

RAMS for Mega Constellations

Jacopo Baroni^{a*}, Giulia Chinappi^{b*}

^a DLR Gesellschaft für Raumfahrtanwendungen (DLR-GfR), Germany, jacopo.baroni@dlr-gfr.com

^b DLR Gesellschaft für Raumfahrtanwendungen (DLR-GfR), Germany, giulia.chinappi@dlr-gfr.com

* Corresponding Author

Abstract

Space sustainability is becoming an increasingly critical and urgent issue as satellite constellations grow in scale and complexity. In the near future, most infrastructures for connectivity and Internet of Things (IoT) services will rely on large networks of satellites. Some of these constellations are already operational, such as OneWeb and Starlink, and others are expected to follow suit in the coming years. The approach of simply adding additional satellites, while initially a linear solution, leads to an exponential increase in system complexity. This, in turn, amplifies both the operational challenges and the risks associated with such large-scale constellations.

As the number of satellites in orbit increases, the issue of orbital debris becomes even more critical. To address this, new sustainability policies need to be considered to minimize orbit debris and ensure that failed satellites are not left standing in operative orbits. When onboard failures occur, it is essential that satellites are properly transitioned to either graveyard orbits or safely deorbited so they can burn up in the Earth's atmosphere. This process not only reduces the risk of unintentional collisions with other satellites but also ensures the long-term preservation of orbital environments for future generations of space infrastructure.

Managing these increasingly complex constellations requires a more sophisticated approach to understanding how these clusters will evolve over time. Satellite operators and companies must base their management decisions on quantitative data rather than relying on qualitative assumptions. A robust RAMS (Reliability, Availability, Maintainability, Safety) approach is essential for modelling the behaviour of satellite constellations. This methodology allows operators to continuously update data, making it possible to forecast potential issues before they occur and develop strategies to address them proactively.

By leveraging accurate and up-to-date data, companies can make informed, data-driven decisions to ensure that their constellations operate sustainably, minimizing the risks of collisions and optimizing overall operational efficiency. Ultimately, the adoption of such methodologies will be crucial in achieving long-term space sustainability, enabling the safe and efficient operation of satellite constellations while mitigating their impact on the space environment.

Keywords: RAMS, Sustainability, Reliability, Availability, Constellation, Planning

Nomenclature

C_k^N	Combinations of N elements taken k times
p	Probability
$R(t)$	Reliability at time t
S	Subset
T	Mission Time
t_i	i -th instant in time

Acronyms/Abbreviations

DLR	Deutsches Zentrum für Luft- und Raumfahrt (<i>German Aerospace Center</i>)
EoL	End of Lifetime
ESA	European Space Agency
GfR	Gesellschaft für Raumfahrtanwendungen (<i>Space Applications Institute</i>)
LDT	Logistic Time Delay
LEO	Low Earth Orbit
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram

1. Introduction to the current status of constellations

Satellite constellations have become an essential part of space operations, supporting a wide range of applications, from telecommunication and navigation to Earth observation. In recent years we have witnessed the expansion of these constellations and consequently the number of satellites launches has surged significantly, with 2024 marking a record-breaking year with over 250 successful launches [1]. A portion, equal to 35%, of this enormous number is driven by the deployment of the Starlink constellation, which saw nearly 2,000 spacecraft launched in 2024 alone, across almost 90 separate missions, considering an average of 7 launches per month [3]. However, SpaceX is not alone in this expansion. OneWeb has more than 600 satellites deployed, Rivada plans to launch a similar number between 2025 and 2028. These massive numbers present significant challenges for the management of these constellations.

One of the most pressing concerns is the management of aging satellites and the mitigation of space debris. As satellite numbers increase, the risk of anomalies and then collisions grow, which in turn exacerbates the problem of debris in Earth's orbit. Effective measures must be put in place to protect the space environment from such collisions and to ensure that satellites are properly disposed at the end of their operational lives. Moreover, managing these large constellations involves considerable complexity in terms of planning and orbit replenishment. Regularly updating the status of each satellite within a constellation to reflect its current condition is crucial, as failure to do so could lead to inefficiencies and significant cost increases. The method presented here in this paper aims at defining an approach that can be valuable for managing not only the existing constellations but also potential future ones, which could be even larger.

2. Space Policies

With a growing number of actors in the space environment, it has become necessary to strengthen regulations in order to keep space accessible to all. Over the last 20 years, the major issue has been related to the increasing number of debris in orbit, particularly in LEO. These pose a threat to both future missions and existing ones, as danger of collision with clouds of debris might delay and, to a further extent, block the launch windows for the rockets, thus limiting the access to space. As a result, it has been decided to impose requirements on mission's design to ensure proper disposal and avoid collisions between spacecrafts in orbit. In this context, the RAMS discipline plays a crucial role in assisting companies: it helps provide probability estimates for time windows where the satellite is expected to reach its EoL, its condition at the time of disposal, and, importantly, through the method presented in this paper, enables the updating of this evaluation throughout the entire lifetime of a spacecraft, accounting for evolving conditions. In this framework, one of the most important policies is the *Space Debris Mitigation Requirements* by ESA [3], which outlines all the requirements for mitigating the number of dead objects in orbit. Specifically, one of the most pertinent requirements is the, at least, 90% probability of a successful disposal during the entire lifetime of a satellite, if a LEO spacecraft is considered. It is important to note that these guidelines were initially developed for large spacecraft but can also be applied to smallsats, as indicated by the agency.

3. Introduction to RAMS

RAMS, short for *Reliability, Availability, Maintainability and Safety*, is an engineering discipline used to assess and enhance the performance, dependability, and safety of systems, particularly in industries with a high demand for operational characteristics that require a deeper attention to every detail. In particular, Reliability emphasizes the capability of a system or service to function, without any failure, and is defined as the probability that the aforementioned system or service will perform their intended function adequately for a specified period of time without failure. Reliability is closely related to availability, which is typically described as the ability of a component or system to function at a specified moment or interval of time.

This probability is estimated through an assessment that takes into account the architecture of a system, its characteristics and the operating environment. Within this paper, the parameters that are typically considered for the systems are the *Mean Time To Failure (MTTF)* and the *Age* of a component. For repairable systems, typically maintenance parameters such as the *Mean Time To Repairs (MTTR)* are considered, together with *Logistic Time Delays (LDT)* and *Spare Parts*. For the sake of our analysis though, these parameters will not be considered as the focus will be on constellation of satellites, where mechanical maintenance activities are not feasible due to obvious limitations that we leave to the reader to imagine.

