



Reliability and Cost Integration Using Trade-Space Exploration for Satellite Anomalies

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KEYWORDS

*Reliability
Cost
Exponential
Parametric Models
Trade-space exploration*

ARTICLE HISTORY

*Received 23 February 2026
Received in revised form
13 March 2026
Accepted 19 March 2026
Available online 26 March
2026*

ABSTRACT

A satellite is an important component in supplying crucial services such as communications, navigation, and earth observation, which profoundly rely on satellite reliability. Satellite reliability is described as the possibility that a satellite system is operational in stated environments, confirming the satellite operates efficiently and continuously without service disruptions. The effect of satellite anomalies as a major reason for satellite failures, cost, and incompetence of satellite systems has been emphasized in the previous research. But these works generally lack a thorough reliability analysis using constructed mathematical models. Thus, this work fills the gap by working on 87 satellite reliability data points and 42 cost data points from Seradata database using trade-space exploration (TSE). The work was done by considering parametric models (Weibull, Exponential, and Poisson) and non-parametric models (Kaplan-Meier and Monte Carlo Simulation) for reliability. Meanwhile, for cost, we employed parametric models (Weibull, Exponential, and Poisson). The results from both reliability and cost show that the Exponential model proves the best model in terms of performance, with the lowest Root Mean Square Error (RMSE) values for all communication subsystems and the lowest RMSE and RRMSE for one variable (considered cost only) and two-variable (considered cost and design life). Integrating both reliability and cost models shows a good deployment in an engineering decision-support system (DSS).

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1. INTRODUCTION

Satellites are essential for route navigation, Earth surveillance, and global connectivity. After launching into space, they must operate in adverse conditions, for instance, solar storms, solar radiation, and extreme temperatures. The satellites have to be reliable to be flown into space, and most failures occur in the antenna, transponder, amplifier, and battery. Malfunction in these components can cause data loss, which will eventually lead to service disruptions or even total mission failure. This questions the reliability of the satellites and is hence challenging the application of reliability engineering in satellite designs [1].

Moreover, financial aftermaths are also affected when malfunctions occur, or they are usually identified as anomalies,

leading to complete failure. This work aims to fill the gap by developing mathematical models to assess communication subsystem anomalies mentioned above. By considering 87 satellite reliability data and 42 cost data, this work designs a framework with the help of a Trade-Space Exploration (TSE) method to evaluate design life, performance, incorporating reliability and cost of the satellites [1,2]. Reliability prediction models for parametric consist of Weibull distribution, Exponential distribution, and Poisson distribution, and non-parametric, including Kaplan-Meier Estimator and Monte Carlo Simulation, were conducted using MATLAB.

The study dynamically models reliability by combining the design life, the subsystem performance, and failure rate through a Trade Space Exploration (TSE) methodology, which is far

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<https://doi.org/10.56532/mjsat.v6i1.723>

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more advanced than prior studies [1]. This method improves existing models by providing a statistically and conceptually well-founded and applicable framework [1]. As for the cost, parametric models were used, consisting of Exponential, Weibull, and Poisson distributions [2]. These models were chosen to reflect different types of behavior. Exponential for compounding risk over time, Weibull for time-dependent failure rates, and Poisson for discrete event occurrences [2].

This paper is organized as follows. Section 2 discusses the background of the study. Section 3 explains the research methodology, Section 4 demonstrates the findings and analysis, and finally, Section 5 concludes the findings with future work and recommendations.

2. BACKGROUND OF THE STUDY

2.1 Satellite Communication System

Satellites serve and support the contemporary infrastructure for communication, navigation, surveillance, and earth observation. The success of these missions relies largely on the communication subsystems' reliability, including antennas, transponders, amplifiers, and batteries [3]. The performance of these devices degrades rapidly because of radiation, temperature cycling, and power constraints. Research found that several satellite anomalies were caused by subsystem failure, and a portion of them even happened in the post-launched stage [3]. With the growing complexity and cost-sensitivity of space missions, reliability analysis has become crucial to guarantee the subsystems' reliability based on precise modelling, to extend the life of the satellites, keep the service running, and decrease the financial risk [4].

