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OPERATIONAL COST MODELS FOR AN EARTH STATION SYSTEM USING 2-PARALLEL AND 4- PARALLEL CONFIGURATIONS

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ABSTRACT: Operational cost is important in any system. In the case of the earth station system, operational cost is very crucial. The operational cost can be divided into three costs: maintenance, failure, and replacement costs. There are many complex subsystems incorporated in the earth station system, for instance a high-power amplifier, modulators, and antennas, to name a few. In this research, only the replacement cost was considered. Moreover, there are many replacement methods that are available. These replacement methods implicitly influence both the replacement and the replacement costs. The aim of this research is to provide a new cost model based on which replacement method yields the lowest cost. Two replacement methods are involved in this research: failure-triggered and age-based. The failure-triggered and the age-based replacement methods were considered because these methods are the most used in previous research work. Furthermore, three types of cost models were also considered, and they were linear, polynomial, and exponential operational cost models. The outcomes show that the failure-triggered and age-based replacement methods of 2-parallel configuration of polynomial and linear operational cost models yielded the lowest RMSE value of 2.5. Therefore, both polynomial and linear operational cost models of the 2-parallel configuration were the most optimal operational cost models.

ABSTRAK: Kos operasi adalah penting dalam mana-mana sistem. Dalam kes sistem stesen bumi, kos operasi adalah sangat penting. Kos operasi boleh dibahagikan kepada tiga kos: kos penyelenggaraan, kegagalan dan penggantian. Terdapat banyak subsistem kompleks yang digabungkan dalam sistem stesen bumi, contohnya penguat kuasa tinggi, modulator, dan antena. Penyelidikan ini hanya membincangkan tentang kos penggantian. Selain itu, terdapat banyak kaedah penggantian sedia ada. Kaedah penggantian ini secara tersirat mempengaruhi kedua-dua kos penggantian dan penggantian. Matlamat penyelidikan ini adalah bagi menyediakan model kos baharu berdasarkan kaedah penggantian yang menghasilkan kos terendah. Dua kaedah penggantian yang terlibat dalam kajian ini: penggantian yang dicetuskan oleh kegagalan dan berdasarkan umur. Kaedah cetusan kegagalan dan penggantian berasaskan umur telah dipertimbangkan kerana kaedah ini paling banyak digunakan dalam penyelidikan terdahulu. Tambahan, tiga jenis model kos turut dipertimbangkan, iaitu model kos operasi linear, polinomial dan eksponen. Dapatan menunjukkan kaedah penggantian cetusan kegagalan dan berdasarkan umur melalui konfigurasi model 2 selari bagi kos operasi polinomial dan linear menghasilkan nilai RMSE terendah iaitu 2.5. Oleh itu, kedua-dua model kos operasi polinomial dan linear bagi konfigurasi model 2 selari adalah kos operasi paling optimum.

KEYWORDS: *Failure-triggered, Age-based, Operational cost, Earth station system and Polynomial cost model*

1. INTRODUCTION

Operational cost is often overlooked by engineers when calculating the overall earth station system life cycle cost (LCC) because other costs, such as planning and development costs, take a higher priority in calculating the overall earth station system LCC [1-2]. Moreover, there are so many operational cost models developed in the past by researchers. However, most of the operational cost models are hard to understand because of their complicated equations [3-9]. An earth station system has many crucial subsystems that have their own maintenance priority [2]. This priority can be used to determine the subsystems that need replacement the most to minimize the earth station system operational downtime. Parallel configurations are included to study the effect of the operational cost. Hence, 2-parallel, and 4-parallel earth station system architectures are used in the design space to see the differences of the cost values on the operational cost [1]. The 2-parallel configuration means there are two redundant units present in each subsystem. Similarly, the 4-parallel configuration means there are four redundant units present in each subsystem. This research is done to support Sustainable Development Goal (SDG) 9, which is to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation [1]. In this research, the mentioned infrastructure is dedicated towards the earth station system. The RF/antenna system always experiences higher failures than other parts of the earth station system as reported in [6,10]. To prevent excessive and unnecessary costs in operating and maintaining the earth station system, this research is fixated on the impact of two different earth station subsystem replacement methods towards the earth station operational cost model analysis to help the party involved. These two replacement methods are failure-triggered and age-based [9,11]. The failure-triggered replacement comes in handy when any subsystem breaks down. Simultaneously, the age-based replacement method can be used when the subsystems are replaced under a set of intervals [9,11]. Moreover, they have their own advantages and disadvantages that can result in either higher or lower expenses in operating the earth station system [1]. The reason these two replacement methods are chosen is because they are the most practiced ones found from in former research work [9,11]. From these two replacement methods, the lowest operational cost is considered for modelling purposes. The contribution of this research is the development of a new optimal cost model that can be implemented to operate and improve earth station systems. This paper is arranged as follows: Section 2 discusses the existing literature review of this research. Section 3 describes the research methodology used to achieve the designated results. Section 4 demonstrates results and analysis. Finally, Section 5 completes this research with future recommendations.

