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RELIABILITY TRADE-SPACE EXPLORATION MODELLING FOR SATELLITE ANOMALIES USING EXPONENTIAL DISTRIBUTION

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ABSTRACT: The delivery of critical communication, navigation, and earth observation services relies on the reliability of satellite subsystems. However, satellites can be affected by radiation and temperature extremes. Anomalies can cause the system to fail and stop working. This research aims to fix the lack of a high-performance reliability model compared to previous work by integrating trade-space exploration (TSE) techniques and an exponential reliability mathematical model. Data from the Seradata database was analyzed using MATLAB to check for issues with antennas, transponders, amplifiers, and batteries as the prominent components of satellite anomalies. Studies were carried out by building parametric (Weibull, Exponential, and Poisson) and non-parametric (Kaplan-Meier and Monte Carlo Simulation) models, and all were assessed. Results were measured using Root Mean Square Error (RMSE), revealing that the Exponential model performed most accurately compared to other mathematical models. After that, the TSE framework was applied to examine the Design Dependent Parameters (DDPs): reliability, design life, and system performance. The results conclude that the newly developed exponential-based reliability TSE model shows a promising outcome, with RMSE values of 34.2, 10.2, 19.6, and 19.9 compared to Nadirah's model and Shazana's model, which have RMSE values of 16.1, 49.7, 28.2, and 27.6 for antenna, transponder, amplifier, and battery, respectively.

ABSTRAK: Penghantaran Penghantaran perkhidmatan adalah penting dalam komunikasi, navigasi, dan pemerhatian bumi pada kebolehcapaian subsistem satelit. Walau bagaimanapun, satelit boleh terjejas oleh radiasi dan perubahan suhu ekstrem. Anomali boleh menyebabkan sistem gagal dan berhenti berfungsi. Penyelidikan ini bertujuan bagi memperbaiki kekurangan model kebolehcapaian berprestasi tinggi daripada kerja terdahulu dengan mengintegrasi teknik penerokaan ruang dagangan (TSE) dan model matematik kebolehcapaian Eksponen. Data daripada pangkalan data Seradata dianalisa menggunakan MATLAB bagi memeriksa isu antena, transponder, penguat, dan bateri sebagai komponen utama anomali satelit. Kajian dijalankan dengan membina model parametrik (Weibull, Eksponen, dan Poisson) dan non-parametrik (Kaplan-Meier dan Simulasi Monte Carlo). Dapatan kajian diukur menggunakan Ralat Kuadrat Purata Akar (RMSE), menunjukkan bahawa model Eksponen berfungsi paling tepat berbanding model matematik lain. Kemudian, rangka kerja TSE digunakan bagi mengkaji Parameter Bergantung Reka Bentuk (DDPs), yang merangkumi kebolehpercayaan, hayat reka bentuk, dan prestasi sistem. Dapatan kajian menunjukkan bahawa kebolehpercayaan model TSE berasaskan eksponensial yang baru dibangunkan menunjukkan hasil yang memberangsangkan di mana nilai RMSE adalah 34.2, 10.2, 19.6, dan 19.9

berbanding dengan model Nadirah dan model Shazana adalah 16.1, 49.7, 28.2, dan 27.6 untuk antena, transponder, penguat, dan bateri.

KEYWORDS: *Reliability, Trade-Space Exploration, Exponential, DDPs, RMSE, Satellite Anomalies*

1. INTRODUCTION

Satellites are vital in communication, navigation, remote sensing, and data transmission. Transmission is stabilized in these systems by antennas, transponders, amplifiers, and batteries [1]. Nevertheless, satellites located in space constantly face numerous environmental challenges, including radiation, temperature fluctuations, and micrometeoroid impacts [2]. As a result of these factors, there are often issues in the data and signal subsystems, leading to miscommunications, data failure, or shutting down the entire mission [2].

