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Reliability estimation methodology for Liquid Rocket Engines

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Abstract
The launch rate has steeply increased in the last few years. However, the launch success rate in 2020 was the lowest of the last 15 years. Launch failures do not only come at a great economic cost, but also at a large waste of resources on Earth. Moreover, failed upper stages can remain in orbit for long periods of time, adding up to the tonnes of space debris orbiting Earth and threatening future space missions. Consequently, ensuring the reliability of space launch vehicles is essential in order to protect both Earth and space environment, in addition to the missions being launched.

Current methods used to assess the reliability of launch vehicles are very time consuming and strongly rely on the expertise of the team performing the assessment. The goal of this work is to develop a simplified methodology that can be used for early reliability estimation of Liquid Rocket Engines (LREs), which would allow space launch vehicle designers to compare different system architectures and make trade-offs based on the reliability of different design options. The model is not intended to be more accurate than traditional methods. Indeed, it should be highlighted that the methods mentioned before are still required in later stages. However, the current work intends to provide a quicker and easier to use alternative, based on few design parameters that are key reliability drivers, which allows reliability-based decisions in early stages of the design.

1. Introduction

Boosted by the commercialization of the space sector and the appearance of new space actors, the launch rate is continuously increasing. In this context, it is essential to ensure the reliability of space launch vehicles in order to protect both Earth and space environment.

Current methods used to assess the reliability of launch vehicles, such as Failure Modes, Effects and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), Reliability Block Diagram (RBD) and Event Tree Analysis (ETA), are very time consuming and strongly rely on the expertise of the team performing the assessment. Even though these assessments are necessary and must always be performed before the system becomes operational, they are not practical in early stages of the design, when the design is still flexible and several system architectures might be available. However, the launcher design process can be greatly benefited by early reliability assessments, as changes in the design are easier to make in these stages with a lower associated cost.

The goal of this work is therefore to develop a simplified methodology that can be used for early reliability estimation, which would allow space launch vehicle designers to compare different system architectures and make trade-offs based on the reliability of different design options. The model is not intended to be more accurate than traditional methods. Indeed, it should be highlighted that the methods mentioned before are still required in later stages of the design. However, the current work intends to provide a quicker and easier to use alternative, supporting reliability-based decisions in early stages of the design.

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Historical data has shown that more than half of launch vehicle failures originate in the propulsion subsystem [3], more specifically in Liquid Rocket Engines (LREs). Therefore, the modeling efforts have been focused on this subsystem. The model presented in this paper is focused on the reliability estimation of a propulsion system using LREs. Further work will address other subsystems of the vehicle as well as the integration between all of them.

Previous studies have identified key drivers of the reliability of LREs. In this work, empirical and statistical relationships were used to build a model that estimates the reliability of a LRE as a function of these key drivers. It is important to note that, lacking access to actual test data of current LREs, the results presented here are limited and the relationships used are mainly based in different previous studies. Access to real test data would be very beneficial, for instance, for the verification of this model and for the development of more accurate easy-to-use reliability models.

The reliability drivers included in this model, which were identified in [6] as key reliability drivers for LRE, are:

- **Number of engines:** number of engines used in the propulsion system of the launcher stage.

- **Engine cycle:** combustion cycle used by the engine. The main types commonly used can be classified as gas generators, expander cycles and staged combustion. Different engine cycles require of different levels of complexity, which unavoidably affects the reliability of the engine.

- **Propellant:** combination of fuel and oxidizer used in the engine. Different propellants are related to different hazards and different specific designs intending to avoid these hazards, which in turn affects the reliability.

- **Engine operation duration:** thus, the nominal burn time of the engine.

- **Engine thrust size:** the thrust level for which the engine is designed.

- **De-rating or up-rating:** an engine can be designed to provide a certain thrust level and then throttled down in order to improve its reliability, as this would turn into less severe conditions. Similarly, an engine can be throttled up to provide more thrust under some specific conditions, which would turn into a decrease on the reliability of the engine.

- **Engine-out capability:** when a propulsion system is comprised by more than one engine, it can be designed such that the mission can still be accomplished when one of them fails. This is usually related to either an uprating of the other engines after the failure, a previous de-rating and subsequent full operation after the failure, or longer burn times for the other engines. Moreover, an appropriate Health Management System (HMS) is required, which will be in charge of detecting the failure and safely shut down the faulty engine.

- **Engine-out switching reliability:** the probability of success of the process of detecting the failure and safely shutting down the faulty engine.

- **Catastrophic fraction:** even if some failures can be tolerated when the propulsion system is designed for engine-out capability, some of the failures can be uncontained, thus catastrophic, and provoke the unavoidable failure of the mission. The portion of failures that are uncontained with respect to the total number of engine failures is named as the catastrophic fraction C_f.

The individual impact of each of these factors, as well as the expressions used to characterize them, will be shown in Section 2. Then, the process followed by the developed algorithm to calculate the reliability of the propulsion system is explained in Section 3. Finally, some conclusions are presented in Section 4.

2. Impact of the individual key drivers

In this section, the approach used to address the impact on the reliability by each factor is described. Some preliminary results will be shown in order to show the influence of each factor on the reliability of the engine.

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2.1 Burn time

The reliability of an item varies during its operational time. Assuming a constant failure rate, the evolution of the reliability with time can be described by means of an exponential distribution. Even though this assumption carries strong limitations, it is considered to be enough for the simplified model that this work is aiming for. With λ being the failure rate and t the time, the reliability R is expressed as:

$$R(t) = \exp(-\lambda t) \tag{1}$$

2.2 Engine cycle and propellant

The approach used to consider the impact of the engine cycle and the propellant combination on the reliability consisted on deriving a baseline failure rate for each engine cycle, which will be the initial λ that will be further modified according to the other reliability factors.

The first challenge to overcome to derive these baseline failure rates, is the lack of a good database assessing the reliability of existing or historical engines, as well as the lack of testing and failure data from these engines. The best source of information including this type of data that has been made publicly available, to the knowledge of the authors, is the Quantitative Risk Assessment (QRA) of the Space Shuttle Main Engine (SSME). Even though these data have not been directly found online by the author, several sources are available which make use of these data and reproduce it. More specifically, two of these sources will be used in this work: the final report of Pratt & Whitney Propulsion Risk Reduction Requirements Program developed for NASA [1] and the Exploration Systems Architecture Study by NASA [2]. Even more importantly, the study by Pratt & Whitney [1] performs an analysis of 6 engine cycles, comparing them component by component to the cycle of the SSME and deriving a a new failure rate for each engine cycle. Moreover, the failure rates distinguish catastrophic failures from benevolent failures, which allows to also estimate the catastrophic fraction C_f for each engine cycle. The engine cycles that were considered are the following:

- Dual-Burner Fuel-Rich Staged Combustion (DBFRSC).
- Dual-Burner Full-Flow Staged Combustion (DBFFSC).
- Single-Burner Fuel-Rich Staged Combustion (SBFRSC).
- Single-Burner Oxidizer-Rich Staged Combustion (SBORSC).
- Single-Burner Fuel-Rich Gas Generator (SBFRGG).
- Split Expander (SPLTEX).

