Impact of Various Spacecraft Mass Fractions Over Spacecraft Reliability

Malaya Kumar Biswal M[*] and Ramesh Kumar V[†]

Grahaa Space, Bangalore, Karnataka – 560093, India

Reliability poses a significant parameter to define the extent of durable mission and satellite lifespan. Over decades numerous researchers have found numerous factor that affects spacecraft lifespan as well as reliability. In this paper, we have defined three different spacecraft mass fraction parameters relative to the spacecraft's dry mass, propellant mass, and payload. Thereafter, we have related the above-mentioned parameters to spacecraft lifespan and reliability. The result showed that the spacecraft mass fraction imposes a significant impact on satellite reliability thereby affecting its lifespan during the course of a mission. Following, we have hypothesized spacecraft mass fraction limit ideal for a durable mission. In addition to that, we have proposed some factors that play a major role in determining the reliability of spacecraft.

I.Nomenclature

m_G	=	Gross mass of the spacecraft
m_D	=	Dry mass of the spacecraft
m_{PP}	=	Propellant mass
m_{PL}	=	Payload mass
β	=	Payload mass fraction
σ	=	Spacecraft mass fraction
σ_D	=	Spacecraft mass fraction concerning dry mass
σ_{PP}	=	Spacecraft mass fraction concerning propellant mass
σ_{PL}	=	Spacecraft mass fraction with respect to payload mass
δ	=	Spacecraft payload fraction
ζ	=	Propellant mass fraction of the launch vehicle
η	=	Spacecraft Propellant mass fraction
η_D	=	Spacecraft Propellant mass fraction concerning dry mass
η_G	=	Spacecraft Propellant mass fraction concerning gross mass
t	=	Mission lifetime of the spacecraft
k	=	Inverse proportionality constant

II.Introduction

SATELLITE reliability plays a significant role in both planetary and interplanetary missions where a spacecraft's internal and external factors greatly influence its gross lifespan. Parameters such as spacecraft sizing, mass determination, design algorithm, onboard instrumentation system, propulsion systems, and space environment come under internal factors whereas space environment (includes solar flares, cosmic radiation, asteroid impact and miscellaneous), and operating extremity affects the lifespan of both planetary and interplanetary spacecraft [1-6]. Over decades, satellite manufacturers and data scientists have worked on satellite lifespan data to determine the possible factors which affect spacecraft reliability which redefined the era of the global satellite market and autonomous interplanetary missions. However, we cannot recover the satellite projected towards interplanetary space or satellite orbiting at different extremities [7-9]. Therefore, it is significant to consider certain parameters through which we can make the spacecraft survive despite space environmental perturbations. As a primary objective of this satellite reliability

[*] Senior Research Scientist, Grahaa Space, Bangalore, Karnataka, India. Student Member AIAA. ORCID: 0000-0002-0181-8125.
[†] Co-Founder, Grahaa Space, Bangalore, Karnataka, India. Non-Member AIAA. ORCID: 0000-0003-2665-5294.

research, we studied a number of papers and finally, we considered the spacecraft mass resulting in defining three different spacecraft mass fraction parameters proposed in our earlier works [10-11]. In this paper, we have comparatively explained the significance and their impact on satellite lifespan and reliability.

III.Spacecraft Mass Fraction Convention and Reliability Modelling

In our earlier works, we have proposed three spacecraft mass fraction parameters mass fraction convention is shown in the table-1. Relating to the mass fraction convention, we have proposed both non-parametric and parametric modelling whose equations are shown in the table-2. A well-defined mathematical and theoretical modelling and analysis is presented in our earlier works [10-11].

Table 1 Final Equations of Mass Fraction Convention & Reliability Modelling

	Spacecraft Mass Fraction	Propellant Mass Fraction	Payload Mass Fraction
Mass Fraction Conventions	$\sigma = \frac{m_D}{m_G}$	$\eta_G = \frac{m_{PP}}{m_G}$	$\delta_G = \frac{m_{PL}}{m_G}$
Theoretical Modelling	$t = \left(\frac{m_G}{m_D}\right)k$	$t = \left(\frac{1}{k}\right)\left(\frac{m_{PP}}{m_G}\right)$	$k = \left(\frac{m_G}{m_{PL}}\right)t$
Mathematical Modelling	$\sigma = 0.729 - 0.006(t)$	$\eta_G = 0.282 + 0.00498(t)$	$\delta_G = 0.35404 - 0.00903(t)$

