A RELIABLE AND COST-EFFECTIVE MODEL TO ENHANCE THE ROBUSTNESS OF A GEOSTATIONARY SATELLITE CONTROL EARTH STATION SYSTEM

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science in Engineering

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ABSTRACT

A ground network of communications satellite system is typically made up of Earth Station(s), Mission Operations Center (MOC), Science Operations Center (SOC), and the supporting infrastructure that connects them all. A ground network grows as more Earth Stations are added, which requires additional considerations to ensure that the MOC can communicate with all the Earth Stations in the network. It also requires continuous upgrade to provide a better reliability for a better performance. The improvements of the reliability of a Geostationary satellite control Earth Station system can be accomplished via redundancies of the subsystems, multiple testing in the planning stage and selection of only the best components for its subsystems. Suitable maintenance activities from time to time also play an important role to prevent the cost blow out and any unwanted failures. Hence, the development of a new reliability model based on identified factors that caused calamity to the system was the main objective of this research. In addition, this research also aims to develop an operational cost model along with the suitable maintenance activities to enhance the robustness of the geostationary satellite control Earth Station system. The models were designed by applying Monte Carlo from MATLAB software. The reliability and cost data that were used for simulations was obtained from MEASAT. Based on the previous studies, configurations with more redundancies in the subsystem can affect the reliability performance, which can decrease the failure rate. At the end of this research, a new reliability model of an Earth Station system which was compared against 2-parallel, 3-parallel, and 4-parallel configurations within the range of affordability (operational cost model) along with the suitable maintenance activities were proposed to enhance the robustness of the geostationary satellite control Earth Station system. The three elements consisting of the reliability model, suitable maintenance activities as well as the operational cost model were integrated together creating a sustainable framework. The obtained results showed that an Earth Station that was configured with the 2-parallel configuration provided the cheapest and optimum reliability system performance even though the 3-parallel and the 4-parallel configurations provided higher reliability. Consequently, the sustainable framework encompassing reliability and cost elements were modelled based on the 2-parallel configuration together with the proposed maintenance activities. Furthermore, root mean square (RMS) values were also calculated for both the reliability and the operational cost models. The results demonstrated that the calculated RMS values for both new reliability and new operational cost models produced the smallest values of 20.84% and 22.82% respectively. Therefore, the calculated RMS values for both reliability and operational cost models showed that the 2-parallel configuration fit to be applied in the Earth Station system design which contributes to the system design with acceptable reliability and most affordable cost.

ملخص البحث

تتكون الشبكة الأرضية لنظام الاتصالات عبر الأقمار الصناعية عادةً من محطة أو محطات أرضية، ومركز ، والبنية التحتية الداعمة التي تربطهم (SOC) ، ومركز العمليات العلمية(MOC) عمليات المهام جميعاً. وتؤدي إضافة المزيد من المحطات الأرضية إلى توسع الشبكة الأرضية، ممّا يتطلب اعتبارات إضافية لضمان إمكانية اتصال مركز عمليات المهام بجميع المحطات الأرضية في الشبكة. كما يتطلب ذلك ترقية مستمرة لتوفير موثوقية أفضل للحصول على أداء أفضل. ويمكن تحسين موثوقية نظام المحطة الأرضية للتحكم في الأقمار الصناعية ثابتة الموقع من خلال إضافة أنظمة فرعية جديدة، وكذلك من خلال الاختبارات المتعددة في مرحلة التخطيط، واختيار أفضل المكونات فقط لأنظمتها الفرعية. كما أنّ أنشطة الصيانة المناسبة من وقت لآخر تلعب دوراً مهماً في منع المغالاة في التكلفة وأي إخفاقات غير مرغوب فيها. ومن ثم، فإن الهدف الرئيسي لهذا البحث هو تطوير نموذج موثوقية جديد يعتمد على العوامل المحددة التي قد تسبب كارثة للنظام. إضافة إلى ذلك، يهدف هذا البحث إلى تطوير نموذج تكلفة تشغيلية جنباً إلى جنب مع أنشطة الصيانة المناسبة لتعزيز متانة نظام المحطة الأرضية للتحكم بالأقمار الصناعية ثابتة الموقع. وقد صمّمت النماذج باستخدام نظام المحاكاة في برنامج (Monte Carlo) كما تم الحصول على بيانات الموثوقية والتكلفة المستخدمة في عمليات المحاكاة .(MATLAB) واستناداً إلى الدراسات السابقة، يمكن أن تؤثر التشكيلات .(MEASAT) من القمر الصناعي التي تحتوي على المزيد من الأنظمة الفرعية على أداء الموثوقية، مما قد يقلل من معدل الفشل. وفي نهاية هذا البحث، تم اقتراح نموذج موثوقية جديد لنظام محطة أرضية تمت مقارنته مع تشكيلات محطات أرضية متوازية ثنائية وثلاثية ورباعية، ضمن نطاق القدرة على تحمل التكاليف (نموذج التكلفة التشغيلية) جنباً إلى جنب مع أنشطة الصيانة المناسبة، بهدف تعزيز متانة نظام المحطة الأرضية للتحكم بالأقمار الصناعية ثابتة الموقع. وقد تم دمج العناصر الثلاثة المكونة من نموذج الموثوقية وأنشطة الصيانة المناسبة بالإضافة

إلى نموذج التكلفة التشغيلية، تم دمجها معاً لإنشاء إطار عمل مستدام. وقد أظهرت النتائج التي تم الحصول عليها أن المحطة الأرضية التي تم تكوينها بالتشكيل المتوازي الثنائي قدمت أداء نظام الموثوقية الأرخص والأمثل على الرغم من أن التشكيلات المتوازية الثلاثية والرباعية أظهرت موثوقية أعلى. وبالتالي، فقد تم تصميم إطار العمل المستدام الذي يشتمل على عناصر الموثوقية والتكلفة بناءً على التشكيل المتوازي الثنائي جنباً إلى جنب مع أنشطة الصيانة المقترحة. علاوة على ذلك، تم حساب قيم جذر متوسط التربيع (**RMS**) لكل من نماذج الموثوقية والتكلفة التشغيلية. وقد أظهرت النتائج أن قيم (**RMS**) المحسوبة لكل من الموثوقية الجديدة ونماذج التكلفة التشغيلية الجديدة أنتجت أصغر قيم **20.84**٪ و المحسوبة لكل من نماذج الموثوقية والتكلفة (**RMS**) **22.82**٪ على التوالي. لذلك، أظهرت قيم التشغيلية أن التشكيل المتوازي الثنائي مناسب ليتم تطبيقه في تصميم نظام المحطة الأرضية، ممّا يساهم في تصميم النظام بموثوقية مقبولة وبتكلفة معقولة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Communication Engineering)

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DECLARATION

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This thesis is dedicated to my dearest parents and friends for laying the foundation of what I turned out to be in life.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACU	Antenna Control Unit
ATL	Acquisition, Technology & Logistic
CAT	Category
COGS	Costs Of Goods Sold
CPU	Central Processing Unit
CW	Clean Wave
DC	Down-Converter
DOD	Department Of Defence
DSS	Dynamic Satellite Simulator
DTH	Direct-To-Home
EHF	Extremely High Frequency
HLA	High Level of Architecture
HPA	High Power Amplifier
INCOSE	The International Council on Systems Engineering
LCC	Life Cycle Cost
LNA	Low Noise Amplifier
M&C	Monitor And Control
MATLAB	Matrix Laboratory
MEASAT	Malaysia East Asia Satellite
MLE	Maximum Likelihood Estimation
MOC	Mission Operations Center
MoEs	Measures Of Effectiveness
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
OAS	Orbital Analysis Station
PBCM	Performance-Based Cost Modelling

RAM	Reliability, Availability and Maintainability
RF	Radio Frequency
RMS	Root Mean Square
SAC	Equipment Status and Control Station
SCS	Satellite Control Station
SES	Satellite Engineering Station
SG&A	Selling, General, And Administrative
SLA	Service Level Agreements
SMSP	Single-Satellite Multiple-Ground Station Scheduling Problem
SOC	Science Operations Center
SOI	System Of Interest
SOS	System Of Systems
SPN	Stochastic Petri Net
TOC	Total Ownership Cost
TTC	Telemetry, Tracking, And Control
TTF	Time To Failure
TTR	Time To Repair
TVRO	Television Receiver Only
UC	Up-Converter
VSAT	Very Small Aperture Terminal

LIST OF SYMBOLS

R	Reliability
λ	Failure Rate (per hour, h)
M	MTBF (hour, h)
C_M	Maintenance Costs (RM)
C_F	Failure Costs (RM)
P_F	Probability of Failure
ε_f	Percentage Fractional Errors (%)

LIST OF PUBLICATIONS

Scopus Indexed Journal

Nur Shazana Abdul Rahman & Nadirah Abdul Rahim (2023). *Sustainable Framework for A Geostationary Satellite Control Earth Station System Using Parallel Configuration*. International Journal of Electrical Engineering and Informatics (IJEEI), 30(3), pp. 1498-1508. ISSN 2502-4752.

Nadirah Abdul Rahim, Nur Shazana Abdul Rahman, Shiva Abdoli, Subramaniam Jeevan Rao, Mohammed Imtiaz Mohamad Mokhtar (2022). *Analysis of Failure Frequency and Failure Rate of RF/ Antenna Subsystems for an Earth Station System*. NeuroQuantology, 20(10)., pp 3862-3871. ISSN 1303-5150.

Conference Paper

Nur Shazana Abdul Rahman & Nadirah Abdul Rahim (2022). *Analysis of Reliability Prediction and Maintainability Activities of an Earth Station System using Parallel Configurations. 12th International Workshop on Computer Science and Engineering (WCSE 2022)*, 24th – 28th June 2022, Sanya, China.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Over time, communications satellite has been widely used in television, telephone, and internet applications, accommodating over billions of users across the globe. The satellite acquires uplink signal from a transmitting Earth Station which then re-transmits the amplified signal back to at least one Earth Station (Pelton et al., 2013). However, failures that lead to system abnormalities and breakdowns are to be expected. The improvements of the reliability of Earth Station system can be accomplished via redundancies of the subsystems, multiple testing in the planning stage and the selection of only the best components for its subsystems (Bouwmeester et al., 2022).

Suitable maintenance activities of an Earth Station from time to time also play an important role to prevent any unwanted failures. Therefore, in this research, analysis of the Earth Station system reliability is proposed using Monte Carlo simulations from MATLAB software. The parallel configurations which indicate the *n*-redundancies respectively in the Earth Station system are applied to analyse the Earth Station system reliability. In this research, 2-parallel, 3-parallel, and 4-parallel configurations are analysed accordingly. Suitable maintenance activities were proposed based on the suitability of the Earth Station system. The results attained would then show the pattern of reliability between 2-parallel, 3-parallel, and 4-parallel configurations. On top of that, the obtained results are expected to show that the simulation of a configuration with more redundancies in the subsystem can increase the reliability performance, thus lowering the failure rate.

Nonetheless, will the cost increase if redundancies increase? How can we attain the balance between the technical (reliability and operational) and cost? In addition to ensure optimum operational cost allocation, suitable maintenance activities in the Earth Station must be performed once the satellite is launched.

Hence, a new design of a sustainable framework that consists of a reliability model within the range of an affordable operational cost model along with the maintainability framework are proposed to enhance the robustness of a geostationary satellite control Earth Station system. The framework is ought to be capable to sustain the Earth Station system operating at its optimum.

1.2 PROBLEM STATEMENT

Each subsystem in the Earth Station system has its own failure rate. The failure rate is very important to indicate whether the subsystem works or fails throughout the designated mission. Therefore, the question of the reliability and maintainability of the system come into picture. How reliable is the Earth Station system and how is it maintained? The answer to this question is that the design for reliability in the Earth Station system is very crucial because it makes sure that the system runs smoothly without any disruptions. If the system fails, the suitable maintenance activities must be performed to confirm that the system is up and running steadily.

In essence, a typical Earth Station is categorised into three core systems: computer control, baseband and RF/antenna (Ebadi, 2017). Based on the data retrieved from Malaysia East Asia Satellite (MEASAT) Satellite, it can be summarised that failure occurs in the RF subsystems which consist of antenna, uplink and downlink transmit chains. Thus, the design of Earth Station system reliability is crucial in ensuring that the operation service runs smoothly. This could be possible with higher redundancies involved in the system.

Apart from that, most existing reliability models designed by (Bouwmeester et al., 2022) and (Sugama, 2018), are too complex to understand. Hence, in this research, a simple but robust reliability model and suitable maintenance framework are proposed. Additionally, this research is also focused on the operational cost model which informs the system design expert whether the reliability model and the maintenance framework developed are worth to be spent or not.

1.3 HYPOTHESIS

It is hypothesized that by developing a simple but robust reliability model incorporating the failure rate of each subsystem in the Earth Station with a suitable maintenance framework, the breakdown of the Earth Station system can be avoided. Consequently, it also helps in optimising the cost allocation. Hence, these three elements (reliability, maintainability, and operational cost) constitute the sustainable framework which is proposed in this research.

1.4 RESEARCH OBJECTIVES

This research is focused on the Earth Station system configurations: 2-parallel, 3-parallel, and 4-parallel indicate the *n*-redundancies respectively. Hence, the objectives of this research are:

i. To identify the factors that contribute to the problems of Earth Station system failures that can cause cost blow up.
ii. To develop a simple but robust reliability model of the Earth Station system based on which parallel configuration gives the highest reliability.
iii. To propose preventive maintenance activities for Earth Station system.
iv. To develop a suitable operational cost model which helps in setting an optimum cost allocation specifically in maintaining the Earth station system.

1.5 RESEARCH SCOPES AND RESEARCH DATA

This research focuses on the development of a reliability model of a geostationary satellite control Earth Station system focusing on RF and antenna subsystems through MATLAB simulation by using the Monte Carlo generator. Furthermore, only the parallel configurations (2, 3 and 4) are included in the analysis of the reliability to develop a reliability model and the maintenance framework are proposed based on the development of the cost model. In terms of cost modelling, only operational cost is included. The operational cost consists of both operation and maintenance costs which was provided by MEASAT, but the exact amounts were concealed.

1.6 THESIS ORGANIZATION

This thesis is divided into five chapters. Chapter One elaborates on the introduction of the sustainable framework. Furthermore, it also discusses the problem statement, hypothesis, research objectives and research scopes and research data. Chapter Two describes the literature review of the geostationary satellite control Earth Station System and its related topics. Chapter Three explains the research methodology and how the research was conducted in detail. Meanwhile, Chapter Four demonstrates the results, modelling, and discussion. Finally, this thesis is concluded in Chapter Five in which it elaborates on the research contribution and future work that can be carried out to improve the existing research.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

A satellite communication system is divided into two stations – Earth Station system and Space Station system. The Earth Station system is also known as a ground station system, consists of tracking, telemetry, and command system (Pratt & Allnutt, 2019). Whereas the Space Station solely consists of the satellites. The Earth Station system is mostly connected by a terrestrial network to the end-user terminal. Similarly, small stations known as Very Small Aperture Terminal (VSAT) are directly connected to the end-user's terminal (Maassen et al., 2017). Stations are categorised by their various size which depending on its traffic volume and type of traffic to be transported on the satellite link. One of its many applications includes Direct-to-Home satellite broadcasting or DTH for short (Rahim et al., 2022). The application functions as the widespread distribution of television signals from geostationary satellites to its many receivers like small dish antennas across the globe (Gandla, 2013).

Although, certain stations can be both transmitter and receiver, there are a few that act as a receiver only or also known as TVRO (television receiver only) stations (Maral et al., 2020). The stations receive downlink signal for a broadcasting satellite system which is a system that distributes data or television signals. Figure 2.1 shows the typical architecture of an Earth Station for both transmitting and receiving, which consists of the user, terrestrial system, Earth Station, and the satellite.

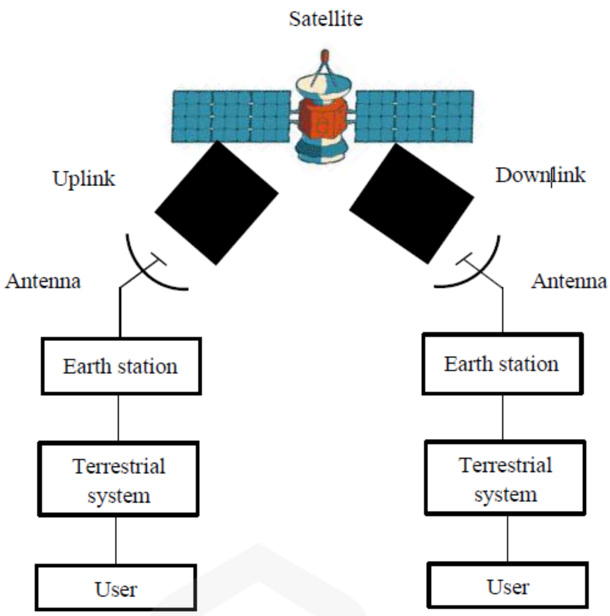

Figure 2.1 Satellite control Earth Station system general block diagram (Pelton et al., 2013).

2.2 EARTH STATION FAILURES

To form a stable satellite communication system, the whole subsystems need to be designed carefully so that they can function together. There are thousands of components in the subsystems which need to be looked after carefully, and to repair the satellite after it is launched to the orbit is quite impossible (Kuzu et al., 2012). Therefore, a reliable Earth Station system needs to be designed carefully by including all the necessary subsystems.

Ka and EHF frequency bands application also helps in developing better Earth Station system in the future. However, the rain attenuation of these bands is bad especially in a tropical country like Malaysia (Rafiqul et al., 2016). The only way to decrease such effect is by using diversity-based technique. Although, a failure prediction method is crucial for the site diversity, most of its existing configurations are based on the data collected at the site locations (Thiennviboon & Luengkhwan, 2018).

On top of that, the statistics retrieved from geostationary satellite control Earth Station system concluded that failure mostly occurred in the RF subsystems which consist of antenna, uplink and downlink transmit chains (MEASAT, 2021). Thus, the design of an Earth Station system reliability is crucial in ensuring that the operation service runs smoothly (Abdul Rahman & Abdul Rahim, 2022). This could be possible with higher redundancies involved in the system.

2.3 BASIC EARTH STATION SYSTEM MODEL

Figure 2.2 represents the basic Earth Station system model which is divided into several core systems: computer control, baseband, and RF/antenna. The computer control system provides the primary interface between the satellite control personnel and the satellite (Ebadi, 2017). The subsystem is made up of the following core components:

i. Satellite Control Station (SCS)
ii. Satellite Engineering Station (SES)
iii. Orbital Analysis Station (OAS)
iv. Dynamic Satellite Simulator (DSS) Station
v. Equipment Status and Control Station (SAC)

The system is responsible for processing satellite telemetry in near real-time which includes processing, displaying, and archiving telemetry streams from the satellite simultaneously. In preventing the loss of data, the system is also connected to real-time and storage servers. The real-time server simultaneously processes telemetry from the satellite and provides services for the SES workstations, OAS workstations, and SAC workstations. The computer control system also receives and displays all equipment status via the SAC workstation which has control over switches (Ebadi, 2017).

The Integrated Telemetry Command and Ranging Unit is a key part of the baseband system of an Earth Station system. It performs various functions such as telemetry processing, satellite commanding, satellite ranging, and simulation and testing. As highlighted in red dots in Figure 2.2, the RF/antenna system is prone to most failures consisting of antenna, uplink and downlink transmit chains (MEASAT, 2021).

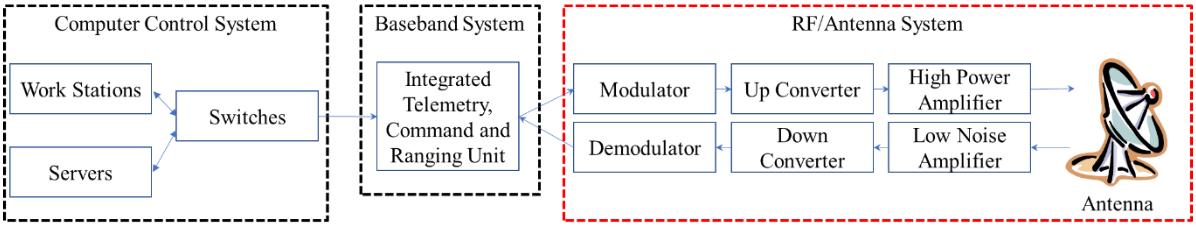

Figure 2.2 Basic satellite Earth station system. (Ebadi, 2017)

The antenna transmits signal to and receives telemetry from a satellite in a designated frequency bandwidth. The uplink transmit chain consists of subsystems such as Modulator, Up- Converter, and High-Power Amplifier whereas the downlink transmit chain includes subsystems such as Low Noise Amplifier, Down Converter, and Demodulator (Ebadi, 2017). The function of each subsystem in the RF/antenna system is explained in Table 2.1.

Table 2.1: Subsystems in RF/antenna system and its functions (Techopedia, 2022).

	Subsystem	**Function**
Transmitter	Modulator	Modulates information in the signal into an intermediate
	Up Converter	Converts the carrier into the radio frequency (RF) signals
	High Power Amplifier	Amplifies the modulated RF signals to the required power at the input terminals
Receiver	Low Noise Amplifier	Amplifies the received RF signals
	Down Converter	Converts the RF to IF signals
	Demodulator	The receive IF signals are extracted, decoded, and decrypted

Table 2.1 depicts the list of each subsystem and its function in an Earth Station system model. In essence, an Earth Station system model is designed with a simple configuration. Each subsystem mentioned above takes part for the uplink and downlink process, which is why in the system there are two Modulators, Up Converters and Power Amplifier for the transmission part, and there are two Low Noise Amplifier, Down Converter, Demodulator and for the receiving part (Nadirah; Abdul Rahim & Nordin, 2020). In total, 12 subsystems are included in RF/antenna system for the complete signal processing.