Detailed schematics of these engine cycles can be found in [1]. The failure rates derived for each cycle in [1], however, could not be directly used for this model, as they are provided as failures per million firings and the duration of these firings is not stated. For this work, the failure rates need to be derived in failures per second, in order to be able to consider the effect of the burn time in the reliability. For this purpose, the data shown in [2] is used. Here, the uncontained failure rate per component of the SSME is shown again, but in this occasion it is expressed as failures per 500 seconds. It is important to note that, even if the data in [2] was already provided as a function of time, the data from [1] was preferred for two reasons: it provides information about both contained and uncontained failures and it provides an analysis and failure rate estimation for 6 different engine cycles in addition to the SSME.

The challenge was therefore to combine both sources in order to obtain the failure rate with time for all engine cycles, including contained and uncontained failures. In order to do so, the failure rates were compared component by component. Even if the component classification differs a bit in these sources, most components can be easily matched from one report to the other. If we call $\lambda_{i,firings}$ to the failure rate of a component i per million firings as shown in [1], $\lambda_{i,secs}$ to the failure rate of the component i per 500 s as shown in [2], and ρ_i to the ratio between both failure rates for each component, which provides the seconds per firing of the test data, the comparison of the failure rates for all components of the SSME provided in average, with a reasonably small deviation:

$$\rho_i = \frac{\lambda_{i,firings}[\text{failures per }10^6\text{firings}]/10^6}{\lambda_{i,secs}[\text{failures per 500 seconds}]/500} = \frac{\lambda_{i,firings}[\text{failures per firing}]}{\lambda_{i,secs}[\text{failures per second}]} \approx 550 \text{ s/firing} \tag{2}$$

This value aligns with the nominal mission profile of the space shuttle, where the SSME is expected to burn for about 8.5 minutes or 510 seconds [7]. However, not all components could be matched from one report to the other.

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When using Eq. (2) to compare the total failure rate of the SSME, it results in ρ = 458 s/firing. In the end, this was the value used to transform the failure rates from all engine cycle into failures per second, aiming to preserve the total failure rate. The values used for the failure rate are therefore derived from the failure rates found in [1] as:

$$\lambda_i[\text{failures per second}] = \frac{\lambda_{i,firings}[\text{failures per } 10^6 \text{firings}]}{10^6 \text{ firings} \cdot 458 \text{ s/firing}} \tag{3}$$

The catastrophic fraction for each component, on the other hand, was derived directly from [1] as:

$$C_{f,i} = \frac{\lambda_{i,uncontained}}{\lambda_{i,contained} + \lambda_{i,uncontained}} \tag{4}$$

Finally, the following failure rates and catastrophic fractions were derived for each engine cycle:

Engine cycle	$\lambda[s^{-1}]$	C_f
DBFRSC	3.29934E-06	0.164052677
DBFFSC	3.07402E-06	0.160238653
SBFRSC	3.23624E-06	0.160302253
SBORSC	3.21616E-06	0.160760353
SBFRGG	3.03319E-06	0.156924849
SPLTEX	2.80502E-06	0.150540982

Table 1: Failure rate and catastrophic fraction for each engine cycle derived from [1]

It is important to highlight the limitations inherent to this data. First of all, it is unavoidably very old data, which might mean that it is outdated from the technologies used nowadays. However, the Space Shuttle was a manned vehicle, rated for human space flight, in addition to being a reusable vehicle. Both factors point towards a higher reliability of the Space Shuttle as compared to unmanned disposable vehicles. Finally, this data only considers the use of liquid hydrogen and liquid oxygen as fuel and oxidizer, respectively. However, it is known that different propellant choices entail different hazards, with a consequent impact in the expected failure rate. An important step in future work will be to perform an assessment to be able to modify the baseline failure rate of the different engine cycles according to the propellant used. However, the limitations in the data found made it impossible to include this assessment in the present work.

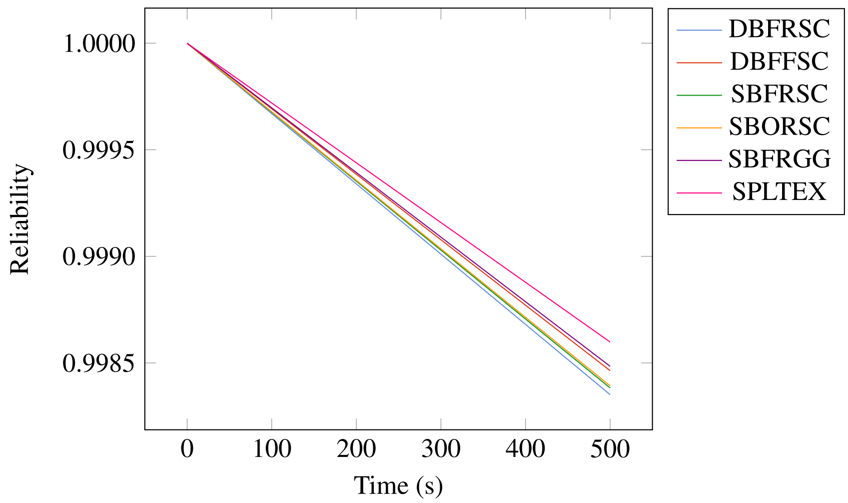

Figure 1: Reliability as a function of time for different engine cycles.

Figure 1 shows the evolution of the reliability with time for a 500 s burn for the different engine cycles studied in this work, using the failure rates shown in Table 1, and therefore assuming the use of liquid oxygen and liquid hydrogen as propellants and a nominal thrust equal to the nominal thrust of the SSME, thus 2278 kN. As it could be expected, the higher reliability is shown in the engine cycles with a lower failure rate. Moreover, the difference between the reliability of the different engine cycles increases with time.

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2.3 Engine thrust size

The design nominal thrust of the engine impacts its reliability. A higher nominal thrust usually implies a bigger engine and more severe conditions that it needs to withstand. Being $\lambda(T_{base})$ the failure rate of a baseline engine with a baseline design thrust T_{base}, and $\lambda(T_{new})$ the failure rate of an engine of the same characteristics, only scaled-up or scaled-down to produce a different nominal thrust when operating at a 100%, [2, 4, 5] describe the relationship between the two failure rates as:

$$\frac{\lambda(T_{new})}{\lambda(T_{base})} = \left(\frac{T_{new}}{T_{base}}\right)^{\delta} \tag{5}$$

With $\delta = 0.1017$ [2,4,5]. Figure 2 shows the change in reliability due to the engine nominal thrust for a DBFRSC engine cycle using LOX/LH2 at the end of a $500s$ burn.

