component	Head Nodes	Compute Nodes	SAN Storage	Power in SC Lab	UPS of SC	AC of UPS Room	Precision AC	Power inside Data	Power outside Data	Generator Issue	Software of SC	Network Switches
Code	H1	C1	S1	S2	U1	A2	A1	P1	P2	G1	E1	N1
Morning	0	3	18	0	3	1	3	0	1	0	4	N/A
Evening	1	0	15	1	2	2	0	1	0	1	4	N/A
Night	0	0	15	0	2	3	0	0	1	0	4	N/A
Total	1	3	48	1	7	6	3	1	2	1	12	N/A
Downtime	1	9	363	2	23	4	2	2	9	1	96	N/A
Downtime	60	540	21780	120	1380	240	120	120	540	60	5760	N/A
Uptime	741900	741420	720180	741840	740580	741720	741840	741840	741420	741900	736200	N/A
MTBF	741900	247140	15003.8	741840	105797.143	123620	247280	741840	370710	741900	61350	N/A
MTTR	60	180	453.75	120	197.142857	40	40	120	270	60	480	N/A
MTBM	741900	247140	15003.8	741840	105797.143	123620	247280	741840	370710	741900	61350	N/A
M	60	180	453.75	120	197.142857	40	40	120	270	60	480	N/A
Availability	0.999919	0.999272	0.970645	0.999838	0.998140	0.999677	0.999838	0.999838	0.999272	0.999919	0.992237	1
Availability	0.999919	0.999272	0.970645	0.999838	0.998140	0.999677	0.999838	0.999838	0.999272	0.999919	0.992237	1
Availability	0.999919	0.999272	0.970645	0.999838	0.998140	0.999677	0.999838	0.999838	0.999272	0.999919	0.992237	1
Failure	0.000001	0.000004	0.000067	0.000001	0.000009	0.000008	0.000004	0.000001	0.000003	0.000001	0.000016	N/A
Repair Rate	0.016667	0.005556	0.002204	0.008333	0.005072	0.025000	0.025000	0.008333	0.003704	0.016667	0.002083	N/A
Reliability	0.367850	0.049678	0.000000	0.367820	0.000900	0.002474	0.049763	0.367820	0.135138	0.367850	0.000006	1

Table 13: Reliability Calculations

4.2.2 Results

The SAN storage has maximum downtime and the Head Nodes have minimum downtime. It means that Head Nodes are the most stable and most available component of data center and SAN Storage is the most unavailable and most unstable component. The availability of software of supercomputer is also very less as compared to other components of data center. Therefore, special attention must be paid to increase the availability of SAN Storage and Software of super computer. The main reason behind unavailability of both these components is frequent shutdown and restart of data center. Hence, the practice of turning off data center at 9 PM must be stopped and it must be operated round the clock.

4.3 Failure Mode and Effect Analysis

4.3.1 Analysis

Failure Mode and Effect Analysis has been performed on RCMS data center. All the processes related to data center have been listed. In second step, all the failure modes for each process have been identified. There are total 19 processes for which potential failure modes have been identified. After identifying failure modes, causes of failures are found and effect of each failure is assessed. Then the current process controls are listed. Finally recommended action is identified and action taken is recorded. In addition to this a Risk Priority Number (RPN) is calculated before and after taking the recommended action. RPN is calculated using the severity, occurrence and detection ratings. The Risk Priority Number (RPN) is used for analyzing the risk associated with potential problems identified during FMEA. If the RPN falls within a pre-determined range, corrective action may be recommended or required to reduce the risk. The rating criterion for severity, occurrence and detection is given below:-

Detection	Occurrence Rating	Severity of Effect	
1. Almost Certain	1. Very Low <.01/1000	No Effect	1. None
2. Very High	2. Low -1/1000000	Annoyance	2. Very Minor
3. High	3. Low -1/100000		3. Minor
4. Moderate High	4. Moderate - 1/100000		4. Very Low
5. Moderate	5. Moderate 1/2000	Loss or degradation of secondary function	5. Low
6. Low	6. Moderate - 1/500		6. Moderate
7. Very Low	7. High - 1/100	Loss or degradation of primary function	7. High
8. Remote	8. High - 1/50		8. Very High
9. Very Remote	9. Very High 1/20	Failure	9. Hazardous with warning
10. Almost Impossible	10. Very High > 1/10	Safety/regulations	10. Hazardous w/o warning

Table 14: Rating Criterion for Severity, Occurrence and Detection

The detailed worksheets for Failure Mode and Effect Analysis of RCMS data center are given below:-

FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Item:	ScREC Data Center, RCMS -NUST	**Responsibility:**	Muhammad Usman	**FMEA number:**	1
Model:	Current	**Prepared by:**	Muhammad Usman	**Page :**	1 of 1
Core Team:	ScREC Data Center, RCMS -NUST			**FMEA Date:**	18/7/2016 Rev: 1

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	RPN
Turn on UPS of Supercomputer	UPS not working properly	Supercomputer Non-Operational	8	Fan Fault	9	Repair/ Replacement is carried out by Lab Technician. Temporarily external fan is installed for cooling	1	72	Replace Fan	Lab Technician, 03-07-2013	External Fan installed as temporary measure and new fan procured as permanent measure	8	1	1	8
〃	〃	Not being switched on	8	Sense Fuse Board has Malfunctioned	2	Repair/ Replacement of sense fuse board is carried out by Lab Technician	5	80	Continue current practices	Lab Technician, 29-07-2013	Board Replaced	8	1	5	40
〃	〃	〃	8	Missing Phase	4	Initial trouble shooting is done by Lab Technician and Complaint is lodged with PMO, NUST for Rectification	1	32	Continue current practices	Lab Technician, 08-09-2014	Faulty Cable replaced	8	3	1	24
Turn on Precision AC	Compressor 1 not starting	Precision AC non-operational for limited time	9	Compressor 1 Overheated, High Pressure Fault	5	Troubleshooting is performed by Lab Technician, Reset pressure switch of compressor 1	1	45	Continue current practices	Lab Technician, 23-07-2014	Pressure Switch Reset	9	5	1	45
〃	〃	〃	9	Power Missing	2	Initial trouble shooting is done by Lab Technician and Complaint is lodged with PMO, NUST for Rectification	1	18	Continue current practices	Lab Technician, 23-07-2014	Faulty Cable replaced	9	1	1	9
〃	Compressor 2 not starting	〃	9	Compressor 2 Overheated, High Pressure Fault	5	Troubleshooting is performed by Lab Technician, Reset pressure switch of compressor 2	1	45	Continue current practices	Lab Technician, 23-07-2014	Pressure Switch Reset	9	5	1	45
〃	Both compressors are not starting	〃	9	VCM card faulty	4	Initial trouble shooting is done by Lab Technician and Complaint is lodged with Vendor M/s CNS Engg for Replacement of VCM Card	2	72	Continue current practices	Lab Technician, 23-07-2014	Faulty VCM Card replaced	9	2	2	36
Turn on Compute Nodes	Some Cuda Nodes are not being initialized	Supercomputer Partially Operational	7	Nodes were in use during the last shutdown	5	Troubleshooting and Reinstallation of Compute Nodes is performed by Lab Engineer	8	280	Update procedures and clearly define shutdown process	Lab Technician, 07-11-2013	Shutdown Procedure updated	7	3	8	168
〃	〃	〃	7	Nodes Shutdown Improperly	5	Troubleshooting and Reinstallation of Compute Nodes is performed by Lab Engineer	8	280	Update procedures and clearly define shutdown process	Lab Technician, 07-11-2013	Shutdown Procedure updated	7	3	8	168
〃	〃	〃	7	Nodes reinstalled because of any other reason	5	Troubleshooting and Reinstallation of Compute Nodes is performed by Lab Engineer	8	280	Trace the process causing the problem and shutdown that process before shutting down the Come Nodes in future	Lab Technician, 07-11-2013	Shutdown Procedure updated	7	3	8	168
Turn on Precision AC	Humidifier Fault in AC, Solved after Restart	Precision AC non-operational for limited time	9	Water flow pipes are Airlocked	3	Troubleshooting /Rectification is performed by Lab Technician by opening the valves on Pipes installed at Roof top of building	2	54	Continue current practices	Lab Technician, 21-01-2014	Airlocking removed	9	1	2	18
〃	〃	〃	9	Water flow pipes are blocked	3	Troubleshooting /Rectification is performed by Lab Technician by clearing the blockage in pipes	2	54	Continue current practices	Lab Technician, 21-01-2014	Blockage removed	9	1	2	18
〃	〃	〃	9	Water flow valves are closed	3	Troubleshooting /Rectification is performed by Lab Technician by opening the valves	2	54	Continue current practices	Lab Technician, 21-01-2014	Valves Opened	9	1	2	18