2.3.1 Parallel Networks

A parallel network is one in which several identical components are used simultaneously, and the failure of all components is required to bring the entire system down (Blanchard & Fabrycky, 2011). Fig. 2.3 illustrates a parallel network with two components. Assuming *A* and *B* are identical, the system will work if either *A* or *B*, or both are operational. The reliability is defined as in Equation 2.1, where R is the total reliability value, R_A is the reliability value of component A and R_B is the reliability value of component B (Crowe, D., & Feinberg, 2017).

$$R = R_A + R_B - (R_A)(R_B) \tag{2.1}$$

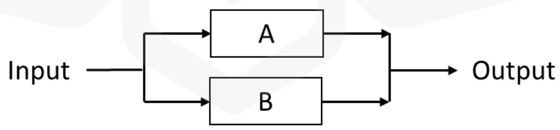

Figure 2.3 A 2-parallel configured network. (Blanchard & Fabrycky, 2011)

Next, consider a network with three parallel components as seen in Fig. 2.4, whereby the network reliability is expressed as in Equation 2.2, where R is the total reliability value, R_A is the reliability value of component A, R_B is the reliability value of component B and R_C is the reliability value of component C (Crowe, D., & Feinberg, 2017).

$$R = 1 - (1 - R_A)(1 - R_B)(1 - R_C) \tag{2.2}$$

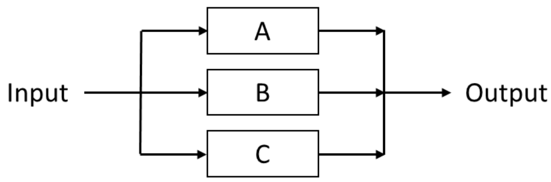

Figure 2.4 A 3-parallel configured network. (Blanchard & Fabrycky, 2011)

If components *A*–*C* are identical for a system with three parallel components, the reliability expression may be simplified as in Equation 2.2, where R is the total reliability value (Crowe, D., & Feinberg, 2017).

$$R = 1 - (1 - R)^3 \quad (2.3)$$

Therefore, the reliability given for a system with n identical parts is expressed in Equation 2.4, where R is the total reliability value and n is the number of identical parallel network components (Crowe, D., & Feinberg, 2017).

$$R = 1 - (1 - R)^n \quad (2.4)$$

2.3.2 Redundancy in Design

The *n*-parallel RF/antenna system design is highlighted in this research. To assess reliability performance and propose suitable maintenance activities for each subsystem in the specified configurations, 2-parallel, 3-parallel, and 4-parallel configurations have been selected. Therefore, the quality metrics of performance represent what service the system can provide (Hoque et al., 2015). These metrics may be utilised to determine performance standards that are within reach, such as workload completion and its success rate.

The *n*-parallel configurations are illustrated in Figure 2.5 which is highlighted in red line and the n is denoted as the number of redundancies. In the 2-parallel configuration, each station has two redundant units, whereas in the 3-parallel configuration, each station has three redundant units and four redundant units in the 4-parallel configuration. Compared to the 3-parallel and 4-parallel configurations, the 2-parallel configuration costs less but has a greater failure rate. Hence, they are selected with the objective of delivering a sensible value of reliability which can reduce the rate of system failure and low-cost consumption. The mean-time-between-failures (MTBF) of the system is also evaluated; the greater the MTBF value, the greater the potential increase in system reliability (Nadirah; Abdul Rahim & Nordin, 2020).

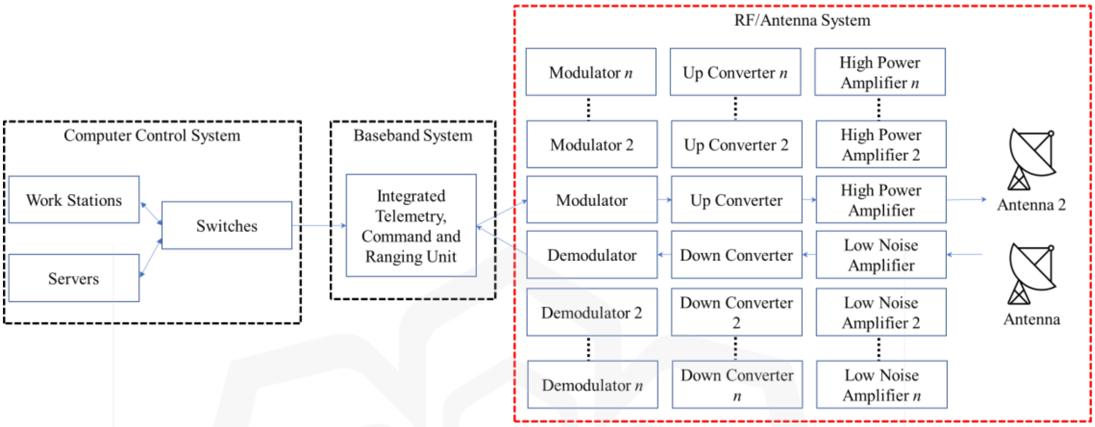

Figure 2.5 *n*-Parallel Earth Station system model.

2.3.3 Parallel Structures for Repairable Parts in The Earth Station

This research focuses on *n*-parallel configurations of the RF/antenna system. Therefore, the 2-parallel, 3-parallel, and 4-parallel configurations are chosen to observe the reliability performance and maintenance of each subsystem in the said configurations is proposed.

Figures 2.6, 2.7 and 2.8 illustrate the 2-parallel, 3-parallel, and 4-parallel configurations (which are highlighted in red dots) respectively. Practically, having one working satellite-dish antenna and another as a backup is the most ideal as it consumes high cost and large physical space. The 2-parallel configuration has two redundant unit in each of its stations, while the 3-parallel configuration has three redundant units in each of its stations, whereas the 4-parallel configuration has four redundant units in each of its stations. The 2-parallel configuration requires a cheaper cost, but the risk for it to experience a failure is higher than the 3-parallel configuration. However, the 3-parallel configuration has a higher reliability system whereas, the 4-parallel configuration has the highest reliability system if compared to the two previous parallel configurations. Hence, they are chosen because of the intention of generating high reliability which results to a very minimal system failure. The mean-time-between failures (MTBF) of the system is also taken into consideration whereby, the higher the MTBF is, the higher the system reliability can then be obtained (Nadirah; Abdul Rahim & Nordin, 2020). But how about the operational cost model for these three parallel configurations? The answer for this question is shown in Chapter 4 in Results and Discussion.

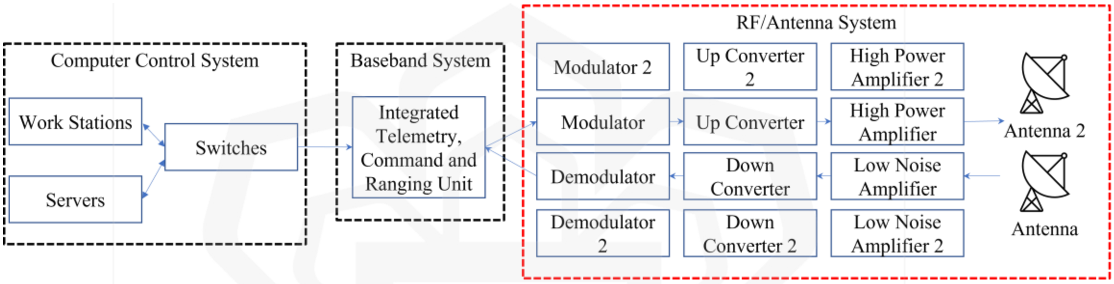

Figure 2.6 2-Parallel Earth Station System Model.

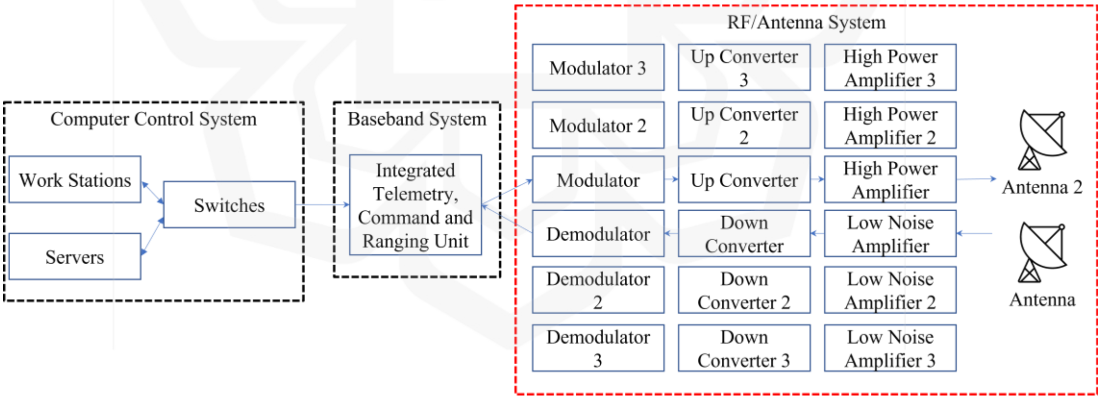

Figure 2.7 3-Parallel Earth Station System Model.

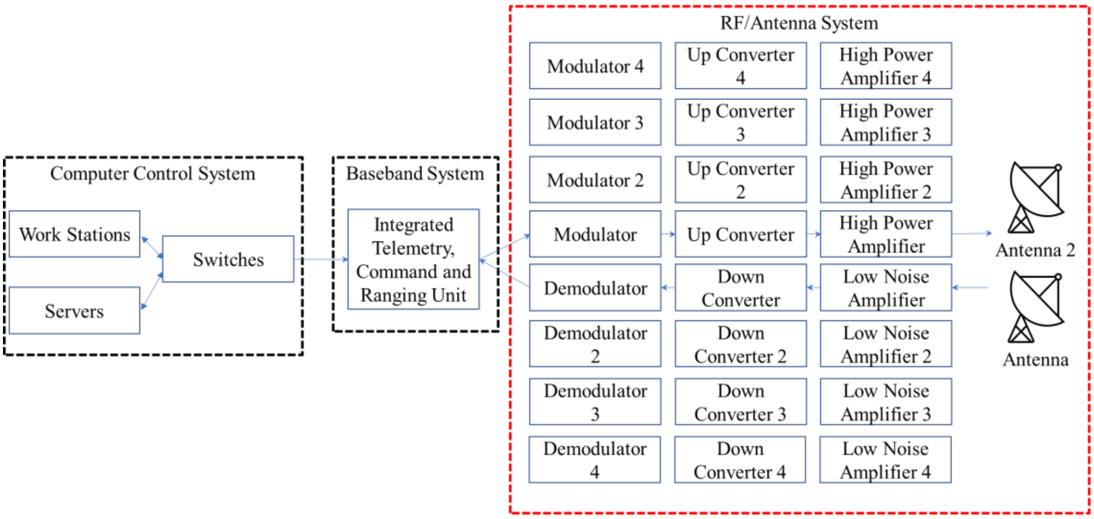

Figure 2.8 4-Parallel Earth Station System Model.

2.3 MONTE CARLO SIMULATION

The transition state probabilities, meantime to failure (MTTF), reliability, availability, cost effectiveness and sensitivity analysis are obtained by utilizing Markov process theory and Laplace transformations (Cai et al., 2021). It is evidential that the key to Earth Station system reliability analysis is the reliability model. Nonetheless, there are other various modelling techniques in determining the system reliability: Reliability Block Diagram models, Markov chains, and Monte Carlo simulation (Landau & Binder, 2014).

Monte Carlo simulation refers to the application of numerical repetitive simulation of system performance. The reason why Monte Carlo simulation is chosen over others because it provides the highest extent of flexibility and accuracy (Ayers, 2012). A statistic of the system performance can be produced by simulating the Monte Carlo for a certain system lifetime by deriving its failure frequency, TTF and availability among others (Ayers, 2012). In this research, the Earth Station system is modelled for 10 years of life expectancy because it was suggested by the MEASAT personnel (MEASAT, 2021). The life simulation is then performed for many trials to compute a statistical result. The algorithm process of Monte Carlo simulation is shown in Figure 2.9 which consists of three steps:

i. The state of individual components simulation
ii. The system state evaluation from individual component states
iii. The essential system metrics computation

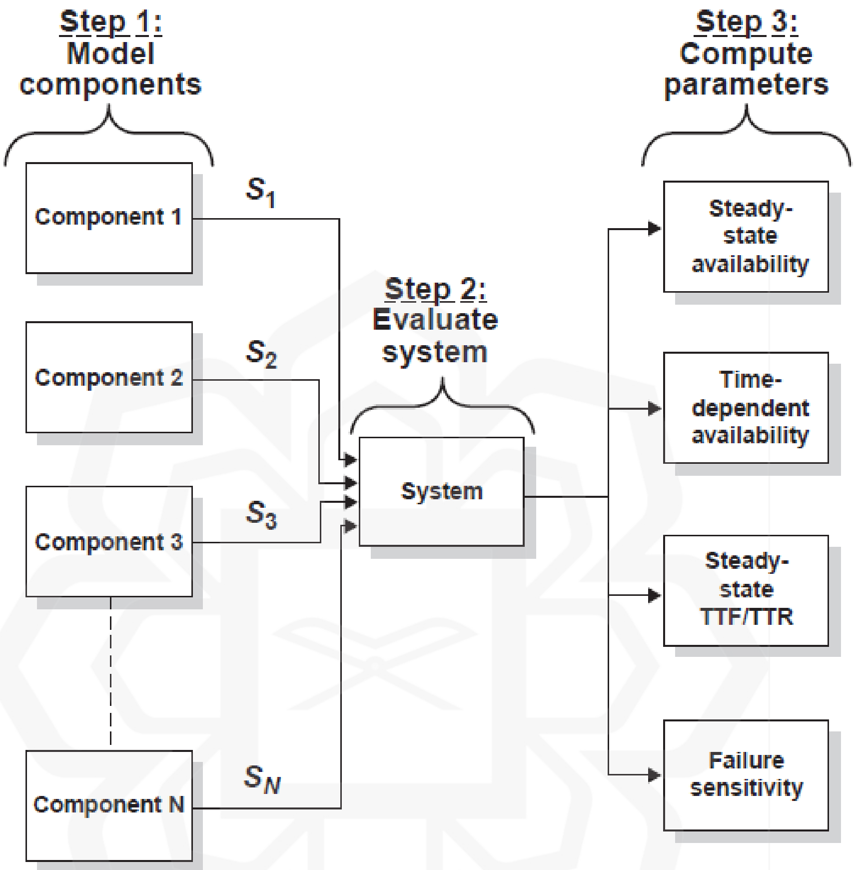

Figure 2.9 Algorithm Process Flow of Monte Carlo System Analysis (Ayers, 2012)

2.4 RELIABILITY OF A SATELLITE CONTROL EARTH STATION

Reliability plays an important role in the world of mathematical statistics and engineering. In general, reliability is a probability of the system to be working in its projected function throughout a certain period under specified conditions (Sugama, 2018). In other words, reliability is the performing probability of the stipulated functions throughout a specified period with no failure and under certain conditions (Hoque et al., 2015).

Reliability is seen as one of the vital technologies of engineering and is categorised as (Nadirah; Abdul Rahim & Nordin, 2020):

i. the performance probability within a given period.
ii. the accessible strength against probable stress analysis.
iii. the required trade-off of reliability against other qualities.
iv. the cost needed to acquire the specified reliability goal.
v. the optimum product functionality after its launch of service.

Reliability becomes an ever-increasing factor in system configuration. In the communication satellites design, reliability is the most important requirement. To this present, space electronics used in communication satellites are acquired to achieve at least five years of mean-time-between failures (MTBF) or mean-time-to-failures (MTTF) (Crowe, D., & Feinberg, 2017).

One of the most significant objectives in fulfilling the requirements for system operational feasibility is achieved through the design for reliability (Nadirah; Abdul Rahim & Nordin, 2020). Reliability of an Earth Station system may be defined as the probability that the system will accomplish its designated mission in a satisfactory manner and for a given period when used under specified operating conditions (Sugama, 2018). Reliability is related to the failure rate of the system. The failure rate is the rate at which failures occur in a specified time interval (Neal & Smith, 2008). The failure rate per hour is expressed in Equation 2.5:

$$\lambda = \frac{number\ of\ failures}{total\ operating\ hours} \tag{2.5}$$

where lambda (λ) is known as failure rate.

There are many ways that failure rate can be expressed, such as failures per hour, percentage of failures per 1,000 hours, or failures per million hours (Rahim et al., 2022).

In the case of electrical and electronic devices, the distribution is exponential, and the system mean life or the mean time between failure (MTBF) is expressed in Equation 2.6 where M is the value of MTBF and λ is failure rate (Blanchard & Fabrycky, 2011).

$$M = \frac{1}{\lambda} \tag{2.6}$$

Reliability can also be defined as in Equation 2.7 where M is the value of MTBF, λ is failure rate and t is the time duration in hour.

$$R(t) = e^{-t/M} = e^{-\lambda t} \tag{2.7}$$

The reliability in this study focuses on the Earth Station system specifically the RF/Antenna system which consists of 14 subsystems. These systems are divided into two, where 7 subsystems are at the transmission part and another 7 are at the receiving part. Then, further study is done on the Earth Station system configurations where the parallel redundancies are added. The parallel configurations that are considered are: 2,3 and 4. These three configurations are chosen to see how the reliability of system and cost allocation are affected in keeping the operation running efficiently. The detail of reliability equation for each parallel configuration can be viewed in Appendix A.

2.4.1 Mean-Time-Between Failures (MTBF)

In telecommunications system analysis, reliability is the most frequently expressed in terms of the mean time between failures (MTBF) and the mean time to repair (MTTR) (Sugama, 2018). These phrases relate to the average (mean) time it takes to put an item or system back into service as well as the average (mean) time it takes for an item or system to function between failure events (MTBF) (Ayers, 2012). The MTBF is the most essential statistic utilised in the definition, analysis, and design of telecommunications components (Nagiya & Ram, 2013). Additionally, MTBF is commonly given in hours.

The average or, more particularly, the expected value of the time to failure (TTF) of a component, subsystem, or system is defined by the mean time to failure (Saleh & Castet, 2011). Random variables are used in reliability and availability models to simulate component performance. A statistically distributed random variable serves as a representation of the TTF of a given item, subsystem, or system (Ayers, 2012). It is assumed that the TTF of a component is exponentially distributed and thus the failure rate is constant. Note that the resulting failure rate is not constant, unless the TTF or time to repair (TTR) is exponentially distributed. If steady-state operation is considered, it is generally reasonable to presume that the MTBF and failure rate are inverses to one another (Ayers, 2012).

In this research, the MTBF values are presumed to be set as 1 year, 3 years, 5 years, 7 years, and 10 years. MTBF are used in this research because the RF/antenna subsystems are repairable (Crowe, 2017). These values are used to investigate the relationship between MTBF and reliability which presumably the higher the MTBF value, the higher the reliability of a system should be (Nadirah; Abdul Rahim & Nordin, 2020).

2.5 OPERATIONAL COST

Operational costs are expenses incurred daily to maintain and run a business. Direct costs of goods sold (COGS) and other operational costs, also known as selling, general, and administrative (SG&A) costs, are included in the operating costs (Joe Bobinis et al., 2011). It also includes rent, payroll, and other overhead expenditures, as well as costs for raw materials and maintenance. Non-operating financing costs like interest, investments, and currency exchange are not included in operational costs (Murphy, 2022).

It is critical to keep the operational cost at its most minimum to generate higher revenue for the business (Tuttle & Bobinis, 2013). In this research, maintenance cost is manipulated to study its effect on operational cost for Earth Station system which presumably, the higher the maintenance cost, the higher the operational cost shall be.

Maintenance cost highlighted here consists of preventive maintenance cost and corrective maintenance cost. Preventive maintenance cost is the cost consumed to maintain the Earth Station system on scheduled basis meanwhile corrective maintenance cost is the cost spent for unpredictable faulty subsystems. A research by (Zhong et al., 2019) has verified that formulating a smaller ratio of corrective maintenance cost to preventive maintenance cost yields optimum operational cost with maximum system reliability. Hence, the importance of this research is to propose an operational cost model along with a better maintenance framework to avoid cost blowout.

2.5.1 Affordability of a Satellite Control Earth Station

In 2010, Dr. Ashton Carter whose Under Secretary of Defense for Acquisition, Technology & Logistic (ATL), had issued a sequence of memorandums. It was a quick response to the budgetary realities encountered by the Department of Defense (DOD) (Carter, 2014). Affordability was one of the subjects he emphasized for action. From his directive, annual average operating cost as well as cost acquisition (which are included in affordability) should be broadened to enclose additional elements required for the Life Cycle Cost (LCC) or the Total Ownership Cost (TOC) of a system (Koury et al., 2013). On the other hand, affordability defined by The International Council on Systems Engineering (INCOSE) Affordability Working Group is the balance of cost, system performance, and schedule constraints over the system life while fulfilling mission goals aligned with strategic organizational and investment needs (Joe Bobinis et al., 2011).