Many mission failures, decreases in system performance, and higher costs can be traced back to satellite anomalies. Despite the significant effects these failures often have, past studies have not thoroughly examined how reliable satellites are using organized mathematical models. A reliable system design is needed to prevent these risks, but it frequently requires sacrifices on cost, weight, and power use [3]. As a result, designers need to use a structured framework to handle these factors in the design process.

To address these issues, this study investigates satellite subsystem anomalies using standard reliability models within a trade-space exploration (TSE) framework. Therefore, reliability analyses using parametric models, such as the Weibull, Exponential, and Poisson distributions, and non-parametric models, such as the Kaplan-Meier and Monte Carlo simulation, are explored in [4,5]. All the proposed models are measured to identify the best and most helpful way to assess satellite reliability. By integrating TSE and reliability modeling, this study is designed to enhance the design choices made in future satellite systems. Building upon prior reliability analysis work by Imran [5], this study entails the satellite reliability analysis using mathematical prediction models for the case study of satellite anomalies.

2. LITERATURE REVIEW

Satellite communication subsystems help to achieve mission success because they play a vital role in data transmission, telemetry, tracking, and control. Devices such as antennas, transponders, amplifiers, and batteries must often contend with solar radiation, significant temperature fluctuations, and tiny particles in space [1]. Environmental factors are known to create satellite anomalies, which can lower how well a mission performs or bring it to an end. Several studies highlight the relationship between anomalies and the sun, mainly when the Earth's magnetic field is disturbed [3,6].

Designers measure a satellite's dependability by determining its likelihood of completing tasks without error over a specified period. An analysis of actual systems shows that initial failures can happen and that failure rates escalate with time [5]. Therefore, an advanced statistical model is needed to represent these changes [4,7]. The actual reliability formula in this research is as in Eq. (1)[4].

$$R_t = 1 - \frac{[x_t - y_t]}{x_t} \quad (1)$$

where x_t is design life in years and y_t is the age since launch.

Techniques in reliability modeling can be classified as parametric and non-parametric. These models work best when a known failure distribution is applied to predict reliability over time accurately [5]. Using Weibull models, the hazard rate may improve, worsen, or remain constant over time. A system's failures may be modelled with an Exponential or Poisson model, depending on whether they are continuous or if there are intervals [5]. For these methods to work properly, very accurate assumptions are needed, as they depend strongly on the amount and quality of available data [4]. With non-parametric Kaplan-Meier and Monte Carlo methods, it is possible to have great flexibility in modeling reliability when the distribution is unclear or the data is censored [5]. When the Kaplan-Meier estimator is used, survival probabilities can be calculated without making specific distribution assumptions, which can be suitable when the reliability data is incomplete [5]. Another approach is the Monte Carlo simulation, which generates random values to determine the probability of reliability outcomes [5].

2.1. Mathematical Prediction Models: Parametric Reliability

Evaluating performance and possible failures in a system relies on reliability prediction. Weibull and Exponential distributions are curved and fitted for reliability prediction, but the Poisson distribution uses a discrete approach [8-10]. With the aid of these models, engineers can learn about a structure's reliability, design lifetime, and performance [11].

Meanwhile, the Weibull distributions are used to model satellite reliability because they can fit an increasing, unchanging, or decreasing trend [12,13]. Reliability predictions are estimated for a Weibull curve fit on the reliability data [12]. Weibull curve fitting is described in Eq. (2) [5].

$$f(x) = abx^{(b-1)}e^{-ax^b} \tag{2}$$

where x represents the time parameter, a the scale parameter, and b the shape parameter.

On the other hand, the exponential distribution is appropriate when failures are not linked by time [10]. The Exponential curve fitting is presented in Eq. (3) [5].

$$f(x) = ae^{-bx} \tag{3}$$

where a denotes the initial reliability and b the rate of decay.