2.2 Satellite Reliability

Satellite reliability had been estimated in former works either by qualitative measures or simple statistical methods. Some had used simulation models, including Monte Carlo or reliability block diagrams, but they do not fully integrate real satellite data and time-varying failure distributions. For instance, in [5], on the other hand, concentrated on modelling ground station configurations; however, they used only simulated reliability figures. Detrimentially, [6] introduced an optimization framework using sustainable ambient energy yet also excluded the subsystems on the cabin-through-earth station aspects. Recent studies, however, emphasized the need for further investigation into design-dependent parameters and predictive modelling approaches that characterize subsystem-specific failure behaviour along mission lifetime [7].

2.3 Satellite Cost

Satellite cost is a critical constraint in satellite design and is influenced by factors such as subsystem complexity, material selection, and manufacturing processes [8]. The total satellite cost is typically divided into three categories: development, launch, and operational expenses. Studies show that integrating cost considerations early in the design process helps prevent overruns in later stages [9]. Advanced methods, such as the Cost as Independent Variable (CAIV) approach, are increasingly being used to manage costs while maintaining performance standards [10]. These models enable engineers to evaluate the trade-offs between cost savings and potential reductions in system effectiveness. For this research, only the

combined cost is considered, which is the sum of launch cost and spacecraft cost.

2.4 Trade-Space Exploration (TSE)

Trade-space exploration (TSE) is an engineering method to analyse and assess multiple models for potential solutions of a problem [11]. This process involves a multidimensional space where each point has a unique combination of design parameters that represent the potential system configurations [11]. The evaluation of these configurations was based on performance, cost, reliability, and other relevant metrics to decide the best specification that meets the needed criteria from a wide range of possible solutions [11].

The TSE's purpose is for decision-makers to make a choice from many possible solutions in designing a system [12]. From several criteria, including cost, performance and reliability, trade-space helps the engineer to figure out the optimal configurations [12]. The most important part of using trade-space analysis was to balance the priorities to optimise the choices [13]. For example, improving the radar resolutions for a satellite might increase the cost and power consumption. Therefore, trade-space was used to analyse these trade-offs.

2.5 Design Dependent Parameters

Design-Dependent Parameters (DDPs) are important variables that influence the structure, performance, and operation of complex systems like satellites [14]. These parameters are unique to the system configuration and operational objectives and directly influence mission success, cost efficiency, and reliability. DDPs often include factors such as design life, cost, and performance, and their relationship creates significant trade-offs during the design phase [14]. For this work, the DDPs chosen are design life, reliability, cost, and performance [1,2].

The design life of a satellite refers to its expected operational lifespan under ideal conditions. It is a key factor influencing subsystem reliability, cost estimation, and maintenance planning. Studies highlight that longer design lifespans often result in higher upfront costs due to the need for robust materials and subsystems to mitigate risks associated with on-orbit failures [15]. However, extending design life can also lead to reduced lifecycle costs as it delays the need for satellite replacement [9]. Optimizing the design life requires careful consideration of mission-specific requirements and potential technological advancements over time.

Next, cost is a critical constraint in satellite design and is influenced by factors such as subsystem complexity, material selection, and manufacturing processes [8]. The total cost is typically divided into three categories: development, launch, and operational expenses. For this research, only the combined cost is considered, the sum of launch cost and spacecraft cost.

Finally, performance covers the satellite's ability to meet mission objectives, including payload capacity, communication capabilities, reliability of the subsystem, and resistance to environmental challenges. Performance parameters are often interdependent on cost and design life. For instance, enhancing payload capacity can increase mass and power requirements, leading to higher launch and manufacturing costs [14]. Performance optimization is frequently addressed through multi-objective trade-space exploration techniques, such as Pareto analysis and genetic algorithms, which provide insights into the best trade-offs between competing objectives [16].

3. METHODS

Figure 1 demonstrates the research methodology flowchart. The first stage is to organize the components of the failed communication subsystems from the Seradata database [17]. Then, the obvious failed components in the communication subsystem are identified from the database.