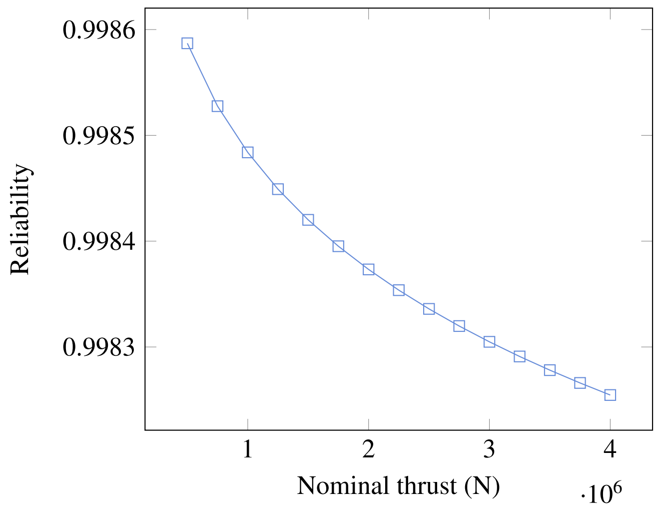

Figure 2: Reliability as a function of the nominal thrust, assuming DBFRSC engine cycle using LOX/LH2 and 500 s burn.

2.4 Number of engines

Sometimes, several engines are required in the propulsion system of a rocket stage in order to achieve the desired thrust. Moreover, as the reliability decreases for a higher nominal thrust, a typical design trade-off is considering the impact of using several small engines as opposed to a single large one. Considering a propulsion system using N equal engines with equal failure rate λ, and assuming that no failure can be tolerated in any engine, the reliability can be expressed as a function of time as:

$$R(t) = \exp\left(-N\lambda t\right) \tag{6}$$

The figure below shows the evolution of the reliability with time of a propulsion system, varying the number of engines providing a total nominal thrust of $T_{nom} = 2278kN$ all together, assuming DBFRSC engine cycle using LOX/LH2. It can be seen that the reliability here decreases when the number of engines is increased. Thus, the impact of adding another engine is bigger than the decrease in the failure rate provoked by the down-scaling of the engine.

2.5 De-rating or up-rating

When an engine operates at a lower thrust level than it is designed for, the less severe operational conditions will have a benefit on the reliability of the engine. Conversely, engines can also be throttled up to operate at a higher thrust level, but this will have a negative effect on the reliability of the engine. Being T_{nom} the nominal design thrust of an engine and T_{op} the thrust at which the engine operates, we can define:

$$\alpha = \frac{T_{op}}{T_{nom}} \tag{7}$$

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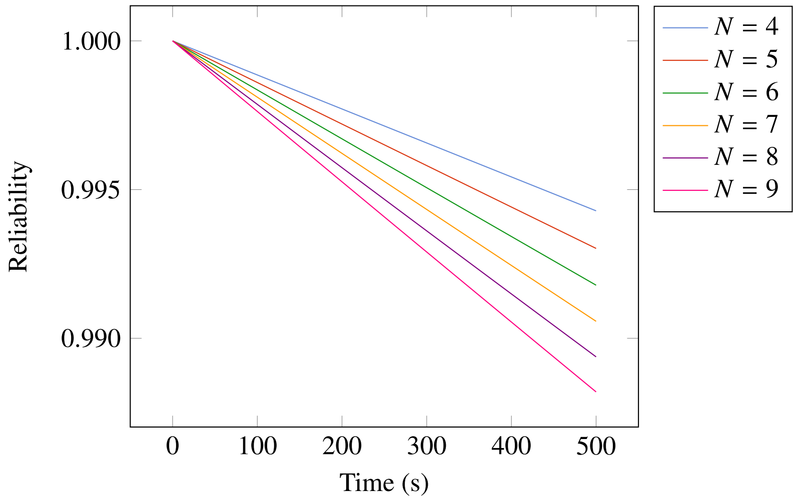

Figure 3: Reliability as a function of time for different number of engines, assuming DBFRSC engine cycle using LOX/LH2 and 500 s burn.

And the relationship between the failure rates of the engine operating in de/up-rated conditions and the nominal one can be expressed as [5]:

$$\frac{\lambda(T_{op})}{\lambda(T_{nom})} = (1-p) + p \cdot \exp\left(-q(1-\alpha)\right) \tag{8}$$

Where $0 < p < 1$ and $q > 0$. The parameter p represents the fraction of the engine failures that are affected by the engine de-rating or up-rating. For instance, failures due to an inadequate assembly are unlikely to be prevented by a lower operational thrust level, while failures caused by wear or fatigue will be directly affected by the less severe operational conditions. The parameter q determines how fast the failures that are affected by the de-rating decrease [5]. Both parameters p and q depend on the propellant used. The following values are provided in [5]:

Propellant	p	q
LOX/LH2	0.35	12.06
LOX/RP1	0.2	5.78

Table 2: p and q parameters for different propellants.

Figure 4 shows the evolution of the reliability for different values of α keeping a constant nominal thrust, equal to the nominal thrust of the SSME, and using the p and q values of the two propellant combinations shown in Table 2. Again a 500 s burn was considered using a DBFRSC engine cycle. Even though the evolution with both propellant combinations is shown in Fig. 4, it is important to highlight that the baseline failure rate has not been modified according to the propellant choice, as it was already explained before. Therefore, further adjustments would be necessary to assess the reliability of a LOX/RP1 engine. However, it is interesting to observe the different evolution of the reliability with α depending on the values of p and q corresponding to the different propellant combinations. The figure shows the positive impact of de-rating on the reliability of the engine, as well as the negative impact of up-rating. A bigger increase in the reliability caused by de-rating can be observed when LOX/LH2 is used, as well as a much steeper decrease in the up-rating case. This is coherent with the values of p and q of each propellant combination and with the meaning of these parameters: as the LOX/LH2 has a higher p, a bigger part of the failures in these engines can be improved (worsened) by de-rating (up-rating), and the higher value of q also indicates that they will improve (worsen) faster.

While Fig. 4 is useful to understand how the use of a specific engine at a lower or higher thrust level than its nominal thrust can affect its reliability, it does not represent the reality of engine designers, as the requirements for this design usually come in the form of a specific operational thrust T_{op} that needs to be delivered by the engine. Therefore, if the engine is designed to operate at a certain de-rated level in order to improve its reliability, it also needs to be initially designed for a higher nominal thrust than the thrust that it needs to provide during operations. As designing an engine for a higher nominal thrust also causes a decrease in reliability, the main question is whether an optimal combination can be found to maximize the reliability of the engine. This is shown in Fig. 5, where the reliability is displayed as a function of α but in this case while maintaining a constant $T_{op} = 2278kN$, and the nominal design thrust

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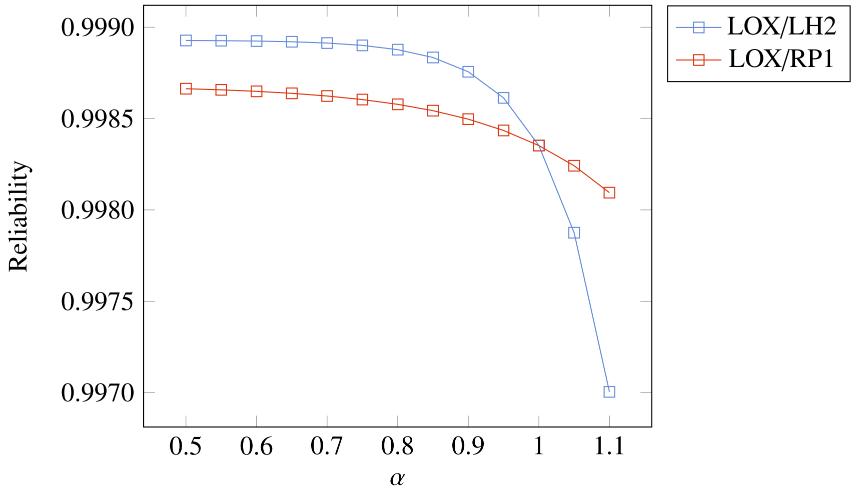

Figure 4: Reliability as function of the de-rating factor α for different propellant combinations with a constant nominal thrust T_{nom}.