Table 15: FMEA of RCMS Data Center

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
											Actions Taken	Sev	Occ	Det	RPN
Turn on SAN Storage	Cache Flush Error	Head Nodes and Compute Nodes inaccessible	8	SAN Storage was in use during the last shutdown	6	Troubleshooting and clearing of Cache is performed by Lab Engineer	1	48	Update procedures and clearly define shutdown process	Lab technician, 31-10-2013	Shutdown Procedure updated	8	6	1	48
〃	〃	〃	8	Read Write Operation hanged or Interrupted	6	Troubleshooting and clearing of Cache is performed by Lab Engineer	1	48	Update procedures and clearly define shutdown process	Lab technician, 03-06-2014	Shutdown Procedure updated	8	6	1	48
〃	〃	〃	8	Cache memory card faulty	6	Troubleshooting is performed by Lab Engineer and Vendor M/s Mushko Electronics is contacted for replacement of faulty Cache Memory Card	1	48	Continue current practices	Lab technician, 03-06-2014	Cache Reset	8	6	1	48
〃	〃	〃	8	SAN Controller is not working	6	Initial troubleshooting is done by Lab Technician and Complaint is lodged with Vendor M/s Mushko Electronics for Repair/ Replacement	1	48	Continue current practices	Lab technician, 11-06-2014	Cache Reset	8	6	1	48
〃	〃	〃	6	Hard Disk has malfunctioned or developed a fault	2	Initial troubleshooting is done by Lab Technician and Complaint is lodged with Vendor M/s Mushko Electronics for Repair/ Replacement	1	12	Continue current practices	Lab technician, 14-06-2014	Fulty Hard Disk Replaced	6	2	1	12
Turn on Data Center	Data Center Off	Supercomputer Non-Operational	8	Lab Technicians have not arrived on time	1	Data Center Operations are delayed till arival of Lab Technicians	1	8	Advise Lab Technicans to come intime	Lab Technicians	Lab Technicians advised	8	1	1	8
〃	〃	〃	1	Cleaning operation or maintenance is being carried out	3	Lab Technicians perform periodic routine cleaning and maintenance	1	3	Continue current practices	Lab Technicians	No Action Required	1	3	1	3
Turn on SAN Storage	System Down due to SAN Controller	Head Nodes and Compute Nodes inaccessible	8	SAN Controller is not booting up	6	Troubleshooting is performed by Lab Engineer	1	48	Continue current practices	Lab Technician, 22-10-2015	Cache and SAN Controller Reset	8	6	1	48
〃	〃	〃	8	Fibre Cable is damaged	3	Troubleshooting is performed by Lab Technician	3	72	Continue current practices	Lab Technician, 22-10-2015	Faulty Cable Replaced	8	3	3	72
〃	〃	〃	8	Read Write Operation hanged or Interrupted	6	Troubleshooting is performed by Lab Engineer	1	48	Continue current practices	Lab Technician, 02-12-2015	Cache Reset	8	6	1	48
Turn on Compute Nodes	Cluster is Working Partially	Supercomputer Partially Operational	7	Some of the Compute Nodes have been reinstalled	5	Troubleshooting and Reinstallation of Compute Nodes is performed by Lab Engineer	8	280	Update procedures and clearly define shutdown process	Lab Technician, 07-11-2015	Shutdown Procedure updated	7	3	8	168
〃	〃	〃	7	Some Compute Nodes are down due to partial power failure	5	Troubleshooting and Reinstallation of Compute Nodes is performed by Lab Engineer	8	280	Continue current practices	Lab Technician, 07-11-2015	Supply of Power resumed	7	3	8	168
〃	〃	〃	7	Some of the Compute Nodes are down due to fault	5	Troubleshooting and Reinstallation of Compute Nodes is performed by Lab Engineer	8	280	Continue current practices	Lab Technician, 07-11-2015	Shutdown Procedure updated	7	3	8	168
Turn on AC's of UPS Room	AC of UPS room U/S	Temperature risen in UPS Room	9	Compressor of AC overheated	4	Initial trouble shooting is done by Lab Technician and diagnosed that power cable is burnt. Subsequently, Complaint is lodged with PMO, NUST for Rectification	1	36	Continue current practices	Lab Technician, 05-01-2014	Replaced Faulty Power Cable	9	2	1	18
〃	〃	〃	9	Power Plug has been burnt	1	Initial trouble shooting is done by Lab Technician and Complaint is lodged with PMO, NUST for Rectification	2	18	Continue current practices	Lab Technician, 08-07-2014	Replaced Faulty Power Plug	9	1	2	18
〃	〃	〃	9	AC Wire connecting Indoor and Outdoor Units have been damaged due to weather effects	4	Initial trouble shooting is done by Lab Technician and cable is repaired, subsequently, complaint is lodged with PMO, NUST for Rectification	1	36	Continue current practices	Lab Technician, 08-07-2014	Damaged Wire Replaced	9	4	1	36