2. LITERATURE REVIEW

Table 1 tabulates the previous work on the cost estimation method, with an eye to each work's contribution and remaining research gap. There are many operational cost models that can be found in the literature review. The problem with those models is that they are very hard to understand and require extensive operational cost data, which is scarce to obtain due to confidentiality [10]. So, the motivational factor in performing this research is to develop a simple and understandable operation cost model based on the simulation results obtained from the 2-parallel and 4-parallel configurations. From Table 1, it can be deduced that the closest research work that matches with this research can be found in Amaitik's [9] and Shazana's [1].

Hence, these two works become the benchmark for this research. On the other hand, Table 2 shows the benchmarked cost values from the two operational cost models [1,9]. From Table 2, it can be concluded that the RMSE value of 22.82 is obtained through the percentage error calculation of both Amaitik's and Shazana's operational cost models. At the end of this research, the RMSE value can be compared to decide which model is the best one.

Table 1. Previous work on cost estimation method

Reference	Title	Contribution	Research Gap
[11]	Operational cost analysis of an earth station system using parallel configuration	Cost calculations such as replacement and operational are shown	No operational models are shown.
[1]	Sustainable framework for a geostationary satellite control earth station system using parallel configuration	Propose a new operational cost model that can be compared with existing Amaitik's [2] model. Provide earth station reliability model that can be related to the operational cost model.	No other configurations are used for the operational cost model.
[9]	Cost Modelling to support optimum selection of life extension strategy for industrial equipment in smart manufacturing	Provide cost modelling for failure triggered replacement method with 2-parallel earth station configuration. Discussing the cost driver and cost estimation relationships to calculate activity cost based on different maintenance strategies.Give detailed explanation on the cost breakdown structure.Provide detailed cost estimation methodology	The maintenance methods are too general. Various cost estimation methods are not compared
[6]	Analysis of failure frequency and failure rate of RF/Antenna subsystems for an earth station system	Clearly mentioned which subsystems in earth station system that need to be maintained. Provide data on the mean time between failure (MTBF) of the subsystems	The data only provides failure frequency of the subsystems
[2]	Maintenance cost-based importance analysis under different maintenance strategies	Discussing the priority on the subsystem maintenance to maximize the earth station system uptime. Suggest different replacement methods with detailed calculation to compare the effectiveness of said method	The calculation complexity level is high
[12]	Cost and performance modelling for earth system data management and beyond	Provide a research methodology and considerations relevant for modeling data centres.Demonstrate how to construct a coarse-grained model	Cost did not integrate fully with I/O middleware

Table 2. Benchmark of two operational cost models [1]

Earth Station Service Year	Operational Cost Model (e10)		Percentage error (%)
	Amaitik	Syazana	Syazana/Amaitik
1	0.00	0.97	-247.00
2	7.23	3.71	48.67
3	9.07	8.39	7.47
4	17.16	13.07	23.81
5	16.57	17.75	-7.10
6	21.65	22.43	-3.58
7	25.57	27.11	-6.03
8	34.36	31.79	7.50
9	39.62	36.47	7.96
10	41.95	41.15	1.92
		RMSE Value	22.82

2.1 Failure Cost

Earth station systems usually have failures with their antennas, which are used to send and receive data signals [13]. Earth station antennas are located on the ground end of satellite links. Higher gain is needed to receive weak signals from the satellite or to transmit strong signals to the satellite. The antenna can be damaged if a lightning surge occurs during thunderstorm weather when the power cord, antenna cable, and Local Area Network (LAN) cable are still connected to the main system. The damage is not limited to the antenna; most of the main devices in the monitoring room may also be affected. These damages can disrupt the operation activity of the satellite system. To prevent this scenario, operators are advised to ensure that there is no possible connection between the devices and the system established after the operation has ended [13].

2.2 Replacement Cost

As mentioned before, there are two types of replacement methods where each result in different replacement costs for the subsystems. The first one is a failure-triggered replacement method, used if any of the subsystems break. The next one is an age-based replacement method, where there is a time interval between each replacement of the subsystems [2]. There are a lot of subsystems that need to be maintained when planning for the earth station maintenance [6]. These subsystems have their replacement cost varying based on their structure complexity and difficulty to repair.

For the first type of replacement method (failure-triggered) only the subsystems that are broken are issued a replacement. From [6], the failure frequency for the 2-parallel and 4-parallel configurations are tabulated in Table 2 and Table 3, respectively. These two tables consist of subsystems, namely HPA, Antenna, LNA, Up Converter, Down Converter, Modulator, and Demodulator, that had their downtime at least once per year. These broken subsystems were replaced as soon as they ceased to function. This automatically increases the efficiency of the earth station operation.

For the second type of replacement method, which is age-based, the management will set up the interval between each replacement of the subsystems of the earth station. This time interval can be of any length, but it will be pointless if the time is too long (for example, 1 year) because, from [6], some of the subsystems were down during the first year of its lifecycle, thus disrupting the whole earth station operation. This method however can produce a different result if the time interval is set up for a shorter time, but it may introduce a hike in replacement cost.