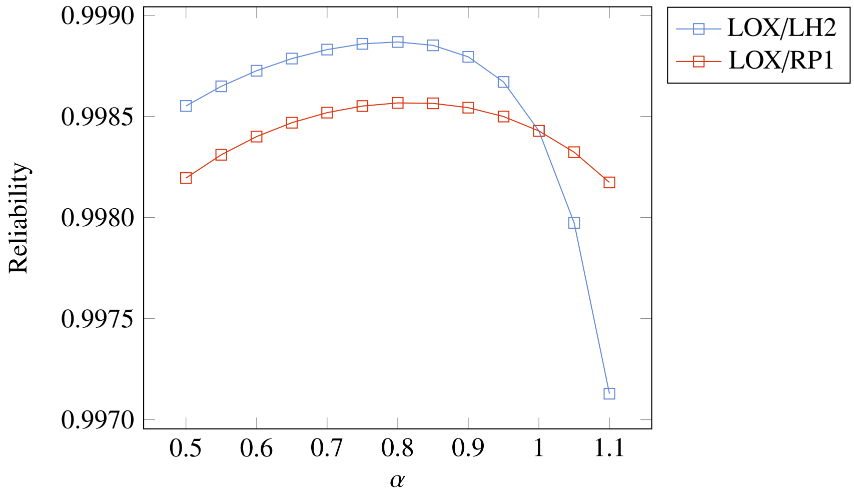

Figure 5: Reliability as function of the de-rating factor α for different propellant combinations with a constant operational thrust.

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is calculated as from Eq. (7) for each value of α. Again, the impact of de-rating or up-rating is bigger when LOX/LH2 is used. However, both propellant combinations show a maximum reliability around $\alpha \approx 0.8$.

2.6 Engine-out capability

When more than one engine is used, the propulsion system can be designed such that it would still be able to complete its mission even when one engine fails, as long as it fails in a contained manner. In order to calculate the reliability of a propulsion system with engine-out design, [6] develops the following expression:

$$R_{PS} = \left(1 - C_f(1 - R_e)\right)^N \left[\left(1 - (1 - C_f)(1 - R_e)\right)^N + N(1 - C_f)(1 - R_e)\left(1 - (1 - C_f)(1 - R_e)\right)^{N-1}\right] \tag{9}$$

Where R_{PS} is the reliability of the propulsion subsystem, C_f the catastrophic fraction, R_e the reliability of each individual engine and N the total number of engines. This expression assumes that the reliability of all the engines is the same and that only one faulty engine can be tolerated by the mission. These assumptions are considered valid, as this design is generally used to tolerate one single failure and it is implemented with several identical engines used in one stage. We can analyse this expression term by term:

- $\left(1 - C_f(1 - R_e)\right)^N$: probability that none of the engines will experience a catastrophic failure. The engine out design allows the completion of the mission only when the failure is contained or not catastrophic.
- $\left(1 - (1 - C_f)(1 - R_e)\right)^N$: probability that no contained failures occur.
- $N(1-C_f)(1-R_e)\left(1 - (1 - C_f)(1 - R_e)\right)^{N-1}$: probability that one contained failure occurs in any of the N engines. Therefore, the entire term in square brackets represents the probability that maximum one contained failure will occur.

However, this expression has some limitations. First of all, it does not account for the reliability of the engine-out switching. This is easy to solve: the switching only needs to be successful when one engine fails in a contained manner, and it is a necessary condition for the success of the mission in this case. Therefore, the probability of success of the switching needs to multiply the third term in the previous expression. Calling R_{sw} to the reliability of the switching we get:

$$R_{PS} = \left(1 - C_f(1 - R_e)\right)^N \left[\left(1 - (1 - C_f)(1 - R_e)\right)^N + R_{sw}N(1 - C_f)(1 - R_e)\left(1 - (1 - C_f)(1 - R_e)\right)^{N-1}\right] \tag{10}$$

Secondly, this expression considers that the reliability of all the engines is constant, even after the shut-down of the faulty engine. However, in order to be able to provide the required Δv, the remaining engines cannot operate at the same level as they would without a failure. There are two options: either the intact engines start to operate at a higher thrust level, or they operate for a longer time. Operating at a higher thrust level would affect the failure rate of the engine according to Eq. (8), which would in turn affect the reliability of the engines. Operating for a longer time would also impact the reliability of the engines, following Eq. (1). Both options would therefore affect the reliability of the remaining engines. A new expression has been derived in order to account for these factors.

There are two scenarios in which the propulsion system would succeed: all the engines work without failure until the end, or one engine fails in a contained manner and the engine switching succeeds. Therefore, the reliability of the propulsion system can be written as:

$$R_{PS,eo} = R_{PS,neo} + R_{sw} \cdot P(1, contained) \tag{11}$$

Where the index *eo* has been used to identify the reliability with engine out capability, while *neo* signals that no engine out capability is included. Therefore, $R_{PS,neo}$ is the probability that all the engines will work until the end without any failure, and $P(1, contained)$ is the probability that there is only one failure and it will be contained. $R_{PS,neo}$ can be easily written as:

$$R_{PS,neo} = R_e^N = \exp\left(-N \cdot \lambda \cdot t_f\right) \tag{12}$$

Where t_f is the final time at the end of the burn. To define $P(1, contained)$ is more complex. The main concern is, as stated above, how to take into account the change in the reliability of the intact engines when one engine fails. If the time between $t = 0$ and $t = t_f$ is discretised in M steps of size $\Delta t = t_f/M$, and we assume that the contained failure can

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happen at any t_i, we can calculate $P(1, contained)$ as the summation over all t_i of the probabilities that the contained failure will occur at that t_i and all engines will continue working after this. Thus:

$$P(1, contained) = \sum_{t_i=0}^{t_f} P(1, t_i) \cdot R'_{PS}(t'_f - t_i) \tag{13}$$

Where $P(1, t_i)$ is the probability that there will be a contained failure at t_i and all engines will work until then and $R'(t'_f - t_i)$ is the modified reliability of the propulsion system between t_i and t'_f, being t'_f the final burn time of the engines after the failure, thus taking into consideration that the remaining engines might have to burn for longer. This modified reliability will take into account the changes on the number of engines working, on the failure rate of the engines working due to up-rating, and on the duration of the burn.