Discrete failures are modelled using the Poisson distribution for each defined time interval [9]. Reliability data is analyzed using the Poisson discrete probability approach to make reliability predictions. Poisson discrete probability can be seen in Eq. (4) [5].

$$f(x) = \frac{e^{-a}a^x}{x!} \tag{4}$$

where a denotes the rate parameter and x the number of failures.

2.2. Mathematical Prediction Models: Nonparametric Reliability

When the failure distribution type is unknown, non-parametric reliability mathematical prediction models are used instead [14]. Statistics is used to estimate the reliability of the information provided by these methods. Kaplan-Meier and Monte Carlo simulations are used to estimate reliability. At the same time, Monte Carlo Simulation uses probability distributions to make predictions about reliability [8].

The failure probability data is used with the Kaplan-Meier method to get the survival function. Eq. (5) [14] shows the technique for calculating failure probability.

$$R(t) = 1 - F(t) \tag{5}$$

The Kaplan-Meier Estimator, defined in Eq. (6) [14], is useful for assessing censored data when the failure time is unknown [15].

$$\hat{S}(t) = \prod_{i:t_i \leq t}(1 - \frac{d_i}{n_i}) \tag{6}$$

Where $\hat{S}(t)$ is the estimated survival probability at time t, t_i is the observed failure times, d_i is the number of failures at time t_i, and n_i is the number of units at risk just before time t_i.

Meanwhile, Monte Carlo simulation utilizes various conditions to identify possible outcomes [16,17]. It is defined in Eq. (7) [16,17].

$$R(t) = \frac{1}{N}\sum_{i=1}^{N} I(T_i > t) \tag{7}$$

where $R(t)$ is the estimated reliability at time t, N is the total number of simulated trials, and $I(T_i > t)$ is the indicator function equal to 1 if the system survives beyond t and 0 otherwise.

2.3. Trade-Space Exploration

Trade-space exploration (TSE) analyzes various ways to design a system to find the best solution for several performance measures [11,18]. TSE allows designers to examine how reliability, cost, and performance are affected by different constraints. Optimizations in radar, power systems, and structures have been performed in satellite design using TSE. Nevertheless, few studies have managed to link fault tree analysis with standard reliability models, especially on real satellite anomaly data [19].

Researchers have proposed new statistical models and mixed approaches; however, these solutions often have shortcomings due to small datasets, insufficient practical validation, or overly restrictive assumptions [2,5,20]. It indicates that more work is needed to use thorough data-supporting reliability approaches in formal TSE [19]. By filling this gap, users can understand component risks better and build more durable satellite networks [18,19]. In this study, an exponential-based reliability TSE model for a case study of satellite anomalies is chosen to be developed based on the lowest root mean square error (RMSE) values obtained from the four most failed components, which are antenna, transponder, amplifier, and battery [5].

3. RESEARCH METHODOLOGY

The methodology for this study is constructed to analyze satellite reliability by identifying anomalies in satellite communication subsystems and investigating the balance between reliability, cost, and performance, ultimately leading to the development of a traditional mathematical reliability model using trade-space exploration (TSE). Previous research focuses on TSE, and traditional mathematical reliability models are reviewed to identify their applicability and research gaps.

Fig. 1 depicts the research methodology flowchart comprising the steps to perform this study. The first step is to arrange the satellite reliability data based on the satellite anomalies obtained from Seradata [21]. Then, the most prominent anomalies are discovered from the database. The discovered anomalies are divided into four primary communication subsystem failures: antenna, transponder, amplifier, and battery [18]. Approximately 87 satellite reliability data points from various satellites and orbits worldwide, sourced from the Seradata database, are analyzed using MATLAB [5, 21]. After obtaining the satellite reliability data for the four mentioned components, the Design Dependent Parameters (DDPs) identified are reliability, design life, and performance. Then, the best mathematical model, which happened to be Exponential, was found to have the best performance in addressing reliability using root mean square error (RMSE) [5]. Then, the model was refined to suit the DDPs. Lastly, this paper applies the TSE method to this mathematical model. A new exponential-based reliability TSE model is developed. This new TSE model must be validated against other existing models, and the RMSE values must be computed.