RAMS nowadays plays a key role in the cost-effectiveness of systems with satellite constellations, such as Starlink (SpaceX), OneWeb, and Galileo (ESA), that rely heavily on it to ensure continuous global operations, coverage, minimize failures, and extend mission lifespans. Since constellations consist of multiple satellites working together, RAMS strategies focus on redundancy, autonomous operations, and efficient optimization.

4. DLR-GfR Method

At *DLR-GfR* our way of thinking how to approach a tangled problem such as the management of a constellation led us to identify the need of a RAMS methodological approach in order to expand our understanding of how a group of satellites would evolve in time, given the problematics that systems so complex bring along with themselves. Problems such as anomaly management, performance/operational requirement and replenishment of an orbit become more complex as the number of satellites increase. For mega constellations, with hundreds of satellites spread among different orbital planes, these problems represent an incredibly difficult challenge that can not be addressed with just pen and paper. Through software-assisted modelling we are capable of establishing an overview on the actual status of the constellations without having to rely on assessments that are just qualitatively based. The method consists of different steps, explained below in details and summarized in Figure 1, that aims at showing the approach developed within *DLR-GfR*.

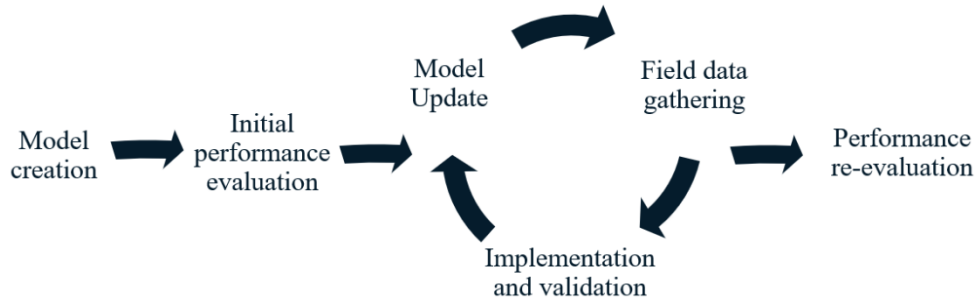


Figure 1 – Visualization of DLR-GfR method

4.1. Definition of the RAMS models for the spacecrafts

Already from the design phase of the constellation, a spacecraft can be modelled, through the use of a commercial software, with a combination of reliability blocks. From the design and technical documents, it is possible to derive the scheme that shall be followed to represent the system, where the blocks are logically connected and used as base elements in the simulation. In the following figure it can be seen how a Reliability Block Diagram (RBD) is built and how we can model the redundancies, standby, series and parallel elements of the system in the diagram.

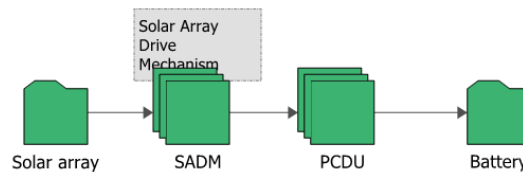


Figure 2 - Example of an RBD for a sub-system in Reliasoft © 2024

In Figure 2, an example of a generic power subsystem is shown for a satellite. Each block has a mathematical model that describes how the component/sub-system is supposed to behave (whether operating normally or in a failed state) during the simulation time, through the dedicated MTBF and its reliability model. In Figure 3 there is an example of a block properties window where all the fundamental parameters can be set in order to obtain a model as close as possible to the real behaviour of the spacecraft's element. Thanks to these blocks, all the system's parameters can be represented and updated when it is necessary to have outcomes that can be used in every moment of the entire lifetime of the constellations. As a matter of fact, the software can analyse all the spacecrafts in the constellation, simply considering different diagram for each of them and run them in separate instances. After the definition of the blocks, the results are collected in a workbook, where they are processed taking into account additional parameters, such as the accumulated age and the remaining design lifetime, in order to determine the probability of the entire system to reach EoL and the probability evolution over the lifespan considered (usually 10 years for a spacecraft and 3 years for a smallsat).

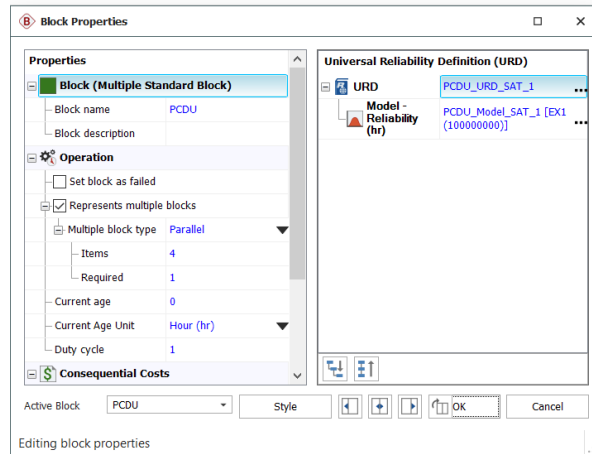


Figure 3 - Parameters setup interface in Reliasoft © 2024

4.2. Collection and implementation of latest available data of the system

As satellites start getting launched into space and become operative, they start providing large amounts of information to the operators on Earth. This information provides a continuous report on the health status of the constellation, allowing to visualize whether there are anomalous situations that will need attention in the future and to start defining the outcome of the evolution of the different orbital plans, according to the mission requirements and objectives. Once an anomaly occurs, the consequent events are then assessed and evaluated to see if there are potential repercussions on the RBD models of the spacecraft: in case there is, the structure of the diagrams is modified accordingly so that the latest status of the system can be reflected and the consequent performances re-evaluated. Each satellite present in the constellation gets a unique dedicated diagram assigned, so that every deviation is tracked and the impact monitored. Collection of field data represents a powerful tool crucial for maintaining a system's health, improving efficiency, and supporting informed decision-making. It transforms raw information into actionable insights, enabling organizations to operate smoothly and adapt to evolving needs.

4.3. Iterative assessment on performance status

After the modelling of the satellite and collecting field data, simulations can be conducted on a recurrent basis. This is an iterative analysis that can be performed on a monthly or quarterly schedule, or even more frequently. Based on these results, the operator can assess the current status of the constellation, identifying which satellites are capable to reach their EoL, which systems are in critical condition, and which are outperforming expectations. This assessment is achieved by comparing the satellite's performances with those of the baseline model, which represents a system that is performing nominally without any anomaly. The results are obtained through the use of a spreadsheet that is properly set to compute the reliability from every satellite considered. The spreadsheet contains the information of every satellite, included the launch date and the expected end of life date, that can be modified by the user. In this way, an overview of the constellation can be obtained and analysed, along with other outcomes discussed in the following sections.