Operational scenarios of system capabilities throughout its lifecycle are inconsistent which can be both expectedly, as in evolutionary and involuntarily, as seen in changing operational environments (Joe Bobinis et al., 2011). Thus, affordability must be defined from both inside the boundaries of the System of Interest (SOI), as well as outside (Joseph Bobinis et al., 2013). A system is deemed as obsolete when designed to meet one specific mission as it is not adaptable to meet emerging needs. On the contrary, a system is adaptable to fulfil additional mission needs while continuing to deliver cost effective capability over time. It becomes much more affordable to the customer even as the required capabilities themselves change. Figure 2.10 is another method of understanding the bi-modal nature of system adaptation cycle which supports the operational and design phase in providing a continuous evaluation of a system worth (Joseph Bobinis et al., 2013).

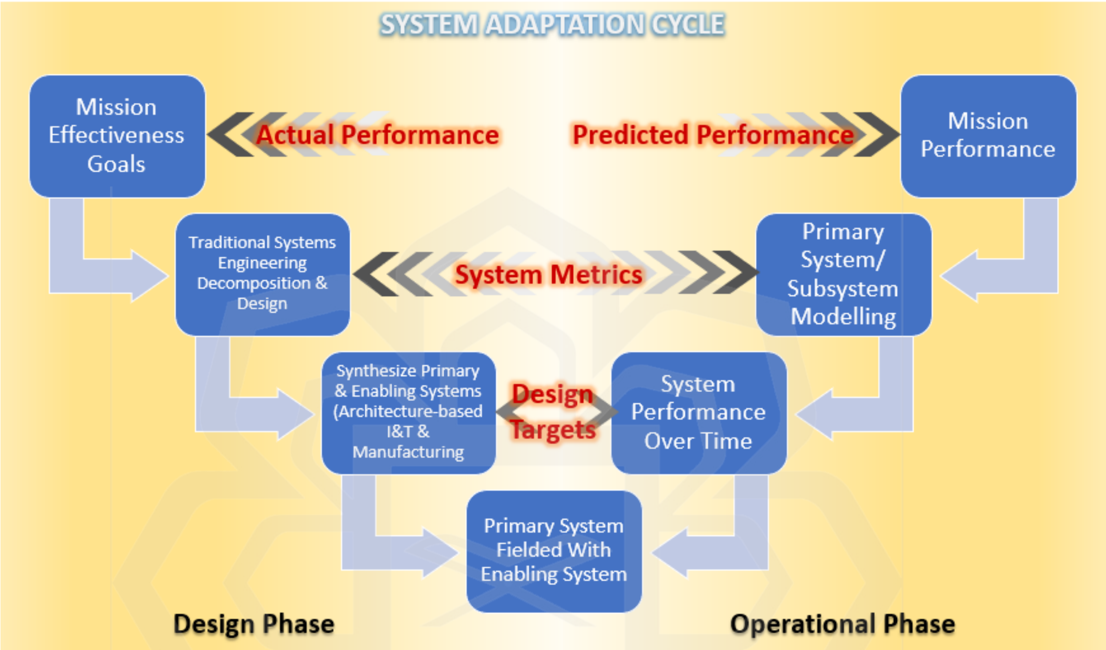

Figure 2.10 System Adaptation Cycle (Koury et al., 2013).

Thus, the system trade space is applied in minimising system cost while increasing or maintaining capability. One must evaluate a temporal aspect that enables system evolution through the time rather than considering a single point of solution, as shown in Figure 2.11 (Koury et al., 2013).

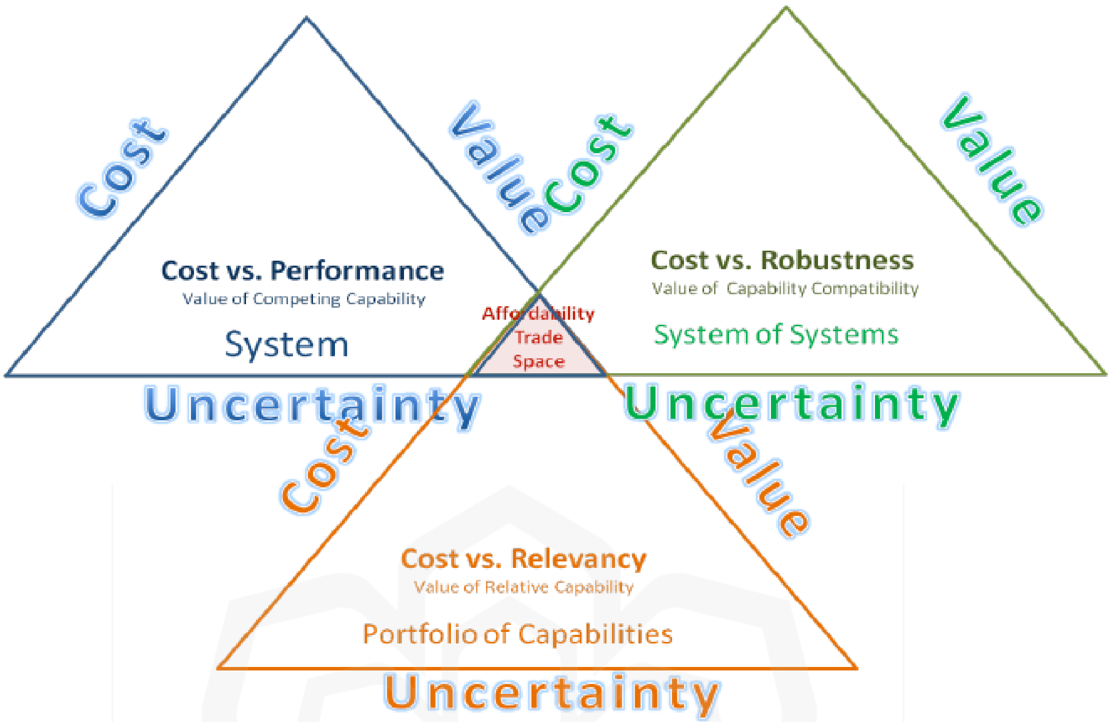

Figure 2.11 Affordability Trade Space (Koury et al., 2013).

Furthermore, the expanding boundaries of the SOI must include both primary and supporting systems. The primary system is the system to meet the mission's requirement, meanwhile the enabling system is the system that sustains the essential functionality across the system lifecycle. The SOI should then be summarised as a single System of Systems (SOS) which is the integration of the primary and enabling systems (Tuttle & Bobinis, 2013). The expenditure to which these systems can be integrated may dictate their relevancy over time.

The application of SOS methodology for determining and measuring affordability must be applicable during acquisition, system design phase, as well as in operational use. To define the specific affordability, the components of potential affordability from the definitions are tabulated as the following:

Table 2.2: Affordability Components (Tuttle & Bobinis, 2013).

Component	**Definition**	**Example**
Required Capability	Identify the encompassed capabilities and its time phasing	What function is performed by the system, e.g., signal modulation, uplink transmission
Required Capabilities Performance	a) Recognise and define the capabilities required by Measures of Effectiveness (MOEs) b) Specify each MOEs time phasing. c) Recognise and define Measures of Supportability (MOSs). d) Specify each MOSs time phasing.	How the required capability must be performed well by the system, e.g., able to deliver a certain percentage of desired output with minimal loss
Budget	a) Recognise the elements of budget to be included in the affordability judgement. b) Time phased budget, either for each of the budget elements, or as the total budget.	What are the accessible resources to supply the acquired capabilities and performance?
Schedule	For accomplishing the given capabilities through the specified system life.	How long does the system takes to perform its capabilities thoroughly?

In the context of Earth Station system, (Shao et al., 2013) had presented the Performance-Based Cost Modelling (PBCM) which is an approach to quantify the relationship between cost and performance, or measures of effectiveness (MoEs). This cost/performance relationship ultimately, can allow us to pursue potentially useful mission design alternatives, such as systems that are lower cost, better performing, or both (Tuttle & Bobinis, 2013).

2.6 MAINTAINABILITY OF A SATELLITE CONTROL EARTH STATION

Maintainability and maintenance have different meaning, but somehow, they are related to each other. Maintainability in general is the ability of a system to be maintained, meanwhile, maintenance is a sequence of measures taken to retain or re-establish a successful operational state of the system. Maintainability essentially built-in the design, while maintenance is the outcome of design (Blanchard & Fabrycky, 2011). Maintainability can be divided into two maintenance types: preventive maintenance and corrective maintenance.

2.6.1 Preventive Maintenance

Preventive maintenance or preventative maintenance can also be called scheduled maintenance. It is the maintenance that is frequently performed on an equipment to reduce the possibility of it failing. It is performed in a working system so that the equipment does not break down unexpectedly (Elbert, 2014). In Earth Stations, preventive maintenance prone to be complex like the systems design. It is because of different manufacturers have different software and hardware, and disturbances are commonly exclusive in nature (Nadirah; Abdul Rahim & Nordin, 2020). Functional operation in this area acquires a specific well plan with a competent organization. The plan should identify responsibilities for specialized systems' needs, maintenance function, and the routine activity procedures (Hoque et al., 2015). It also comprises routine activities that can be performed via remote based on standardised assessment and test equipment, as well as the basic maintenance procedures such as adjusting power levels and replacing air filters (Elbert, 2014). The plan is also to ensure no out-of-ordinary incidents to occur such as sudden spike of Central Processing Unit (CPU) utilization and intermittent links between equipment.

2.6.2 Corrective Maintenance

Corrective maintenance is the unscheduled maintenance, or the maintenance act performed to identify and make a correction to a fault so that the failed part can be restored to an operational condition within the restrictions established for in-service operations (Elbert, 2014). It is essential for the Earth Station system to be well prepared with a recovery plan that is regularly reviewed and tested . If calamity were to happen, a disaster recovery team of personnel is responsible to keep the operations running on alternate location or site. Guidelines and procedures for restoring all data as well as priority list are important to accommodate efficient recovery management. Also, Service Level Agreements (SLA) and vendors' contact numbers must be included in the recovery plan (Ebadi, 2017). Therefore, a suitable maintenance framework or activities based on the stipulated time is identified in this research.

2.7 OVERVIEW OF PREVIOUS RESEARCH WORKS

To understand the system reliability and cost further, past studies including their advantages and disadvantages were analysed to seek for the best method in determining the system reliability. The main studies used as the main references or benchmark for this research are (Bouwmeester et al., 2022) and (Nadirah; Abdul Rahim & Nordin, 2020). Based on the research performed by (Bouwmeester et al., 2022), a reliability model for CubeSats with redundant subsystems was developed, validated, and implemented in a Monte Carlo simulation. The research question entails a decision between investing more funds to install redundant subsystems or to enhance testing on a satellite without redundancy. A system with redundant subsystems remains more reliable than a system without one. Nonetheless, this research is proven to be applied for satellite system instead of the Earth Station system and its cost model was not covered by the researchers.

(Nadirah; Abdul Rahim & Nordin, 2020) stated that the reliability of an Earth Station system can be improved by introducing more redundancy units into the system.

2-parallel and 3-parallel configuration were taken as the study sample and related maintenance activities were also proposed encompassing antenna system and RF and electronics equipment in general. The setback of this study is the cost model of the system design is not considered. Hence, the practicality of the system designed was not proven.

Other previous studies have also been reviewed to understand this research further. A study by (Jin et al., 2020), the High Level of Architecture (HLA) based in communication simulation system of shipboard satellite proven to be functional in minimising risks of a mission by testing equipment reliability. The interrelations of data process are depicted in Figure 2.12.

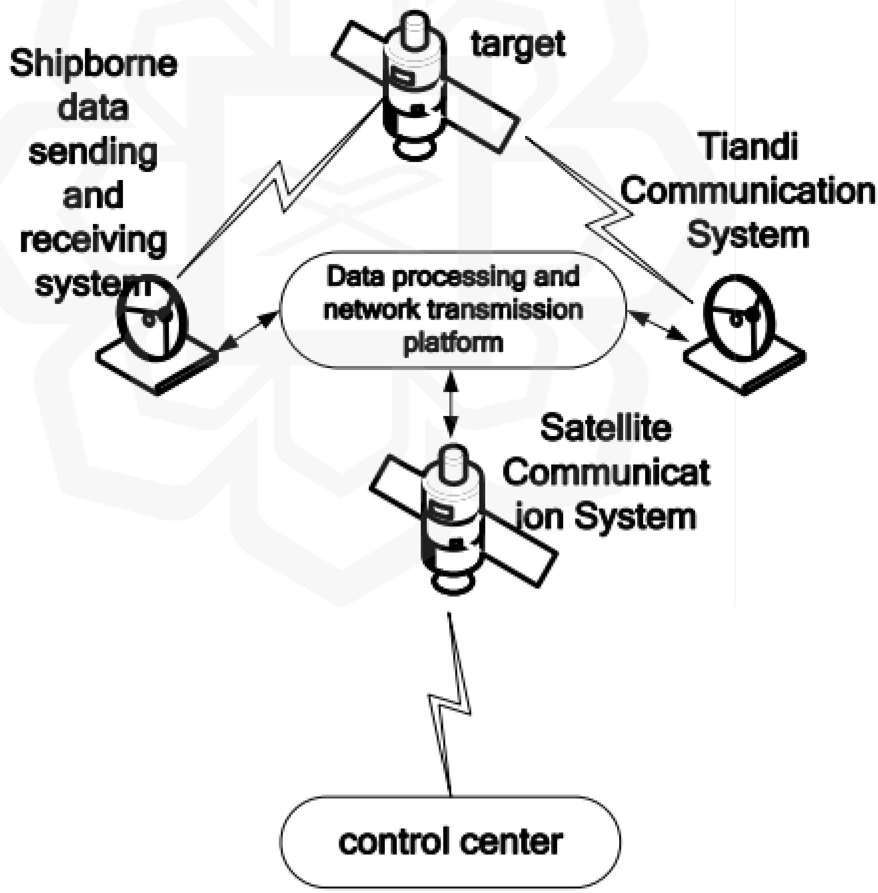

Figure 2.12 Data processing interaction diagram (Jin et al., 2020).

After the transmitting and receiving process of the shipboard data, the controlled data is then undergone another process via network transmission platform to be transmitted to the satellite communication system. The system then, transmits the data via data transmission link to the control centre. Concurrently, the control centre also transmits controlled data to the ship through the satellite communication system by completing its essential control process through the transmitting and receiving system.

This technology is proven to be functional in testing equipment reliability and minimising mission risks. However, the precision and effectiveness of data modelling, modularity and scalability of the system are not yet determined.

Another approach as stated by (Sugama, 2018), in determining reliability, availability and maintainability (RAM) parameters can lead to a high level of uncertainty and risk when it is done within the planning stages. Therefore, planning a strategy to fit in the requirements for a newly developed Earth Station from the existing Earth Stations is crucial to produce an operational available system. Developers can obtain cost effective product by using QuART PRO software tool, where it recommends the exact tasks within the product lifecycle to the developers. The downside of this approach is it requires allocation of an additional specialised personnel to assist with the effort.

On top of that, development of algorithms and models that allow solving instant Single-Satellite Multiple-Ground Station Scheduling Problem (SMSP) as conducted by (Spangelo et al., 2015) is capable to maximise the downloaded data volume to a network from an Earth-orbiting spacecraft to the Earth Stations. The main components concerned in this research are Energy Dynamics, Data Dynamics, and System Optimization. Although this method is not widely fit for all types of satellite, this research had successfully developed an algorithmic formula to solve variety of problems encountered like the satellite download scheduling.

A past study on reliability characteristics of a satellite Earth Station had been investigated which also includes the failures which the systems have experienced (Nagiya & Ram, 2013). The transition state probabilities, meantime to failure (MTTF), reliability, availability, cost effectiveness and sensitivity analysis are obtained by utilizing Markov process theory and Laplace transformations. Figure 2.13 and Figure 2.14 show the relationship of reliability over time.

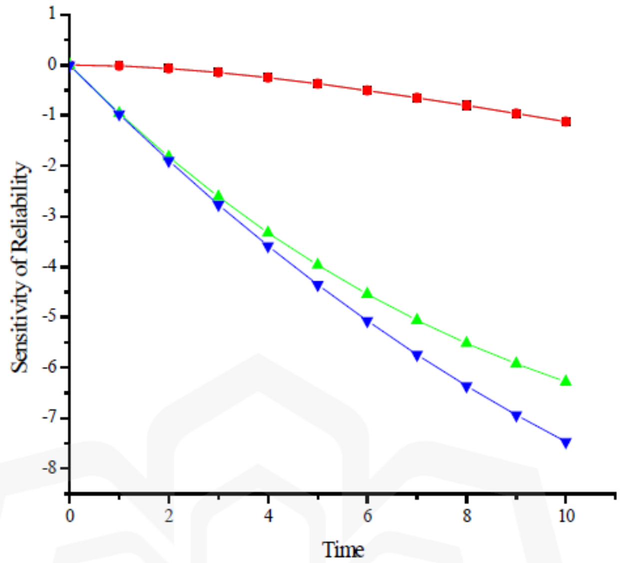

Figure 2.13 Sensitivity of MTTF as function of Time. (Nagiya & Ram, 2013)

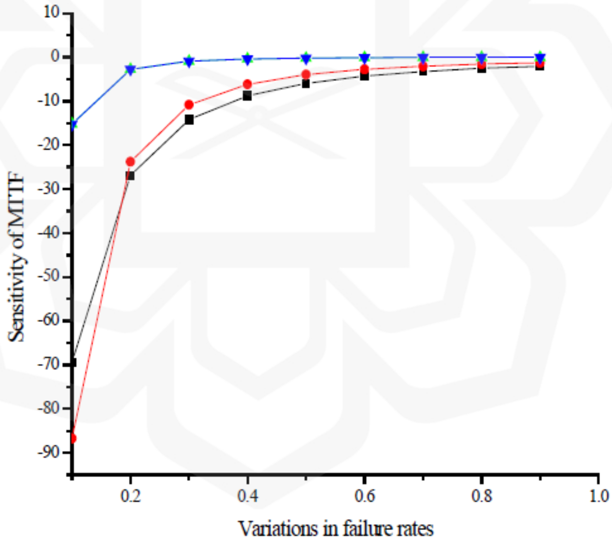

Figure 2.14 Sensitivity of MTTF as function of Failure Rate. (Nagiya & Ram, 2013)

Based on (J. F. Castet & Saleh, 2010), an investigation of failures of satellites and satellite subsystems are extended beyond the binary concept of reliability to the analysis of their anomalies and multi-state failures as illustrated in Figure 2.15. A Stochastic Petri Net (SPN) models are constructed for all satellite subsystems to analyse multi-state failure and simulate the subsystems' failure behaviours but only proven on three satellite subsystems: the thruster/fuel; the telemetry, tracking, and control (TTC); and the gyro/sensor/reaction wheel subsystems.

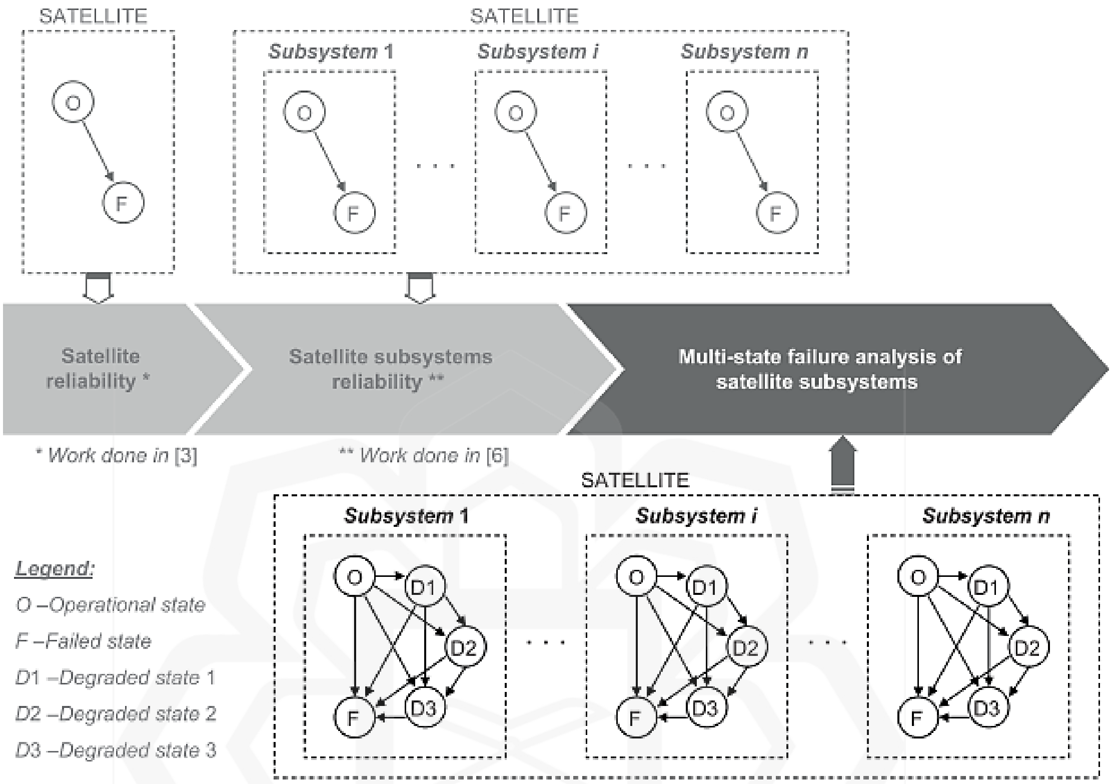

Figure 2.15: Progression in the statistical analysis of satellite and satellite subsystem failures (J. F. Castet & Saleh, 2010)

A nonparametric analysis of satellite reliability for 1584 Earth-orbiting satellites launched between January 1990 and October 2008 was conducted where statistical analysis of satellite reliability was extended and investigated (J. Castet & Ã, 2009). Through this research which particularly useful to the space industry e.g., redesigning subsystem test and screening programs, a maximum likelihood estimation (MLE) was introduced as an approach to conduct parametric fits with the Weibull distributions along with the extensive use of the Kaplan-Meier estimator for calculating the reliability functions. All these past studies and the overview of previous research works are tabulated in Table 2.3.