2.3 Operational Cost Models

There are three types of operational cost models configured for each replacement method for the 2-parallel and the 4-parallel earth station system configurations, respectively. Those operational cost models are linear, exponential, and polynomial [14]. The linear operational cost model is characterized by a straight-line graph and showcases a constant rate of change in operational cost as replacements are made. It offers a simplistic yet valuable perspective, allowing decision-makers to evaluate the linear relationship between replacement frequency and corresponding cost implications [14]. As mentioned in the previous section, the existing cost models available are hard to comprehend due to their complex equations [15-21].

On the other hand, the exponential operational cost model presents a more dynamic scenario, where the graph curves upwards in an accelerating fashion. This signifies that operational costs escalate exponentially as replacements occur [14]. The exponential operational cost model captures situations where the relationship between replacement frequency and operational costs is highly nonlinear, indicating that even slight increases in replacements can lead to significant cost escalations [14].

Lastly, the polynomial operational cost model, as depicted by a curved graph with varying degrees of complexity, accounts for even more intricate relationships between replacement frequency and operational costs. It enables decision-makers to analyse scenarios where the cost implications are influenced by multiple factors, potentially leading to non-uniform growth patterns [14]. By incorporating polynomial equations of different degrees, this model caters to a wide range of situations, accommodating both moderate and highly complex cost relationships [14]. These operational cost models are compared directly to their measured operational cost, which yields varying Root Mean Square Error (RMSE) value that can show which model is the most optimal. By having a lower RMSE value, a model becomes more optimal as it has higher accuracy than the one with higher RMSE [14]. The RMSE value can be derived from Eq. (1).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)} \quad (1)$$

where x is the cost difference between measured cost and model cost for *n,* which is the number of years.

3. RESEARCH METHODOLOGY

There are several steps that need to be included to achieve the designated results. There are two parts in the methodology: the first part is the overall methodology of this research, and the second part is the replacement method selection [11]. As for the overall methodology, the explanation is in the following flowchart, as shown in Fig. 1. Fig. 1 illustrates the research methodology flowchart.

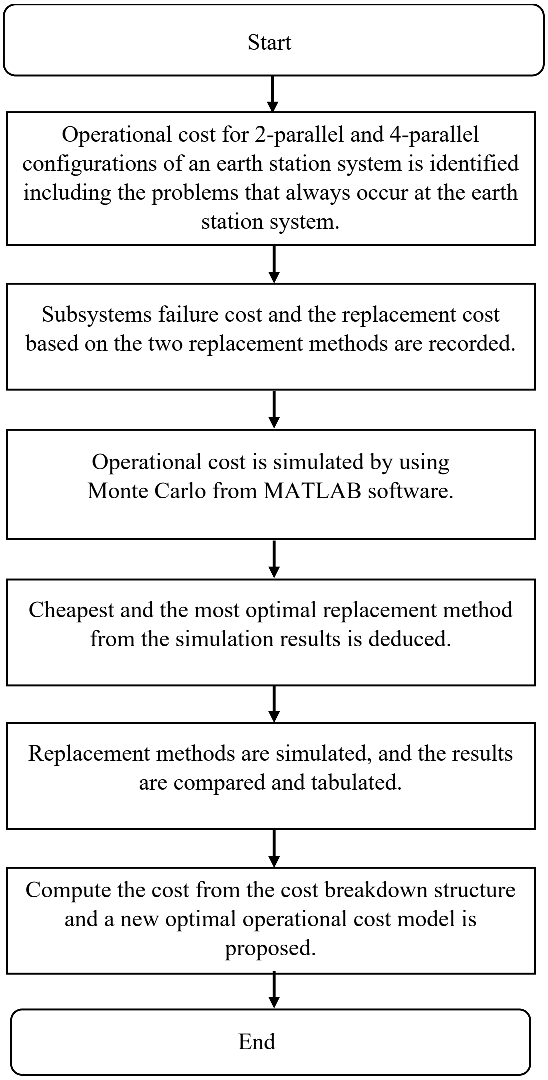

Figure 1. Research methodology flowchart.

Firstly, the operational cost for 2-parallel and 4-parallel configurations of an earth station system is identified including the problems that always occur at the earth station system. The 2-parallel and 4-parallel diagrams can be found in Fig. 2 and Fig. 3 respectively.