4.4. Estimates for End-of-Life, De-Orbiting and Constellation Evolution

After the definition of the model and the gathering of the information about the current status of the constellation, the analysis can be done. The obtained results are useful for the estimates for end of life, de-orbiting and evolution of the entire constellation. Specifically, in the "End of Life" analysis, is determined the probability of a spacecraft of reaching the estimated EoL: within the context of this article, we consider typically 10 years for a generic spacecraft and 3 years if it is a smallsat. Within the "De-Orbiting" analysis, results are representing the probability of having the spacecraft capable of carrying out the disposal manoeuvres and, within the "Evolution" analysis, outcomes are representing the evolution, over the timespan considered, of the reliability of every spacecraft of the constellation.

4.4.1. End-of-Life

Every satellite is designed for a specific mission time that, as we already listed previously, can span between 3 to 10 years according to many variables such as the scope, cost, quantity and requirements of the mission. As time passes, each satellite progresses in its mission and get closer and closer to the desired target time, accumulating operating

cycles and hours: anomalies and/or degradations encountered during the mission might affect the capability of each satellite to reach its mission lifespan so it becomes beneficial to have a tool capable of determining whether the spacecraft is still capable of reaching the objective within the requirements of each constellation. The analysis for the assessment of the EoL takes into account two parameters:

- Accumulated Lifetime
- Remaining Lifetime

The probability that a system is operating after a certain period of usage is determined through the conditional probability, defined in probability theory as a measure of the probability of an event occurring, given the information that another event has occurred. As the accumulated lifetime increases, the remaining lifetime becomes increasingly shorter and the expected behaviour for the probability curve is to slowly approach the 100%, as the probability to reach the target increases up to certainty, since we know that system has managed to arrive up to that point in working conditions and as consequence of less remaining lifetime, the probability to expect a failure in a shorter timeframe gets lower and lower.

$$R(T - t_1 | t_1) > R(T - t_2 | t_2) \text{ where } t_1 > t_2 \quad (1)$$

The above statement (1), which expresses a derived result of the conditional reliability, is valid for systems in which no anomaly has occurred: as one is identified, the underlying equation regulating the success probability changes and the results produce a decrease of probability, with respect to a baseline configuration in which the system was working. This behaviour can be compared to the mission requirements and from there new strategies can be derived, based on the plans and the risk tolerance of the operator. An example of calculation performed for progressing periods is shown in Figure 4.

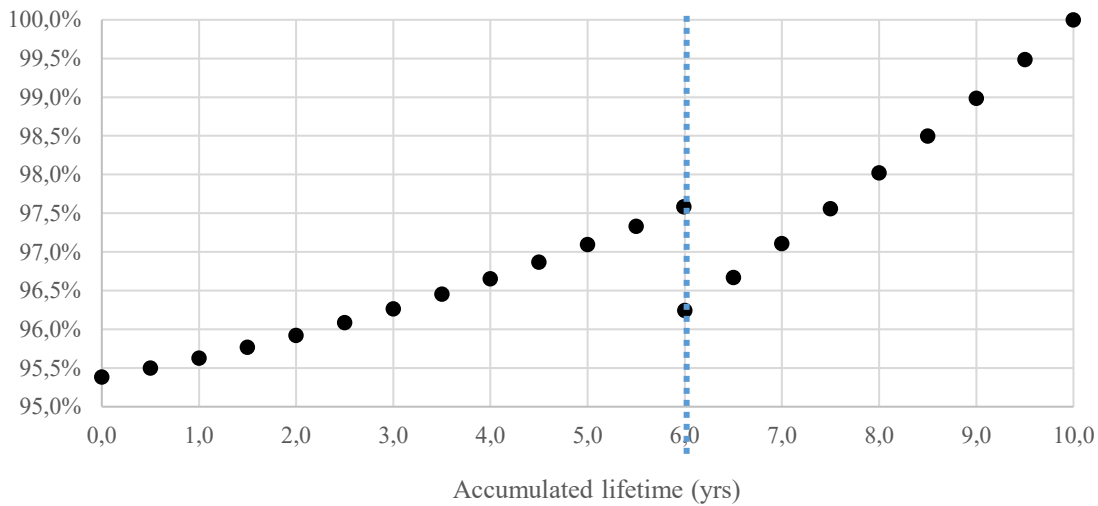


Figure 4 - Example of the evolution for the conditional reliability for a satellite with anomaly happening on the 6th year

4.4.2. De-Orbiting

The spacecrafts' disposal process is a critical issue for the space sustainability, especially if the spacecrafts are small satellites. With the exponential increase in the number of satellites in LEO, managing their End-of-Life disposal and preventing the creation of space debris has become a priority for both space agencies and private companies. Typically, the de-orbiting, in case of LEO satellites, is done through the so-called controlled re-entry, thanks to the propulsion system or new technologies such as the drag devices, where the satellite is re-directed towards Earth and performs a controlled burn while re-entering the atmosphere. In this scenario, the application of RAMS analysis during the operational life is crucial for the proper disposal. Therefore, this emphasizes the importance of spacecrafts reliability models, which can help simulate issues that may affect the critical systems required for a proper disposal. The models enable the consideration of combinations of multiple and, also different, failures in the system that might pop up during the operational life of the satellite.

In Figure 5 and Figure 6 here shown below an analysis is presented for a disposal activity's estimate in satellites with anomalies on the thrusters. In the calculations, the results are determined as the probability of the system to perform the manoeuvre given the health status of the satellite, the elapsed and the remaining mission time. They are representative for two different conditions:

- Configuration with 2 out of 4 thrusters available;
- Configuration with 3 out of 4 thrusters available.

In this case, up to two failures have been injected, obtaining the shown reliability trend. Specifically, when a propulsion system made up of 4 thrusters, 3 of which must be operational at the time of disposal, is considered it can not withstand 2 failures on 2 different thrusters; while in the second configuration, when the manoeuvre can be performed also with only two thrusters, the system can withstand 2 failures because the required number of thrusters in this case is 2. The reliability of the system decreases in the second case with 2 failures respect to the system without failures. In these scenarios, the finding can be applied to check if the spacecraft can respect the guidelines set by regulatory bodies [3] and, eventually, decide how to proceed to correct the results and to protect the space environment.