The probability of a failure to happen in an specific discrete time cannot be calculated, but rather only for time intervals (for instance $R(t_i)$ is the probability that a failure will occur between $t = 0$ and $t = t_i$). Therefore, in order to derive an expression for $P(1, t_i)$, the contained failure will be considered to occur between t_i and t_{i-1}. $P(1, t_i)$ can then be described as the probability that no catastrophic failure will take place before t_i, no contained failure will occur before t_{i-1} and a contained failure will occur in one of the engines between t_i and t_{i-1}, while the other engines remain working during that period:

$$P(1, t_i) = \left(1 - C_f\,(1 - R_e(t_i))\right)^N \cdot \left(1 - (1 - C_f)\,(1 - R_e(t_{i-1}))\right)^N \cdot N(1 - C_f)\,(1 - R_e(t_i - t_{i-1}))\,(R_e(t_i - t_{i-1}))^{N-1} \tag{14}$$

In order to calculate $R'_{PS}(t'_f - t_i)$, the new failure rate and the new burn time need to be calculated. The requirement for the propulsion system can be expressed as achieving a specific Δv. The total Δv_{tot} that needs to be transmitted to the system can divided in the Δv_{0-i} that was generated before the instant t_i and the Δv_{i-f} that still needs to be generated after the t_i. Making use of Tsiolkovsky's rocket equation, it can be written:

$$\Delta v_{tot} = c_e \cdot \ln\left(\frac{m_0}{m_i} \cdot \frac{m_i}{m_f}\right) = c_e \cdot \ln\left(\frac{m_0}{m_i}\right) + c_e \cdot \ln\left(\frac{m_i}{m_f}\right) = \Delta v_{0-i} + \Delta v_{i-f} \tag{15}$$

Where c_e is the effective exhaust velocity of the engines, m_0 is the initial mass before the burn starts, m_i is the mass at any instant t_i and m_f is the final mass, thus the mass when all the propellant has been burnt. Using $\Delta t_{i-f} = t_f - t_i$ as the time interval remaining between the time i and the end of the burn and $\dot{m}_T$ as the total mass flow rate of all the engines, it can be written:

$$\Delta v_{i-f} = c_e \cdot \ln\left(\frac{m_i}{m_i - \dot{m}_T \cdot \Delta t_{i-f}}\right) \tag{16}$$

Considering that a contained failure occurs at t_i and that the Δv generated needs to be constant in spite of the failure, and using the apostrophe to identify the quantities that correspond to the scenario in which this failure occurs, it can be deduced:

$$\Delta v_{i-f} = \Delta v'_{i-f} \rightarrow \dot{m}_T \cdot \Delta t_{i-f} = \dot{m}'_T \cdot \Delta t'_{i-f} \tag{17}$$

Which can be rewritten as a function of the individual mass flow rates of the engines $\dot{m}_j$:

$$N \cdot \dot{m}_j \cdot \Delta t_{i-f} = (N - 1) \cdot \dot{m}'_j \cdot \Delta t'_{i-f} \tag{18}$$

Considering that the effective exhaust velocity c_e does not vary with the failure of one engine, Eq. (18) can be expressed as:

$$N \cdot T_{op} \cdot \Delta t_{i-f} = (N - 1) \cdot T'_{op} \cdot \Delta t'_{i-f} \tag{19}$$

An up-rating factor for the engine out functionality can be defined as:

$$\alpha_{eo} = \frac{T'_{op}}{T_{op}} \tag{20}$$

And the total up-rating/de-rating factor of each engine after one engine has failed would be:

$$\alpha' = \alpha_{eo} \cdot \alpha = \frac{T'_{op}}{T_{op}} \cdot \frac{T_{op}}{T_{nom}} = \frac{T'_{op}}{T_{nom}} \tag{21}$$

Consequently, the new failure rate λ' can be calculated from Eq. (8) using α'.

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For a chosen α_{eo}, the new required burn time is calculated from Eq. (19) as:

$$\Delta t'_{i-f} = \frac{N}{N-1}\frac{1}{\alpha_{eo}}\Delta t_{i-f} \tag{22}$$

And the reliability of the propulsion system after the failure can be written as:

$$R'_{PS}(t'_f - t_i) = R'_e(\Delta t'_{i-f})^{N-1} = \exp\left(-\lambda'(N-1)\Delta t'_{i-f}\right) \tag{23}$$

Finally, the reliability of a propulsion system with N engines and engine out capability can be written as:

$$R_{PS,eo} = R_e(t_f)^N + R_{sw} \cdot \sum_{t_i=0}^{t_f}(1 - C_f(1 - R_e(t_i)))^N \cdot (1 - (1 - C_f)(1 - R_e(t_{i-1})))^N \cdot \\ \cdot N(1 - C_f)(1 - R_e(t_i - t_{i-1})) \cdot R_e(t_i - t_{i-1})^{N-1} \cdot R'_e(\Delta t'_{i-f})^{N-1} \tag{24}$$

It is first interesting to analyze how much the reliability can be improved with the engine out design. Figure 6 shows the evolution of the reliability with time for configurations with different number of engines, with and without engine out capability, assuming a DBFRSC engine cycle using LOX/LH2 for a 500 s burn and a total operational thrust provided by the propulsion system equal to the nominal thrust of the SSME. It can be observed that the configurations using a greater number of engines remain to have a lower reliability than those with a lower number of engines. However, the improvement in reliability by the use of engine out design with respect to the configurations that do not use it remains significant, and the loss of reliability by the use of additional engines is lower. Moreover, the reliability obtained with configurations using 7 engines or less with engine out capability provide a higher reliability than the most reliable configuration without engine out capability, thus the configuration using a single engine.

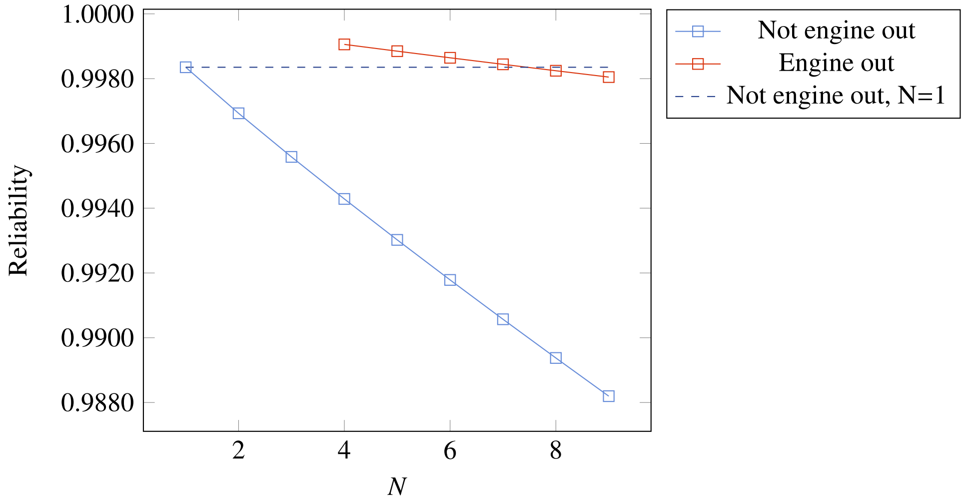

Figure 6: Reliability as a function of the number of engines, for engine out capability and not engine out capability, assuming DBFRSC engine cycle using LOX/LH2 with $T = 2278kN$ for a 500 s burn, with $\alpha = 1$ and $\alpha_{eo} = 1$. The dashed line represents the reliability using only one engine to be used as a reference for comparison with the engine out case.