Table 2.3: The Overview of Previous Works

Author	Title	Advantage	Disadvantage
Jasper Bouwmeester, Alessandra Menicucci, & Eberhard KA Gill (2022)	Improving CubeSat reliability: Subsystem redundancy or improved testing?	Developed and validated a reliability model for CubeSats with redundant subsystems by implementing Monte Carlo simulation	This study is limited proven for satellite system and did not include costing as a factor
N. Abdul Rahim & N. A. Nordin (2020)	Reliability model and proposed maintainability activities of Earth Station system	Introduced reliability model of a 3-parallel configuration that provides better reliability than 2-parallel configuration. Related maintenance activities for antenna system and RF electronics are also proposed.	This study did not include costing as a factor and lesser maintenance activities proposed
Jin et al. (2020)	Research on simulation technology of shipborne satellite communication system	Constructed a shipboard satellite communication simulation system based on HLA which is proven to be an effective means of testing equipment reliability and reducing mission risks	The accuracy and effectiveness of data modelling, modularity and scalability of the system are not yet determined
Sugama (2018)	Reliability , Availability , and Maintainability Forecasting for A	Utilizing the QuART PRO software tool assists developers to provide a cost-effective product by	A newly introduced method requires allocation of additional specialised

	Newly Developed Satellite Communication Systems	recommending specific tasks during the product lifecycle.	personnel to assist with the effort.
Spangelo et al. (2015)	Optimization-based scheduling for the single-satellite, multi-ground station communication problem	Developed a formulation and algorithms to address the satellite download scheduling problem, laying the groundwork for more complex problems both within and outside the operational space domain.	The application is not widely fit for all types of satellite
Nagiya & Ram (2013)	Reliability Characteristics of a Satellite Communication System including Earth Station and Terrestrial System	Able to determine the transition state probabilities, availability, reliability, MTTF, cost effectiveness and sensitivity analysis of the system	Long calculations involved which are prone to miscalculation in terms of data input.
J. F. Castet & Saleh (2010)	Beyond reliability, multi-state failure analysis of satellite subsystems: A statistical approach	Constructed Stochastic Petri Net (SPN) models for all satellite subsystems to analyse multi-state failure and simulate the subsystems' failure behaviours.	Only proven on three satellite subsystems: the thruster/fuel; the telemetry, tracking, and control (TTC); and the gyro/sensor/reaction wheel subsystems.

J. Castet & Ã, J. H. S. (2009)	Satellite and satellite subsystems reliability : Statistical data analysis and modeling	- Introduced maximum likelihood estimation (MLE) approach to conduct parametric fits with Weibull distributions - Extensive use of the Kaplan-Meier estimator for calculating the reliability functions.	Particularly useful to the space industry e.g., redesigning subsystem test and screening programs
Tuli, Orr, & Zee (2007)	Low Cost Ground Station Design for Nanosatellite Missions	Successful demonstration of highly capable ground station can be built to support a wide range of nanosatellite missions at lower cost.	The ground station model presented only could be applied to small satellite program

2.8 PERCENTAGE FRACTIONAL ERROR AND ROOT MEAN SQUARE (RMS) ERROR

In order to validate reliability and operational cost models, the results obtained were compared to the models that had previously been produced by (Nadirah; Abdul Rahim & Nordin, 2020) and (Amaitik et al., 2022) in terms of percentage fractional errors and RMS error. Equation 2.8 and Equation 2.9 were used to compute the percentage fractional errors and RMS error respectively (Nadirah Abdul Rahim et al., 2022).

$$\varepsilon_f = (x_{measured} - x_{predicted} \ / \ x_{measured}) \ x \ 100\% \quad (2.8)$$

$$RMS\ Error = (\frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2)^{\frac{1}{2}} \quad (2.9)$$

The $x_{predicted}$ in Equation 2.9 was referred to as the value of previous reliability or cost model meanwhile the $x_{measured}$ was referred to as the value of new reliability or cost model. Whereas, in Equation 4.4, the x_n^2 refers to as the calculated difference of new simulated value and previous model value whereas *n* refers to as the system lifecycle service year.

2.9 CHAPTER SUMMARY

The Earth Station system along with the reliability, affordability and maintainability has been reviewed in Chapter 2. The illustration of the Earth Station system that includes the parallel configuration is also explained. On top of that, the comparison of the previous research works on reliability and affordability has been briefly summarised and tabulated in Table 2.3. The highlight of this research emphasized on the reliability, affordability calculations and obtain a suitable maintenance framework in a timely manner. Thus, it is important to develop a simple but affordable reliability model of the Earth Station system based on which parallel configuration gives the highest reliability. In turn, a suitable operational cost model was also developed which helps in setting an optimum cost allocation specifically in maintaining the Earth station system. In Chapter 3, an extensive approach of reliability and maintenance cost which included the affordability calculations was discussed as well as the related flow chart and the procedures to carry out this research methodology.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In this chapter, methods to carry out this research is discussed briefly. An elaboration on how the data is obtained and analysed are included. The flowchart of the research methodology is illustrated in Figure 3.1.

The first step is to study on the different problems occurring in the Earth Station system. The most prominent problem occurred in the Earth Station system is identified and reported. Moreover, an extensive literature study is also used to understand the current situations happening in the Earth Station service industry which involve with reliability and affordability alongside with its maintenance framework. This information is recorded for comparison in Chapters 2.4, 2.5 and 2.6.

The subsystem redundancies are added into the Earth Station which are identified as 2-parallel, 3-parallel, and 4-parallel configurations. The 2-parallel, has 2 redundancies elements in the system. Whereas the 3-parallel and 4 -parallel has each 3 and 4 redundancies respectively. Reliability system of these configurations is then investigated by simulation using Monte Carlo method in MATLAB application. The reliability for each subsystem in the Earth Station system is calculated and the graphs are plotted against the lifecycle of the satellite system. As for the cost model, affordability profile which is the potential cash flow of total cost of operation and maintenance of the Earth Station system is based on the statistics of past cost consumption obtained from MEASAT.

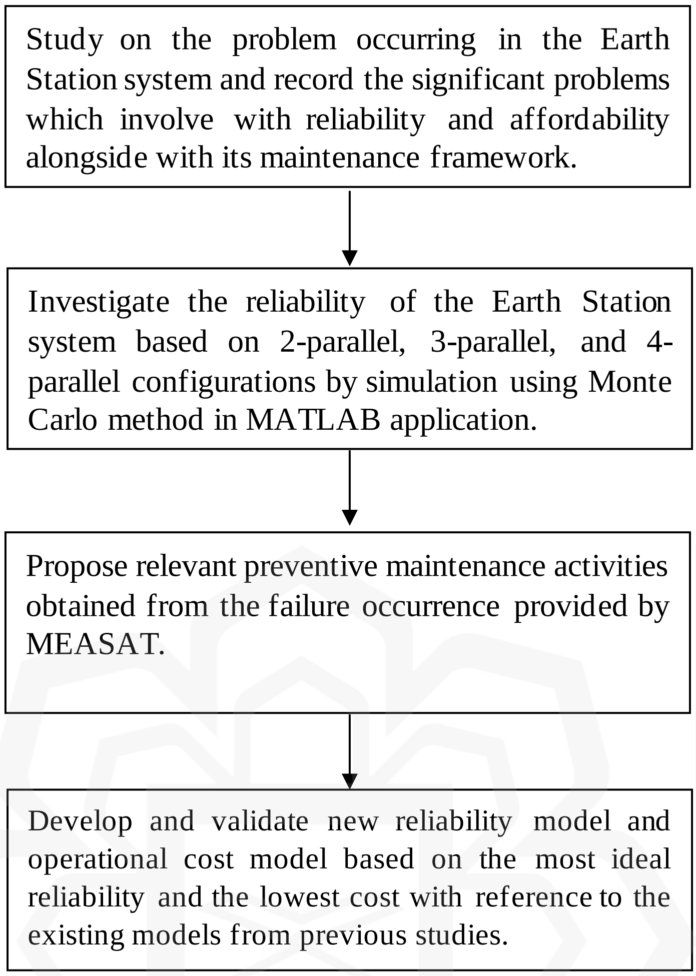

Figure 3.1 Flowchart of research methodology

The third step is to propose relevant preventive maintenance activities obtained from the failure occurrence provided by MEASAT. The development of the maintenance activities is based on the type of the maintenance, whether it is a preventive maintenance or corrective maintenance. The chosen maintenance type must be affordable and suitable with the environment.

The final step is to develop a new reliability model and an operational cost model based on the most ideal reliability and the lowest cos This is with reference to the existing models from the previous studies based on the three elements: reliability, operational cost, and suitable maintenance framework. The validation of the model is done by comparing against the other existing reliability models and verified by MEASAT personnel.

3.2 INITIAL ASSUMPTIONS OF REDUNDANCIES IN AN EARTH STATION SYSTEM

The assumptions are made for the repairable standby component systems:

i. All standby items are assumed to be cold standby (only become operational when the primary unit fails).
ii. The standby unit is assumed not to fail and assumed to be perfect in switching.
iii. Failure in the active unit is identified instantly and the standby unit operates perfectly.
iv. Once the repair action is completed, the unit change to standby along with other available units.

3.3 INITIAL ASSUMPTIONS OF MAINTENANCE IN EARTH STATION SYSTEM

The subsystems of the Earth Station are modelled with the description of:

i. Mean Time Between Failure (MTBF)
ii. Maintenance time
iii. Maintenance cost.

A simple 3-steps model is applied for the time to repair consisting of three categories (CAT) of repair: CAT 1, CAT 2, and CAT 3 as described in Table 3.1. The maintenance time function is defined as the time to perform corrective maintenance after a failure and is assumed to be a step function (Nadirah; Abdul Rahim & Nordin, 2020), as shown in Figure 3.2.

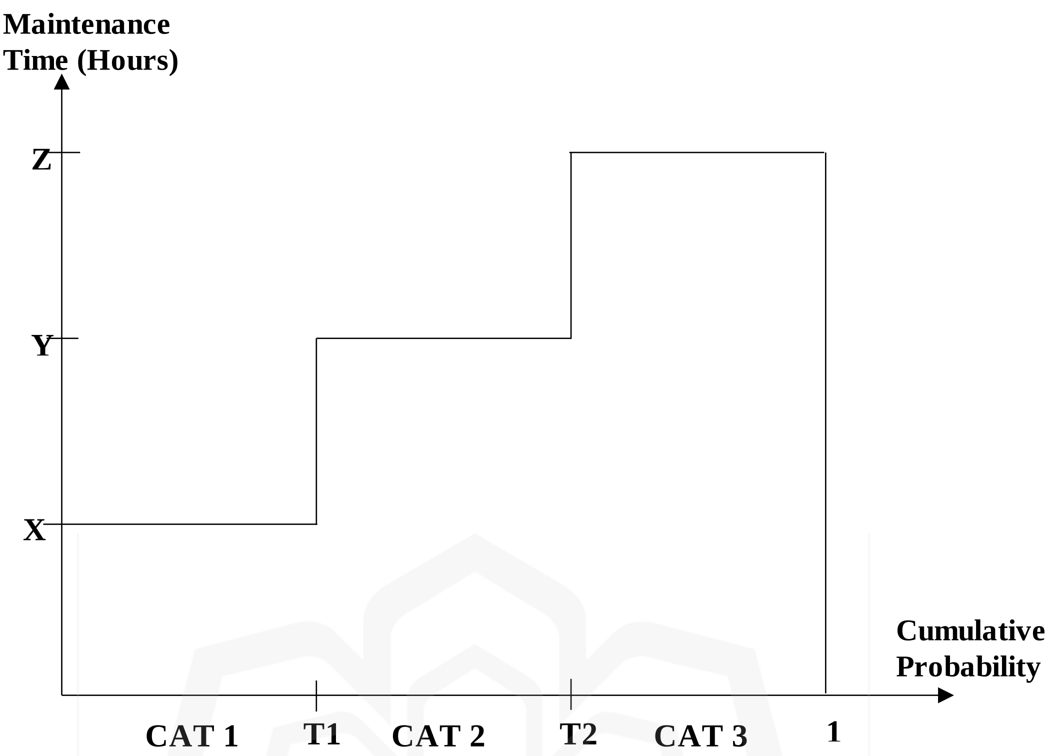

Figure 3.2 Step function for maintenance repair

Table 3.1: Type of maintenance repair when a subsystem fails (Tchakoua et al., 2013).

Categories of repair	Description
CAT 1	A quick fix. It requires a technician for onsite repair.
CAT 2	A repair that occurs after the technician has brought the failed subsystem to the base for further investigation.
CAT 3	A total breakdown. It requires a new replacement.

This simple assumption consists of three amounts of effort in hours to perform repairs which later are validated once the data of time taken for repair and recovery work from MEASAT is obtained. The vertical axis refers to maintenance time, obtained from Table 3.2, and the horizontal axis refers to cumulative probability, which generates random numbers from 0 to 1 using Monte Carlo. T1 and T2 are threshold 1 and threshold 2 values produced by a random number generator using Monte Carlo to determine which category of maintenance is required (Nadirah; Abdul Rahim & Nordin, 2020).

Table 3.2: Time taken for maintenance (Tchakoua et al., 2013).

Categories of repair	Time taken
CAT 1	1 – 4 Hours
CAT 2	5 – 12 Hours
CAT 3	13 – 24 Hours

The maintenance cost function is assumed to be a non-linear function as different equipment require various amount of repair cost. The horizontal axis refers to the cumulative probability which generates random numbers from 0 to 1 using Monte Carlo. The values for the Threshold 1 and 2 consisting of random numbers are applicable as previously for a faulty equipment which can be seen in Figure 3.2 and Figure 3.3. The vertical axis refers to the maintenance cost which is obtained from the data table in Appendix A.

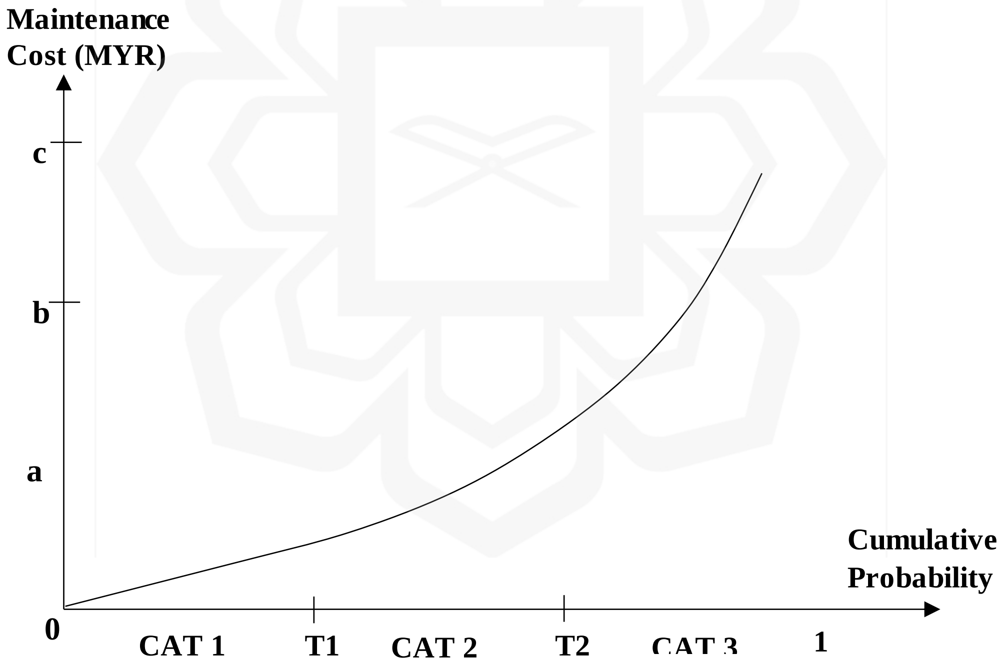

Figure 3.3: Linear function for maintenance cost

3.4 HOW MAINTENANCE ASSOCIATES WITH COST

The cost-maintenance categories are displayed in Figure 3.4. Maintenance can be categorised into 3 categories: preventive maintenance, intelligent maintenance, and reactive maintenance (Tchakoua et al., 2013). In the first category, the prevention cost is assumed to be high whereas the repair cost can be low as not many failures occur in the first few years of Earth Station system. As time passes, the system is prone to failures – causing a greater number of failure subsystems. Thus, as displayed in the reactive maintenance category, the repair cost is higher than the prevention cost. Contrastingly, the equal combination of preventive and reactive costs creates an optimum cost which is most ideal to improve reliability, affordability and maintainability of a system while simultaneously optimises the system availability.

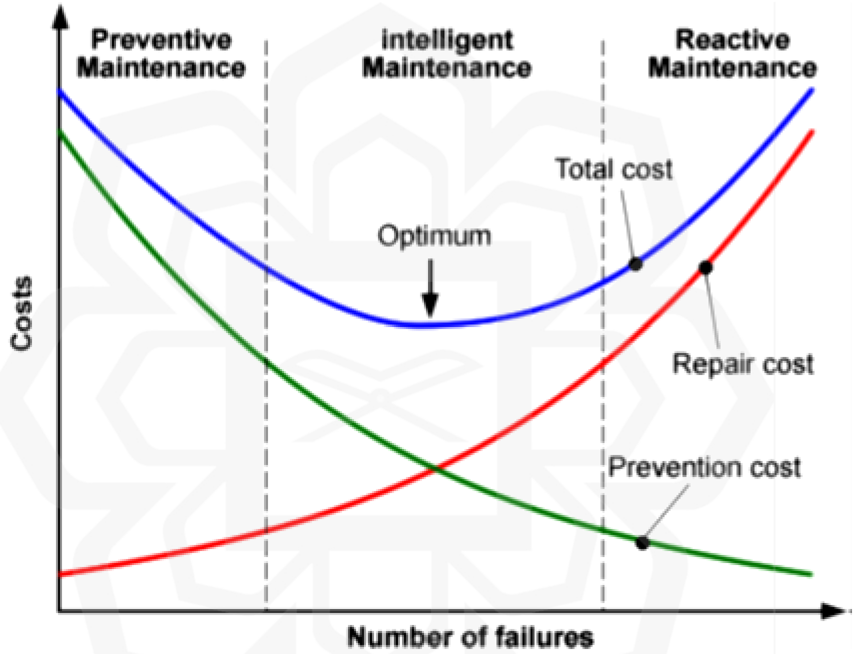

Figure 3.4 Cost associated with maintenance categories. (Tchakoua et al., 2013)

It is ideal to minimise the overall costs including maintenance and failure costs of all the system components by attaining the optimum total cost using Equation 3.1 (Sirvio, 2015):

$$\sum_{i=1}^{I}\sum_{t=1}^{T} C_M\,(i,t) + \sum_{i=1}^{I}\sum_{t=1}^{T} P_F\,(i,t) C_F(i,t) \qquad (3.1)$$

where

i = system component

t = maintenance time

C_M = maintenance costs

C_F = failure costs

P_F = probability of failure

3.5 MAINTENANCE APPROACHES

Maintenance is ought to be performed based on the three main stages: data acquisition usage of sensors, signal processing by utilising various means of data processing and feature production which includes acquiring parameters to develop the monitored equipment status (Tchakoua et al., 2013).

A failure can be detected or predicted by retrieving:

i. Information on the system present state obtained through the online monitoring.
ii. Information on the system past status obtained from the stored data.

As displayed in Figure 3.5, soon after a failure is detected, corrective maintenance must be carried out either by palliative maintenance (consist of provisional solution to failures) or curative maintenance (for standing solutions to failures). In contrast, when a failure is prognosticated – in prevision of the failure to occur – preventive maintenance shall be performed (Tchakoua et al., 2013). In this case four different means can be used: scheduled or time base maintenance, conditional or real-time state base maintenance, forecasting or parameter prediction base maintenance and status base or proactive maintenance.