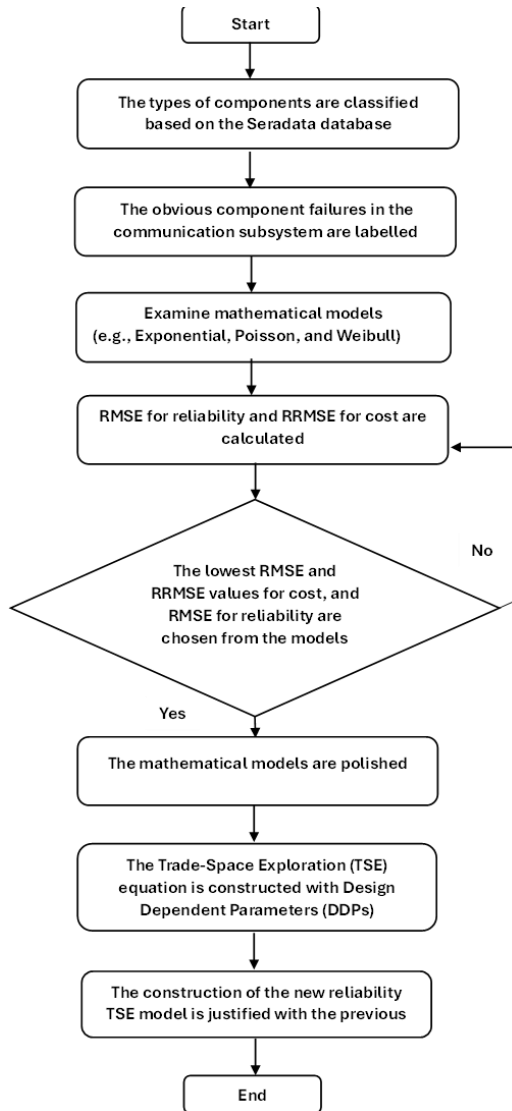


Fig. 1. Research Methodology Flowchart

Around 87 satellite reliability data and 42 cost data were analysed from different satellites and orbits globally, using the Seradata database and MATLAB [1,2],[17]. The focus is not on types of satellites, mission duration ranges, and orbit classifications. Rather, it is focused only on the reliability and cost data in general. These data are filtered and grouped into four main communication subsystem failures: antenna, transponder, amplifier, battery, payload, power system, and attitude control [1,2],[18].

Referring to previous work, the Exponential distribution is usually employed for systems that demonstrate a constant failure rate [6]. In the case of electrical and electronic systems, the reliability model usually exhibits the Exponential distribution because of its constant failure rate [6]. After exploring satellite reliability, we considered both parametric and non-parametric models. The parametric models consist of

the Exponential, Weibull, and Poisson distributions. While the non-parametric models comprise the Kaplan-Meier Estimator and the Monte Carlo. The Root Mean Square Error (RMSE) of each model was calculated to compare which model has the lowest value. The computed lowest RMSE value demonstrates the best-performing model. Then, the next stage is to select design-dependent parameters (DDPs) [1]. In this work, the appropriate dependent parameters were reliability, design life, and performance. With the best-performing model, which contributes to the lowest RMSE value, the trade-space exploration method is applied [1]. Finally, the newly developed TSE model was validated with the reliability models from the preceding work [1].

Unlike reliability, for cost, we only considered parametric models consisting of Exponential, Weibull, and Poisson to investigate how the design life could have changed the cost of anomalies. For DDPs, the datasets considered were design values, linked anomaly costs, and the performance of the main communication subsystems. The costs comprised the combined satellite damage cost and insurance loss [2]. About the three parametric models, each model was arranged in two directions: one-variable fitting and two-variable fitting. Like reliability, the model's performance was assessed using Root Mean Square Error (RMSE) and Relative Root Mean Square Error (RRMSE). It is because these metrics assist in measuring how well each model fits the actual data. The lowest RMSE and RRMSE of the model is deemed the best model [2]. Ultimately, a trade-space exploration method was conducted using the model. This investigation proves that when the subsystem's life increases, there are no significant cost savings achieved, which in turn untangles the best design zone that stabilizes both reliability and cost values [2].