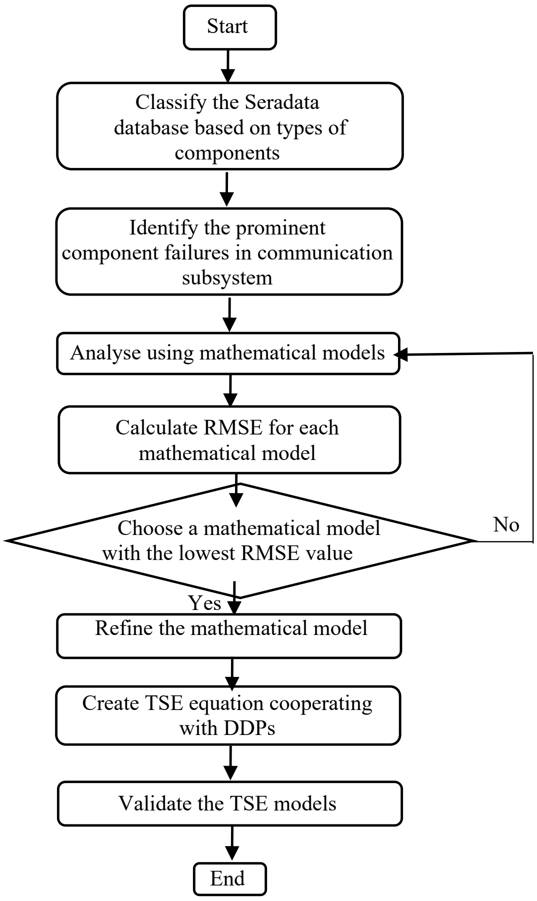

Figure 1. Research methodology flowchart

4. RESULTS AND DISCUSSION

The graphical representations for Weibull, Exponential, Poisson, Kaplan-Meier, and Monte Carlo distributions can be found in [5]. This paper focuses on the development of the exponential-based reliability TSE model for a case study of satellite anomalies. The TSE framework is created to study the correlation between reliability, design life, and performance over time. It makes it possible to match various subsystems and decide on the best choice by assessing their reliability over the system's life.

This method selects a mathematical model that accurately describes the wear and tear of components. At the first phase of analysis, various models, such as Weibull, Poisson, and Exponential, as well as Kaplan-Meier and Monte Carlo functions, were compared with the reliability data gathered from observing component performance [5]. By examining the performance using Root Mean Square Error (RMSE), it was found that the Exponential model best fit the data [5]. The RMSE values obtained from the Exponential model were the lowest, indicating that it fits the actual reliability data the best. The results can be found in Imran's work [5]. According to reliability literature, the exponential function is commonly applied to

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systems where the hazard rate remains relatively constant [2]. As a result, the exponential reliability function was adopted and adapted for this study. The classical exponential reliability equation is defined as in Eq. (8) [5].

$$R(t) = e^{-\lambda t} \tag{8}$$

where $R(t)$ denotes the reliability at time t and λ denotes the failure rate of the component.

However, given the high failure rate values in the collected data, the resulting reliability curves turned out to be too steep when this formula was applied. Therefore, to obtain more realistic reliability trends for the entire operational time, the scaling coefficient α was added to the model. The earlier expression can be modified as in Eq. (9).

$$R(t) = e^{-\alpha\lambda t} \tag{9}$$

where $R(t)$ denotes the reliability at time t, λ is the failure rate of the component, and α is the scaling coefficient.