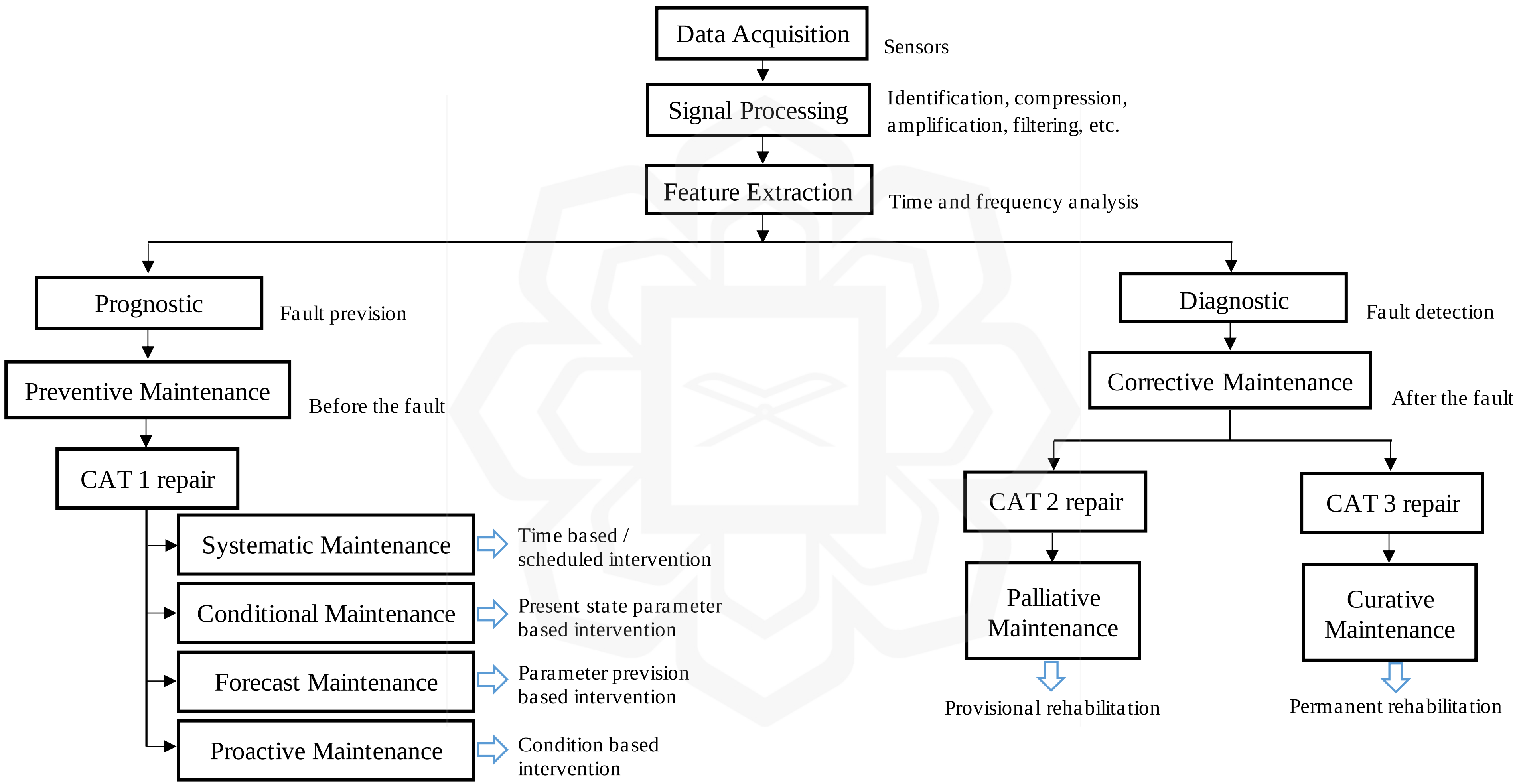

Figure 3.5 Overview of maintainability of Earth Station system. (Tchakoua et al., 2013)

3.6 PROPOSED MAINTENANCE ACTIVITIES

The list of components that need to take into consideration in choosing the best maintenance activities are identified. Also, the operation and maintenance requirements suggested have been investigated. Table 3.3 depicts the operation and maintenance requirements for the functional area or subsystem in the Earth Station as well as the maintenance activities. According to Table 3.3 (Elbert, 2014), the best maintenance activities that need to be done on every equipment listed is normally based on the condition of the subsystem itself. The replacement part is done when the subsystem has failed to function. The maintenance activities listed must be done periodically. In Chapter 4, the complete proposed maintenance activities are demonstrated.

Table 3.3: The Required Maintenance Activities by Functional Subsystem. (Elbert, 2014)

Subsystem	Required Maintenance
Antenna	Regular inspection on its physical features, alignment, and system performance
RF terminal electronics	Close monitor on electronic equipment and its functionality
Baseband multiplexing	Periodic inspection of optimum bit rate transmission
Computers and peripherals	Configure computer management with only the best software and upgrade frequently
Facilities systems	Periodic environment check-ups on building, supplies and tools needed

3.7 TECHNICAL MODELLING

A response to repair may be triggered if any of the subsystem fails. This failure is modelled in the simulation code implemented in this research. In this research, the Monte Carlo simulations from MATLAB software are used in the Earth Station system specifically RF/antenna system which consists of 7 subsystems at the receiving part and 7 subsystems at the transmission part. Each of the functional module is modelled by *n*-parallel redundant units. The n-subsystems of each module provides resilience as follows: There is only one subsystem working at a time and n-subsystems become the backups. Table 3.4 shows the modes used to identify the state of a subsystem.

Table 3.4 State numbers and their description

States	Description
1	Working mode
2	Standby mode, ready to replace the working subsystem if it fails or in the repair state
0	Failed subsystem, needs to be repaired or replaced

The subsystems change between states 0,1 and 2 according to the events that are portrayed in Figure 3.6 and further explanation is tabulated in Table 3.5.

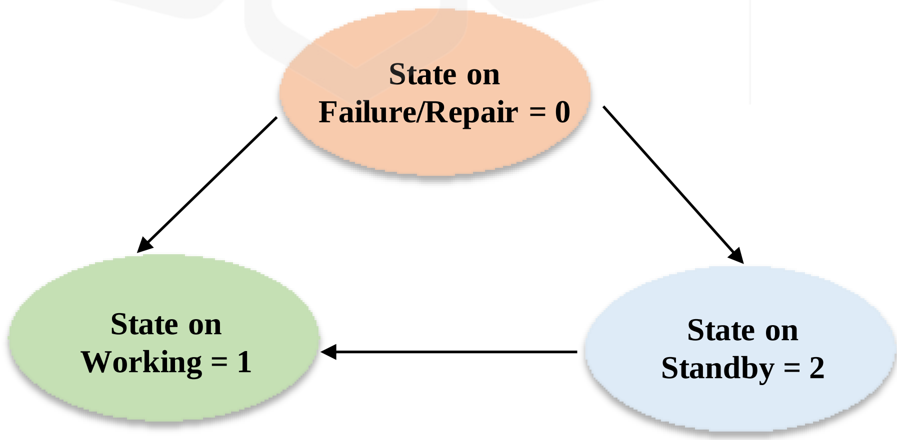

Figure 3.6 State diagram for RF/antenna subsystems.

Table 3.5: State transition details

States	Description
Working	A subsystem is working (State 1)
Failure	A subsystem has failed (Subsystem transitions from State 1 to State 0)
Repair	A failed subsystem is being repaired (Subsystem remains at State 0)
Standby	A subsystem that has been repaired (Transitions from State 0 to State 2)
Standby	A subsystem that is in standby mode (State 2)
Switch into service	The subsystem transitions from State 2 to State 1

Time is used to determine the occurrence of an event. For the event labelled as 'failure', a 1 x *n* (the number of subsystems) matrix called TOF (time of failure) is created and specified as follows:

1. Each item in the matrix represents the time of failure of the subsystem.
2. The times of failure are generated by the random generator using the failure function for the subsystem type in MATLAB.
3. Failure times are calculated independently for each event of failure.

Next, the event is labelled as 'repair', a 1 x *n* matrix called TOR (time of repair) is created and specified as follows:

1. Each item in the matrix represents the time of repair of each subsystem in hours.
2. Each item is generated using the random generator in MATLAB and the repair time function.
3. Repair times are calculated independently for each event of failure.

The flowchart in Figure 3.7 shows the steps taken to obtain the technical simulations to determine the system reliability and affordability, using Monte Carlo. Table 3.6 illustrates the matrix subsystems in MATLAB.

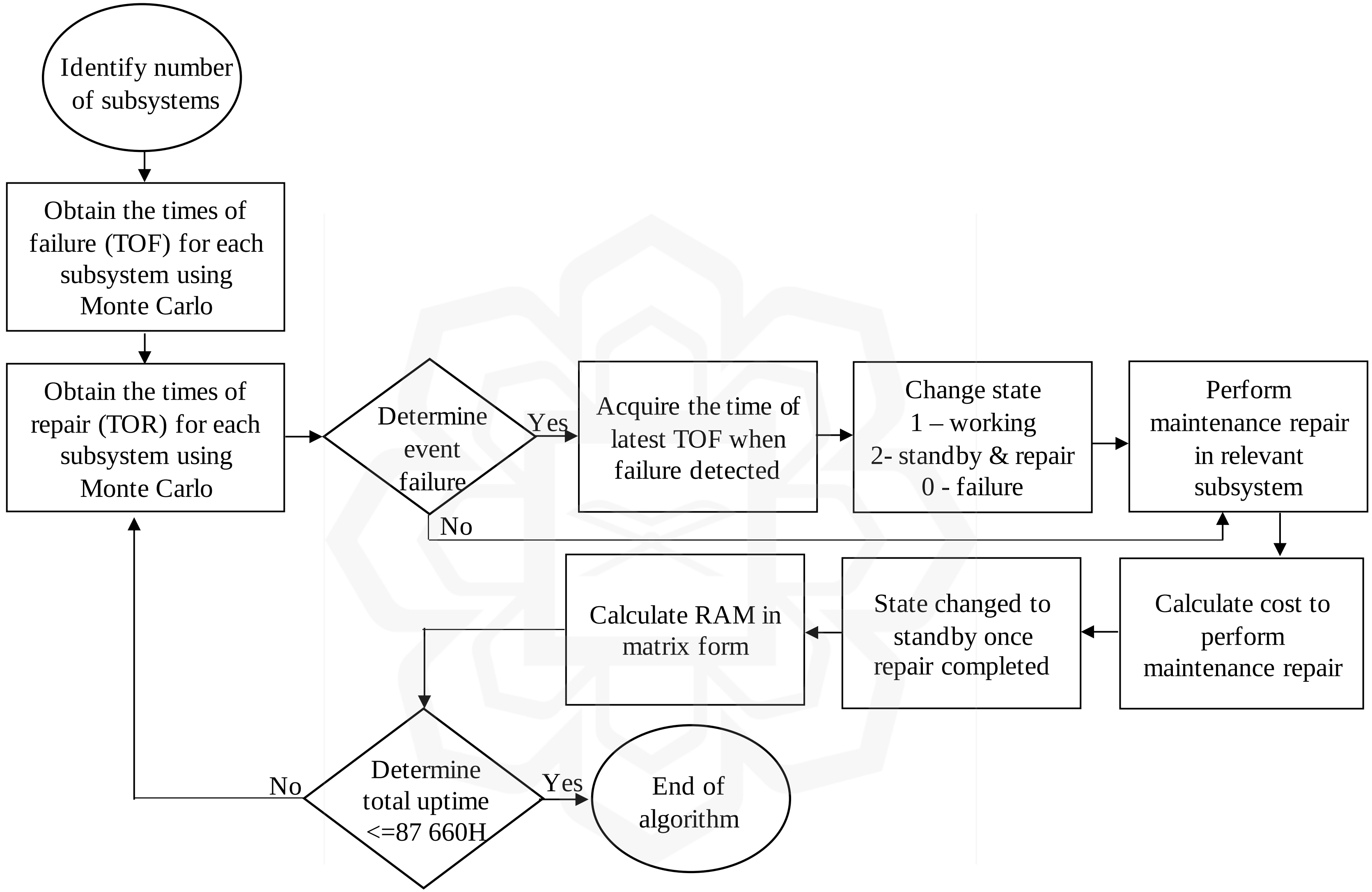

Figure 3.7 Flowchart of the technical simulation to determine the Reliability by using Monte Carlo.

Table 3.6: Subsystem representation in MATLAB matrix form.

Subsystem	Modulator			Up Converter			HPA			Demodulator			Down Converter			LNA			Antenna		
The column in the matrix	1	…	*n*	2	…	*n*	3	…	*n*	4	…	*n*	5	…	*n*	6	…	*n*	7	…	*n*

Further explanation on technical simulation based on Figure 3.8 is tabulated in Table 3.7 as below:

Table 3.7: Brief explanation on technical simulation

Step	Technical description	Input example
1	Algorithm start: Input number of subsystems	4 = [1 2 2 2 1 2 2 2 1 2 2 2 1 2 2 2 1 2 2 2 1 2 2 2 1 2 2 2]
2	Produce times of failure of subsystem using Monte Carlo generator	[1087 1497 1025 679 449 1073 1018 569 736 523 768 718 985 984 1349 1399 1165 855 987 1369 117 877 399 432 1087 1497 1025 679]
3	Produce times of repair of subsystem from given data	[8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900]
4	Determine which subsystem number fails	Subsystem which is located at position 4 fails
5	State transition on failed subsystem	State number is 0
6	Subsystem state at position 13 will be zero	[1 2 2 2 1 2 2 2 1 2 2 2 0 2 2 2 1 2 2 2 1 2 2 2 1 2 2 2]
7	The redundant of subsystem state at position 14 will be 1	[1 2 2 2 1 2 2 2 1 2 2 2 0 1 2 2 1 2 2 2 1 2 2 2 1 2 2 2]
8	Next event is a repair. Choose the time of repair from the given data	[8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900 8 40 100 900]
9	Obtain the cost to repair from given data	[250 375 667 1000 250 375 667 1000 250 375 667 1000 250 375 667 1000 250 375 667 1000 250 375 667 1000 250 375 667 1000]

10	Change the state to standby (state 2) after it has been repaired	[1 2 2 2 1 2 2 2 1 2 2 2 2 1 2 2 1 2 2 2 1 2 2 2 1 2 2 2]
11	Update the total up time, stop when it reaches 10 years of operation	87 660 Hours
12	Algorithm complete	Algorithm has reached 87 660 Hours

3.8 FINANCIAL MODELLING

As illustrated in Figure 3.8, the cost to perform maintenance repair is considered to calculate the total expenditure for each year of the system lifecycle. The cost calculation is primarily based on the complexity of the system repair as described in Table 3.1. The total cost calculation is obtained based on Equation 3.1. The more complex the system repair, the higher the cost should be. Subsequently, the annual cost would then be analysed into an affordability profile which shows the potential cash flow happening in each year.

The affordability profiles generated for each MTBF values would be useful to distinguish the type of repairs that are commonly performed. It is important to study the relationship between cost and repair of the system because it would then help to propose suitable maintenance activities. The system maintainability is the most ideal when equipped with more preventive maintenance than corrective maintenance (Hoque et al., 2015). As corrective maintenance is often occurred beyond expectation, the system would consume higher cost to repair. In contrast to preventive maintenance, the maintenance or repair activities can be done without causing the whole system to fail (Amaitik et al., 2022).

3.9 CHAPTER SUMMARY

This chapter was written to explain how the research methodology was carried out. There are three important methods namely, technical modelling which explains the reliability model, the financial modelling which explains the cost model and affordability profile and lastly the proposed maintenance framework which explains the preventative maintenance activities.

CHAPTER FOUR

RESULTS, MODELLING AND DISCUSSION

4.1 INTRODUCTION

As this research progresses further, the reliability of Earth Station subsystems based on the 2-parallel, 3-parallel, and 4-parallel configurations with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years were investigated. These MTBF values were presumed as experimental values to study the hypothesis of this research as lesser failure occurred in a system with high MTBF value which provided a longer system functionality and a better system reliability.

4.2 SIMULATION OF NON-FIXED FAILURE RATE OF RF/ANTENNA SYSTEM

A basic simulation has been formulated to predict the random failure rates of 7 subsystems as shown in Figure 4.1, Figure 4.2, and Figure 4.3. The mean of all the failure rates were calculated and depicted as lambda (λ). This lambda, λ was then used to measure the reliability of the Earth Station system.

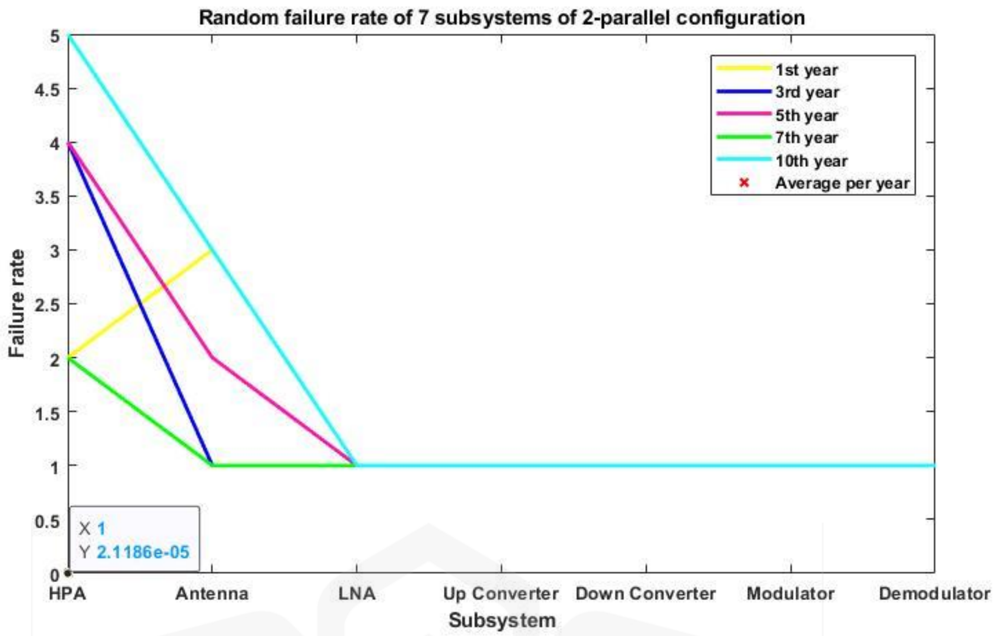

Figure 4.1 The random failure rate of Earth Station subsystems for 2-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years.

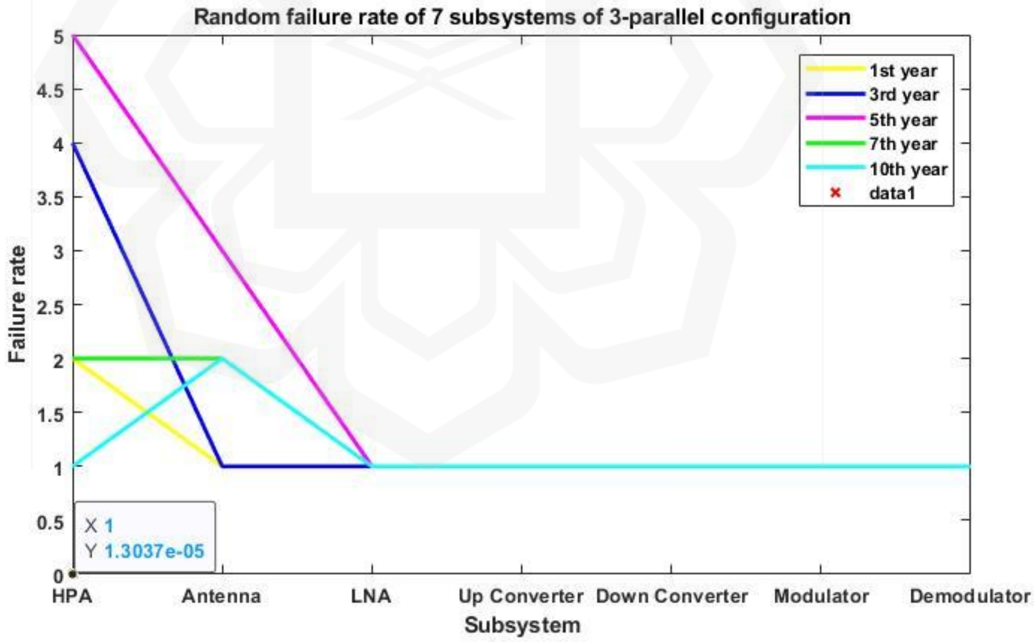

Figure 4.2 The random failure rate of Earth Station subsystems for 3-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years.

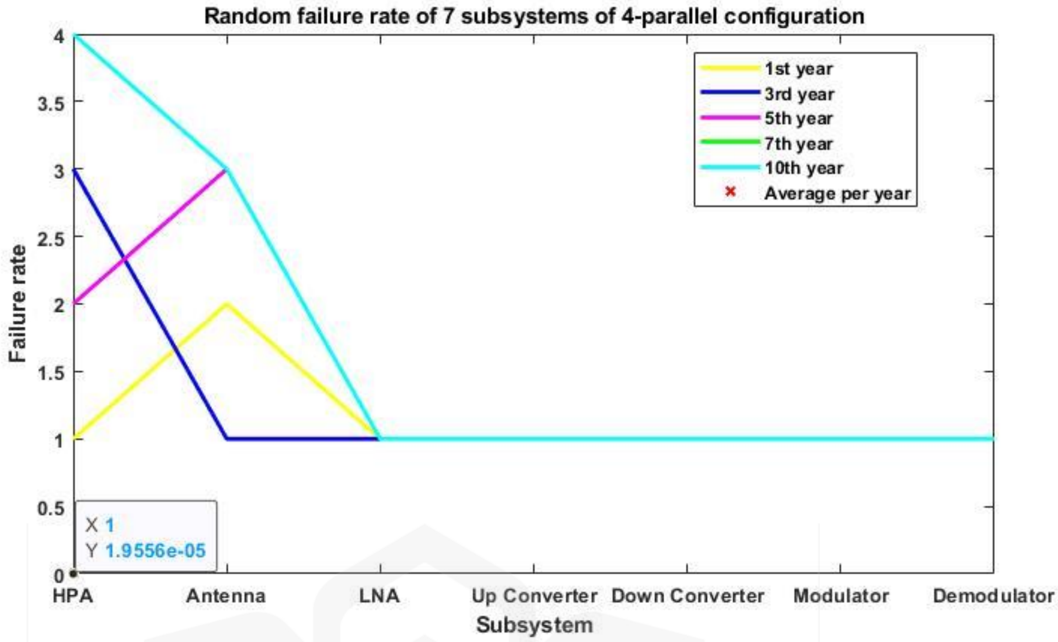

Figure 4.3 The random failure rate of Earth Station subsystems for 4-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years.