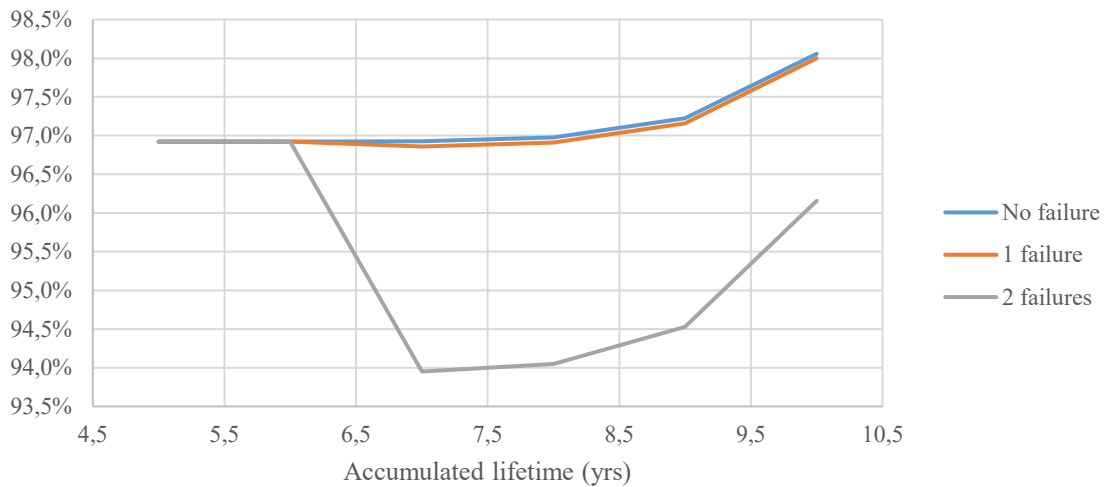


Figure 5 - Reliability of propulsion subsystem with 2 thrusters needed for deorbiting

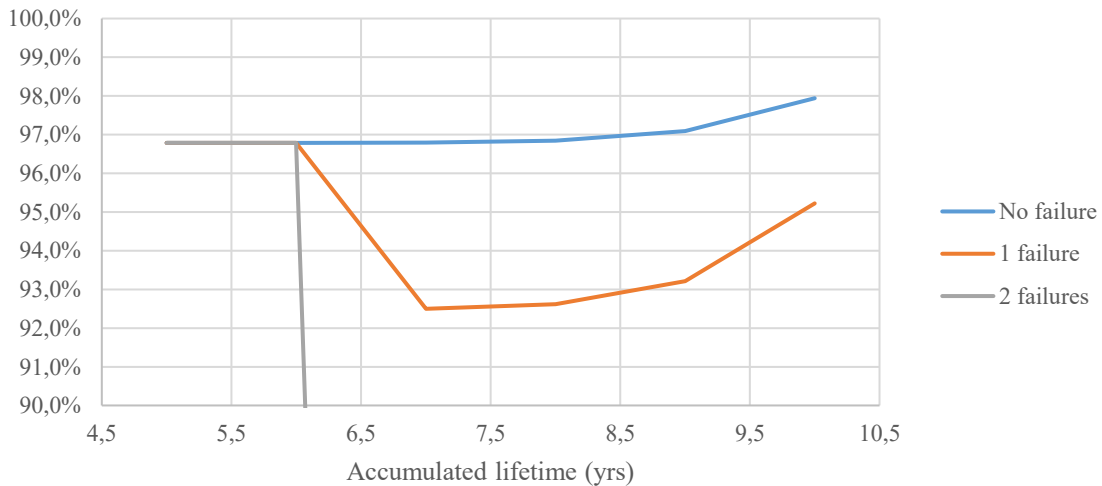


Figure 6 - Reliability of propulsion system with 3 thrusters needed for deorbiting

4.4.3. Constellation Evolution

The “Evolution analysis” concerns the trend of a spacecraft reliability over a user-defined period: this analysis is particularly beneficial, for the scopes presented in this article, as it allows the operator to determine for each moment of the near future the amount of confidence with which a satellite will still be operational and performing its mission. As this is applicable to every satellite, it represents a powerful tool to visualize the entire evolution of a constellation.

In the simulation analysis made for this article, a simulation period of 10 years was considered, starting from the analysis date of 01/02/2025. In the presented graphs, the period can be truncated to a few years earlier, as the results after that point are not considered relevant or are too negligible.

The analysis was conducted using a generalized model of both a spacecraft (here intended as a generic medium sized satellite) and a smallsat in order to visualize how the two families of satellites behave differently; the main reason for the reliability difference between the two models lies in a different design approach for the components and the redundancies, due typically to different mission targets, and consequently different operational life: 10 years for the spacecraft, compared to 3 years for the smallsat.

In the initial part of the “Evolution analysis”, the models are fed with the accumulated lifetime (fixed) and the temporal delta to the target (dynamic range) in order to calculate, for each instance, the probability of reaching that moment, differently from what done for the EoL analysis, where the total window time is fixed. This dynamic range allows to determine the curves that are representative of the probability of the spacecraft to reach the objective, as of the time of the analysis, and on which the strategies for the management of the constellation can be based. The first set of results, presented in Figure 7 and Figure 8, represents the reliability trend of a generic platform and payload of six smallsats belonging to a constellation of 100 satellites, launched with a frequency of 10 per month. As it can be noticed the smallsats are planned to fail earlier than normal spacecrafts. Considering that all of them have been launched in 2020, it can be noticed that the reliability reaches a value near the 80% in 2025, which is typically a reference value for the reliability in a mission time of 5 years.