Another question can be which values of α_{eo} yield a bigger improvement of the reliability. Two limit cases can be distinguished, which set the limit values for α_{eo}:

1. The missing engine is compensated solely by the up-rating of the remaining engines: $\alpha_{eo} = \frac{N}{N-1}$ and, of course, $\Delta t'_{i-f} = \Delta t_{i-f}$.
2. The missing engine is compensated solely by means of a longer burn: $\Delta t'_{i-f} = \frac{N}{N-1}\Delta t_{i-f}$ and, of course, $\alpha_{eo} = 1$.

It is also important to note that other limitations may apply. For instance, a longer burn could lead to a more eccentric orbit than desired. Furthermore, technical constraints might limit the up-rating possibilities of the engine.

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However, these considerations are out of the scope of this simplified model.

Figure 7, Fig. 8 and Fig. 9 show the reliability of a propulsion system with engine out design depending on the α_{eo} used, for different propellant combinations and number of engines. A required total nominal thrust of 2278 kN has been considered, distributed evenly among all the engines, and a DBFRSC engine cycle was assumed for a nominal burn time of 500 s. Again, the impact of propellant choice is considered in the values of p and q used to quantify the impact of the de-rating of the engines. The impact of the propellant on the baseline failure rate of the engine requires further study and should be assessed in future work.

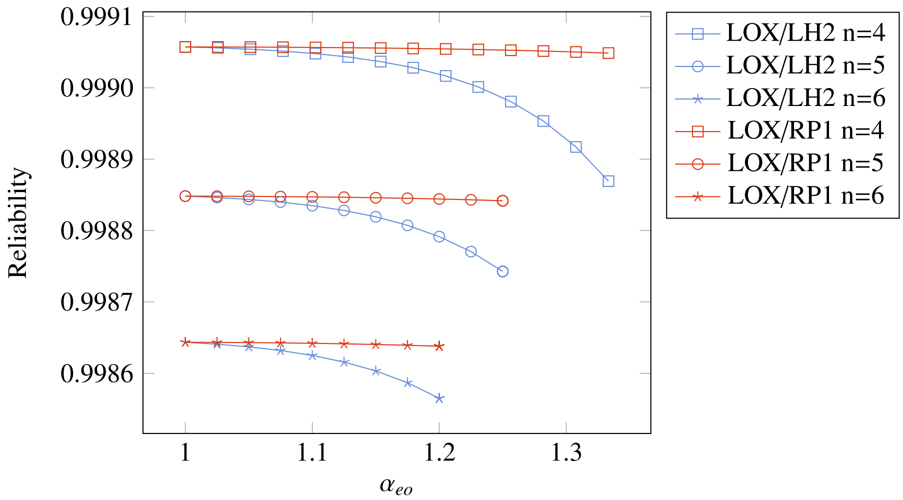

Figure 7: Reliability of a propulsion system with engine out capability as function of α_{eo} for a different number of engines and different propellant combinations. An initial de-rating factor of $\alpha = 1$ was considered in all cases.

In Fig. 7 it can be observed that, especially, when LOX/LH2 is used, the reliability decreases for increasing values of α_{eo}. Even though due to the scale it is not possible to appreciate it in the figure, the result is the same when LOX/RP1 is used. Therefore, the reliability appears to be more affected by the increase in the failure rate provoked by the up-rating of the engines than by the increased burn time. However, these results do not consider a previous de-rating of the engine, which is a common practice when the propulsion is designed for engine out capability, as it is envisaged that a subsequent up-rating might be required and it was already shown in Fig. 4 that the decrease in reliability becomes very steep for values of $\alpha > 1$.

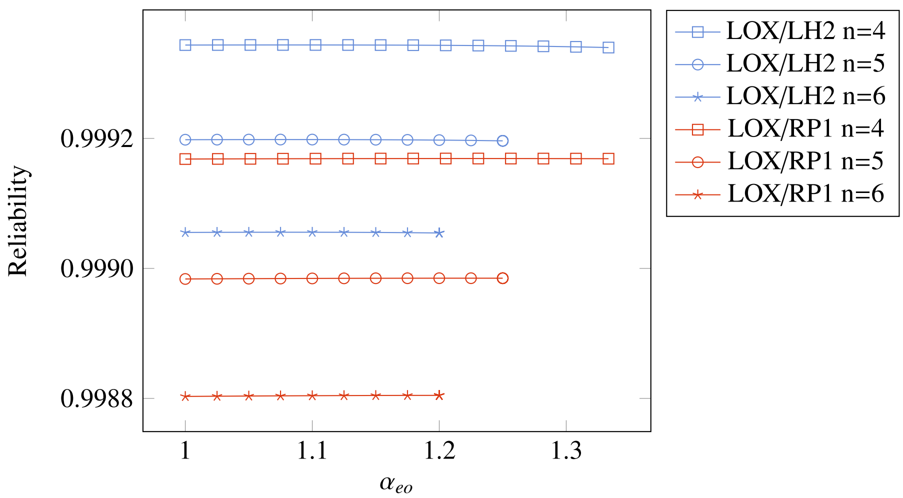

Figure 8: Reliability of a propulsion system with engine out capability as function of α_{eo} for a different number of engines and different propellant combinations. An initial de-rating factor of $\alpha = 0.8$ was considered in all cases.

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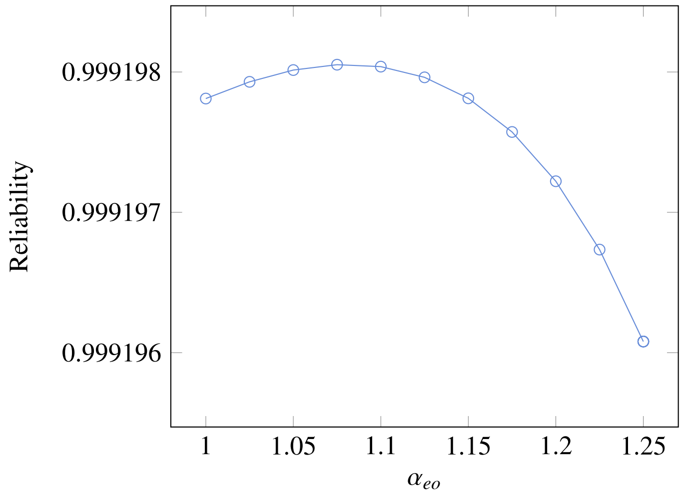

Figure 9: Reliability of a propulsion system with engine out capability as function of α_{eo} for a different number of engines and different propellant combinations. An initial de-rating factor of $\alpha = 0.8$ was considered.