4. RESULTS AND DISCUSSION

4.1 Development Of Exponential-Based Reliability Model Using Trade-Space Exploration (TSE)

As mentioned in the methodology section, the parametric and non-parametric models were analysed. After careful analysis, the Exponential model was deemed to prove the best model fit across all four subsystems due to its lowest RMSE. Table 1 tabulates the computed Root Mean Square Error (RMSE) values for antenna with 0.22, transponder with 0.27, and 0.30 for both amplifier and battery for the Exponential model [1].

Table 1. RMSE Values For Exponential Model [1]

Component	RMSE
Antenna	0.22
Transponder	0.27
Amplifier	0.30
Battery	0.30

The prior models are unable to link reliability to design life and performance. Therefore, the Exponential-based mathematical TSE model can, and it is proven to have clearer design trade-off decisions [1]. (1) depicts the newly developed Exponential-based mathematical TSE model [1].

$$TSE_{R(t)} = e^{-\lambda t} (1 - RMSE) \quad (1)$$

Where:

$R(t)$ = reliability at time t

λ = failure rate of the component

α = scaling coefficient

The model's accuracy was assessed by computing the difference between predicted and actual reliability values. The RMSE is inversely proportional to the model's performance. Meaning, if the computed RMSE values are lower, the performance is higher, and vice versa. The (1-RMSE) was added in Equation (1) because some models with large RMSE received a lower reliability prediction, compared to those with lower RMSE [1]. This model modification, in turn, helps to predict reliability values accurately. Accordingly, the lower RMSE indicates that the predictions are more reliable [1].

4.2 RMSE and RRMSE for One-Variable and Two-Variable Parametric Cost Models

Three parametric cost models consisting of Exponential, Weibull, and Poisson were applied. The communication subsystems analysed were antenna, payload, power system, and attitude control. The Root Mean Square Error (RMSE) and Relative Root Mean Square Error (RRMSE) of each model were computed to determine which model performed the best. Following model fitting and evaluation, a trade-space analysis was performed to evaluate how variations in subsystem design life impact the overall cost of anomalies. Both one-variable and two-variable fitting approaches were used during this process. The one-variable fitting focused on the relationship between design life and cost for individual subsystems, allowing for a clearer understanding of how each subsystem behaves independently [19]. In contrast, two-variable fitting considered the interaction between design life and cost across multiple subsystems simultaneously, offering a broader view of how combined subsystem behaviour influences overall cost trends. This approach was necessary to capture both isolated and interdependent effects on cost [18]. These insights contribute to making informed decisions on how to allocate design resources efficiently while balancing reliability and cost considerations [18]. Table 2 tabulates the RMSE and RRMSE results for both one-variable and two-variable parametric cost models [2].

Table 2. Results Of RMSE And RRMSE For Both One-Variable And Two-Variable [2]

Subsystems	RMSE (One-Variable)	RRMSE (One-Variable)	RMSE (Two-Variable)	RRMSE (Two-Variable)
<i>Exponential</i>				
Antenna	194.94	71.56%	218.16	45.72%
Payload	121.84	44.73%	115.73	41.66%
Power System	128.17	47.05%	134.70	46.73%
Attitude Control	114.15	41.91%	110.57	40.59%
<i>Weibull</i>				
Antenna	271.85	99.80%	455.24	95.40%
Payload	239.07	87.76%	186.21	67.03%
Power System	229.69	84.32%	434.17	150.64%
Attitude Control	194.22	71.30%	307.02	112.71%
<i>Poisson</i>				
Antenna	431.14	158.27%	489.87	102.65%
Payload	304.71%	111.86%	240.17	86.45%
Power System	295.86	108.61%	442.79	153.63%
Attitude Control	310.01	113.80%	290.91	106.79%

The limited sample size of cost data, consisting of 42 data points, is the main reason for the high RMSE values for each model because it has fewer data points to make accurate predictions. Most satellite companies cannot provide comprehensive total cost data due to confidentiality issues. The cost values in this study comprise total financial loss, involving the satellite's manufacturing cost and any insurance claims from the anomaly [2]. The Exponential cost model steadily surpassed the Weibull and Poisson models across all communication subsystems, demonstrating the lowest RMSE and RRMSE values for both one-variable and two-variable. This finding suggests that its exceptional analytical capability in catching subsystem cost behaviour with respect to the Weibull and Poisson models. Furthermore, this finding also acknowledges that the subsystem's cost variations exhibit a reasonably even form, which can be represented by an Exponential distribution. However, the inclusiveness of the two-variable improved the model performance in most subsystems because of the reduction in RRMSE values, especially for Antenna.