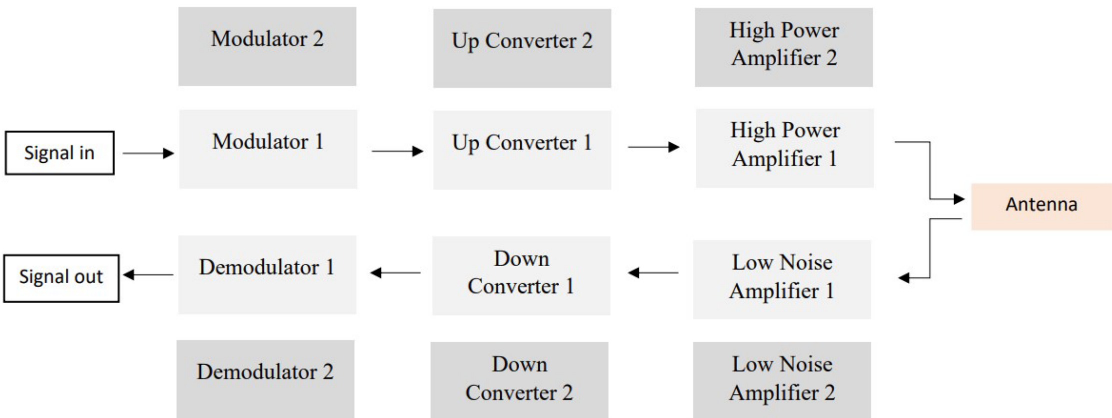

Figure 2. 2-parallel configuration.

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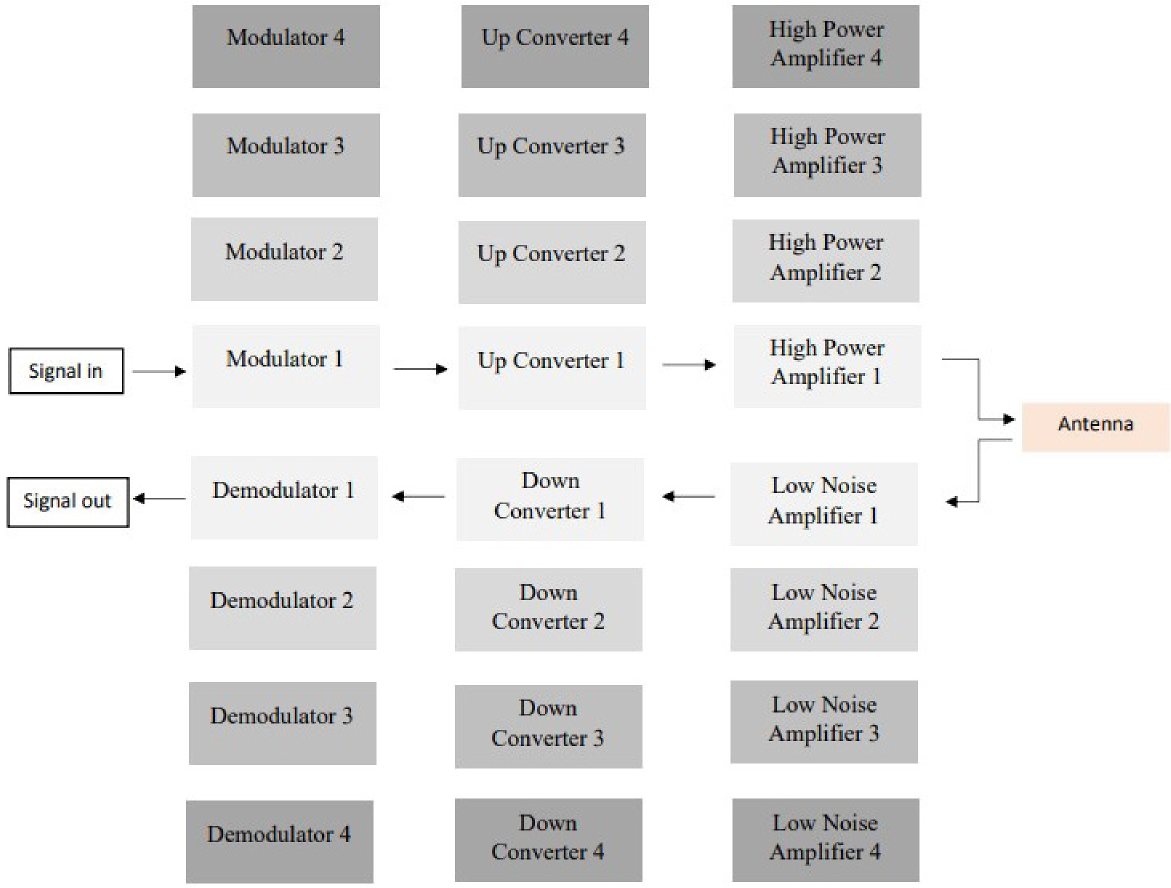


Figure 3. 4-parallel configuration.

In this case, 2-parallel and 4-parallel configurations are chosen because of Malaysia East Asia Satellite (MEASAT) recommendations [6]. MEASAT adopts these two configurations in their earth station system design [6]. Whereas 3-parallel configuration is not recommended by MEASAT because the configuration is less desirable in their earth station system design [6]. Then, the subsystems failure and the replacement costs based on the two replacement methods are recorded. Next, the operational cost is simulated by using Monte Carlo from MATLAB software [11]. After that, the cheapest and the most optimal replacement method from the simulation results is deduced. For the replacement method selection, there are two types of replacement methods: failure-triggered and age-based. Both replacement methods were simulated, and the results were compared and tabulated [11]. The last step is to compute the cost from the cost breakdown structure. The cost that is considered in this research consists of only replacement cost and based on this cost; a new optimal operational cost model is proposed.