Figure 8 shows the reliability for the same configurations as in Fig. 7, but considering an initial de-rating factor of $\alpha = 0.8$ for all the engines, which continue to provide 2278 kN of operational thrust. As the tendency of the curves cannot be observed due to the scale when all of them are represented together, Fig. 9 shows the evolution of the reliability with α_{eo} for a propulsion system designed for engine out with 5 engines and using LOX/LH2. It can be seen that, in contrast to the tendency observed in Fig. 7, the reliability shows an increase at the beginning, until a maximum is reached for a certain α_{eo} and then the reliability decreases again. This tendency can be observed also for other values of N and propellant combinations, and it suggests that there might be an optimal value to be found for α and α_{eo} to improve the reliability of a propulsion system.

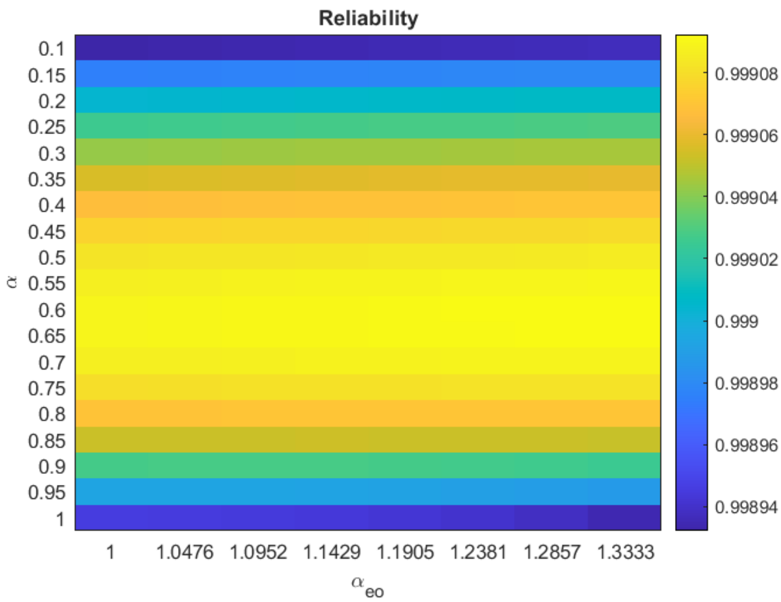

Figure 10: Heatmap showing the reliability as a function of α and α_{eo}, for $0.1 \leq \alpha \leq 1$ and $1 \leq \alpha_{eo} \leq 1.333$. The configuration with 4 engines providing 2278kN of operational thrust for a 500s burn using DBFRSC cycle was used.

Aiming to find this optimal configuration of α and α_{eo} Fig. 10 shows a heatmap with the reliability obtained for a propulsion system using 4 engines to provide $T = 2278kN$ during a 500 s burn. It can be observed that horizontal lines, thus displaying a fixed α, seem to be constant. This is mainly due to the fact that the range of α represented in this figure is much broader than the range of α_{eo}. Consequently, the variations along α_{eo} are smaller than the variations

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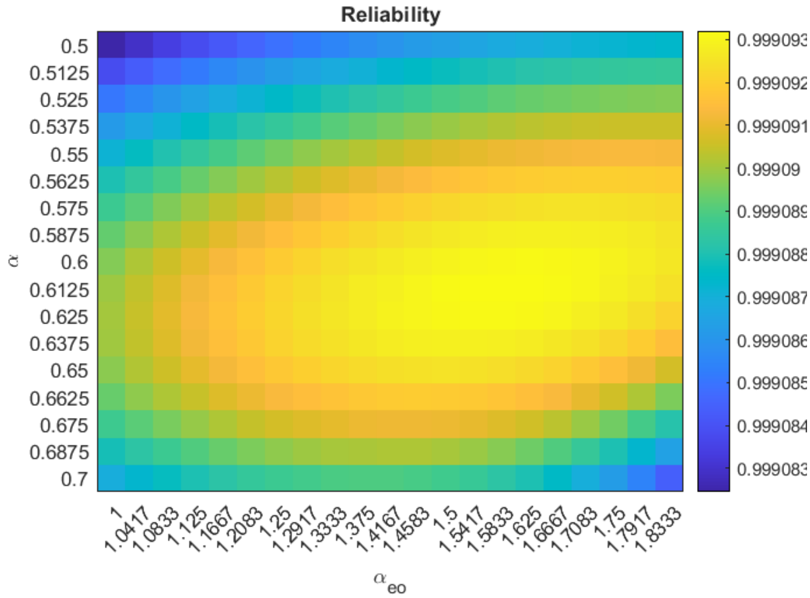

Figure 11: Heatmap showing the reliability as a function of α and α_{eo}, for $0.5 \leq \alpha \leq 0.7$ and $1 \leq \alpha_{eo} \leq 1.833$. The configuration with 4 engines providing $2278kN$ of operational thrust for a $500s$ burn using DBFRSC cycle was used.

along α for the values represented, which makes it impossible to observe the variations along α_{eo} for the used colour scale. As the optimal values seem to be found for values in the range of $0.5 < \alpha < 0.7$, a closer look is taken at these values at Fig. 11. Moreover, the values of α_{eo} were expanded to values higher than the previously set limit of $\alpha_{eo} = N/(N-1)$. It can be observed that, indeed, the maximum reliability in this case was found for values of α_{eo} higher than $N/(N-1)$. This is possible because the optimal combination of α and α_{eo} features a relatively low value of α, so the actual de-rating level of the engine after one engine fails $\alpha' = \alpha \cdot \alpha_{eo}$ remains below 1.

Figure 12 shows the reliability obtained for configurations using different number of engines when the combination of α and α_{eo} is optimized. The improvement of the reliability is clearly visible. Moreover, It is interesting to highlight that the reliability of the configuration with 8 engines after the optimization becomes also higher than the reliability with one engine.

3. Methodology

The model described in the previous section was implemented in python. In order to calculate the reliability of the propulsion system, the following inputs are required, which are provided to the python code as a dictionary called `prop_config`:

- `engine_cycle`: must be a string containing any of the abbreviations in Table 1.
- `propellant`: it can be $LOX/LH2$ or $LOX/RP1$. However, it should be kept in mind that this only affects the values of p and q used to assess the impact of the de-rating of the engine. The impact of the change of propellant in the baseline failure rate, as well as the addition of new propellants, will be addressed in future work.
- `nominal_thrust`: design thrust of the engine in Newtons.
- `n_engines`: number of engines in the propulsion system, must be an integer number.
- `alpha`: de-rating factor α, only necessary in case that the engine operates at a different thrust than its nominal thrust. By default it is set to $\alpha = 1$.
- `engine_out`: a boolean variable, which is true if the engine is designed for engine out capability and false if it is not.
- `alpha_eng_out`: value of α_{eo}, it only has an effect `engine_out` is set to true. If no value is provided, it is set to $N/(N-1)$ by default, being N the number of engines.