On the contrary, the Poisson model shows the highest RMSE and RRMSE values over all subsystems. The Poisson distribution's character is suitable for a discrete event. Therefore, the continuous cost estimation, which is presented in this study, is incompatible with the Poisson model. It is also the same for the Weibull model, even though it provides extra flexibility through its shape parameter.

4.3 Integration of Trade-Space Exploration Reliability Exponential-Based Model with Cost Model

Looking at both reliability and cost models, the Exponential model consistently shows the lowest RMSE value for reliability and RRMSE for cost. Thus, integrating these two elements is possible to achieve a deployable engineering decision-support system (DSS), which has already been developed in [20]. The Web AI-based DSS features mission planning dashboards that populate the failed satellites' historical data obtained from the Seradata database [20]. This prototype was developed in conjunction with Space Situation Awareness (SSA) to promote space sustainability, reduce satellite failures, and space debris caused by particles from failed satellites that, over time, crowd the orbit [20,21].

Moreover, integrating reliability and cost models into Web AI-based DSS will assist stakeholders in their informed decisions for emerging space programs, especially in developing countries. Furthermore, the TSE model, which incorporates reliability and cost, may also serve as a cost-conscious reliability planning method for small-satellite developers such as CubeSats in the future. For educational purposes, this framework can be integrated into the aerospace engineering curriculum to enhance students' understanding of space systems and the critical importance of maintaining space sustainability. By incorporating this approach into coursework, students can develop a more comprehensive perspective on subsystem interactions, cost modelling, and long-term sustainability considerations within complex space missions.

5. CONCLUSION AND FUTURE WORK

The newly trade-space exploration (TSE) Exponential-based reliability model yields the lowest RMSE square for each communication subsystem, that is, antenna, transponder,

amplifier, and battery. This is the same for cost anomaly prediction, where the Exponential model is the most reliable because it has the lowest RMSE and RRMSE for one-variable and two-variable. From an engineering point of view, the assumption of a constant failure rate offers simplicity, systematic flexibility, and robustness for subsystem-level reliability evaluation, especially under uncertainty. This aids scalable reliability provision, maintainability scheduling, and mission lifetime prediction, specifically for satellite systems working in non-stable conditions. Cost-effectively, the Exponential cost model facilitates visible lifecycle cost prediction by precisely combining failure amounts with maintenance overheads, replacement allocation, and downtime consequences. Such a design establishes adjusted budget provision, preventive maintenance planning, and long-term asset management plans that eventually reduce the total cost of ownership and improve mission sustainability.

For future reference, exponential-based reliability and cost models integration with Artificial Intelligence (AI) and digital twin designs would substantially improve next-generation aerospace analytics. AI-driven systems can update reliability factors by anomaly detection algorithms and real-time telemetry, whereas digital twin systems can replicate degradation routes and cost growth dynamically in the mission lifecycle. This integration, in turn, helps in predictive decision-making, adaptive maintenance optimization, and real-time risk-informed cost control, placing the future methodology as an introductory intelligent aerospace system management element. For future work, it is recommended to have more substantial cost data, and machine learning models can be applied to get smaller RMSE and RRMSE values. As for the reliability study, Artificial Intelligence and Machine Learning models can be investigated as an addition, not a substitution for the mathematical model.

ACKNOWLEDGEMENT

This research is funded by the Asian Office of Aerospace Research and Development (AOARD) with Grant Numbers: FA2386-23-1-4073 and SPI23-179-0179. The data for this research were obtained from Seradata under Slingshot Aerospace. The authors express their heartfelt gratitude for the IIUM CPS Khair Award for tuition fees support.

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