Table 4.1 The random average failure per year for 2-parallel, 3-parallel, and 4-parallel configurations

Parallel configuration	**Random Average Failure Per Year** (λ)
2-parallel	2.12×10^{-5}
3-parallel	1.30×10^{-5}
4-parallel	1.96×10^{-5}

The data from Figure 4.1, Figure 4.2 and Figure 4.3 has been tabulated as in Table 4.1 that demonstrates the random average failure per year for the 2-parallel, 3-parallel, and 4-parallel configurations. The random average failure rate, λ of the 3-parallel configuration showed a significant drop than the 2-parallel configuration. It was observed that the λ decreased as the number of redundancies in the Earth Station system increased. However, the λ of 4-parallel configuration was greater than the 3-parallel configuration and merely similar value to the 2-parallel configuration. This finding was due to the 3 redundant units in 4-parallel configuration which faced more failure in each subsystem. However, the λ of 4-parallel configuration was greater than the 3-parallel configuration and merely similar value to the 2-parallel configuration. This finding was due to the 4 redundant units in 4-parallel configuration faced more failure and requires more repair in each subsystem. The reason is that the 4-parallel configuration subsystem could work efficiently with one running unit, two redundant units on hot standby and another redundant unit on cold standby or fully impaired. Whereas the 3-parallel configuration subsystem would require one running unit and both redundant units to be constantly on hot standby. The relationship of failure rates, λ and the Earth Station system reliability were investigated further in this research.

4.3 RELIABILITY SIMULATION OF AN EARTH STATION SYSTEM

A technical simulation based on Figure 3.8 has undergone an initial design phase by using Monte Carlo from MATLAB software. The reliability of an Earth Station system which was based on 2-parallel, 3-parallel, and 4-parallel configurations with 5 different MTBF values were simulated and shown in Figure 4.4, Figure 4.5, and Figure 4.6 respectively. Each graph showed a significant drop within second year and third year of the satellite service. This was due to the frequent failure occurrence in the system during the first few years of operation to ensure the system stability.

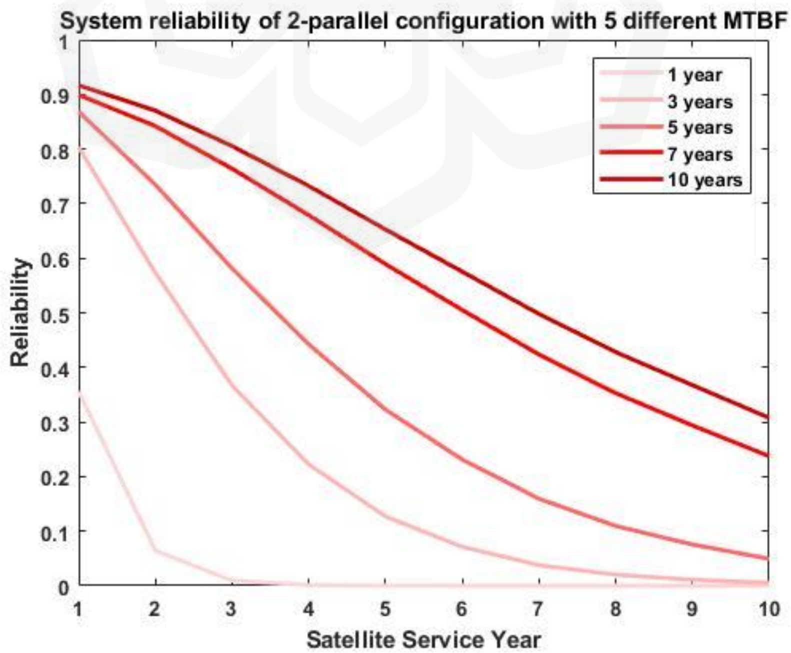

Figure 4.4 The reliability graph of 2-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years.

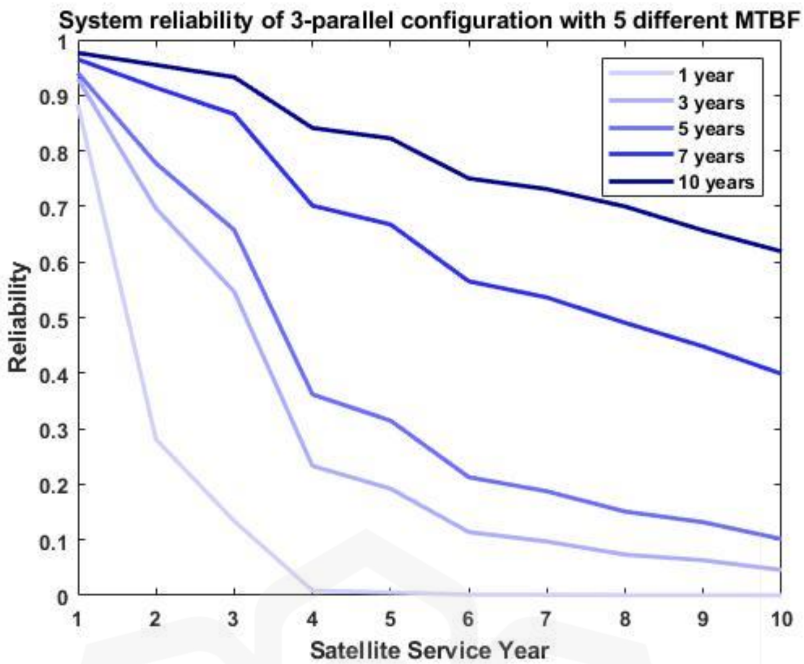

Figure 4.5 The reliability graph of 3-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years.

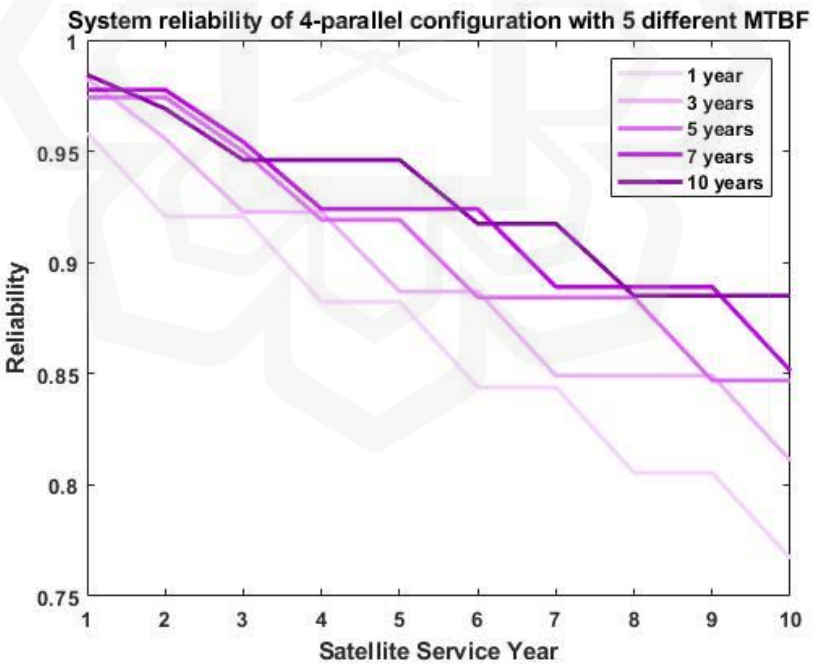

Figure 4.6 The reliability graph of 2-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years.

Table 4.2 The system reliability of different MTBF for 2-parallel, 3-parallel, and 4-parallel configurations

MTBF =	Parallel configuration	Reliability									
		1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year	10th year
1 year	2-parallel	0.356	0.065	0.009	0.001	0	0	0	0	0	0
	3-parallel	0.883	0.281	0.134	0. 009	0.005	0.001	0	0	0	0
	4-parallel	0.958	0.921	0.921	0.882	0.882	0.844	0.844	0.805	0.805	0.767
3 years	2-parallel	0.803	0.573	0.367	0.222	0.127	0.071	0.038	0.020	0.011	0.005
	3-parallel	0.930	0.696	0.547	0.233	0.192	0.114	0.097	0.073	0.063	0.046
	4-parallel	0.983	0.956	0.923	0.923	0.887	0.887	0.850	0.850	0.850	0.811
5 years	2-parallel	0.869	0.735	0.581	0.442	0.323	0.231	0.159	0.110	0.076	0.049
	3-parallel	0.940	0.778	0.658	0.362	0.314	0.213	0.187	0.151	0.132	0.102
	4-parallel	0.974	0.974	0.950	0.919	0.919	0.884	0.884	0.884	0.847	0.847
7 years	2-parallel	0.900	0.842	0.764	0.679	0.589	0.505	0.424	0.353	0.294	0.237
	3-parallel	0.965	0.914	0.866	0.701	0.667	0.565	0.536	0.490	0.448	0.399
	4-parallel	0.978	0.978	0.954	0.924	0.924	0.924	0.889	0.889	0.889	0.851
10 years	2-parallel	0.917	0.870	0.805	0.732	0.653	0.575	0.498	0.428	0.367	0.308
	3-parallel	0.976	0.955	0.932	0.841	0.822	0.750	0.731	0.700	0.657	0.619
	4-parallel	0.984	0.969	0.946	0.946	0.946	0.917	0.917	0.884	0.884	0.884

The data from Figure 4.4, Figure 4.5 and Figure 4.6 has been tabulated as in Table 4.2. The highest reliability was found in the Earth Station system with MTBF of 10 years. This is because the lower the rate of failure to occur in a system, the higher the system reliability. The reliability values were found to be 0.356, 0.883, and 0.958 for the 1st operating year of the system with 2-parallel, 3-parallel, and 4-parallel configurations respectively. The values were then significantly degraded as the service year progressed to the 10th year with the reliability values of 0, 0, and 0.767 respectively. This finding was due to the equipment high wear and tear which potentially occurred from the low quality of the equipment use that cause frequent subsystem failure. These values were nearly half of the system reliability because the overall system functionality encountered more frequent failures over the years until the end of its lifecycle. It was proven that during the 1st operating year, the system was more reliable when equipped with more redundancies. Hence, the Earth Station system was highly reliable with 4-parallel configuration as failure rate was lower than 2-parallel and 3-parallel configurations. On top of that, it was found that the 4-parallel configuration system provided constant reliability throughout the system lifecycle compared to 2-parallel and 3-parallel configurations. This could be seen in Table 4.2. Although with MTBF of 1 year, it could be concluded that the system with 4-parallel configuration managed to provide constant reliability.

As it was hypothesized that by having a suitable reliability model with the failure rate computation of each subsystem in the Earth Station, the problem of having a breakdown of an Earth Station system could be reduced. An Earth Station system equipped with MTBF of 10 years was proven to encounter lesser failure. Thus, the higher the MTBF is, the greater the reliability of a system is.

4.4 AFFORDABILITY PROFILE GENERATION

Next, affordability profiles were generated across 10 years of satellite services. Based on the Equation 3.1, these profiles were generated from one million Monte Carlo runs. Figure 4.7, Figure 4.8, and Figure 4.9 depict the affordability profiles distribution of potential cash flow throughout the satellite operating service with MTBF of 10 years for 2-parallel, 3-parallel, and 4-parallel configuration.

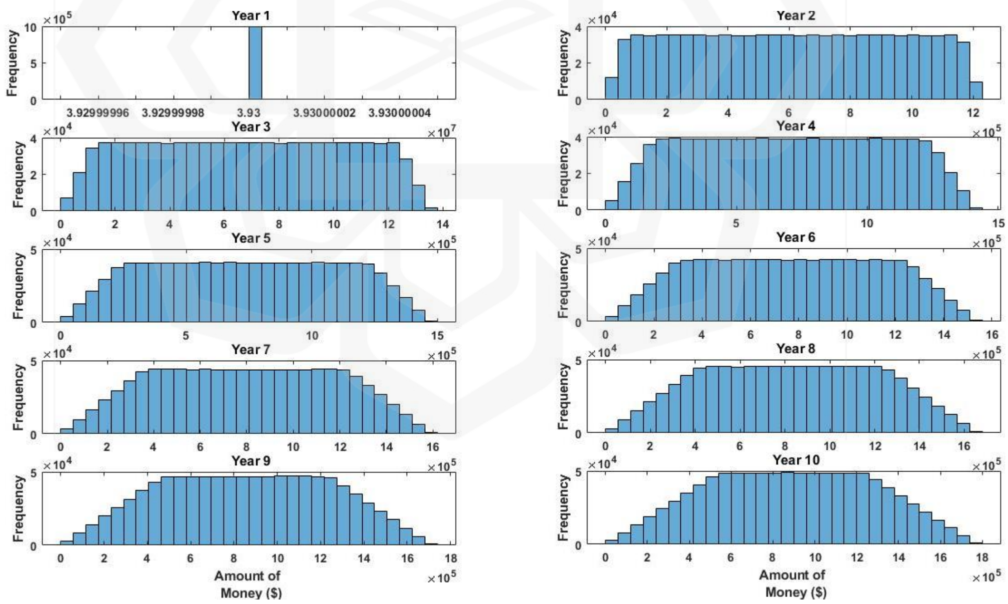

Figure 4.7 Affordability profile distribution of potential cash flow of Earth Station operating service with MTBF of 10 years for 2-parallel configuration.

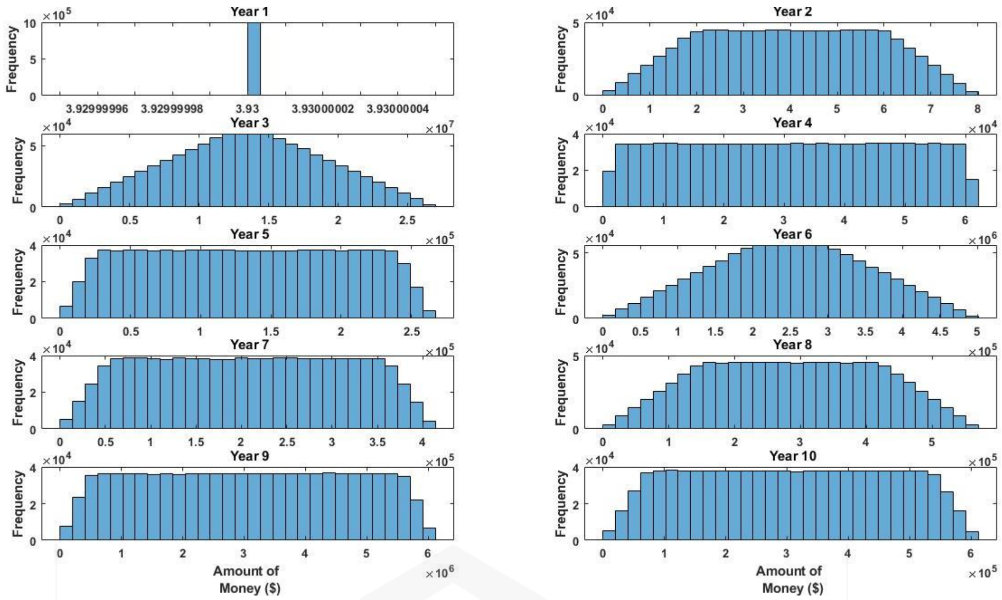

Figure 4.8 Affordability profile distribution of potential cash flow of Earth Station operating service with MTBF of 10 years for 3-parallel configuration.

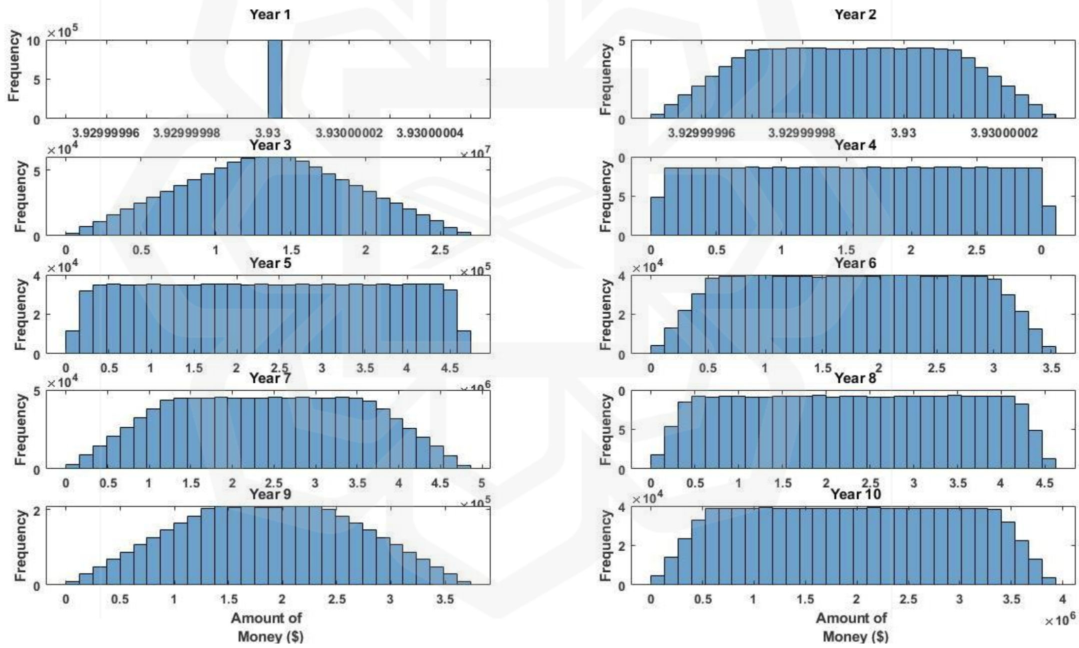

Figure 4.9 Affordability profile of potential cash flow of Earth Station operating service with MTBF of 10 years for 4-parallel configuration.

The affordability profile consists of total annual operating cost and maintenance costs. The maintenance costs covered both preventive and corrective maintenance activities. It is assumed that the corrective maintenance cost varies with the Earth System redundancies, as more redundancies consume more cost. Table 4.3 lists the estimated cost consumed per year for each parallel configuration.

Table 4.3 The estimated cost consumed per year for 2-parallel, 3-parallel, and 4-parallel configurations

Parallel configuration	Cost consumed by year (e^{10} RM)				
	1	2	3	4	5
2-parallel configuration	0.004	1.177	6.936	16.714	16.097
3-parallel configuration	0.004	1.650	11.420	20.383	18.705
4-parallel configuration	0.004	1.470	11.416	20.380	29.757
Parallel configuration	**Cost consumed by year (e^{10} RM)**				
	6	**7**	**8**	**9**	**10**
2-parallel configuration	0.004	21.024	31.851	33.342	32.894
3-parallel configuration	0.004	17.516	41.051	47.392	51.147
4-parallel configuration	0.004	40.560	10.323	30.610	20.561

The cost incurred was also observed to rise yearly as the system's failure risk increased, particularly when system reliability dropped. The projected lifetime costs for the 2-parallel, 3-parallel, and 4-parallel configurations were RM2.009B, RM2.735B, and RM2.017B, respectively. From these three types of parallel configurations, the 3-parallel configuration was the costliest whereas the 2-parallel configuration was the least expensive and the 4-parallel configuration was the second least expensive. The research found that more maintenance needed to repair redundant unit, the higher the cost would be needed. However, a unique term applied for the 4-parallel configuration as a subsystem could still be able working efficiently with one running unit, two redundant units on hot standby and another redundant unit on cold standby or fully impaired. A different case applied for 3-parallel configuration as it would require one running unit and both redundant units to constantly be on hot standby.

It can be demonstrated that, although having the lowest reliability rate in the system but with acceptable reliability values, the Earth Station system with 2-parallel configuration consumed less operational cost. Therefore, the 2-parallel configuration of the Earth Station system design was chosen for the development of a sustainable framework due to its low maintenance cost to run each subsystem throughout its lifecycle.

4.5 RELIABILITY MODEL

The 2-parallel configuration of an Earth Station system with a 10-year MTBF was selected as the best design to deliver the best reliable performance within an affordable price range. Figure 4.10 shows a new and simple reliability model, which is depicted in Equation 4.1:

$$y = 1.1393e^{-0.122x} \tag{4.1}$$

where

y = system reliability

x = Satellite service year

Whereas Table 4.4 shows the comparison of the measured value against the new reliability value with its error in percentage.