The simulation duration was set to run for 10 years to collect sufficient operational cost data from those years. The operational cost data comprises operation and maintenance costs which were supplied by MEASAT, but the exact amounts were camouflaged. There are six parts of simulation: failure-triggered replacement linear operational cost model of the 2 and 4-parallel configurations, failure-triggered replacement exponential operational cost model of the 2 and 4-parallel configurations, failure-triggered replacement polynomial operational cost model of the 2 and 4-parallel configurations, age-based replacement linear operational cost model of the 2 and 4-parallel configurations, age-based replacement exponential operational cost model of the 2 and 4-parallel configurations, and age-based replacement polynomial operational cost model of the 2 and 4-parallel configurations. The data was then analyzed to find the most optimal replacement method using a certain configuration. The results are elaborated further in the next subsection.

4. RESULTS AND ANALYSIS

In this section, two types of replacement methods are shown. They are the failure-triggered and age-based replacement methods. For each replacement method, three types of operational cost models were developed: linear, exponential, and polynomial operational cost models. For each type of operational cost model, the unit is in US dollars.

4.1. Failure-triggered Replacement Linear Operational Cost Model

The first part of the cost modeling is for the failure-triggered replacement linear cost model. Fig. 4(a) shows the linear cost graph for the failure-triggered replacement of a 2-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The y-axis refers to the operational cost whereas the x-axis refers to the life services of the earth station system. The original measured cost can be viewed in [10]. The newly derived linear operational cost model is shown in Eq. (2).

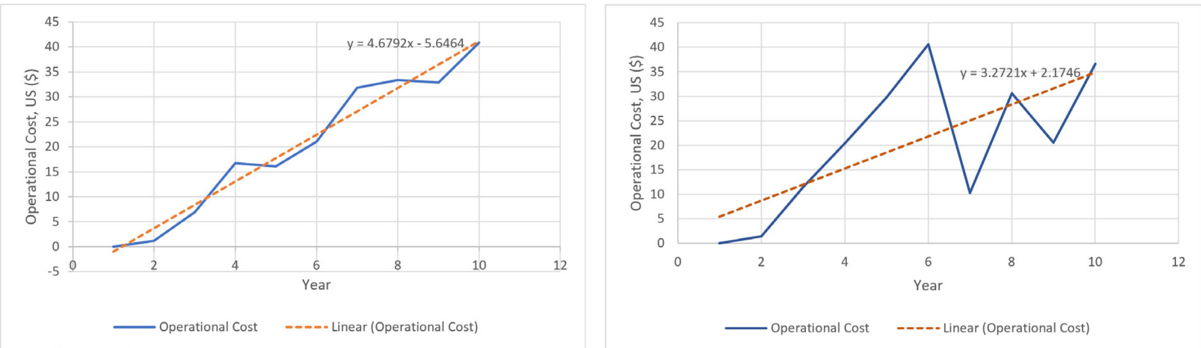
$$y = 4.6792x - 5.6464 \tag{2}$$

where x refers to the number of years and y is the linear operational cost model.

Fig. 4(b) shows the linear cost graph for the failure-triggered replacement of the 4-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived linear operational cost model is shown in Eq. (3).

$$y = 3.2721x + 2.1746 \tag{3}$$

where x refers to the number of years and y is the linear operational cost model.



(a) (b)

Figure 4. (a) Linear model for 2-parallel configuration, (b) Linear model for 4-parallel configuration.

4.2. Failure-triggered Replacement Exponential Operational Cost Model

The second part of the cost modeling is for the failure-triggered replacement exponential operational cost model. Fig. 5(a) shows the exponential cost graph for the failure-triggered replacement of a 2-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived exponential cost model is shown in Eq. (4).

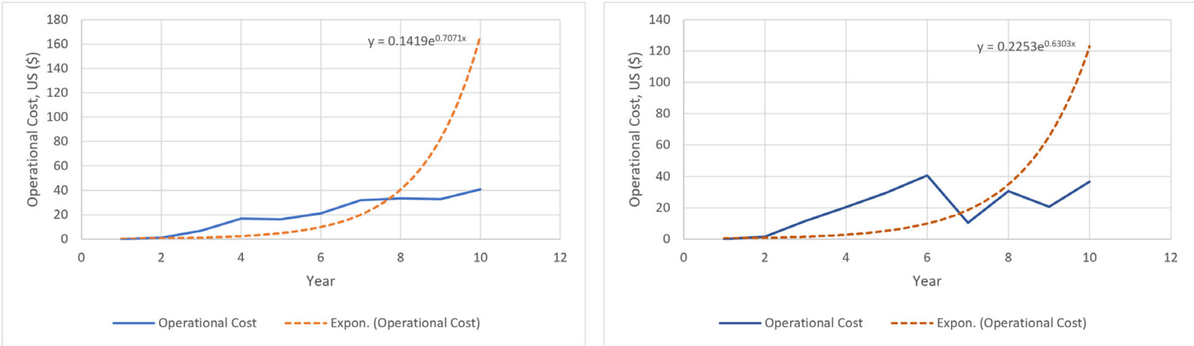
$$y = 0.1419e^{0.7071x} \tag{4}$$

where x refers to the number of years and y is the exponential operational cost model.