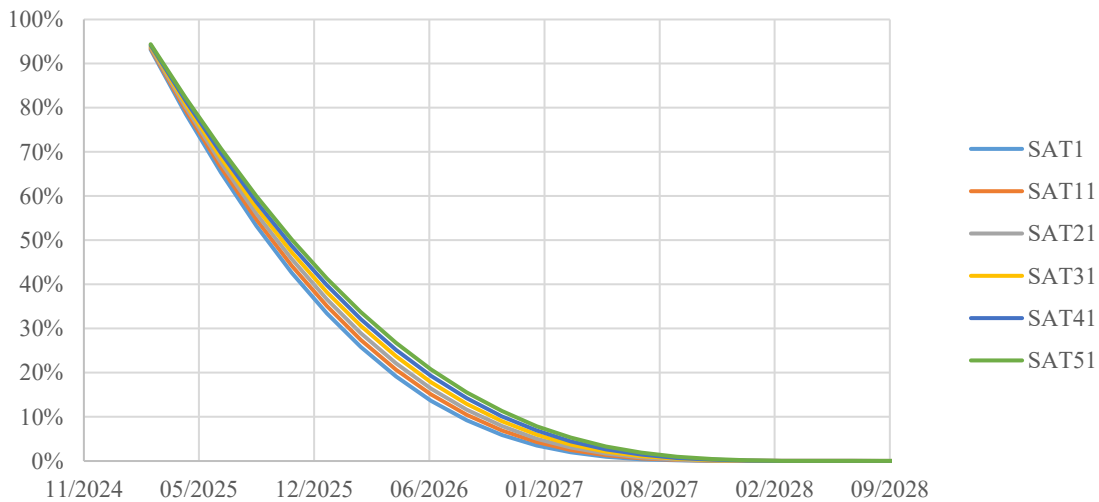


Figure 7 – Reliability trend of platform sub-system during the SmallSat lifetime

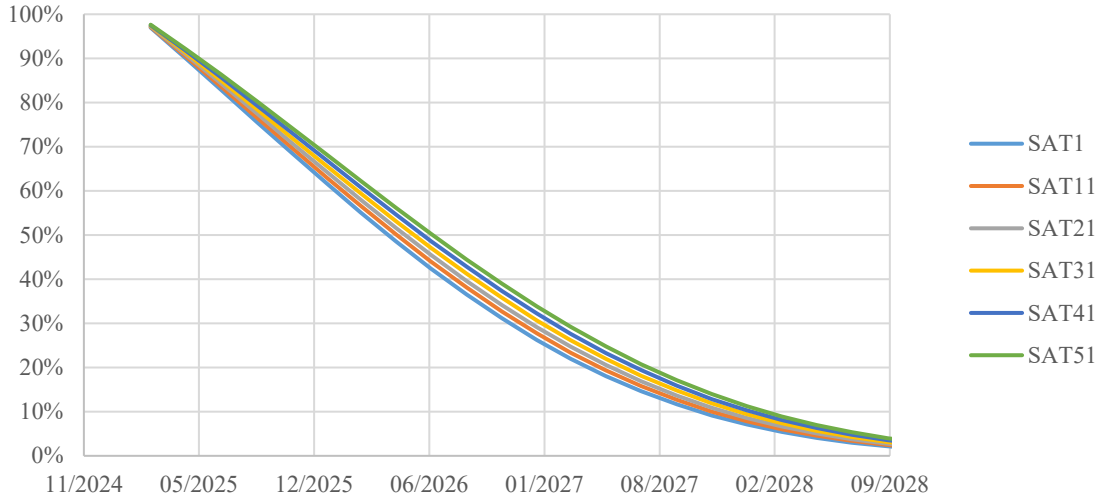


Figure 8 - Reliability of payload sub-system during the SmallSat lifetime

The second set of results, presented in Figure 9 and Figure 10, refers to a number of spacecrafts, specifically to a constellation consisting of six identical spacecraft, launched with a frequency of 2 per year. As can be observed, the spacecrafts' reliability shows a smoother decline compared to the smallsats, as expected, due to an architecture based on redundances and longer target lifespan, as previously mentioned. Because of that, during the entire lifetime span the value of reliability is always between 100% and 92% compared to the lower value of the previous figures.

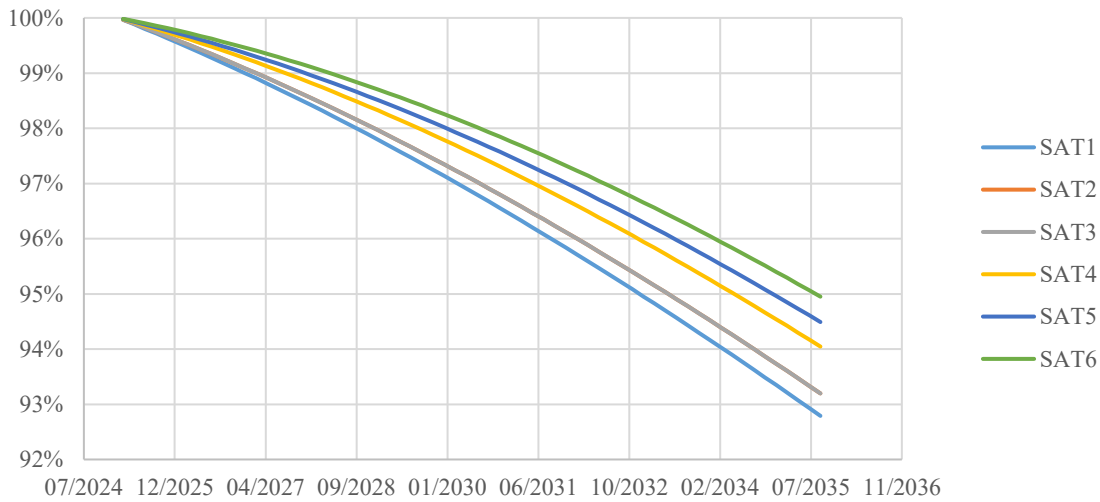


Figure 9 - Reliability trend of platform sub-system during the Spacecraft lifetime

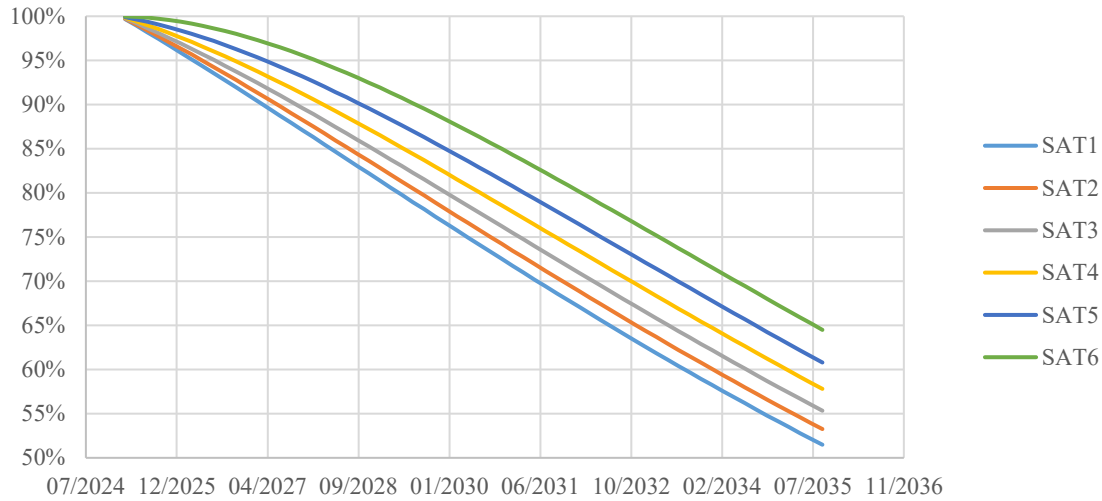


Figure 10 – Reliability trend of payloads during the Spacecraft lifetime

The capability to amend the model in order to introduce failures, both in platform and payload, allows to compare the results with the baseline behaviour. As shown in Figure 11, the trend of spacecraft number 2 (SAT2), to which the failures are applied, is compared with the baseline model. As expected, a failure in the payload has a major detrimental impact on the spacecraft’s reliability trend than a failure in an element of the platform, as shown in Figure 12.