IV.Comparative Analysis and Results on Spacecraft Reliability Analysis

A. Non-Parametric Modelling (Using Kaplan-Meier Estimation Method)

Spacecraft Mass Fraction vs Reliability

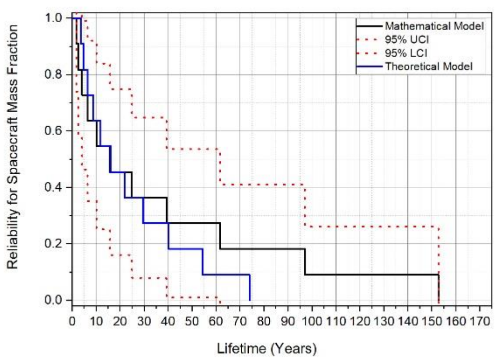


Fig 1 Reliability Modelling for Mass Fraction

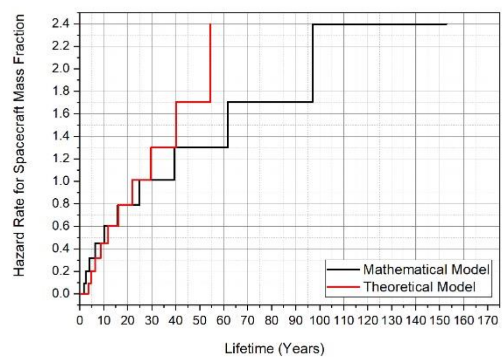


Fig 2 Hazard Rate from Reliability Model

Initially, we gathered spacecraft mass parameter data from Seradata's Spacetrak Database [12]. Uncategorized data has been sorted in ascending order for reliability modelling. Here, we estimated the mass fraction parameter of each spacecraft using the spacecraft mass fraction convention presented in the table [1]. Following the mass fraction data was reorganized in ascending order for reliable results. In addition to that, we approximated the lifespan of each spacecraft through our theoretical modelling, the dataset for this model can be found in [10-11]. Further, we executed the mass fraction data relative to spacecraft lifespan (in years) into the Kaplan-Meier algorithm (a non-parametric model), which produced comparable results shown in the figure-1. Moreover, we predicted the hazard rate from the reliability model shown in the figure-2.

Figure-1 Description: The figure reflects the final resultant reliability curve acquired from the non-parametric estimation method through executing spacecraft mass fraction versus lifespan. It reflects that spacecraft having a mass fraction limit of $0.1 \leq \sigma \leq 0.5$ exhibits a lifespan variance of 25 to 60 years with $95\% \leq R(t) \leq 35\%$ reliability through the mathematical model, whereas it tends to exhibit $95\% \leq R(t) \leq 30\%$ reliability through the theoretical model. Following, a spacecraft with a mass fraction limit of $0.6 \leq \sigma \leq 1.2$ tends to survive less than 15 years with a reliability variance of $30\% \leq R(t) \leq 10\%$ interpreted through mathematical and theoretical models.

Figure-2 Description: Comparable to the reliability, we also observed that the spacecraft tends to experience a hazard rate of 10% (minimum) and 25% (maximum) which readily increases with an increase in the operational period of spacecraft presented in the second figure. Furthermore, from both graphs, we predicted that the spacecraft mass fractions significantly influence the lifespan of the spacecraft hypothetically as our reliability model produced comparable results. So, there might be unidentified factors in the mass fraction and spacecraft sizing which adversely creates a significant impact on the reliability during the operational period at different spacecraft extremity. However, based on our analysis and research study, we have hypothesized some of the influential factors that affect both lifespan and reliability of any spacecraft in later sections.

Spacecraft Propellant Mass Fraction vs Reliability

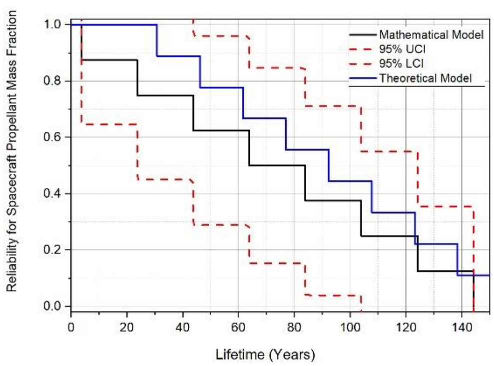


Fig 3 Reliability Model for Propellant Mass Fraction

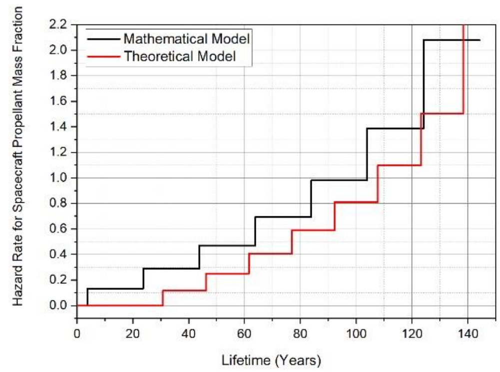
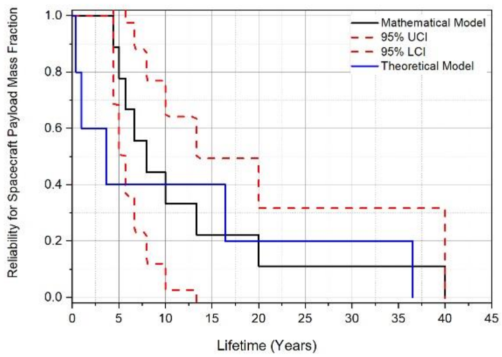