Fig. 5(b) shows the exponential cost graph for the failure-triggered replacement of the 4-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived exponential operational cost model is demonstrated in Eq. (5).

$$y = 0.2253e^{0.6303x} \tag{5}$$

where x refers to the number of years and y is the exponential operational cost model.



(a) (b)

Figure 5. (a) Exponential model for 2-parallel configuration, (b) Exponential model for 4-parallel configuration.

4.3. Failure-triggered Replacement Polynomial Operational Cost Model

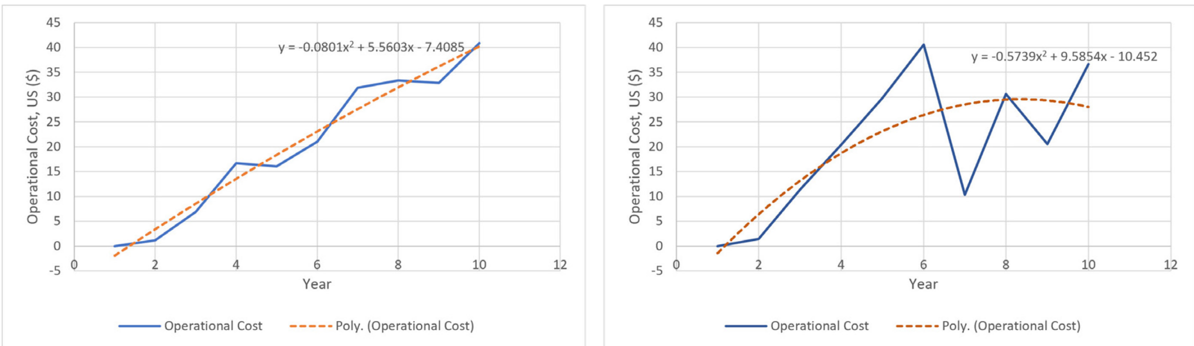
The third part of the cost modeling is for the failure-triggered replacement polynomial operational cost model. Fig. 6(a) shows the polynomial cost graph for the failure-triggered replacement of 2-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived polynomial operational cost model is depicted in Eq. (6) where x refers to the number of years and y is the polynomial operational cost model.

$$y = -0.0801x^2 + 5.5603x - 7.4085 \tag{6}$$

Fig. 6(b) shows the polynomial cost graph for the failure-triggered replacement of the 4-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived polynomial operational cost model is depicted in Eq. (7).

$$y = -0.5739x^2 + 9.5854x - 10.452 \tag{7}$$

where x refers to the number of years and y is the polynomial operational cost model.



(a) (b)

Figure 6. (a) Polynomial model for 2-parallel configuration(b) Polynomial model for 4-parallel configuration

4.4. Age-Based Replacement Linear Operational Cost Model

The fourth part of the cost modeling is for the age-based replacement linear cost model. Fig. 7(a) shows the linear cost graph for the age-based replacement of the 2-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived linear operational cost model is demonstrated in Eq. (8).

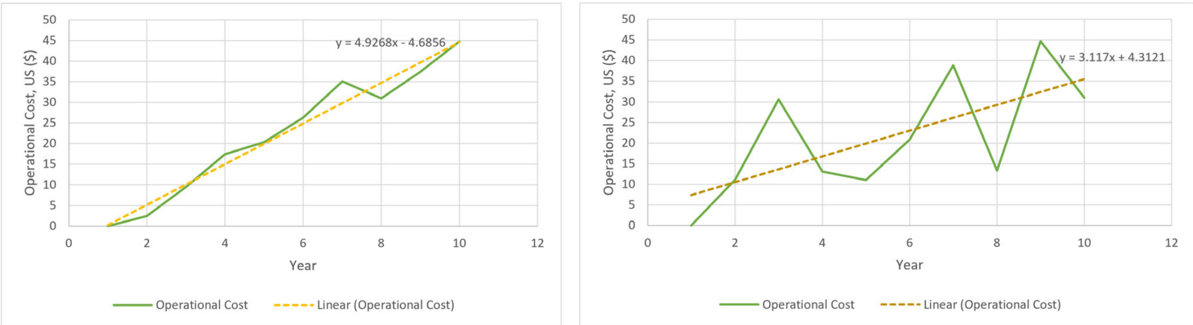
$$y = 4.9268x - 4.6856 \tag{8}$$

where *x* refers to the number of years and *y* is the linear operational cost model.