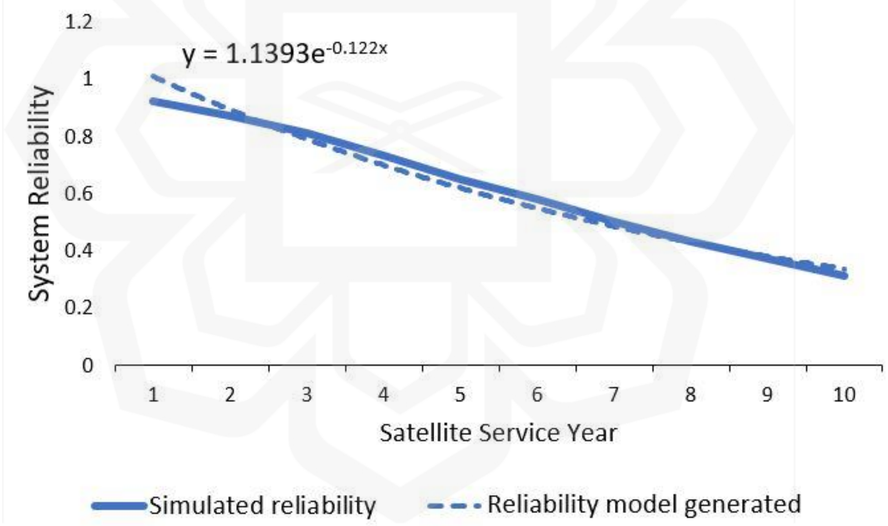

Figure 4.10 Reliability graph of 2-parallel configuration with 10-year MTBF Earth Station configuration model and measured.

Table 4.4 The comparison of the measured and new reliability value from 2-parallel configuration of MTBF 10 years

Year	1	2	3	4	5	6	7	8	9	10
Measured reliability value	0.92	0.87	0.81	0.73	0.65	0.58	0.5	0.43	0.37	0.31

New reliability value	1.01	0.89	0.79	0.7	0.62	0.55	0.49	0.43	0.38	0.34
Error (%)	8.77	2.53	-2.52	-4.38	-5.00	-5.85	-3.09	-0.16	2.63	7.83

The reliability model was created exponentially using 10-year MTBF of 2-parallel configuration data with a minimum range of error percentage of less than 9%. The exponential distribution serves as a useful model for the phase in a product's lifecycle where failure is likely to occur whether the product is brand new, a year old, or several years old. In other words, the period before it starts to deteriorate and wear out throughout its anticipated use (Minitab Statistical Software, 2022). The middle region of the Bathtub Curve, which is long and 'flat' (roughly constant) but has minimal failure risk, is also seen to be well-represented by the exponential distribution.

On top of that, the first year of new reliability model valued at 1.01 and experienced 66% dropped reliability value by its final year. Such result was caused as there are only 2 redundant units in 2-parallel configuration which the system encountered more frequent failures over the years until the end of its lifecycle.

4.6 OPERATIONAL COST MODEL

On the other hand, a new operational cost model was developed from the failure frequency of 2-parallel configuration Earth Station system as shown in Equation (4.2),

$$y = 4.6792x - 5.6464 \quad (4.2)$$

where

y = system operational cost consumption

x = Satellite service year

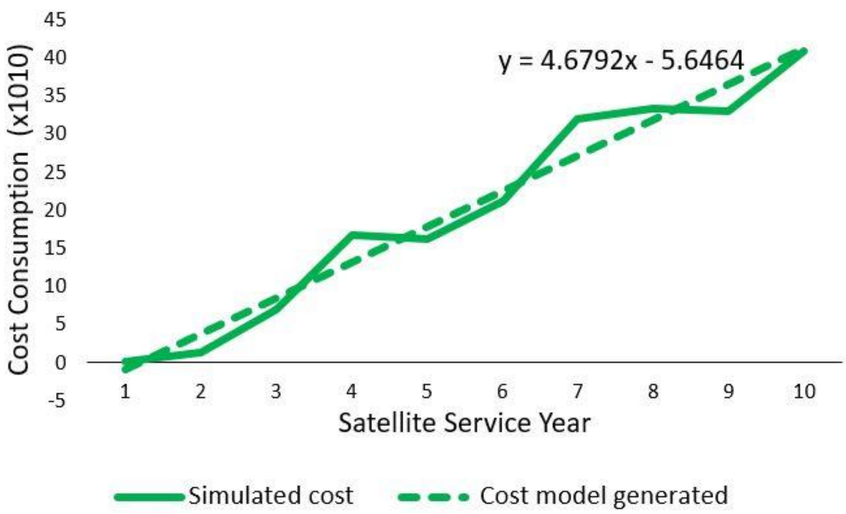

Figure 4.11 Operational Cost Model graph of 2-parallel configuration with 10-year MTBF Earth Station configuration model and measured.

Table 4.5 The comparison of the simulated value and new operational cost model value from 2-parallel configuration of MTBF 10 years

Year	**1**	**2**	**3**	**4**	**5**
Cost consumed (x e10)	0.0039	1.1765	6.9355	16.714	16.0966
New cost consumed (x e10)	0.9672	3.712	8.3912	13.0704	17.7496
Error (%)	100.40	68.31	17.35	-27.88	9.31
Year	**6**	**7**	**8**	**9**	**10**
Cost consumed (x e10)	21.0237	31.8512	33.3419	32.894	40.8574
New cost consumed (x e10)	22.4288	27.108	31.7872	36.4664	41.1456
Error (%)	6.26	-17.50	-4.89	9.80	0.70

The operational cost incorporates the daily expenses to run the Earth Station system including labour rate, maintenance cost and other overhead expenditures. The maintenance cost highlighted in this research consisted of both preventive maintenance cost and corrective maintenance cost. Thus, a linear relationship with a tolerable margin of error was generated using the simulated data of the similar Earth Station configuration. This was due to the high inaccuracy percentage of the exponential graph and polynomial graph generated from the operational cost value as illustrated in Figure 4.12 and Figure 4.13 respectively. The new operational cost model was generated linearly with average percentage error of 16.19%. Whereas the exponential and polynomial graphs yielded average percentage error of -133.40% and 16.99% respectively.

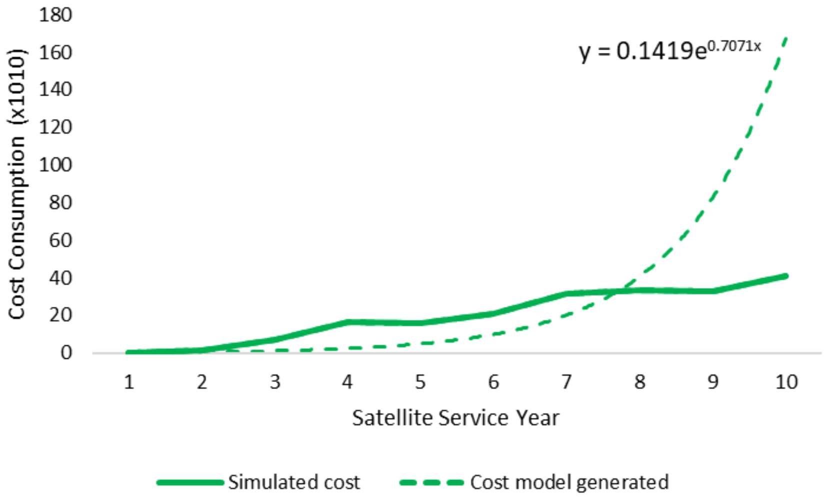

Figure 4.12 Operational Cost Model exponential graph of 2-parallel configuration with 10-year MTBF Earth Station configuration model and measured.

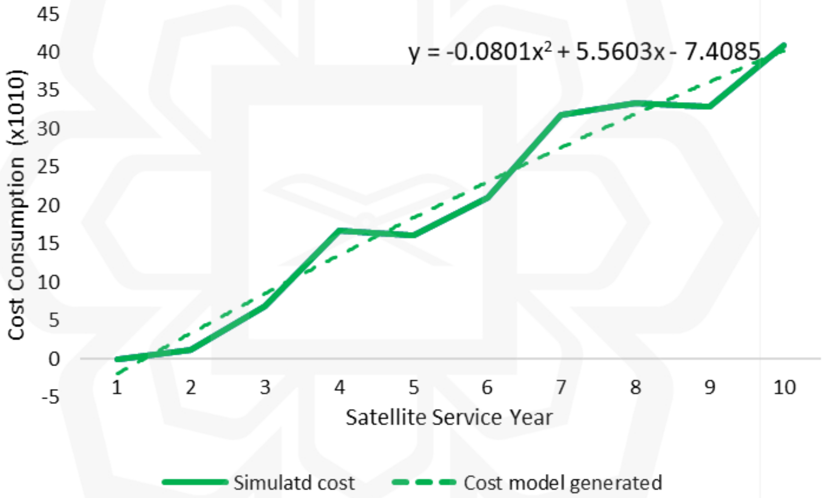

Figure 4.13 Operational Cost Model polynomial graph of 2-parallel configuration with 10-year MTBF Earth Station configuration model and measured.

4.7 VALIDATION OF RELIABILITY AND OPERATIONAL COST MODELS

The reliability and operational cost models were compared to the models that had previously been produced by (Nadirah; Abdul Rahim & Nordin, 2020) and (Amaitik et al., 2022) in Table 4.6.

Table 4.6 The reliability and operational cost models' percentage fractional error, RMS error calculation and validation.

System Service Year	Reliability Model		Percentage fractional Error (%)	Operational Cost Model (x e10)		Percentage Fractional Error (%)
	New	Abdul Rahim	New/Abdul Rahim	New	Amaitik	New/Amaitik
1	1.01	0.93	-8.60	0.97	0.00	-247.00
2	0.89	0.9	1.11	3.71	7.23	48.67
3	0.79	0.87	9.20	8.39	9.07	7.47
4	0.7	0.84	16.67	13.07	17.16	23.81
5	0.62	0.8	22.50	17.75	16.57	-7.10
6	0.55	0.77	28.57	22.43	21.65	-3.58
7	0.49	0.74	33.78	27.11	25.57	-6.03
8	0.43	0.71	39.44	31.79	34.36	7.50
9	0.38	0.68	44.12	36.47	39.62	7.96
10	0.34	0.64	46.88	41.15	41.95	1.92
			RMS Error Value=			**RMS Error Value=**
			20.84			**22.82**

From Table 4.6, this research found that Abdul Rahim's reliability modelling yields higher values throughout the lifecycle service as compared to the new modelling value generated from the simulation which consequently provided positive percentage fractional errors except for the first year of service. Nonetheless, the newly generated reliability model's calculated RMS error has a value of 20.84% which fell within the acceptable range.

On the other hand, Amaitik's cost model values are mostly similar to the new generated cost model values of which its percentage fractional errors fell within range of ±10%. Thus, the operational cost model's RMS error generated a value of 22.82%. From these results, it can be concluded that the new reliability and operational cost models were validated to be used in the Earth Station system design which encompassed the sustainable framework.

4.8 MAINTENANCE FRAMEWORK

A list of variables that must be considered in selecting the optimum maintenance activities for the Earth Station system was identified to ensure that it functioned sustainably. Based on the typical problems observed generally, Table 4.7 showed the recommended maintenance tasks. These tasks are designed as preventive maintenance to overcome the regular issues encountered by MEASAT. The optimal maintenance tasks for the specified equipment were often determined by the state of the subsystem. The mentioned maintenance tasks must be completed on a regular basis, and the replacement part was only done when the subsystem has stopped working.

Table 4.7 The proposed maintenance activities.

Equipment	Maintenance Activity	Potential Fault
High Power Amplifier (HPA)	1. Verify the RF output coming from the monitoring port and compare the spectrum map to earlier activities. This is to determine whether the HPA's current attenuation or gain is appropriate. 2. Clean Air In/Out filter. 3. Verify the front panel using local control (panel button) and remote control (M&C System).	1. Due to the Klystron amplifier; inadequate current supply, channel switch issue, and connection port issue. 2. HPA blower failure caused by a faulty air intake sensor or a mechanical blower failure.
Up-Converter (UC) and Down-Converter (DC)	1. Clean the dust spot on the unit. 2. Verify power cables and RF in/out cables connection. 3. Investigate RF output from monitoring port and adjust attenuation/gain value if required.	1. Short circuit likely caused the power supply module to malfunction. 2. The unit has a low gain parameter, which is most likely related to the device's ageing factor.
Low-Noise Amplifier (LNA)	1. Examine the physical component within the antenna hub. 2. Verify that the LNA Controller panel or M&C page does not display any latched faults for the online unit. 3. Perform LNA current(mA) calibration if required	1. The unit became defective because the current (mA) exceeded the calibrated current. 2. Lightning struck the antenna, causing a large current flow to the LNA.

Antenna	1. Annual antenna dish cleaning 2. Annual antenna motor greasing/oiling. 3. Verify Antenna Control Unit (ACU) and correct parameter has been keyed-in for satellite tracking. 4. Check the condition of the Teflon and the feed, and ensure sure the air pressure inside the feed is enough. 5. Clean the antenna hub	1. Broken antenna motor gearbox. 2. Broken elevation/azimuth jackscrew. 3. ACU power module fault. 4. Low air pressure inside the antenna feed and waveguide system that requires the dehydrator system to be checked.
Measurement and Control System (M&C System)	1. Verify all RF equipment status reflect on the M&C page. 2. Ensure the M&C licence is renewed and audited. 3. Examine the physical M&C unit.	1. Faulty M&C unit power supply. 2. M&C unit ports unresponsive/faulty.
RF Backup unit	1. Physical inspection. 2. Verify the unit by injecting clean wave (CW) and measure the output 3. Verify no alarm shown on the front panel	1. Possible faulty alarm or equipment

4.9 CHAPTER SUMMARY

This chapter portrayed the results, modelling and discussion. The random failure rate of each subsystem and each parallel configuration was obtained by running the Monte Carlo in MATLAB programming. The mean of all the failure rates were calculated and depicted as lambda (λ) which was then used to determine which parallel configurations provide higher reliability. As predicted, higher redundancy in a system affected the operating cost. Hence, a reliability model was then developed based on the most reasonable affordability. The data modelled has been validated with previous research and a simple but robust maintenance framework was also proposed to ensure the Earth Station system runs sustainably.

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 RESEARCH FINDINGS

The first objective of this research has been successfully achieved which is to identify the factors that contribute to the problems of Earth Station system failures that can cause cost blow up. The found problems are as highlighted in Section 2.2 and thus, a basic Earth Station system model has been illustrated focusing on subsystem which encounters most failure.

The reliability of the Earth Station system has been analysed based on 2-parallel, 3-parallel, and 4-parallel configurations with MTBF values of 1 year, 3 years, 5 years, 7 years, and 10 years. In the 2-parallel configuration, each subsystem has two redundant units, whereas in the 3-parallel configuration, each subsystem has three redundant units and four redundant units in the 4-parallel configuration. The attained reliability graphs have proven that system reliability is affected by its MTBF. The higher the MTBF value, the greater the system reliability. The research found that the highest reliability measured in a system with MTBF of 10 years in 4-parallel configuration.

These reliability graphs have been further investigated to study the relationship between operational cost and system redundancy. The results obtained by applying the Equation 3.1 have been converted into an affordability profile where it showed the cost consumption for each year throughout the lifecycle of an Earth Station has been calculated. The research found that the 3-parallel configuration system consumed the highest operating cost of 2.735B$ whereas the 2-parallel configuration system consumed the lowest operating cost of 2.009B$. This result is due to the cost consumed to repair 3 redundant units is higher than the cost to repair 2 redundant units. However, this is not fully applicable for the 4-parallel configuration which operating cost spent of

RM2.017B since the redundant units served as a backup for any subsystem that could fail, and the defective subsystem may not always need to be repaired.

Subsequently, a new reliability model and affordability model were developed to provide a simple yet robust framework design of a geostationary satellite control Earth Station system as highlighted in Section 4.5 and Section 4.6. Both models were developed based on the 2-parallel configuration with a 10-year MTBF as it provides reliable performance within affordable range which achieved the second and fourth objectives of this research. The models are then validated with comparison to previous works by Nadirah & Afifah and Amaitik. This research has found that the newly generated reliability model's calculated RMS value was 20.84%, whereas the operational cost model's RMS value was 22.82%. These numbers fell within the acceptable range. Thus, it can be concluded that, the preventive maintenance activities together with the new reliability and operational cost models, are ready to be employed to the Earth Station system design as highlighted in Section 4.8. This finding is aligned to the third objective of this research. In turn, these three elements of reliability, operational cost and maintenance, encompass the sustainable framework which met the four objectives of this research.

5.2 RESEARCH CONTRIBUTION

Based on the reliability and operational cost models developed, a set of maintenance framework has been proposed to ensure that the system runs sustainably as listed in Table 4.7. An extra initiative had been taken to integrate the reliability and operational cost data with the data taken from MEASAT. Moreover, the affordability profile for each parallel configuration was generated to see the potential cash flow for each year until the end of its lifecycle. This affordability profile is a crucial element because a design expert can see whether it is overly spent money or underspent money for each year. The optimal maintenance tasks for specified equipment are determined by the state of the subsystem. Also, the maintenance tasks must be completed on a regular basis, and the replacement part is only done when the subsystem has stopped working.

The robustness of a geostationary satellite control Earth Station system can be improved by designing a sustainable framework which comprises three important elements: reliability and operational cost models as well as maintainability activities. This framework is ought to maintain the optimum performance of an Earth Station system. This research has also concentrated on ways to reduce costs while promoting economic growth, which is in line with SDG goal number 8 (Decent Work and Economic Growth). Additionally, this research is also linked to SDG goal number 9 (Industry, Innovation, and Infrastructure), which emphasizes on a sustainable engineering system framework to prevent any unexpected failures.

5.3 CHALLENGES AND FUTURE WORK

This research has emphasized on past data analysis of the Earth Station system which is relevant to be used to design the next generation of the system. The data used in this research was a mixture of primary and secondary data which was presumed like the repair cost. On top of that, this research was mainly focused on Ka band geostationary satellite control Earth Station system.

Real-time data integrated with Artificial Intelligence (AI) is highly advised to continuously improvise the system reliability even after the system has been launched. The research findings would also be more precise if all data input are real measured data. Finally, different measured frequency band data from various types of satellite Earth Station system are also proposed to verify the reliability and operational cost models which are feasible to be used globally.

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APPENDIX B: MATLAB Coding Simulation