The α parameter helps control the failure rates' role over time. A value of α = 0.001 was chosen in this study to prevent the effects of high failure rates and to demonstrate a more likely rate of reliability decline. If this adjustment were not added, the exponential curve would fail to capture reliability and show irrelevant component performance. In addition, the model was improved by adding a parameter that measured its predictive accuracy. In particular, (1−RMSE) was used as a multiplier in the reliability function to form the final exponential-based reliability TSE developed model as in Eq. (10).

$$TSE_{R(t)} = e^{-\alpha\lambda t}(1 - \text{RMSE}) \tag{10}$$

RMSE indicates the difference between the predicted and actual reliability values to evaluate the model's accuracy. The higher the RMSE, the lower the performance. Because (1−RMSE) is included, models with significant RMSE errors receive a lower reliability prediction than those with lower RMSE errors. Making this modification guarantees that the model's accuracy affects the reliability of the projections. Thus, in this situation, the lower the RMSE, the more reliable the prediction, upholding the goal of picking models supported by practical results and theory. This is the RMSE value obtained from previous research, where the values are 0.22 for antenna, 0.27 for transponder, and 0.30 for both amplifier and battery [5]. For this analysis, the TSE approach relies on three DDPs: design life in years, reliability, as the result of the model function, and RMSE, which represents the model's performance. The strategy developed by the TSE framework makes it easier for engineers to evaluate subsystem components and decide how to design the system. Combining theory, measurement, and priority, the TSE method makes it possible to understand and boost the reliability of satellite parts while choosing and updating the design for engineering needs [11].

The TSE equation aims to evaluate the reliable performance of each subsystem component in the long term using a set approach. Using the same exponential decay model and parameter values for every subsystem allows for a fair and even comparison of systems. The space created by the trade-offs between DDPs demonstrates the reliability of each component and identifies situations where it might be sensible to have higher redundancy or tougher components [4]. Using this method, a better design for satellite subsystems can be chosen with more reliable information. Tables 2 and 3 compare Nadirah's and Shazana's reliability models against the new exponential-based reliability TSE model [2, 20]. The new proposed exponential-based reliability TSE model and two existing reliability models by Nadirah and Shazana are compared in Table 1 for validation purposes. The processes used to determine reliability are assessed over a ten-year design life for the antenna, transponder, amplifier, and battery. The findings make it clear that the new TSE model tends to estimate declining reliability over the years. The model now provides more reliable and component-focused estimates of failure, demonstrating greater accuracy in how materials or components wear out over time. For instance, the reliability value in the new model for Antenna is declining steadily from 0.72 in year one to 0.37 in year 10, similar to the other three components. However, the reliability value in Nadirah's model remains high, beginning with 0.94 in year one but still retaining 0.64 in year ten, suggesting slower degradation. Meanwhile, Shazana's model demonstrates a more aggressive decline from 1.01 in year one to 0.34 in year ten, indicating a degradation over time.

Table 1. Validation of Exponential-based reliability TSE model against two existing reliability models [2,20]

Design life	Previous study		New			
	Nadirah	Shazana	Antenna	Transponder	Amplifier	Battery
1	0.93	1.01	0.72	0.77	0.75	0.75
2	0.9	0.89	0.67	0.76	0.72	0.72
3	0.87	0.79	0.62	0.75	0.69	0.69
4	0.84	0.7	0.58	0.74	0.67	0.67
5	0.8	0.62	0.54	0.73	0.64	0.64
6	0.77	0.55	0.5	0.72	0.62	0.61
7	0.74	0.49	0.46	0.71	0.59	0.59
8	0.71	0.43	0.43	0.7	0.57	0.57
9	0.68	0.38	0.4	0.69	0.55	0.55
10	0.64	0.34	0.37	0.68	0.53	0.52

Table 2. Exponential-based reliability TSE model and two existing models' validation by RMSE value [2,20]