Fig. 7(b) shows the linear cost graph for the age-based replacement of the 4-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived linear operational cost model is shown in Eq. (9).

$$y = 3.117x - 4.3121 \tag{9}$$

where *x* refers to the number of years and *y* is the linear operational cost model.



(a) (b)

Figure 7. (a) Linear model for 2-parallel configuration, (b) Linear model for 4-parallel configuration.

4.5 Age-Based Replacement Exponential Operational Cost Model

The fifth part of the cost modeling is for the age-based replacement exponential cost model. Fig. 8(a) shows the exponential cost graph for the age-based replacement of a 2-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived exponential operational cost model is shown in Eq. (10).

$$y = 0.2103e^{0.6699x} \tag{10}$$

where *x* refers to the number of years and *y* is the exponential operational cost model.

Fig. 8(b) shows the exponential cost graph for the age-based replacement of the 4-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived exponential operational cost model is demonstrated in Eq. (11).

$$y = 0.4527e^{0.5418x} \tag{11}$$

where *x* refers to the number of years and *y* is the exponential operational cost model.

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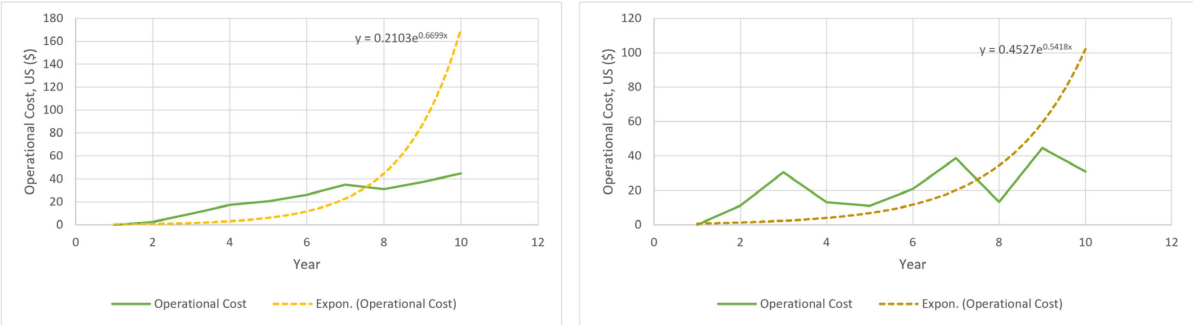


(a) (b)

Figure 8. (a) Exponential model for 2-parallel configuration(b) Exponential model for 4-parallel configuration.

4.6. Age-Based Replacement Polynomial Operational Cost Model

The last part of the cost modeling is for the age-based replacement polynomial cost model. Fig. 9(a) shows the polynomial cost graph for the age-based replacement of the 2-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived polynomial operational cost model is depicted in Eq. (12).

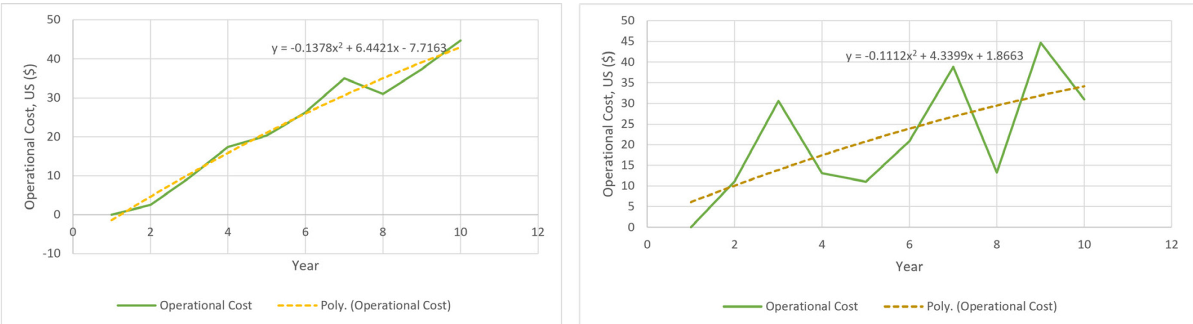
$$y = -0.1378x^2 + 6.4421x - 7.7163 \quad (12)$$

where x refers to the number of years and y is the polynomial operational cost model.

Fig. 9(b) shows the polynomial cost graph for the age-based replacement of the 4-parallel configuration in comparison to the original measured cost for 10 years of simulation duration. The newly derived polynomial operational cost model is shown in Eq. (13).

$$y = -0.1112x^2 + 4.3399x + 1.8663 \quad (13)$$

where x refers to the number of years and y is the polynomial operational cost model.



(a) (b)

Figure 9. (a) Polynomial model for 2-parallel configuration(b) Polynomial model for 4-parallel configuration.