Table 16: FMEA of RCMS Data Center

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
											Actions Taken	Sev	Occ	Det	RPN
Turn on UPS of Supercomputer / Turn on AC's of UPS Room	UPS and AC not working	Supercomputer Non-Operational	9	Power phase is missing	4	Initial trouble shooting is done by Lab Technician and diagnosed that power cable is burnt. Subsequently, Complaint is lodged with PMO, NUST for Rectification	1	36	Continue current practices	Lab Technician, 15-04-2014	Damaged Wire Replaced	9	2	1	18
Turn on Data Center	System Down	Supercomputer Non-Operational	1	System Upgrade activity is being carried out	2	Lab Engineer informs all users regarding the downtime via email	1	2	Continue current practices	Lab Engineer, 17-02-2015	No Action Required	1	2	1	2
Turn on UPS of Supercomputer	UPS is Down	Supercomputer Non-Operational	1	Periodic Service/ Maintenance is being carried out	3	Service/ Maintenance is performed by Lab Technician and users are informed by Lab Engineer via email	1	3	Continue current practices	Lab Technician, 21-07-2014	No Action Required	1	3	1	3
〃	〃	〃	1	Battery Bank is being replaced	1	Service/ Maintenance and replacment of batteries is performed by Lab Technician	1	1	Continue current practices	Lab Technician, 14-09-2015	No Action Required	1	1	1	1
〃	〃	〃	8	Interface Card has Malfunctioned	1	Repairing of faulty components of Interface Card is carried out by Lab Technician	7	56	Continue current practices	Lab Technician	Faulty Card Repaired	8	1	7	56
〃	〃	〃	8	Power Supply Card has Malfunctioned	4	Repairing of faulty components of Power Supply Card is carried out by Lab Technician	5	160	Continue current practices	Lab Technician	Faulty Card Repaired	8	4	5	160
〃	〃	〃	8	Sense Fuse Board is burnt out	1	Repair/ Replacement of Sense Fuse Board is carried out by Lab Technician	5	40	Continue current practices	Lab Technician	Faulty Card Repaired and spare card manufacured locally by Lab Technician	8	1	5	40
〃	〃	〃	8	Fuse on AC Fuse Board burnt out	3	Replacement of AC Fuse is carried out by Lab Technician	4	96	Continue current practices	Lab Technician	Faulty Fuse Replaced	8	3	4	96
〃	〃	〃	8	Permanent FAN or Temperature Fault occured	9	Troubleshooting and Resetting of UPS is carried out by Lab Technican and temporarily external fan is installed for cooling and pursued purchasing of new fan	1	72	Replace Fan	Lab Technician, 09-06-2015	Faulty Fan Replaced	8	1	1	8
Turn on Circuit Breakers	Input Circuit Breaker sparks	Supercomputer Non-Operational	10	Circuit Breaker Faulty	1	Initial trouble shooting is done by Lab Technician and Complaint is lodged with PMO, NUST for Rectification	3	30	Continue current practices	Lab Technician, 23-07-2014	Faulty Circuit Breaker Replaced	10	1	3	30
Super Computer accessed remotely	System Hanged	Head Nodes and Compute Nodes occasionally inaccessible	7	Overloaded due to submission of Jobs on Head Node	3	Troubleshooting / Restart of both Head Nodes is performed by Lab Engineer	8	168	Update procedures and clearly define utilization of each node	Lab Technician, 22-10-2015	Utilization Procedure Defined/ Updated	7	2	8	112
〃	〃	〃	8	Operating System Files became corrupt	2	Operating System is reinstalled by Lab Engineer	4	64	Continue current practices	Lab Technician, 22-10-2015	OS Re-installed	8	2	4	64
Students working in Supercomputer Lab	Sparking and High voltages in SC Lab	Supercomputing Lab unavailable	10	High Voltages due to Loose Connection in SC Lab DB	1	Initial trouble shooting is done by Lab Technician and Complaint is lodged with PMO, NUST for Rectification	2	20	Continue current practices	Lab Technician, 17-04-2014	Connection Tightened	10	1	2	20
Data Center in normal operation	Generator Problem System Down	Supercomputer Non-Operational	7	Generator Fuel Finished	1	Complaint is lodged with NUST Compalint Office at PMO for Rectification	1	7	Continue current practices	Generator Operator	Re-fueling of Generator Done	7	1	1	7
〃	〃	〃	1	Periodic Service/ Maintenance of Generator is being carried out	1	Complaint is lodged with NUST Compalint Office at PMO for Rectification	1	1	Continue current practices	Generator Operator, 15-07-2014	No Action Required	1	1	1	1
〃	〃	〃	8	Generator has malfunctioned	1	Complaint is lodged with NUST Compalint Office at PMO for Rectification	1	8	Continue current practices	Generator Operator	Generator Problem Rectified	8	1	1	8
Students working in Supercomputer Lab	Lab AC not Working	Temperature risen in SC Lab	8	Compressors have become overheated	2	Initial trouble shooting is done by Lab Technician and Complaint is lodged with PMO, NUST for Rectification	1	16	Continue current practices	Lab Technician, 04-08-2014	Faulty compressors replaced	8	2	1	16

Table 17: FMEA of RCMS Data Center

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
											Actions Taken	Sev	Occ	Det	RPN
〃	〃	〃	8	Refrigerating Gas needs to be recharged	3	Complaint is lodged with PMO, NUST for Rectification	2	48	Continue current practices	Lab Technicians	Refrigerating Gas Recharged	8	3	2	48
〃	〃	〃	8	Electronic component has malfunctioned	2	Complaint is lodged with PMO, NUST for Rectification	2	32	Continue current practices	Lab Technicians	Faulty component replaced	8	2	2	32
Turn on UPS	Super Computer UPS Fan Issue	Supercomputer Non-Operational	8	UPS Fan has been burnt	9	Repair/ Replacement is carried out by Lab Technician, Faulty Fan disconnected, temporarily external fan installed	1	72	Replace Fan as permanent measure	Lab Technicians	Fan Replaced	8	1	1	8
〃	〃	〃	8	Capacitors of FAN have become faulty	2	Capacitors replaced by Lab Technician	1	16	Continue current practices	Lab Technicians	Capacitors Replaced	8	1	1	8
〃	〃	〃	8	FANs are moving slowly due to dusty bearings and require cleaning	1	Cleaning & Lubrication carried out by Lab Technician	1	8	Continue current practices	Lab Technicians	Cleaning & lubrication done as temporary measure and new fan procured as permanent measure	8	1	1	8
〃	〃	〃	8	Life of FAN has expired	1	Troubleshooting is carried out by Lab Technician and New Fan is purchased to replace the life expired fan	1	8	Continue current practices	Lab Technicians	External Fan installed as temporary measure and new fan procured as permanent measure	8	1	1	8
Turn on Precision AC	Temperature of Data Center cannot be controlled	Specific Temperature cannot be maintained	7	Gas was insufficient in Compressors	1	Initial troubleshooting is done by Lab Technician and Complaint is lodged with Vendor M/s CNS Engg for refilling of Gas	1	7	Continue current practices	Lab Technicians	Refrigerating Gas Recharged	7	2	1	14
〃	〃	〃	7	Pressure of Compressor was less	1	Initial troubleshooting is done by Lab Technician and Complaint is lodged with Vendor M/s CNS Engg for rectification	1	7	Continue current practices	Lab Technicians	Pressure Maintained	7	2	1	14

Table 18: FMEA of RCMS Data Center

After taking recommended action on each failure mode, RPN is again calculated. Then the initial and revised RPN is compared to find out the percentage reduction in RPN. Additionally, as part of analysis, severity and occurrence rating of each failure has been compared. Likelihood of occurrence before and after taking recommended action has also been analyzed and compared. Revised RPN provides an indication of the effectiveness of corrective actions and can also be used to evaluate the value to the organization of performing the FMEA.

Initial RPN	Revised RPN	% Reduction in RPN
72	8	88.89
80	40	50.00
32	24	25.00
45	45	0.00
18	9	50.00
45	45	0.00
72	36	50.00
280	168	40.00
280	168	40.00
280	168	40.00
54	18	66.67
54	18	66.67
54	18	66.67
48	48	0.00
48	48	0.00
48	48	0.00
48	48	0.00
12	12	0.00
8	8	0.00
3	3	0.00
48	48	0.00
72	72	0.00
48	48	0.00
280	168	40.00
280	168	40.00
280	168	40.00
36	18	50.00
18	18	0.00
36	36	0.00
36	18	50.00
2	2	0.00
3	3	0.00
1	1	0.00
56	56	0.00
160	160	0.00
40	40	0.00
96	96	0.00
72	8	88.89
30	30	0.00
168	112	33.33
64	64	0.00
20	20	0.00
7	7	0.00
1	1	0.00
8	8	0.00
16	16	0.00
48	48	0.00
32	32	0.00
72	8	88.89
16	8	50.00
8	8	0.00
8	8	0.00
7	14	-100.00
7	14	-100.00

(A)

Sev	Occur
8	9
8	2
8	4
9	5
9	2
9	5
9	4
7	5
7	5
7	5
9	3
9	3
9	3
8	6
8	6
8	6
8	6
6	2
8	1
1	3
8	6
8	3
8	6
7	5
7	5
7	5
9	4
9	1
9	4
9	4
1	2
1	3
1	1
8	1
8	4
8	1
8	3
8	9
10	1
7	3
8	2
10	1
7	1
1	1
8	1
8	2
8	3
8	2
8	9
8	2
8	1
8	1
7	1
7	1

(B)

Initail Occur	Revised Occur
9	1
2	1
4	3
5	5
2	1
5	5
4	2
5	3
5	3
5	3
3	1
3	1
3	1
6	6
6	6
6	6
6	6
2	2
1	1
3	3
6	6
3	3
6	6
5	3
5	3
5	3
4	2
1	1
4	4
4	2
2	2
3	3
1	1
1	1
4	4
1	1
3	3
9	1
1	1
3	2
2	2
1	1
1	1
1	1
1	1
2	2
3	3
2	2
9	1
2	1
1	1
1	1
1	2
1	2

(C)

Table 19: FMEA Analysis

4.3.2 Results

Severity versus occurrence and initial versus revised occurrence values have been compared.