Design life	Percentage Error (%)							
	Antenna		Transponder		Amplifier		Battery	
	Nadirah/ New	Shazana/ New	Nadirah/ New	Shazana / New	Nadirah / New	Shazana / New	Nadirah / New	Shazana / New
1	-22.6	-28.71	-17.2	-23.76	-19.4	-25.74	-19.4	-25.74
2	-25.6	-24.72	-15.6	-14.61	-20	-19.10	-20	-19.10
3	-28.7	-21.52	-13.8	-5.06	-20.7	-12.66	-20.7	-12.66
4	-31	-17.14	-11.9	5.71	-20.2	-4.29	-20.2	-4.29
5	-32.5	-12.90	-8.8	17.74	-20	3.23	-20	3.23
6	-35.1	-9.09	-6.5	30.91	-19.5	12.73	-20.8	10.91
7	-37.8	-6.12	-4.1	44.90	-20.3	20.41	-20.3	20.41
8	-39.4	0.00	-1.4	62.79	-19.7	32.56	-19.7	32.56
9	-41.2	5.26	1.5	81.58	-19.1	44.74	-19.1	44.74
10	-42.2	8.82	6.3	100.00	-17.2	55.88	-17.2	52.94
RMSE value	34.2	16.1	10.2	49.7	19.6	28.2	19.9	27.6

Table 2 shows the calculation of RMSE values to indicate the difference between the previous and the new TSE models for a ten-year design life. Each subsystem's errors are computed and benchmarked each year, and the last row gives the overall RMSE for every case in comparison. The individual RMSE value indicates that Nadirah's model has the least agreement with the new TSE model among all the subsystems, with RMSE values of 34.2 for the antenna, 49.7 for the transponder, 19.6 for the amplifier, and 19.9 for the battery. Meanwhile, Shazana's model seems to have a better alignment, mainly during the early years of design life, showing RMSE values of 16.1 for the antenna, 28.2 for the transponder, 28.2 for the amplifier, and 27.6 for the battery. Yet, as the design life increases, the error associated with Shazana's model for the transponder and amplifier subsystems also increases noticeably. The data demonstrate that the new TSE model is now more accurate in predicting changes in subsystem reliability, as supported by a low RMSE value across all components, with the same trend.

The results of the exponential-based reliability TSE model for a satellite system's antenna, transponder, amplifier, and battery components, shown as reliability prediction curves, are presented in Fig. 2 (a). The curves display the predicted reliability of every element over the ten-year design life period. This TSE model gradually shows that each component slowly experiences a decline in reliability as time goes on, which reflects the normal wear and tear from age and heavy use [4]. The antenna starts with moderate reliability, and its value decreases gradually, whereas the transponder keeps reliability at a higher level for a more extended period, suggesting better durability. The amplifier and the battery display similar behaviors, but in the early years, the battery stays slightly more reliable until it levels off with the amplifier around year 6. Contrarily, the previous Exponential model does not consider changes over time. The earlier-developed approach uses an independent value of multiple satellites' reliability to predict reliability, failing to demonstrate how it may change with time. However, the previous Exponential model approach is still functional when the satellites are arranged by the launch date [5]. By this approach, the Exponential model helps assess the predicted reliability of satellites by their age compared to others. It allows the Exponential model to compare the difference between satellites from the older and current versions [5]. However, the time-dependent approach in the TSE model provides a better view by illustrating how reliability keeps deteriorating continuously. It is beneficial for observing and analyzing how the satellite behaves and helping with planning during its entire operation.

Fig. 2(b) illustrates different trends in reliability predictions that emerge when the proposed exponential-based reliability TSE model is compared with the two models from Nadirah and Shazana [2,20]. A smooth and uninterrupted decrease is seen in reliability values on the new TSE model for each subsystem: the antenna, transponder, amplifier, and battery. This trend indicates that satellites lose performance over time, as is common, giving a reasonable picture of their reliability. In contrast, Nadirah's model maintains higher reliability rates throughout the design period, decreasing only slightly. This may indicate a promising trajectory that does not align with satellite aging trends. Meanwhile, Shazana's model predicts that reliability begins above average but soon drops after the midpoint of design life, with a noticeable change from year five onwards. Shazana's model appears to overstate the drop in reliability later. This new TSE model is superior to the previous ones because it accounts for the impact of failure rate and model error by incorporating design-dependent parameters. The new TSE model also obtains low RMSE values for all systems, demonstrating its accuracy in making predictions. The model's continuous decline ensures it is well-suited for anticipating long-term problems and supporting decisions in satellite upkeep and planning.