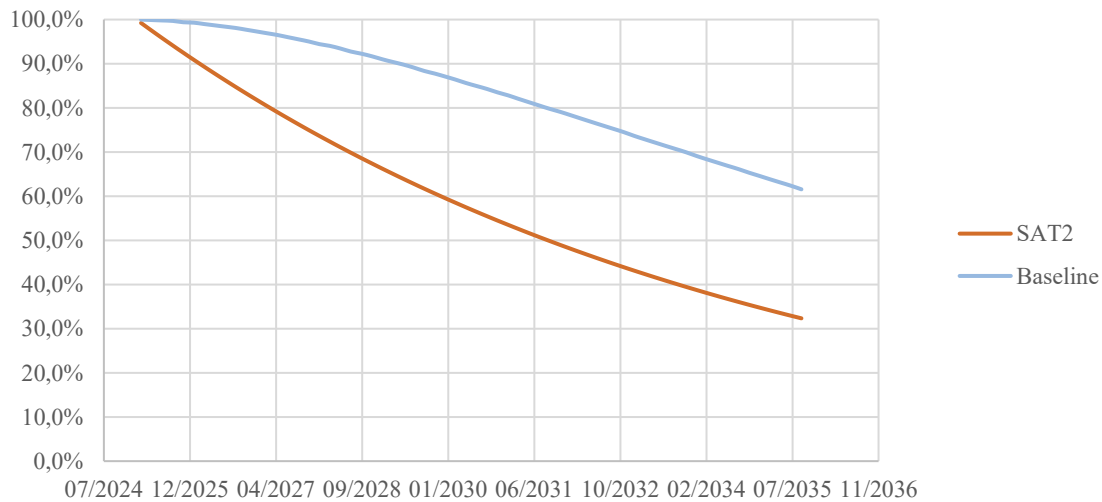


Figure 11 - Comparison between baseline and a satellite with payload failure

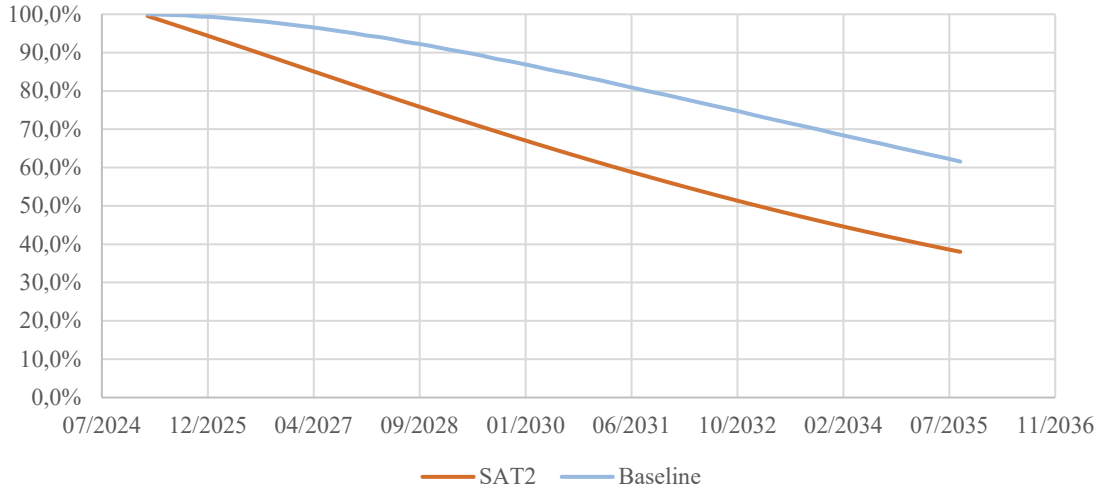


Figure 12 - Comparison between baseline and a satellite with platform failure

When the results for each satellite become available, it gathers interest the possibility to cluster these values together so that it becomes feasible the capability to analyse them as a group (orbit or constellation) rather than individually: through the identification of the mathematical combinations for a given set (Figure 13) it is possible to determine for each instance of time the probability of having a determined number of satellites available (k-out-of-N combinations).

This probability is calculated as per the following equation:

$$p_{N,k}(t) = \prod_{x \in S, S \in \binom{N}{k}} p_x(t) \prod_{y \notin S, S \in \binom{N}{k}} 1 - p_y(t) \quad (2)$$

where p_x, p_y represent the probabilities, at the generic time t , of the satellites respectively included and excluded from the subset.

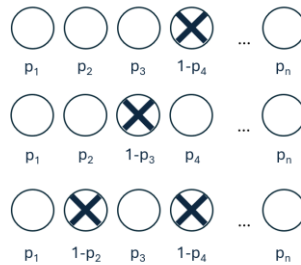


Figure 13 - Example of combinations and the associated probabilities

This proves to be a useful result as operators have now a quantitative solution to base their strategies. Based on these results, several decisions can be made, including determining when new satellites should be launched, when they should be put into production, and other relevant considerations.

An example of this outcome is shown in the Figure 14. It represents the number of active satellites in orbit, specifically smallsats. Through a Python code the combinations have been computed, estimating the evolution of the probability of having between 0 and 6 active satellite in an orbit. As expected, the probability of having 0 satellites left is higher as the EoL is approached.