The graphs are given below:-

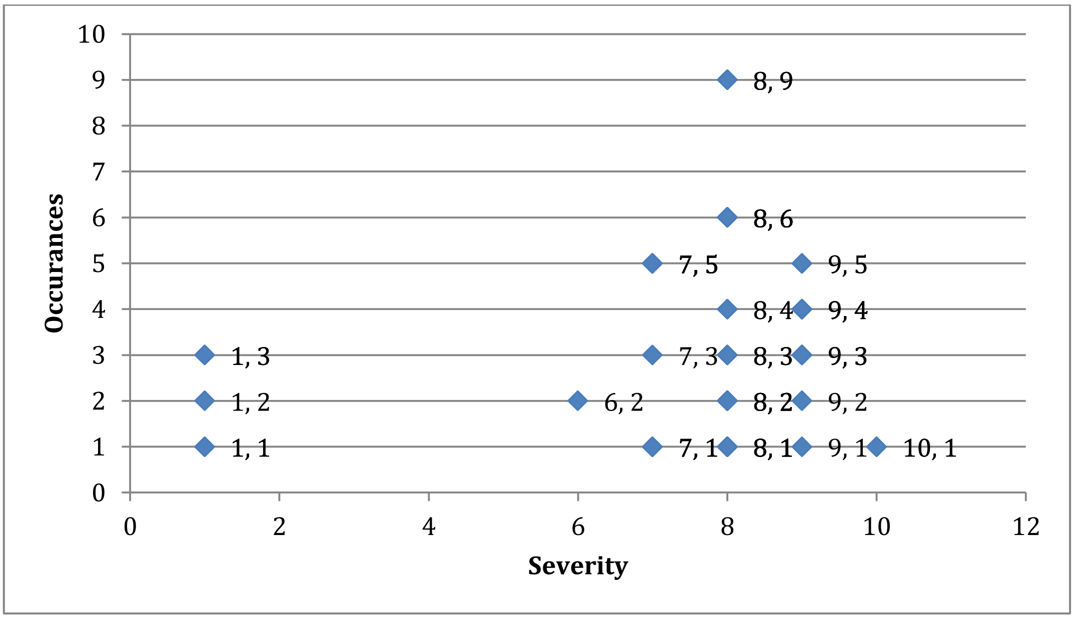


Figure 13: Graphical Representation of Potential Causes of Failures

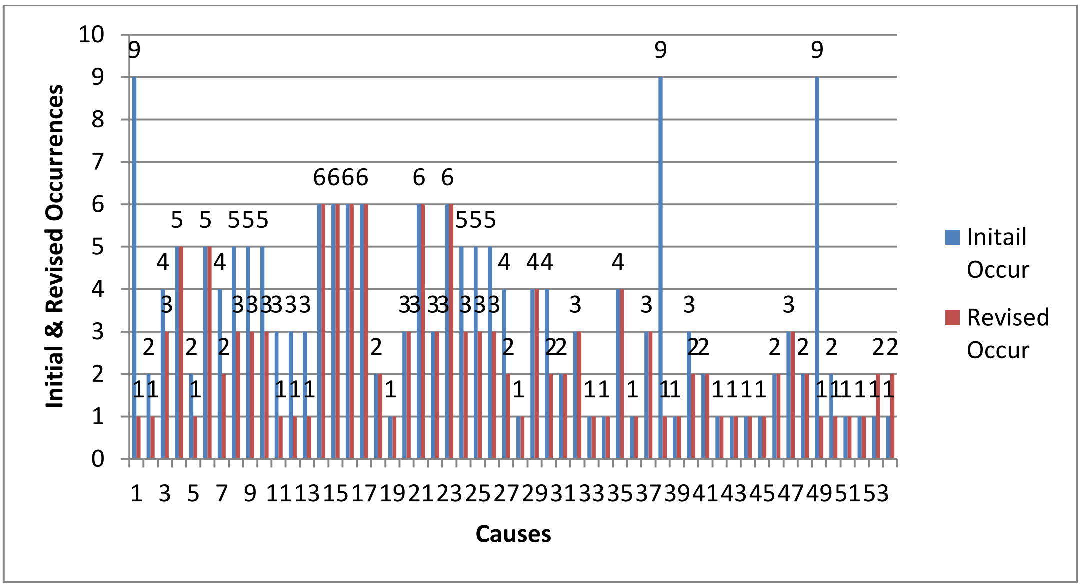


Figure 14: Initial versus Revised Occurrence Graph

The severity versus occurrence graph displays the Occurrence scale vertically and the Severity scale horizontally. Points are marked at the location where Severity and Occurrence ratings intersect. These points represent potential causes of failures. Boundaries can be established on the graph to identify high, medium and low priorities.

Revised RPN provides an indication of the usefulness of corrective actions and can also be used to evaluate the value of performing the FMEA. Potential problems can be analyzed by ranking issues according to their individual Severity, Occurrence or Detection ratings. From FMEA, it can be concluded that:-

(a) Failures having high severity and high occurrence rating should be addressed earlier and must be accorded priority.

(b) In case RPN reduces after recommended action is taken, it means that action is effective

(c) Failures having high RPN must be treated on priority

(d) RPN and occurrence rating significantly reduces if a recommended action is taken.

4.4 Reliability Block Diagrams

4.4.1 Analysis

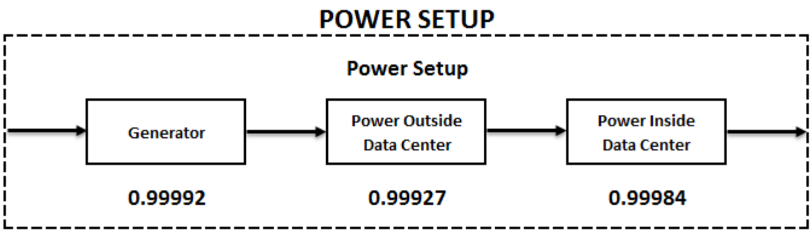


Figure 15: RBD of Power Setup

$$R = R1 \times R2 \times R3 \quad (22)$$

$$R = 0.9992 \times 0.99927 \times 0.99984 = 0.99903 \quad (23)$$

All components of power setup are connected in series. In case of series reliability, reliabilities of all individual components are multiplied. The components of power setup include generator, power cabling outside data center and cabling inside data center. Reliabilities of all these components are multiplied which gives the resultant reliability of overall power setup i.e. 0.99903.

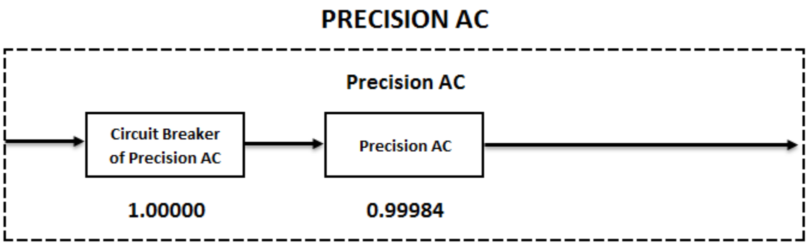


Figure 16: RBD of Precision AC

$$R = R1 \times R2 \tag{24}$$

$$R = 1.00000 \times 0.99984 = 0.99984 \tag{25}$$

The precision AC sub-system consists of two major components which include circuit breakers and precision AC. Both these components are connected in series.