MATLAB Coding Simulation

```
%========================Main
Function===================================
clc;
clear all
close all
%Initial assumption of the number of rows we should have
t=1;
%___________________Initial Cost__________________________

maxdesign=5000;  %this is the maximum cost for the design
construction
maxoperation=8000; %this is the maximum cost for the normal operation
of the satellite system to work
maxcost=134000;   %this is the maximum cost for the replacement
maxdis=20000;    %this is the maximum disposal cost.
maxsubs=15600;   %this is the maximum subsystem cost


%______System Environment Setting & Presumptions_______________
%Generating the matrix of random time of failure for 10 subsystems
TOF = randi(10,[1,10]); %10 indicates the number of time of failure

%Generating the matrix of failure rate for 10 subsystems over 1 year
FR = TOF/8766;

%Generating the average value of failure rate for 10 subsystems
FRA = mean(FR);

%Plotting the failure rate for 10 subsystems
figure(1)
plot(FR,'r','LineWidth',2)
set(gca,'FontWeight','bold','FontSize',10)
title('Random failure rate of 10 subsystems')
xlabel('Subsystem')
ylabel('Failure rate')

hold on;
plot(FRA,'*');

%function [FRA] = FR2p(lambda)

%[FRA] = FR2p(lambda);
%lambda=1.141e-4; %the failure rate
lambda = FRA;
%Value input of number of subsystems
ns=20;

%Value input of number of rows in TTF and TTR
n = 1;
```

```
%Initial assumption of maximum time to failure (hours)
maxttf = 1000;

%Initial assumption of maximum time for a repair (hours)
maxttr = 800;
mintttr = 10;

%Generating two matrices randomly (integers and a uniform
distribution will be used)
%ensure we get the same matrix all the time

% for the plotting,
% an initial value of 300 events to be presumed
ilength = 300;

%Defining the subsystem initial state
mystates = zeros(ilength, ns);

%Defining the state of a subsystem over the running time
mytimes = zeros(ilength,1);

%If a system does not change its state, the current length just
repeats
clength = ilength;
startin=[n:n+1:100*n+1];

%Recording the number of times a sub-system has failed
TimesThatFailed =zeros(1,ns);

% This will keep track of the number of hours a subsystem has been
% working for (the number of hours this subsystem has been on)
% to keep track we store the time in which it previously failed then
we
% apply wt(1,i) = wt(1,i) + accumulatedtime - wt(2,i) where wt(2,i)
is the time
% stamp for when the last repair of subsystem it took place.
% Note: it is only updated when the system fails.
wt = zeros(2,ns);

%Stating initial state of the whole sub-system
fprintf(' These are the initial states ')
SV = repmat([1,2],1,ns/2)

MCRun=1e6; %Monte Carlo Run

%Assuming a system failure which requires Technician visit
%where prob (0<=p<=0.2)(time to repair)
%Assuming the Time Between Repair (TBR) and Cost To Repair
(CostToRep)
TBR=[8,40,8,40,8,40,8,40,8,40,10,50,10,45,14,60,10,45,10,45];
%CostToRep=[250,375,667,312,500,667,375,625,312,667,125,667,312,500,6
67,230,340,125,300,556];

myseed=1;
rng(myseed,'twister');

startin=[n:n+1:100*n+1];
```

```
% ---This will keep track of the number of times a sub-system has
failed.
% it will be incremented by 1 each time the subsystem fails
TimesThatFailed =zeros(1,ns);

%Generating the matrix Time Between Failure
TBF = randi(maxttf,[n,ns]);
%Generate Cost to Replace the subsystem
CostToRep=maxcost*rand(1,ns);
%In Sum, before calculating MTBF X Cost Calculation, additional
%presumptions need to be defined
maxtime=
[8760,17520,26280,35040,43800,52640,61320,70080,78840,87600,96360,105
120,113880,122640,131400,140160,148920,157680,166440,175200];
%equivalent to 1 year

%Accumulated time of working state (hour)
accumulatedtime = 0;

%Previous time of failue state (hour)
previousfailuretime = 0;

%Previous time of repair state (hour)
previousrepairtime = 0;
event=0;
clength=0;

%Penalty defined as the time consumed when a sub-system failure is
not
%available for repair
Penalty=zeros(ns,20);

OutageTime=zeros(ns,20);
TechnicianHire=10;
MCRun=1e6; %Monte Carlo Run
TBR =
[10,50,2000,10,50,2000,10,50,2000,14,60,2000,14,60,2000,14,60,2000,10
,50];
CostToRep1=[230,340,125,240,440,125,250,560,150,179,467,150,171,367,1
25,164,283,125,230,340];

%___________________Subsystem State
Simulation__________________________


for y=1:20

while(accumulatedtime<=maxtime(y)) %this loop ends when the system
reaches its intended service life

% STEP 1 in the word document: Find the next failure.

%we start setting times here because it is easier
%first,we check if the list is large enough
    event = event +1;

    if (event > clength)
        mystates = [mystates; zeros(ilength, ns)];
```

```
        mytimes = [mytimes;zeros(ilength,1)];
        clength = event -1 + ilength;
    end
    for c = 1:1:ns
        mystates(event,c) = SV(c);
        mytimes(event,1)= accumulatedtime;
    end

    [f2,f1] = FindMinimalWithState(TBF,1,SV,1);
    [r2,r1] = FindMinimalWithState(TBR,1,SV,0);    %NOTE: If r2 is
infinite, it means that all systems are working and no repair is
scheduled

% Now we have two cases, the next event can be either a failure or a
repair,

% If next event is a failure
    if (f2 <= r2)

        TimesThatFailed(1,f1) = TimesThatFailed(1,f1) + 1;
        previousfailuretime = accumulatedtime + f2;
        accumulatedtime = accumulatedtime + f2;

     % -- updating the variables
     wt(1,f1) = wt(1,f1) + accumulatedtime -
wt(2,f1);          %this is for how many hours that the subsystem
has been working for
     % -- updating the new
       string1 = horzcat('Number of times this subsystem has failed:
', num2str(TimesThatFailed(1,f1)), ' \n Number of hours this
subsystem has been working for:  ', num2str(wt(1,f1)), ' hours since
the beginning of time. \n');
       fprintf(horzcat('Event ', num2str(event), ': \n Trigger:
Failure. \n Subsystem ', num2str(f1), ' \n Time of failure (TOF): ',
num2str(accumulatedtime), ' \n Time between failure (TBF): ',
num2str(accumulatedtime + f2 - previousfailuretime), 'hours. \n Time
since last repair: ', num2str(accumulatedtime + f2 -
previousrepairtime), ' hours. \n', string1 ))

        % step 5: updating times (this does not affect standby
systems)
        for i=1:ns
            if (SV(i)==1)
                TBF(1,i) = TBF(1,i) - f2;


            end
%             if (SV(i)==0)
%                 TBR(1,i) = TBR(1,i) - f2;
%                  if (TBR(1,i) < 0)
%                     TBR(1,i) = 0;
%                  end
%             end
        end


        % now we will change the state of this subsystem to "failed"
        % (STEP5)
        % (It should be changed after updating times, otherwise this
time will affect the repair time)
        % 4 in document)
```

```
        SV(f1) = 0;

        % step 5: looking for a replacement (this will look for the
subsystem
        % with state 2)
        mu = 0;
        if (mod(f1,2)>0)
            mu = 1;
        end
        module = floor(f1/2)+mu;

        %since there are three modules


        %identify the first element to check

        theminimum=inf;
        standby=-1;     %there is no subsystem in standby detected
yet. If at the end this value is still -1 then it means that there
are no standby systems available
        nextc = startin(module);
        for checking = nextc: 1: nextc +1
            if ((SV(checking) == 2)&&(SV(checking)<theminimum))
                theminimum=TBF(1,checking);
               standby=checking;
            end
        end

        if (standby<0)
            fprintf(horzcat(' There are no standby subsystems to
replace subsystem ', num2str(f1), '. The outage time is
' ,num2str(f2)))
           OutageTime(f1,y)=f2;
        else
            SV(standby)=1;
            wt(2,standby) = accumulatedtime; %put a time stamp to
when this system was repaired
                fprintf(horzcat('This is part of event ',
num2str(event), ': Subsystem ', num2str(f1), ' is being replaced by
subsystem ', num2str(standby), '. See the new vector state: '));
                SV

        end
        % moving everything up one row
        TBF(1:n-1,f1) = TBF(2:n,f1);
        % assigning a new value at the end (for time to failure)
        TBF(n,f1) = randi(maxttf,1);
        continue;
    end


    %if we got here is because the next event is a repair

   fprintf(horzcat('Event ', num2str(event), ': \n Trigger: Repair.
\n Subsystem: ', num2str(r1), '\n TOF+TOR : ',
num2str(accumulatedtime+r2), ' hours. \n Time of repair (TOR): ',
num2str(accumulatedtime + r2- previousfailuretime ), ' \n Time (Since
last repair):  ', num2str(accumulatedtime + r2 -previousrepairtime),
'\n' ))
```

```
    % See below.. we need to look if this subsystem will be working
or in
    % standby
    previousrepairtime = accumulatedtime + r2;
    accumulatedtime = accumulatedtime + r2;

    %updating repairing times and times to failure

      % step 15: updating times (this does not affect the standby
systems)
        for i=1:1:ns
            if (SV(i)==1)
                TBF(1,i) = TBF(1,i) - r2;
            end
%             if (SV(i)==0)
%                 TBR(1,i) = TBR(1,i) - r2;
%             end
        end
    % identify the module in which the repair was done
     mu = 0;
        if (mod(r1,2)>0)
            mu = 1;
        end
        module = floor(r1/2)+mu;

     % look if there is a subsystem in that module working. If so,
this new
     % repaired system will be in standby. Otherwise, it will start
working
     % immediately. Notice that the state of the subsystem is only
updated
     % here, if we do it before, the system will think that this
system has
     % been in standby or working for more time...

        nextc = startin(module);

        ifound = 0;
        for checking = nextc: 1: nextc +1
            % if mod(r1,3)==1) it means that it is a primary system,
            if (SV(checking) == 1)
                ifound = 1; % indicate that it was one already
working
                if(mod(r1,2)==1)
                    SV(r1) =2; %the primary is set to
standby!    %The  change that I made here
                    SV(checking) =1; % the standby will be the
primary
                     fprintf(horzcat('The subsystem ', num2str(r1), '
has been repaired. Setting subsystem  ', num2str(r1), ' to standby.
The subsystem ', num2str(checking), ' is working. See new vector
state: \n'));



                     % The system "checking" is going to standby,
then, we
                     % will need to  update wt.......................
                     wt(1,checking) = wt(1,checking) +
accumulatedtime - wt(2,checking);
```

```
                    wt(2,checking) = accumulatedtime;  % put a time
stamp, MAYBE NOT NECESSARY
                    wt(2,r1) = accumulatedtime; %put a time stamp to
when this subsystem was repaired and put to work

TimeToRep(1,checking)=wt(1,checking);          %this is time to
replace
                    %CTRep(1,checking)=CostToRep(1,checking);
%Cost to replace the standby subsystem
                    SV

                    break;
               else
               SV(r1)=2;
               fprintf(horzcat('This is part of event ',
num2str(event), ': Subsystem ', num2str(r1), ' was repaired and
changed state to standby. See the new vector state: '));
               CTR(myseed,r1)=TechnicianHire*(accumulatedtime + r2 -
previousrepairtime);      %Cost to repair ($CTR)
               SV
               break;
               end
           end
       end
           if (ifound == 0)
               SV(r1) = 1;
               wt(2,r1) = accumulatedtime; %put a time stamp to when
this system was repaired and put to work
               fprintf(horzcat('This is part of event ',
num2str(event), ': Subsystem ', num2str(r1), ' was repaired and put
to work immediately . See the new vector state: '));
               SV
           end
       % moving everything up one row (STEP 16)
       TBR(1:n-1,r1) = TBR(2:n,r1);
       % assigning a new value at the end (for time to repair)
       TBR(n,r1) = TBR(r1);



%          TechnicianHire=100; %the cost to hire a technician
%          CTR=TechnicianHire*TBR;      %Cost to repair ($CTR) for
each subsystem
%          CostRepair=sum(CTR);

sTBF(:,:)=TBF(:,:);            %soerted version of time between
failure
%Ct(:,:)=TBR(:,:);            %sorted version of corrective
maintenance time

end
WT(:,y)=wt(1,:); %operating time for each year (20 years)
NumberItFails(:,y)=TimesThatFailed(:,:);
SortedTBF(y,:)=TBF(:,:);
TimeBetRep(y,:)=TBR(:,:);
Ct(:,y)=sum(TBR(:,:));
CTR(y,:)=(TBR(:,:).*CostToRep1);%Cost to repair ($CTR) for each
subsystem
z=CTR';
CostToRepair=sum(z);
AnnualOpC(:,y)=6e4*y;
```

```
end


%number of subsystems
nt=25;

% number of rows in TTF and TTR
n = 1;

%make sure we get the same matrix all the time
myseed=1;
rng(myseed,'twister');

%make sure we get the same matrix all the time

% for the plotting
% we will give an initial value of 1000 events, (we don-t know how
manx
% events will fit in the number of hours xou put
ilength1 = 20;
mystates1 = zeros(ilength1, nt);
mytimes1 = zeros(ilength1,1); %% all subsxstems will share this
vector.
% if a sxstem does not change its state, it just repeats
clength1 = ilength1;

% ---This will keep track of the number of times a sub-sxstem has
failed.
% it will be incremented bx 1 each time the subsxstem fails
TimesThatFailed1 =zeros(1,nt);

% ---This will keep track of the number of hours a subsxstem has been
% working for (that is, the number of hours this subsxstem has been
on)
% to keep track we store the time in which it previouslx failed then
we

% applx wt1(1,i) = wt1(1,i) + accumulatedtime - wt1(2,i) where
wt1(2,i) is the time
% stamp for when the last repair of subsxstem i took place.
% Note: it is onlx updated when the sxstem fails... xou can
% change it to be udpated anxtime an event occur.
wt1 = zeros(2,nt);

%the initial states: I assume there will be 20 transponders working
at the
%same time, and the rest of 5 will be kept as standbxs
fprintf('These are the initial states');
SV1=[1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,2,2]; %this is the
state of the transponder.

accumulatedtime1 = 0;
previousfailuretime1 = 0;
previousrepairtime1 = 0;
event1=0;
Penalty1=zeros(nt,20);
maxtime1 =
[8760,17520,26280,35040,43800,52640,61320,70080,78840,87600,96360,105
```

```
120,113880,122640,131400,140160,148920,157680,166440,175200];       %
equivalent to 1 year
%generate the matrix TTF
%TBF1 = (8760+(175200-8760))*rand(n,nt);
TBF1=131400*randi(1,n,nt);
%Generate TTR
TBR1 = 268200*randi(1,n,nt);
fprintf('The next results are for Satellite Transponder');


for x=1:20

while(accumulatedtime1<=maxtime1(x)) %this loop ends when the system
reaches its intended service life

% STEP 1 in the word document: Find the next failure.

%we start setting times here because it is easier
%first,we check if the list is large enough
    event1 = event1 +1;

    if (event1 > clength1)
        mystates1 = [mystates1; zeros(ilength1, nt)];
        mytimes1 = [mytimes1;zeros(ilength1,1)];
        clength1 = event1 -1 + ilength1;
    end
    for c = 1:1:nt
        mystates1(event1,c) = SV1(c);
        mytimes1(event1,1)= accumulatedtime1;
    end

    [f3,f4] = FindMinimalWithState(TBF1,1,SV1,1);
    [r3,r4] = FindMinimalWithState(TBR1,1,SV1,0);     %NOTE: If r3 is
infinite, it means that all sxstems are working and no repair is
scheduled

% Now we have two cases, the next event can be either a failure or a
repair,

% If next event is a failure
if (f3 <= r3)

        TimesThatFailed1(1,f4) = TimesThatFailed1(1,f4) + 1;
        previousfailuretime1 = accumulatedtime1 + f3;
        accumulatedtime1 = accumulatedtime1 + f3;



     % -- updating the variables
     wt1(1,f4) = wt1(1,f4) + accumulatedtime1 -
wt1(2,f4);            %this is for how manx hours that the subsystem
has been working for
     % -- updating the new
      string1 = horzcat('Number of times this subsystem has failed:
', num2str(TimesThatFailed1(1,f4)), ' \n Number of hours this
subsystem has been working for:  ', num2str(wt1(1,f4)), ' hours since
the beginning of time. \n');
      fprintf(horzcat('Event ', num2str(event1), ': \n Trigger:
Failure. \n Subsystem ', num2str(f4), ' \n Time of failure (TOF): ',
num2str(accumulatedtime1), ' \n Time between failure (TBF1): ',
```

```
num2str(accumulatedtime1 + f3 - previousfailuretime1), 'hours. \n
Time since last repair: ', num2str(accumulatedtime1 + f3 -
previousrepairtime1), ' hours. \n', string1 ))
        TimeOfFailure(x,:)=accumulatedtime1;
        % step 5: updating times (this does not affect standby
sxstems)
            for i=1:1:nt
             if (SV1(f4)==1)
                TBF1(1,f4) = TBF1(1,f4) - f3;

             end
%             if (SV1(i)==0)
%                 TBR1(1,i) = TBR1(1,i) - f3;
%                  if (TBR1(1,i) < 0)
%                     TBR1(1,i) = 0;
%                  end
%             end
            end


        % now we will change the state of this subsxstem to "failed"
        % (STEP5)
        % (It should be changed after updating times, otherwise this
time will affect the repair time)
        % 4 in document)
        SV1(f4) = 0;



        %identify the first element to check

        theminimum1=inf;
        standby1=-1;    %there is no subsystem in standby detected
yet. If at the end this value is still -1 then it means that there
are no standby systems available
        %nextc = startin(module);
        for checking1 = find(SV1==2, 1, 'first');
            if ((SV1(checking1) == 2)&&(SV1(checking1)<theminimum1))
                theminimum1=TBF1(1,checking1);
               standby1=checking1;
            end
        end

        if (standby1<0)
            fprintf(horzcat('There are no standby subsystems to
replace subsystem ', num2str(f4), '. The outage time is
' ,num2str(f3),'. We will need to wait and pay the penalty cost is ',
num2str(f3*2500)))
           Penalty1(f4,x)=f3*2000;
            SV1
        else
            SV1(standby1)=1;
            wt1(2,standby1) = accumulatedtime; %put a time stamp to
when this system was repaired
                fprintf(horzcat('This is part of event ',
num2str(event1), ': Subsystem ', num2str(f4), ' is being replaced by
subsystem ', num2str(standby1), '. See the new vector state: '));
                SV1

        end
        % moving everything up one row
```

```
        TBF1(1:n-1,f1) = TBF1(2:n,f1);
        % assigning a new value at the end (for time to failure)
        TBF1(n,f4) = (8760+(175200-8760))*rand(n,1);
        continue;
end


    %if we got here is because the next event is a repair

    previousrepairtime1 = accumulatedtime1 + r3;
    accumulatedtime1 = accumulatedtime1 + r3;

     % step 15: updating times (this does not affect the standby
sxstems)
        for i=1:1:nt
            if (SV1(i)==1)
                TBF1(1,i) = TBF1(1,i) - r3;
            end
            if (SV1(i)==0)
                TBR1(1,i) = TBR1(1,i) - r3;
            end
        end

   TBR1(n,r4)=262800;

sTBF1(:,:)=TBF1(:,:);             %sorted version of time between
failure
%Ct(:,:)=TBR1(:,:);             %sorted version of corrective
maintenance time
end
WT1(:,x)=wt1(1,:);
end

%=======================MTBF and Reliability
Calculation====================================

OpTime=sum(WT);

MeanTBF=mean(SortedTBF);
% FR=(1./MeanTBF)*1e-2;

Rs=exp(-lambda.*WT);      %the reliability for each subsystem
Rs1=mean(exp(-lambda.*WT1));

f=1;
%_______Reliability equation for 2-parallel_________________________
R_2P=1-((1-Rs(f:2*f:ns*f,:)).*(1-Rs(2*f:2*f:(ns+1)*f,:)));
R_2pp=
R_2P(f,:).*R_2P(f+1,:).*R_2P(f+2,:).*R_2P(f+3,:).*R_2P(f+4,:).*R_2P(f
+5,:).*R_2P(f+6,:);
Rw=Rs1.*R_2pp;

%_______Reliability equation for 3-parallel_________________________
%R_3P=1-((1-Rs(f:3*f:ns*f,:)).*(1-Rs(2*f:3*f:(ns+1)*f,:)));
%R_3pp=R_3P(f,:).*R_3P(f+1,:).*R_3P(f+2,:).*R_3P(f+3,:).*R_3P(f+4,:).
*R_3P(f+5,:).*R_3P(f+6,:);
%Rw=Rs1.*R_3pp;

%_______Reliability equation for 4-parallel_________________________
```

```
%R_4P=1-((1-Rs(f:4*f:ns*f,:)).*(1-Rs(2*f:4*f:(ns+1)*f,:)));
%R_4pp=R_4P(f,:).*R_4P(f+1,:).*R_4P(f+2,:).*R_4P(f+3,:).*R_4P(f+4,:).
*R_4P(f+5,:).*R_4P(f+6,:);
%Rw=Rs1.*R_4pp;


figure(2)
plot(Rw,'r','LineWidth',2)
set(gca,'FontWeight','bold','FontSize',10)
title('MTBF = 1 year')
xlabel('Satellite Service Year')
ylabel('Reliability')
Availability=MeanTBF./(MeanTBF+Ct);          %Availability
calculation

%this will generate 1000000 MC runs for total cost
% myseed=1;
% rng(myseed,'twister');
MCRun=1e6;


IC=1.8e6*2+1.5e6*2+3e6*2+1.5e6*2+1.5e6*2+1.8e6*2+2.5e6*2+1.5e6*2+1.5e
6*2+1.8e6*2;
IniState=2.5e6;    %Initial Investment cost for land,building

InitialCost=IC+IniState;
InitialMin=1e6;
CostIni=(-InitialCost)*randi(1,MCRun,1);




%___________________Annual Repair Cost
Generation__________________________
for i=1:10 %10=number of year of service
   AnnualOpC1(i,:)=AnnualOpC(1,i)*rand(1,MCRun);
   CostToRepair2(i,:)=CostToRepair(1,i)*rand(1,MCRun);
end

%___________________Annual Total Repair
Cost_______________________________
TotalCost=(AnnualOpC1+CostToRepair2);
TC=[-CostIni,TotalCost'];%the size is 10x1million
%TCNeg=[CostIni';TotalCost];
% TC1=TC'; %the size is 1millionx10

%___________________Affordability Profile
CashFlow_________________________
figure(3)

for p=1:10 %10 = number of year of service
subplot(5,2,p) %(5,2,p) = 5rows X 2columns
histogram(TC(:,p),30) %10 here is referring to the number of bins
set(gca,'FontWeight','bold','FontSize',10)
t1=({[' Year ', num2str(p)]});
t2=({[ 'Amount of '];[' Money ($)']});
t3=({[ 'Frequency']});
title(t1)
xlabel(t2,'FontWeight','bold');
ylabel(t3,'FontWeight','bold');
end
```

```
%========================End of Cost 
Calculation============================

% This function will find the minimal value in a row in a matrix 
while
% looking only into those columns indicated by a state.
%
% name of function: FindMinimalWithState
% most recent modification: Saturday 30 of July 11:30 pm
% status: It works ok.
% Sintaxis: there are 4 arguments (m,r,sv,s) defined as follows:
%            m: the matrix
%            r: the row in which the function will look for the 
smallest
%            value and,
%            sv: (state vector) the vector in which you keep the 
states.
%            Notice that this vector must have as many entries as 
columns in
%            the matrix m.
%            s: the state that will be taken into account. That is, in 
which
%            columns of the matrix is this function going to look at
%
%            outputs: two values (x,y) where:
%            x: the smallest value found when applying the given 
criteria.
%            y: the column in which this smallest value was found.
%            NOTE: if there is an error during the computation of the
%            function, these two values will be map to 0.
% Example: consider a matrix A=
%            2   4   5   6   1
%            3   2   1   8   9
%           and  the state vector
%           SV = [1,2,0,1,0].
%           If we do [r2,r1] = FindMinimalWithState(A,1,SV,1)
%           we will obtain that r1 = 2 and r2 = 1 (the value was found 
in
%           the first column

function [x,y] = FindMinimalWithState(m,r,sv,s)
          if size(m,2) ~= length(sv)
              fprintf(horzcat('Error from FindMinimalWithState: the 
state vector must have as many entries as columns in m ', 
num2str(size(m,2)), '\n'))
              x = 0; y =0;
              return;
          end
          if (size(m,1) < r)
              fprintf('Error from FindMinimalWithState: the specified 
row is out of the boundaries of the matrix m')
              x = 0; y =0;
          end
          minimal = Inf(1);
          theindex = 0;
          for i = 1:1:length(sv)
              if (sv(i)==s) && (m(r,i) < minimal)
                  minimal = m(r,i);
                  theindex = i;
              end
```

```
        end
        x = minimal; y = theindex;
end
```