Fig 4 Hazard Rate from Reliability Model

Similar to the spacecraft mass fraction-reliability model, we modelled propellant mass fraction vs reliability which produced proportional results in terms of reliability curve and hazard function shown in the above figures. Here, our model produced contradictory results relative to the model of spacecraft mass fraction versus reliability. Results show that a spacecraft with a higher propellant mass fraction tends to exhibit marginal reliability compared to a spacecraft which have a lesser propellant mass fraction, this relation can be understood from the figure-3. Mathematically, spacecraft with a propellant mass fraction difference of $0.1 \leq \eta_G \leq 0.5$ tends to exhibit lesser reliability (ranges from 50% ≤ R(t) ≤ 40%) with greater lifespan ranges from ~10-20 years. Subsequent to this, spacecraft with propellant mass fraction variance $0.6 \leq \eta_G \leq 1.0$ exhibits maximum reliability from 60-90% (90% ≤ R(t) ≤ 60%) with a gross lifespan of 40-80 years. In addition to the reliability of spacecraft, we interpreted the hazard function or hazard rate from the reliability model, the results show that spacecraft during their initial operating period, experience a maximum hazard rate of 20-40% which exponentially increases with an increase in spacecraft lifespan (refer figure 2). Moreover, the results and model presented here relatively match the results presented in our earlier paper [10-11].

The spacecraft propellant mass fraction or propellant quantity needs to consider for every spacecraft before deploying into any interplanetary orbit as it plays a significant parameter in greater lifespan and normal spacecraft operations. There are examples where spacecraft simply deorbited and disposed into the atmosphere due to propellant exhaustion. In addition, malfunction of the spacecraft attitude control system, micro-thruster propulsion system, inability to cut down the delta-velocity during orbital injection, failure of trajectory raising manoeuvring, and failure of spacecraft orientation system are some of the accountable factors which arise due to propellant exhaustion and improper propellant fueling. Therefore, in order to maintain an optimal propellant parameter with respect to the spacecraft gross mass, we exclusively presented the spacecraft propellant mass fraction and its reliability nature in this section. More detailed analysis and other accountable factors contributing to the lifespan and reliability of the spacecraft can be understood from our earlier research work presented at the 2022 AIAA Science and Technology Forum [11]

Spacecraft Payload Mass Fraction vs Reliability



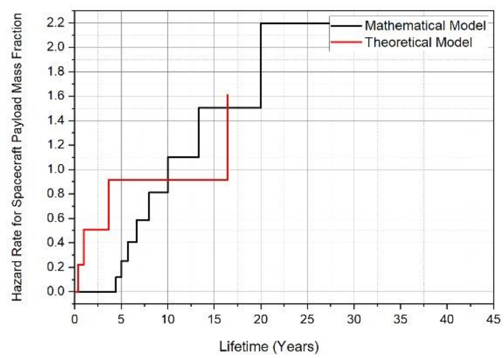


Fig 5 Reliability Model for Spacecraft Payload Mass Fraction Fig 6 Hazard Rate from Reliability Model

In this section, we tried to relate the spacecraft payload mass to its spacecraft lifespan resulting in reliability modelling presented in the earlier section of this paper. The payload mass fraction doesn't contribute much to the reliability parameter, but it produced significant results similar to mass and propellant mass fraction. Alike, mass and propellant mass fraction, we approximated payload mass fraction using the equations shown in the table-1 and executed a non-parametric reliability model to define the impact of spacecraft payload mass fraction over the reliability. Our reliability model showed that, a spacecraft whose payload mass fraction ranges from 0.5 to 1.0 ($0.5 \leq \delta_G \leq 1.0$) tends to exhibit maximum reliability (90% ≤ R(t) ≤ 80% from mathematical modelling and 80% ≤ R(t) ≤ 40% from theoretical modelling), wherein the spacecraft is expected to operate for 4-5 years in any planetary orbit. Contradictory to this, spacecraft with a payload mass fraction variance of $0.1 \leq \delta_G \leq 0.4$ are found to exhibit lesser reliability. Following, during the operational period of the spacecraft, we found that the spacecraft experiences a hazard rate of 10-20% throughout the mission duration.