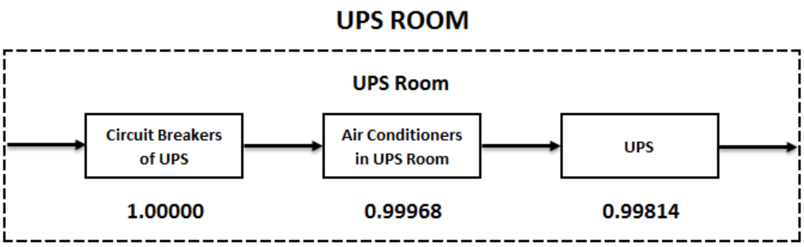


Figure 17: RBD of UPS Room

$$R = R1 \times R2 \times R3 \tag{26}$$

$$R = 1.00000 \times 0.99968 \times 0.99814 = 0.99782 \tag{27}$$

The UPS Room sub-system consists of three components which include circuit breakers, ACs in UPS room and the UPS itself. The components of this sub-system are also connected in series, so there is no redundancy. The overall reliability of UPS Room is 0.99782.

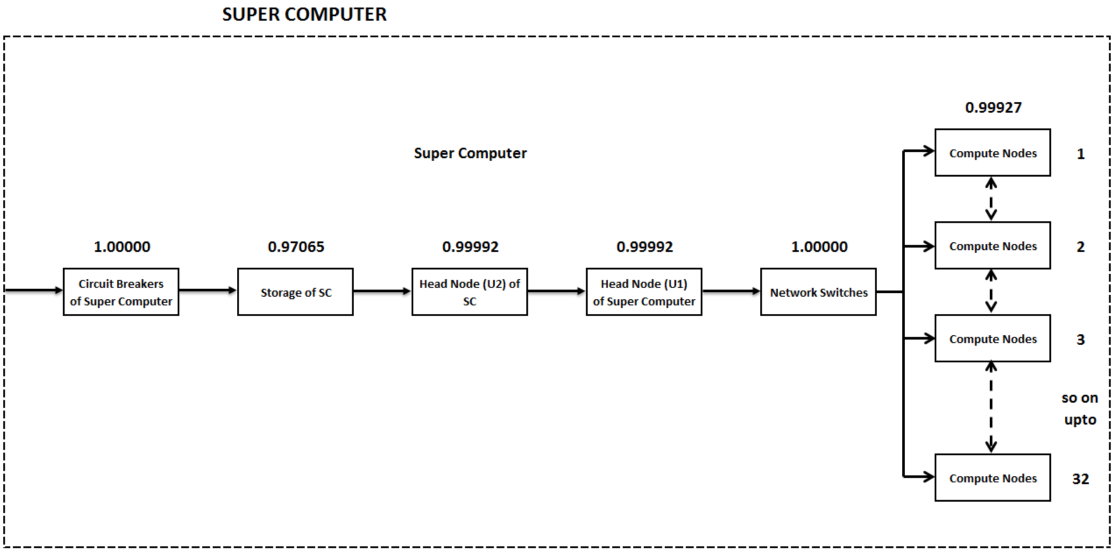


Figure 18: RBD of Supercomputer

$$R = R1 \times R2 \times R3 \times R4 \times R5\, X (1 - (1 - R6) \times (1 - R7) \times (1 - R8) \times (1 - R9) \times (1 - R10) \times \ldots\ldots (1 - R37)) \quad (28)$$

$$R = 1.00000 \times 0.97065 \times 0.99992 \times 0.99992 \times 1.00000 \times (1 - (1 - 0.99927) \times (1 - 0.99927) \times (1 - 0.99927) \times (1 - 0.99927) \times (1 - 0.99927) \times \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1 - 0.99927)) \quad (29)$$

$$R = 0.97733 \times (1 - 0.0235) \quad (30)$$

$$R = 0.97733 \times 0.97664 \quad (31)$$

$$R = 0.95450 \quad (32)$$

The Supercomputer sub-system has most of the components connected in series except the compute nodes which are connected in parallel. So, compute nodes have redundancy. Reliabilities of individual components and complete sub-system have been calculated as shown above. The overall reliability of supercomputer is 0.95450.

On the basis of RBDs of individual sub-systems, the RBD of complete system has been prepared. Additionally, reliabilities of individual sub-systems have been used to calculate the reliability of overall system.

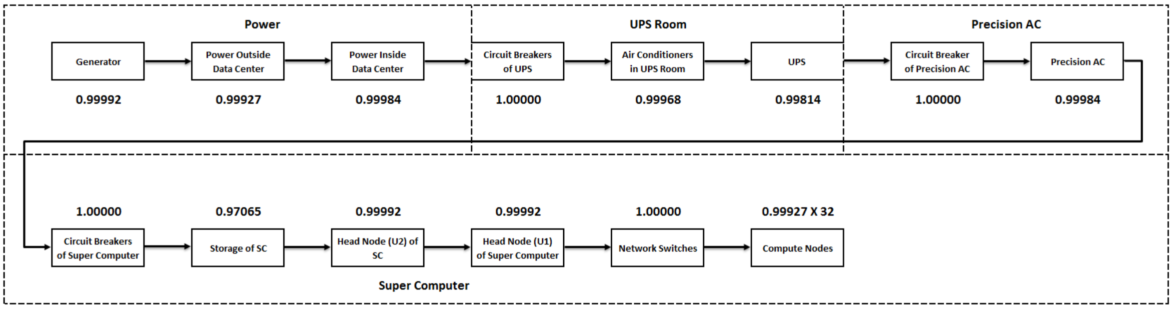


Figure 19: RBD of Complete Data Center

$$R = R(Power) \times R(UPS) \times R(Precision\ AC) \times R(Super\ Computer) \quad (33)$$

$$R = 0.99903 \times 0.99782 \times 0.99984 \times 0.95450 \quad (34)$$

$$R = 0.95160 \quad (35)$$

4.4.2 Results

RBD is a graphic method for depicting how component reliability contributes to the success or failure of a large system. Each block represents a component or part of the system with a failure rate. No component of RCMS data center has redundancy except the compute nodes. All components are connected in series. Only compute nodes work in parallel. Therefore, only RBD of Supercomputer has reliability in parallel. In case, components are connected in parallel, system will have alternate paths to remain in operation. Even if one path becomes unavailable due to a faulty component, system will be operable due to a parallel path. However, if components are connected in series, system will become inoperable if any component fails due to unavailability of alternate or redundant components. Data center must have critical components connected in parallel to provide redundancy in case of failure.

CHAPTER 5

Conclusions & Future Work

5.1. Conclusions and Recommendations

Following conclusions have been drawn:-

(a) Components of Data Center that have more Weightage/ Importance Value in House of Quality are more significant and critical. Therefore, they must be acquired earlier. Priority wise list of all components is available in Table 10.

(b) Downtime of Head Nodes is least and that of storage is greatest. It means that Head Nodes are the most stable and most available component of data center and SAN Storage is the most unavailable and most unstable component

(c) The availability of SAN Storage and software of supercomputer is least. The main reason behind unavailability of both these components is frequent shutdown and restart of data center. Hence, the practice of turning off data center at 9 PM must be stopped and it must be operated round the clock because with frequent shutting down wear and tear of machine increases.

(d) Failures having high severity and high occurrence rating should be addressed earlier and must be accorded priority because such failures have greater RPN and are more hazardous.

(e) In case, RPN reduces after recommended action is taken, it means that action was effective

(f) Failures having high RPN must be treated on priority

(g) RPN and occurrence rating significantly reduces if a recommended action is taken.

(h) No component of RCMS data center has redundancy except the compute nodes. All components are connected in series. Only compute nodes work in parallel. Therefore, only RBD of Supercomputer has reliability in parallel.