4.7. Replacement Methods and Cost Models Comparison

Tables 3 and 4 compare all the operational cost models with their respective parallel configurations and replacement methods. The operational cost model with the lowest RMSE value is the most optimal. For the failure-triggered replacement method of the 2-parallel configuration, the polynomial operational cost model has the lowest RMSE value of 2.5, while the linear and exponential operational cost models have values of 2.6 and 24.3, respectively. Meanwhile, for the failure-triggered replacement method of the 4-parallel configuration, the polynomial operational cost model has the lowest RMSE value of 8.7, while the linear and exponential operational cost models have values of 9.7 and 24.3, respectively.

Proceeding with the age-based replacement method, the 2-parallel configuration of the linear operational cost model has the most optimal RMSE value of 2.5 compared to the exponential and polynomial operational cost model values of 26.6 and 2.9, respectively. For the last configuration, the age-based replacement method of the 4-parallel configuration, the most optimal operational cost models are linear and polynomial operational cost models because they have the same value of 10.1 compared to the exponential operational cost model, which has a value of 25.3. From the four types of operating cost models, it can be deduced that the polynomial and linear operational cost models for the failure-triggered and the age-based replacement methods of the 2-parallel configuration are chosen to be the most optimal operational cost model because both have the same RMSE value of 2.5.

Table 3. Cost model comparison between two replacement methods for failure 2-parallel and failure 4-parallel configuration

Earth Station Service Year	**Operational Cost Model (e^{10})**					
	Failure Triggered (2-Parallel)			Failure Triggered (4-Parallel)		
	Linear	Exponential	Polynomial	Linear	Exponential	Polynomial
1	-1.0	0.3	-1.9	5.4	0.4	-1.4
2	3.7	0.1	3.4	8.7	0.2	6.4
3	8.4	1.6×10^{-2}	8.6	12.0	0.1	13.1
4	13.1	4.0×10^{-3}	13.6	15.3	2.3×10^{-2}	18.7
5	17.7	1.0×10^{-3}	18.4	18.5	9.1×10^{-3}	23.1
6	22.4	3.0×10^{-3}	23.1	21.8	3.6×10^{-3}	26.4
7	27.1	1.0×10^{-3}	27.6	25.1	1.4×10^{-3}	28.5
8	31.8	0	31.9	28.4	5.0×10^{-4}	29.5
9	36.5	0	36.1	31.6	2.0×10^{-4}	29.3
10	41.4	0	40.2	34.9	1.0×10^{-4}	28.0
RMSE Value	**2.6**	**24.3**	**2.5**	**9.7**	**24.3**	**8.7**

Table 4. Cost model comparison between two replacement methods for 2-parallel and 4-parallel configuration

Earth Station Service Year	**Operational Cost Model (e^{10})**					
	Age based (2-Parallel)			Age based (4-Parallel)		
	Linear	Exponential	Polynomial	Linear	Exponential	Polynomial
1	0.2	0.4	-1.4	7.4	0.7	6.1
2	5.2	0.1	4.6	10.5	0.4	10.1
3	10.1	4.4×10^{-2}	10.5	13.7	0.3	13.9
4	15.0	1.5×10^{-3}	15.8	16.8	0.2	17.4
5	19.9	5.4×10^{-3}	21.0	19.9	0.1	20.8
6	24.9	1.9×10^{-3}	26.0	23.0	0.1	20.8
7	29.8	7.0×10^{-3}	30.6	26.1	5×10^{-2}	26.8
8	34.7	2.0×10^{-4}	35.0	29.2	3.2×10^{-2}	29.5
9	39.7	1.0×10^{-4}	29.1	32.4	2.1×10^{-2}	31.9
10	44.6	0	42.9	35.5	1.4×10^{-2}	34.1
RMSE Value	**2.5**	**26.6**	**2.9**	**10.1**	**25.3**	**10.1**

5. CONCLUSION AND FUTURE WORK

In summary, the aims of this research were accomplished. The first one was to analyze the differences between failure-triggered replacement and age-based replacement methods using 2-parallel and 4-parallel earth station system configurations, and the second one was to propose the most optimal cost model based on the two types of replacement methods. From the analysis, it can be concluded that the polynomial operational cost model for the failure-triggered and the linear operational cost model for the age-based replacement methods of the 2-parallel configuration of the earth station system were the most optimal cost models because both yielded the lowest operational cost and have among the lowest RMSE value compared to the other types of cost models of the 4-parallel configuration. The justification for this finding is that MEASAT prefers to adopt a 2-parallel configuration in their earth station system design because it is way cheaper than the 4-parallel configuration. In terms of reliability value, as mentioned in [1], the wear and tear caused failure rates to increase over the years. Hence, when it reaches the end of its life cycle for the 2-parallel configuration, the reliability value of 0.24, as mentioned in [1], is still acceptable.

However, there is still room for improvement in this research. For example, there are still other types of replacement methods and earth station configurations that can be explored and used to run the simulations. One of the other replacement methods, which is a hybrid between failure-triggered and age-based replacement methods, needs to be further explored. This hybrid method may produce a good result in terms of producing the lowest operational cost and a replacement cost curvature, thus giving the most optimal operational cost to be implemented in an earth station system design.

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