B. Parametric Modelling (Using Weibull-Probability Distribution Method)

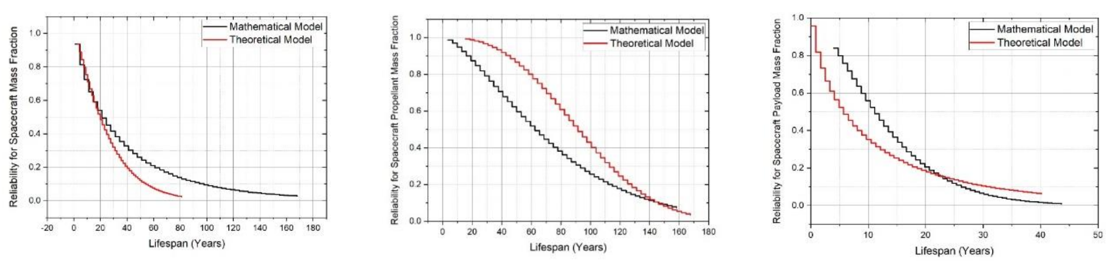


Fig 7 Parametric Modelling (Spacecraft Mass-Propellant-Payload Mass Fraction vs Reliability)

Kaplan-Meier reliability model produced comparable results in the preceding sections. Here, we attempted to revalidate our analysis through a parametric Weibull distribution algorithm. For parametric modelling, we executed different spacecraft mass fraction data into the Weibull-distribution algorithm which produced matching results analogous to the non-parametric method. The resultant graphs of this analysis can be recognized from the above graphs. The left figure depicts the spacecraft mass fraction versus reliability, the middle figure depicts the spacecraft propellant mass fraction versus reliability, and the right figure portrays the spacecraft payload mass fraction versus reliability. Finally, comprehending the final mass fraction parameter, we have predetermined optimal mass fraction limits in the result section.

Note: To get a more detailed report on theoretical and mathematical modelling; spacecraft mass, propellant, and payload data; and equations and formulations for this model can be explored from our preceding reports referenced in the last section and supplementary resources. [13-15].

V. Conclusion

As a result of our reliability modelling and analysis, we intend to state that spacecraft mass parameter significantly influences the lifespan as well as reliability. Hence from our analysis, we assert that the spacecraft mass fraction also has an adverse impact on the satellite lifespan and reliability of all the orbital spacecraft. In addition, intending to re-establish a significant relation between satellite mass and lifespan interpreted by G.F Dubos in 2010 [16], we proposed a novel mathematical method to revalidate the data to correlate the mass-lifespan relation. Finally, based on our analysis, we conclude that a spacecraft of optimal mass fraction limit presented in the below table is expected to have greater reliability with a longer lifespan.

Table 2 Optimal Mass Fraction Limit for Longer Lifespan and Reliability

Scripts	Meaning	Fraction Limit	Optimal Fraction Limit	Reliability
$\boldsymbol{\sigma}$	Mass Fraction	$0.1 \le (\sigma) \le 1.0$	$0.2 \le (\sigma) \le 0.7$	95% ≤ R(t) ≤ 35%
$\boldsymbol{\eta_G}$	Propellant Mass Fraction	$0.1 \le (\eta_G) \le 1.0$	$0.2 \le (\eta_G) \le 0.6$	90% ≤ R(t) ≤ 60%
$\boldsymbol{\delta_G}$	Payload Mass Fraction	$0.1 \le (\delta_G) \le 0.8$	$0.1 \le (\delta_G) \le 0.4$	90% ≤ R(t) ≤ 80%

This research paper delves into the crucial aspect of satellite reliability analysis, with a specific focus on the optimization of spacecraft mass fraction to achieve greater lifespan and operational dependability. As satellite missions serve as precursors to human crewed expeditions, it becomes paramount to consider significant spacecraft mass parameters that contribute to the overall reliability of the mission [17-23]. Through an extensive review of scientific research and analysis, this study aims to provide valuable insights into the factors influencing satellite reliability, offering a novel perspective for satellite manufacturers and data scientists involved in future research. By investigating the relationship between spacecraft mass fraction and mission success, this research endeavours to contribute to the development of more robust and durable satellite systems, ultimately advancing the reliability and effectiveness of space-based operations.

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Conflict of Interest and Funding

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Supplementary Resources

Theory and Modelling of Various Spacecraft Mass Fractions and their Influence over Spacecraft Lifespan and Reliability. In *ASCEND 2021*. https://arc.aiaa.org/doi/abs/10.2514/6.2021-4220

Spacecraft Reliability and Lifetime Modelling: Impact of Spacecraft Mass and Mass Fractions on Spacecraft Lifespan and Reliability. In *AIAA SCITECH 2022 Forum*. https://arc.aiaa.org/doi/abs/10.2514/6.2022-1140

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