(i) In case, components are connected in parallel, system will have alternate paths to remain in operation. Even if one path becomes unavailable due to a faulty component, system will be operable due to a parallel path. However, if components are connected in series, system will become inoperable if any component fails due to unavailability of alternate or redundant components.

(j) Data center must have critical components connected in parallel to provide redundancy in case of failure.

5.2. Future Work

1. The RBDs of data center prepared in this research can be modified and diagrams for individual parts can be prepared to perform analysis in depth. A success tree can also be generated in case series paths are substituted with AND gates and parallel paths are substituted with OR gates.
2. Further analysis can be performed on the success tree using the De Morgan’s theorem. Success tree may be converted into fault tree and fault tree analysis can be performed.
3. “RC Tool” Software can be further enhanced to perform Failure Mode and Effect Analysis. It can be modified to predict failures and correlate type of failures with the potential causes of failures.

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Appendix A

"RC Tool" Software Documentation

The software "RC Tool" has been developed to assist users in calculation of different parameters related to reliability. Several software are available online. However, no software provides single interface to perform calculation of all parameters. Therefore, new software named "RC Tool" has been developed. First version of RC Tool i-e 1.0 can calculate the following parameters:-

(a) Mean Time Between Failures (MTBF)

(b) Mean Time to Repair (MTTR)

(c) Mean Time Between Maintenance (MTBM)

(d) Inherent Availability (A_I)

(e) Achieved Availability (A_A)

(f) Operational Availability (A_O)

(g) Failure Rate

(h) Repair Rate

(i) Reliability

The software takes following parameters as input:-

(a) Total Operational Time

(b) Total Uptime

(c) Total Downtime

(d) Number of Downtime Instances

The software takes input parameters and save them in the database. Then those input parameters are loaded from database into the software for calculation. The interface of software has been kept simple to facilitate users. Figure 32 shows the graphical user interface of software.

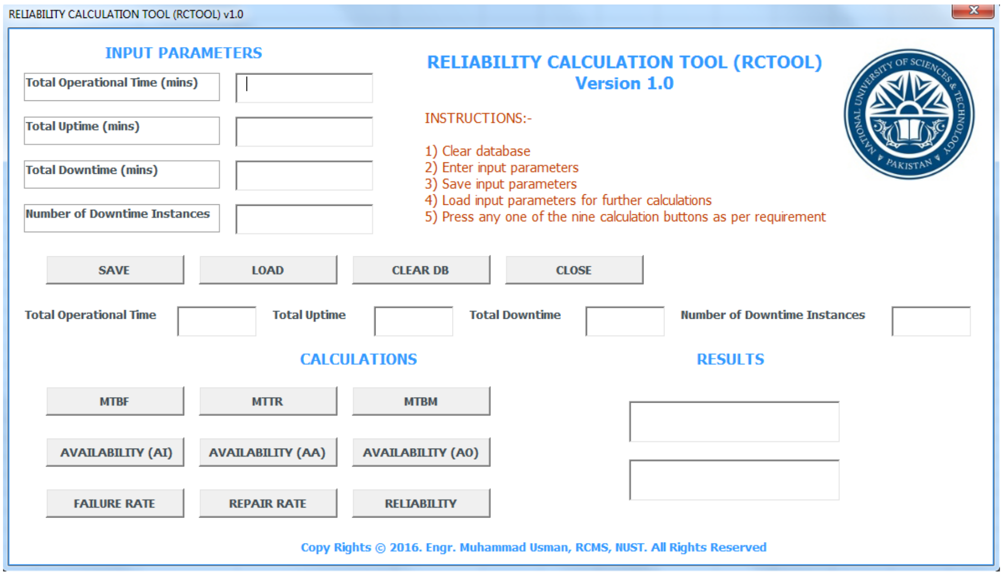

Figure 20: Graphical User Interface of "RC Tool"

A step-by-step procedure to calculate different parameters is given below:-

1. In first step, Total Operational Time, Total Uptime, Total Downtime and Number of Downtime Instances are entered in the software.