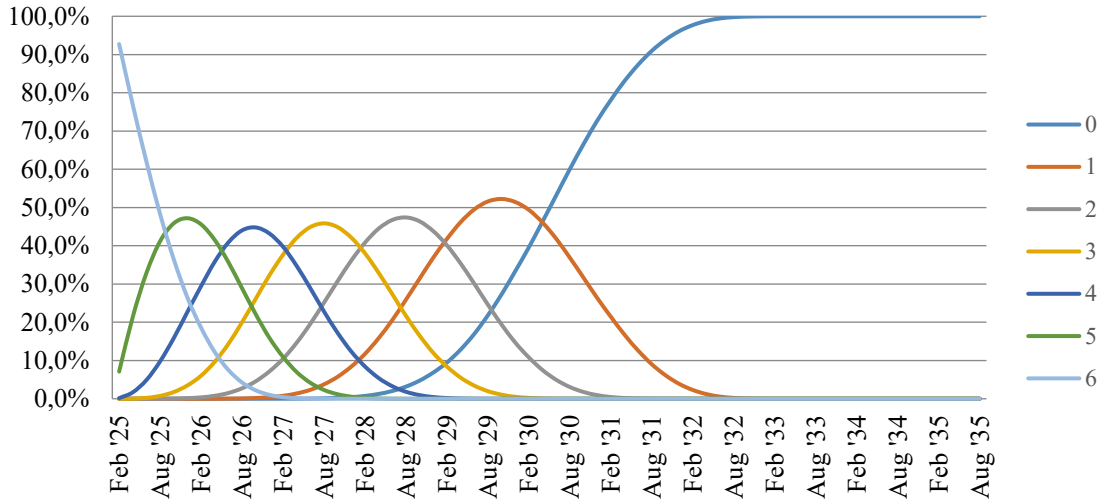


Figure 14 – Evolution of probability of having # active satellites at a specific time

For a constellation, where a refurbishment plan is defined, it is also possible to integrate this information within the process: this approach allows the operator to have a complete overview of how the orbits will be covered and these outcomes can support the decision-making process. As shown in the Figure 15, the probability for every combination increases back to higher level of reliability as soon as new satellites are launched and this is particular useful for constellations that need to guarantee a certain amount of units per orbit in order not to undermine the minimum levels of performance; after a minimum threshold of probability is established, launch windows can be relocated according to when the probability is estimated to reach the limit.

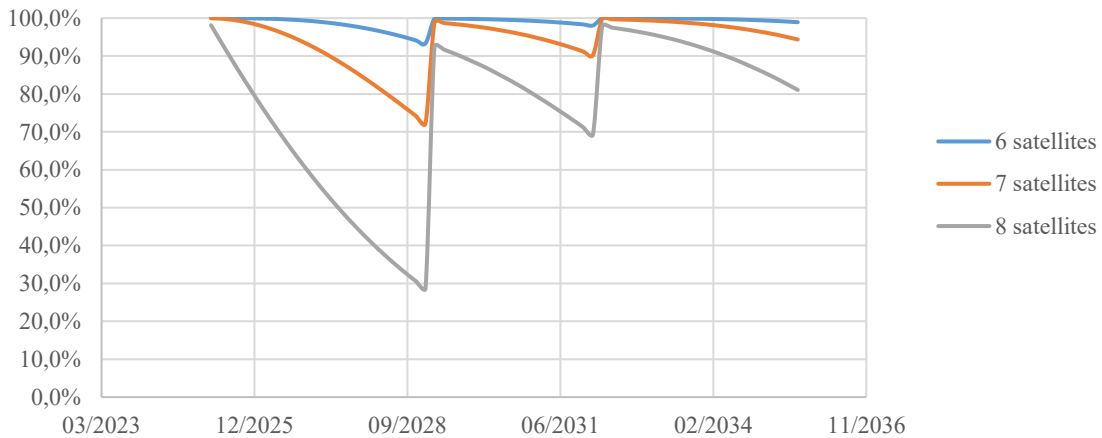


Figure 15 – Example of evolution of probability of having an orbit with k spacecrafts, with new launches

5. Benefits of the proposed method

The idea that sparked the development of this methodology through the use of RAMS was to shift from approaches that were opinion-based to ones that are data-driven. Classic methodologies typically rely on approaches defined as “pen-and-paper” where decisions are taken based on simple assumptions (remaining design lifetime, number of anomalies etc) without having much data to support the assessments and putting trust in the past experience, with the hope that things will “work out fine”.

The proposed method shows several advantages over these existing solutions. First, the continuous gathering of data throughout the satellite’s lifetime provides a significant benefit, helping to achieve highly accurate outcomes in terms of reliability that are always representative of the updated status of every system. Additionally, the method is highly scalable and can be applied to both small and large constellations, accommodating a wide range of satellite types, from a smallsat to a larger spacecraft. It is not restricted to a specific orbit, making it applicable to various types of space missions.

The key advantage is its ability to support decision-making processes. Thanks to the results provided, the constellation management benefits largely as now the operators have the possibility to link probabilities to the associated risks, and from there define evolution plans where priorities can be assigned to the satellites more in need. Launch schedules can be then adapted to the new needs and adjusted based on the predicted future status of the constellation. Moreover, the method allows for the planning of the future spacecraft production by evaluating the probability of meeting mission requirements at the specific stages of their operational lifetimes. Furthermore, the ability of the method to provide real-time monitoring of satellite health and performance allows for swift responses to potential issues, enhancing the overall resilience of the constellation. The method also improves risk management by providing accurate predictions of satellite behaviour, minimizing the periods in which unexpected failures might leave the constellations with unused orbital slots.

Besides these advantages, this method also addresses the growing attention on disposal policies. The ever-increasing concern about space environment and its protection is central to discussion among major agencies and companies. Thanks to the analysis performed on each individual subsystem, operators can define a timespan in which the spacecraft will be ready for the disposal, ensuring a 90% probability of success as required by the guidelines.

Space sustainability is the main beneficiary of this method as all these improvements can positively address the issue of space debris mitigation and pollution reduction, as the needs for productions become more tailored and the risk for debris creation is better managed.

6. Blocking issues and open points

Although the proposed method offers several benefits, there are still some open issues that need to be addressed in order to obtain results in a “shorter time” frame that might adapt with the requirements of the market, especially in a fast paced one as it can be observed in the past years. The primary issue is the evaluation of the different options for the management of very large constellation.

As we want to identify the probability for an orbit of N satellites of having a determined amount k active, we need to first identify the combinations that satisfy our request: this problem has a factorial increase correlated to the number of satellites, as the combinations’ formula shows.

$$C_k^N = \binom{N}{k} = \frac{N!}{k!(n-k)!} \quad (3)$$

This increment in terms of total combinations that need to be identified is represented in Figure 16. The drawback of having such an enormous amount of combinations is that a computational effort is mandatory to identify uniquely each of them.