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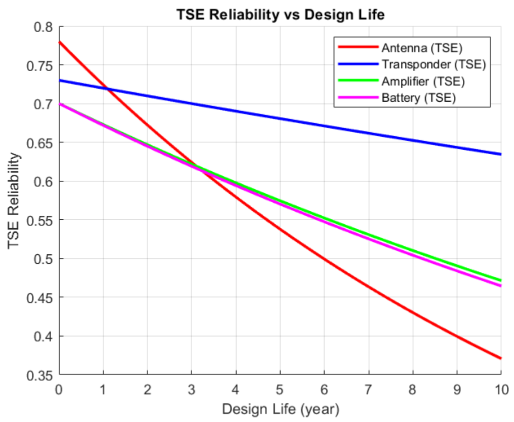

a)

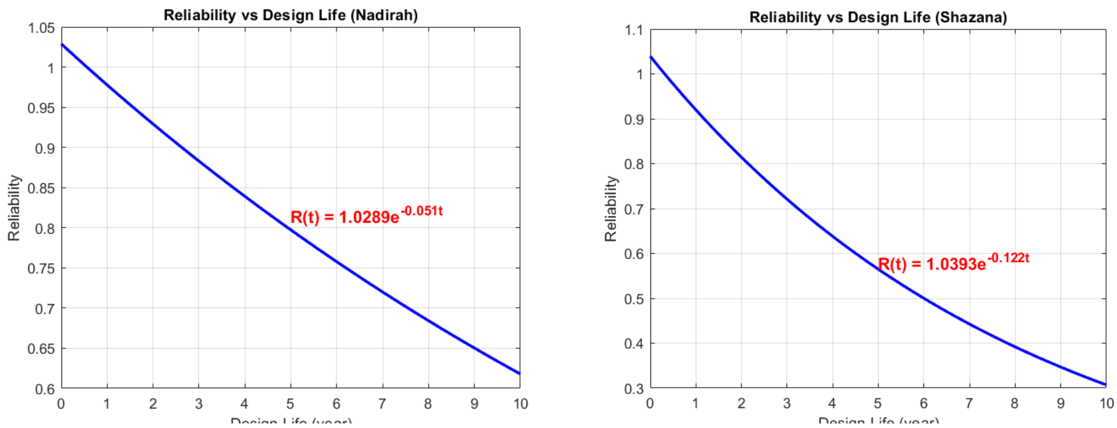

Figure 2. Reliability exponential-based TSE model prediction for each satellite anomaly against the two existing models (a) New Model, (b) Previous Models

5. CONCLUSION

The result of the new reliability TSE model developed by this research shows a promising outcome where RMSE values are 34.2, 10.2, 19.6, and 19.9 when compared with Nadirah's model and Shazana's model of 16.1, 49.7, 28.2, and 27.6 for antenna, transponder, amplifier, and battery, respectively. The model developed in this study provides a more accurate and realistic way to view the reliability of a satellite's subsystem than the previous models. By cooperating with failure rate, design life, and RMSE as parameters that vary with design, the TSE model accurately indicates a smooth and continuous reduction in reliability, which shows realistic subsystem performance. Before, most models remained reliable or decayed unrealistically. TSE shows better accuracy since the model consistently has low RMSE values in all subsystems. Because the model shows how performance or strength changes over time, it is helpful for preparations, design improvements, and assessing the product's lifetime performance. In the future, this model can be more accurate and valid by adding more subsystems to improve its predictive power. Moreover, considering environmental conditions, such as radiation and extreme temperature, the TSE reliability model can be more accurate in real-life situations. Therefore, the TSE approach can be used for maintenance scheduling, planning duplication, and assessing risk in past and future missions.

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