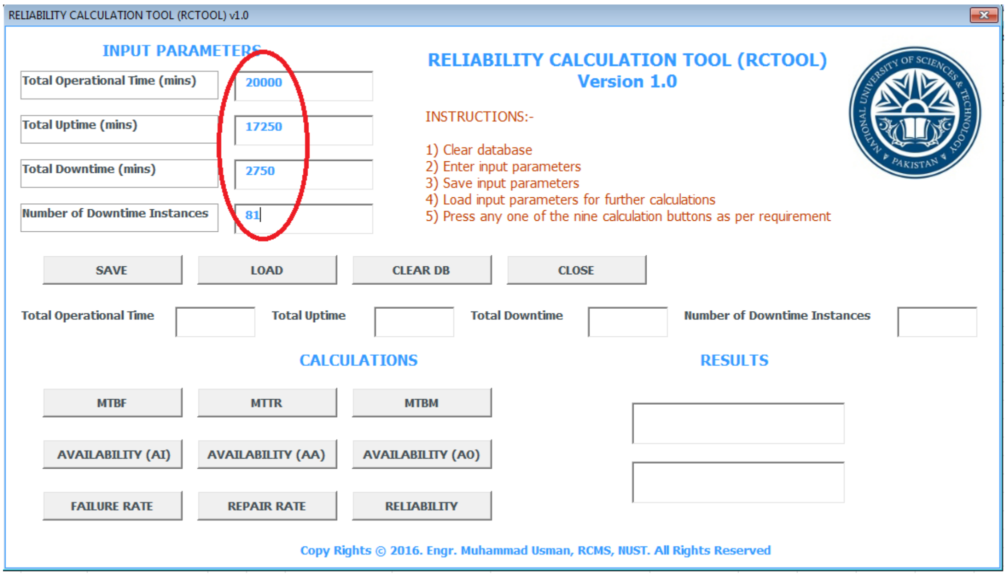

Figure 21: Enter Input Parameters in Software

2. Then the "save" button is pressed to save the input parameters in database

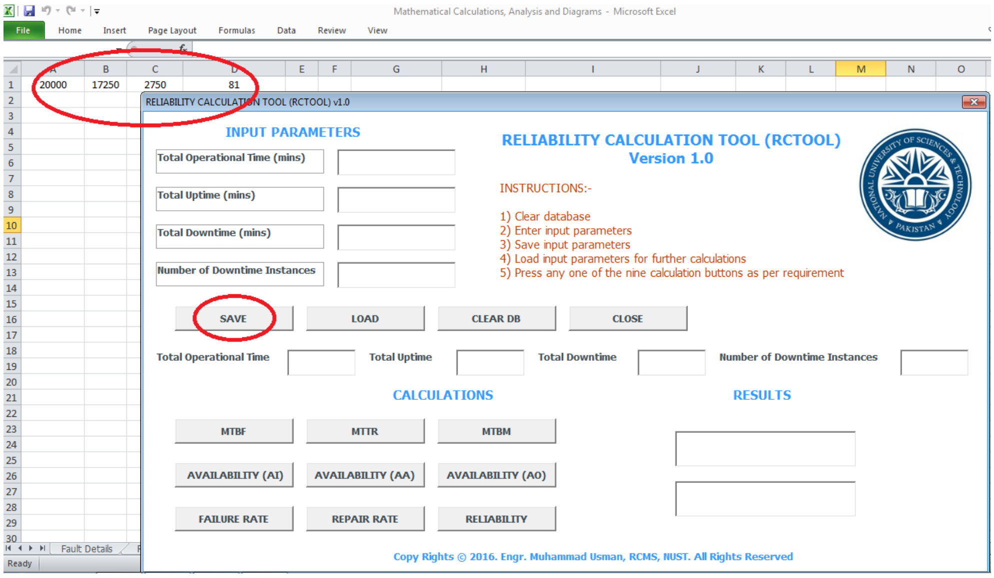

Figure 22: Save Input Parameters in Database

3. In next step input parameters are loaded into the software using the "Load" button

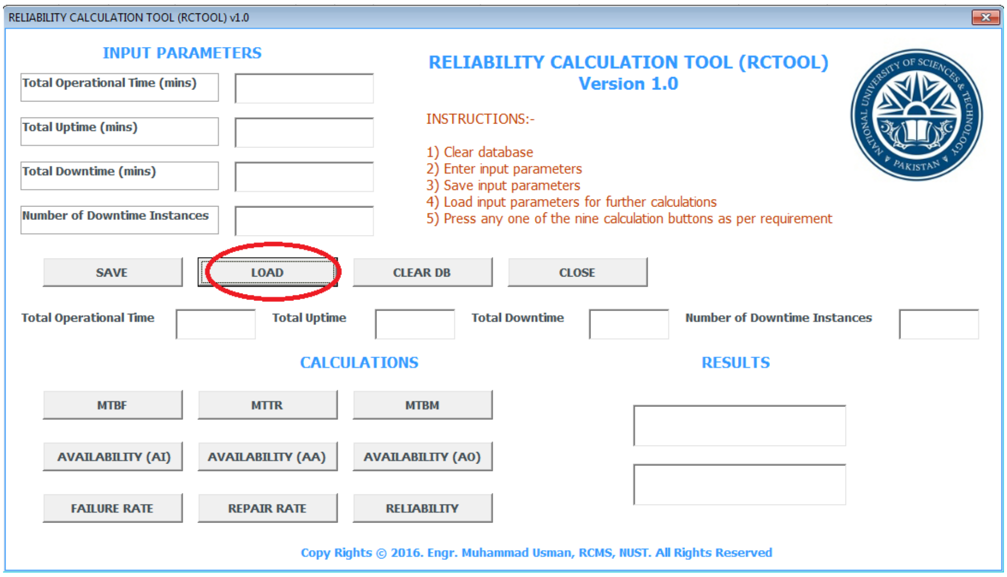

Figure 23: Load Input Parameters from Database

4. "ClearDB" button is used to clear the database and "close" button is used to close the Graphical User Interface of software

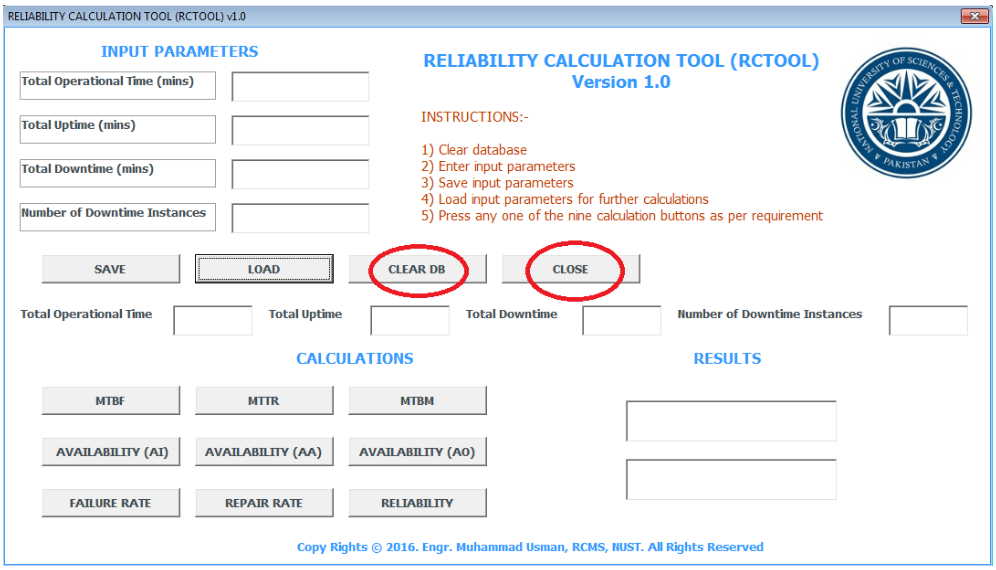

Figure 24: "Clear DB" and "Close" Buttons of Software

5. Once loaded into software, the input parameters will be displayed in software in designated fields

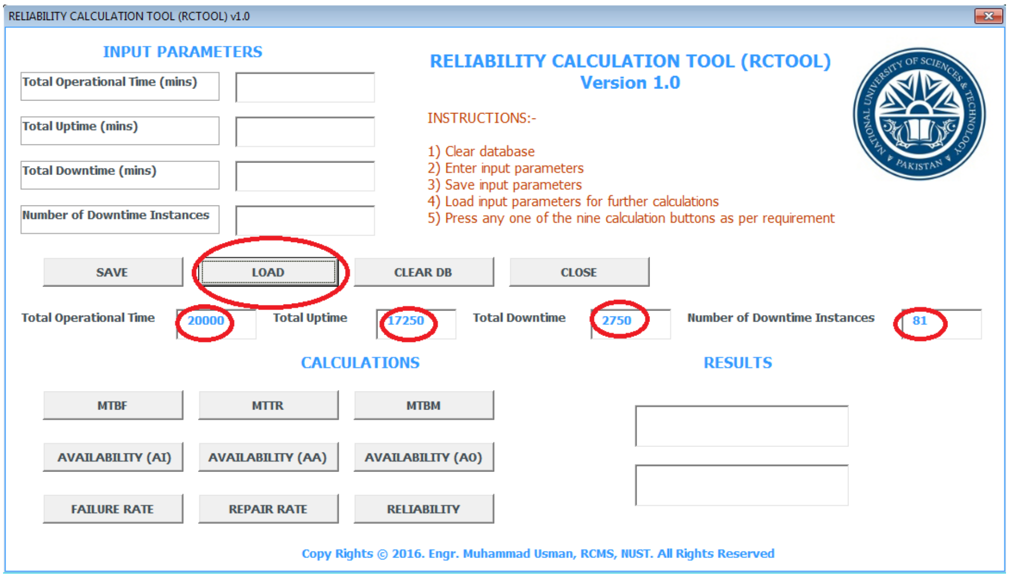

Figure 25: Input Parameters loaded in Software GUI

6. After loading the input parameters in software, following calculations can be performed one by one as per requirement:-

i. Mean Time Between Failures (MTBF)

ii. Mean Time to Repair (MTTR)

iii. Mean Time Between Maintenance (MTBM)

iv. Inherent Availability (A_I)

v. Achieved Availability (A_A)

vi. Operational Availability (A_O)