The Python software code developed for this task, used to compute the combinations of satellites in an orbital plane, has limitations in terms of computational time required. As shown in Figure 17, despite the implementation of parallel computing, the computational time increases exponentially with the number of satellites considered. There are several ways to solve this problem, with one of the simplest being converting the Python code into more efficient languages, e.g. C or C++ code. This should reduce the computational time, allowing the code to handle larger constellations more efficiently. Another technical issue is the limitation of the software used to model the spacecrafts, as a custom interface needs to be built to achieve an automation for the process of updating the block diagrams, which can become time-consuming when dealing with hundreds of satellites, particularly if failures need to be injected differently for each one.

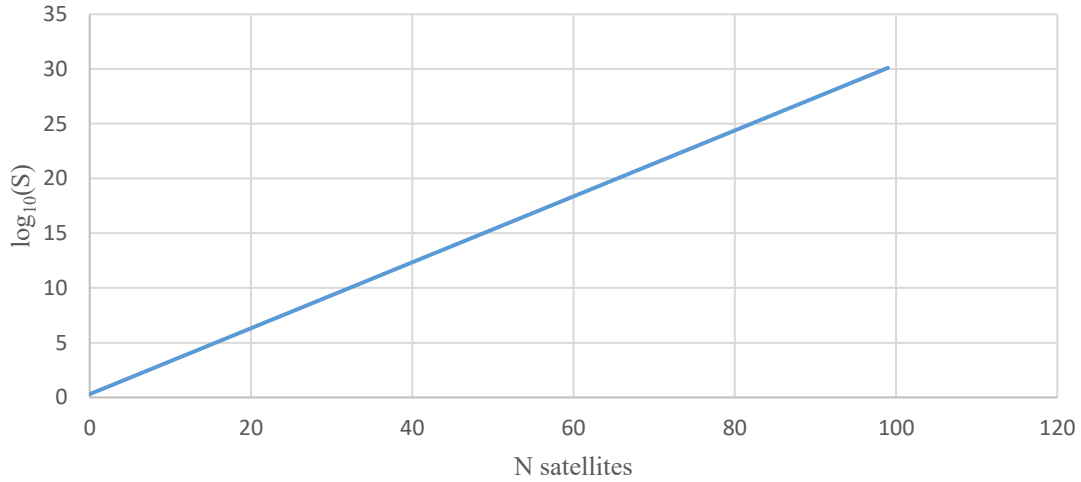


Figure 16 - Curve of total number of combinations S for an increasing number of satellites N

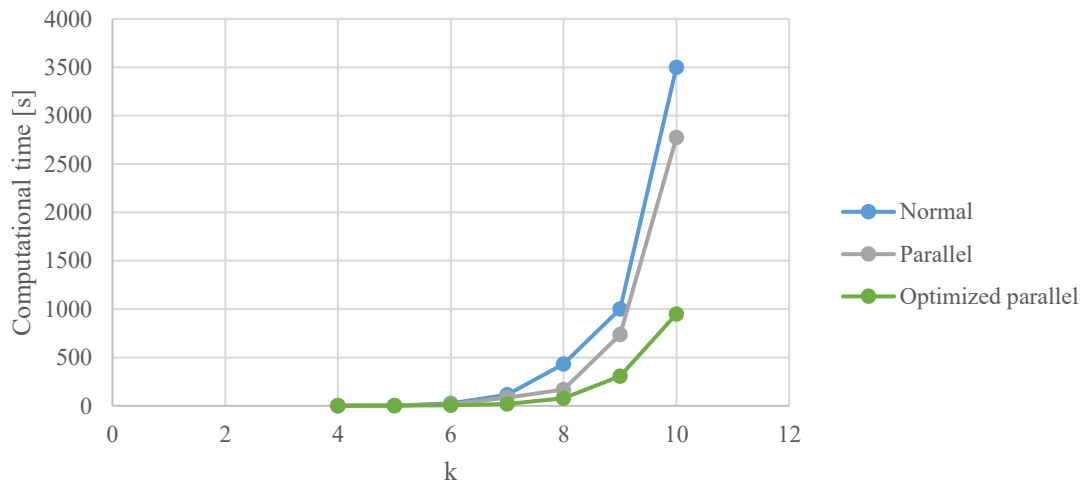


Figure 17 - Example of computational time requested for evaluating k -out-of-30 satellites

7. Conclusions

The aim of this paper is to address new techniques for improving the sustainability of space operations, both in terms of orbit handling of mega constellations and proper satellite disposal, in order to avoid debris generation; the method proposed offers several advantages from multiple perspectives through the use of the RAMS discipline, which allows to shift from an approach opinion-based to one that is data-driven. By utilizing feedback data, the health status of the mega constellations can be continuously assessed particularly with regard to the probability of reaching the targeted end of life and to ensure service continuity as it enables ongoing monitoring and updates throughout the satellite constellation's lifetime, incorporating the latest data to enhance our understanding of how the constellation will evolve over time.

Another key result relates to the de-orbiting phase, which is gaining increasing attention due to the growing awareness of space debris. The proposed method can evaluate the reliability evolution of individual spacecraft subsystem, providing operators with insights into the likelihood of having functional systems during the de-orbiting process, such as the electrical and propulsion systems.

As noted in the previous section, a key limitation of the method lies in the determination of the combinations used to calculate the probability of having a specific number of active satellites at a given moment during their lifetime. The main issue is the computational time required for this calculation, which could potentially be addressed by utilizing a different programming language, such as C or C++. In addition to this limitation, the interface with the software used to model the constellation may result in additional challenges, as the number of spacecraft increases.

The primary objective of the method remains to support decision-making in the management processes, particularly concerning the scheduling of new launches, handling of the aging satellites and de-orbiting campaigns. The availability of quantitative data allows management to make informed decisions regarding the decrease or increase of satellite manufacturing, avoiding unnecessary costs and improving production timelines.

8. References

- [1] (2025, March 4). *2024 in spaceflight*. Retrieved from https://en.wikipedia.org/wiki/2024_in_spaceflight
- [2] (2025, March 10). *List of Starlink and Starshield launches*. Retrieved from Wikipedia: https://en.wikipedia.org/wiki/List_of_Starlink_and_Starshield_launches
- [3] (2023). *ESA Space Debris Mitigation Requirements*. ESA. Retrieved from https://www.esa.int/Space_Safety/Space_Debris/Mitigating_space_debris_generation