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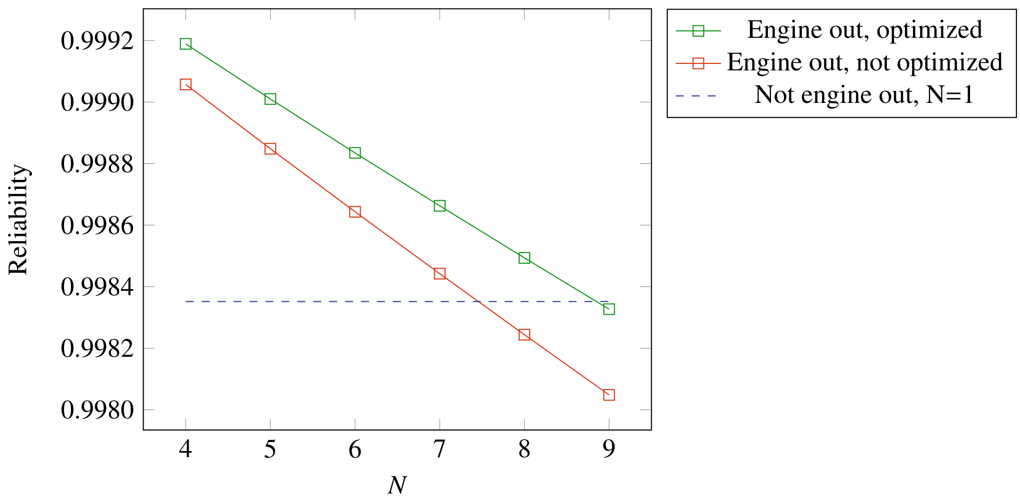

Figure 12: Reliability as a function of the number of engines, assuming engine out capability, DBFRSC engine cycle using LOX/LH2 with $T = 2278kN$ for a 500 s burn. The green represents the reliability obtained with the optimal combination of α and α_{eo}, meaning the combination that was found to provide the highest reliability. The red line, on the other hand, shows the results using $\alpha = 1$ and $\alpha_{eo} = 1$. The dashed line represents the reliability using only one engine to be used as a reference for comparison with the engine out case.

- `switch_rel`: reliability of the switching when there is a contained failure in one engine. It only has an effect if `engine_out` is set to true. It must be between 0 and 1, and if no value is provided it is set to 1 by default.

The process that the algorithm follows is described in Fig. 13. From the propellant and engine cycle, an initial estimation of the failure rate (λ_0) and the catastrophic fraction C_f are derived from the tabulated values shown in Table 1. At the moment this table only contains values for the different engine cycles, without any distinction regarding the propellant. As stated before, this assessment is expected to be performed in future work. However, it was considered useful to show the part of the process in which it will be included. The initial failure rate λ_0 is related to the thrust level provided by the baseline engine, thus the SSME. The failure rate is therefore modified to be adjusted to the design nominal thrust of the new engine by using Eq. (5), obtaining a new estimation of the failure rate λ_1. However, the engine might operate at a different thrust level than it was designed for. The de-rating factor α that was defined in Eq. (7) is used to account for this circumstance, and a new failure rate λ_2 is derived using Eq. (8). It is important to note that Eq. (8) uses the parameters p and q, whose values also depend on the propellant and can be found in Table 2. Finally, the number of engines, engine out capability and burn time are taken into account. If the system is not designed for engine out capability Eq. (6) is used, while for systems featuring an engine out design Eq. (24) is used.

4. Conclusion

The paper has introduced a methodology for the estimation of the reliability of a propulsion system using LREs. This methodology only requires as inputs a few key design parameters, which are expected to be known from early stages of the design, and the process is automated by a simple algorithm written in python which is described in Fig. 13.

However, this model has strong limitations that should be kept in mind. For instance, the baseline failure rates were derived from the failure rates of the SSME. The limitations on this data were already discussed before. A wider engine database would be necessary in order to ensure that the data is significant for the engine that is being developed. Furthermore, the impact of the propellant choice on this baseline failure rate was not addressed in this paper. The main limiting factor to introduce this assessment in the model was, again, the lack of data available. Additionally, this lack of data also made it impossible to validate the current model, which would be a necessary step to ensure its applicability.

The sharing of further engine test data would therefore be extremely helpful for the development and validation of this or similar models, which can help to improve of the reliability of future launch vehicles.

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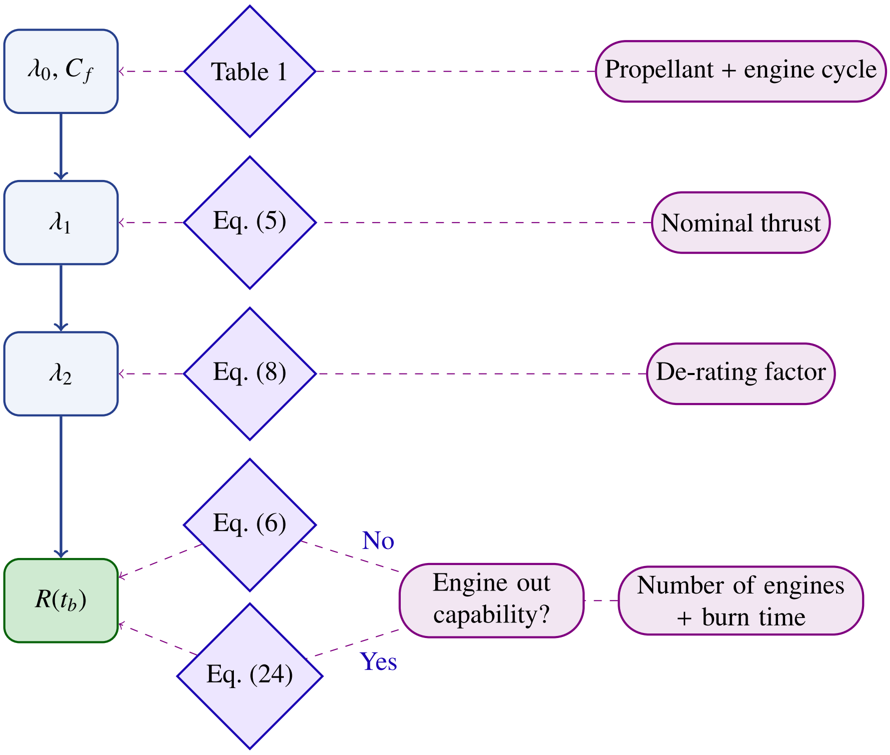

Figure 13: Process followed to calculate the reliability of the propulsion system.

Moreover, it is important to highlight that there are many constraints in the design of a LRE that are not considered in this model. The goal of the present model is to provide a quick assessment of the reliability, which should be integrated with other considerations by the engine designers.

5. Acknowledgments

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