vii. Failure Rate

viii. Repair Rate

ix. Reliability

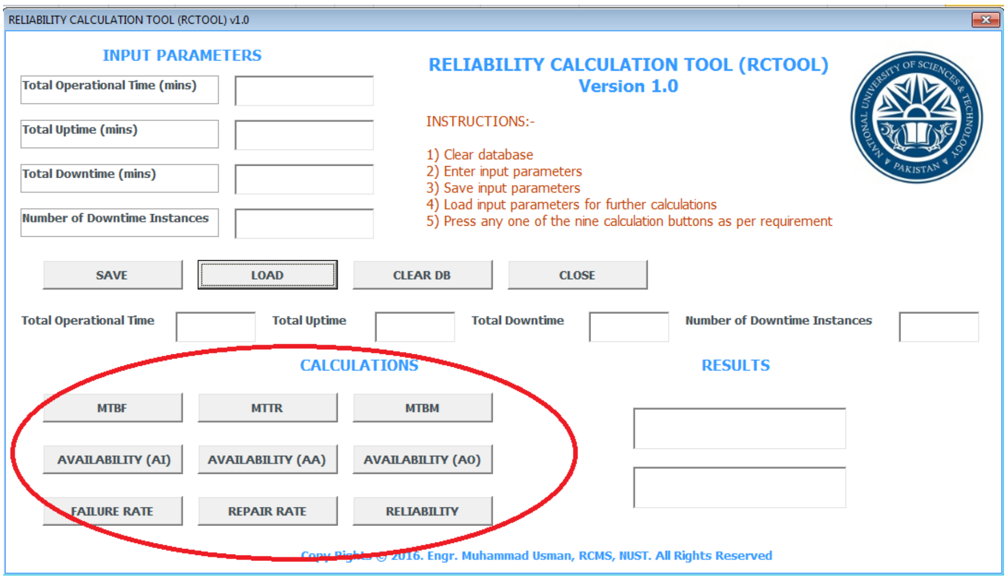

Figure 26: Calculations of different Parameters

7. Results of all calculations will be displayed in result fields.

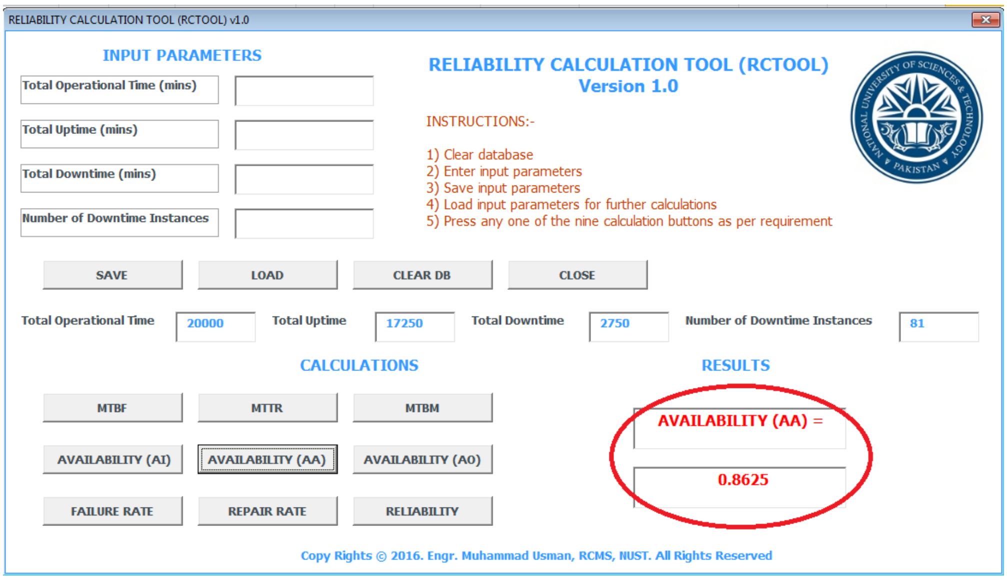

Figure 27: Results of Calculations Displayed in Result Fields

Appendix B

RC Tool Software Source Code

```
Private Sub CommandButton1_Click()
Dim iRow As Long
Dim ws As Worksheet
Set ws = Worksheets("RCTool")

'iRow = ws.Cells.Find(What:="", SearchOrder:=xlRows, _
    SearchDirection:=xlPrevious, LookIn:=xlValues).Row

iRow = ws.Cells(ws.Rows.Count, "A").End(xlUp).Row
If Trim(Me.TextBox1.Value) = "" Then
  Me.TextBox1.SetFocus
  MsgBox "Please enter Total Operational Time"
  Exit Sub

End If
With ws
  .Cells(iRow, 1).Value = Me.TextBox1.Value
  .Cells(iRow, 2).Value = Me.TextBox2.Value
  .Cells(iRow, 3).Value = Me.TextBox3.Value
  .Cells(iRow, 4).Value = Me.TextBox4.Value
```

```
End With
Me.TextBox1.Value = ""
Me.TextBox2.Value = ""
Me.TextBox3.Value = ""
Me.TextBox4.Value = ""
Me.TextBox1.SetFocus
End Sub

Private Sub CommandButton10_Click()
TextBox9.Value = "AVAILABILITY (AA) = "
TextBox10.Value = (CStr(CDbl(TextBox6.Value)) / CDbl(TextBox8.Value)) / ((CStr(CDbl(TextBox6.Value)) / CDbl(TextBox8.Value)) + (CStr(CDbl(TextBox7.Value)) / CDbl(TextBox8.Value)))
End Sub

Private Sub CommandButton11_Click()
TextBox9.Value = "AVAILABILITY (AO) = "
TextBox10.Value = CStr(CDbl(TextBox6.Value)) / CDbl(TextBox5.Value)
End Sub

Private Sub CommandButton13_Click()
TextBox9.Value = "FAILURE RATE = "
TextBox10.Value = 1 / (CStr(CDbl(TextBox5.Value) - CDbl(TextBox7.Value)) / CDbl(TextBox8.Value))
End Sub
```

```
Private Sub CommandButton14_Click()
TextBox9.Value = "REPAIR RATE = "
TextBox10.Value = 1 / (CStr(CDbl(TextBox7.Value)) / CDbl(TextBox8.Value))
End Sub

Private Sub CommandButton15_Click()
TextBox9.Value = "RELIABILITY = "
TextBox10.Value = Exp(-((1 / (CStr(CDbl(TextBox5.Value) - CDbl(TextBox7.Value)) /
CDbl(TextBox8.Value))) * CDbl(TextBox5.Value)))
End Sub

Private Sub CommandButton2_Click()
  Unload Me
End Sub


Private Sub CommandButton3_Click()
readdata
End Sub

Private Sub CommandButton4_Click()
Sheets("RCTool").Cells.ClearContents
End Sub


Private Sub CommandButton5_Click()
```

```
TextBox9.Value = "MTBF = "
TextBox10.Value = CStr(CDbl(TextBox5.Value) - CDbl(TextBox7.Value)) / CDbl(TextBox8.Value)
End Sub

Private Sub CommandButton6_Click()
TextBox9.Value = "MTTR = "
TextBox10.Value = CStr(CDbl(TextBox7.Value)) / CDbl(TextBox8.Value)
End Sub

Private Sub CommandButton7_Click()
TextBox9.Value = "MTBM = "
TextBox10.Value = CStr(CDbl(TextBox6.Value)) / CDbl(TextBox8.Value)
End Sub

Private Sub CommandButton9_Click()
TextBox9.Value = "AVAILABILITY(AI) = "
TextBox10.Value = (CStr(CDbl(TextBox5.Value) - CDbl(TextBox7.Value)) / CDbl(TextBox8.Value)) / ((CStr(CDbl(TextBox5.Value) - CDbl(TextBox7.Value)) / CDbl(TextBox8.Value)) + CStr(CDbl(TextBox7.Value)) / CDbl(TextBox8.Value))
End Sub

Private Sub Label1_Click()
End Sub

Private Sub Label13_Click()
```

```
End Sub


Private Sub UserForm_QueryClose(Cancel As Integer, CloseMode As Integer)
  If CloseMode = vbFormControlMenu Then
    Cancel = True
    MsgBox "Please use the CLOSE button!"
  End If
End Sub


Private Sub readdata()
Dim columnA As Integer
Dim columnB As Integer
Dim columnC As Integer
Dim columnD As Integer


columnA = 1
columnB = 2
columnC = 3
columnD = 4


Dim optime As String
Dim uptime As String
Dim downtime As String
Dim instances As String
rowcounter = rowcounter + 1
```

```
optime = Sheets("RCTool").Cells(rowcounter, columnA).Value
If optime = "" Then
rowcounter = 1
End If

optime = Sheets("RCTool").Cells(rowcounter, columnA).Value
uptime = Sheets("RCTool").Cells(rowcounter, columnB).Value
downtime = Sheets("RCTool").Cells(rowcounter, columnC).Value
instances = Sheets("RCTool").Cells(rowcounter, columnD).Value

TextBox5.Value = optime
TextBox6.Value = uptime
TextBox7.Value = downtime
TextBox8.Value = instances
End Sub
```