Validated reliability based models for end of life operations

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CONTEXT

Spacecraft that survive their nominal mission lifetime are generally proposed for a mission extension to maximize their return on investment. The current criteria supporting mission extension decision are mainly based on consumables (e.g. remaining propellant) and basic operational considerations on units' performance and status.

Nowadays there is an ever increasing pressure to comply with Space Debris Mitigation (SDM) regulations since the population of space debris is expected to grow. This is mainly due to the launch of large constellations and to the satellites left in orbit or lost after the occurrence of failures occurred during the mission.

It is therefore clear that some improvements are needed in order to be able to dispose the satellite in a reliable manner, and especially at the right time meaning before the complete loss of the disposal capability.

In turn, this will allow to be fully compliant to Space Debris Mitigation standards / regulations and to guarantee a safe access to space for future missions by limiting the proliferation of space debris in already crowded Earth orbits.

For this purpose, a R&T study has been performed in 2020-2021 by Thales Alenia Space for ESA (contract n° 4000129786/20/NL/AR).

OBJECTIVE OF THE STUDY

The main objectives of this study have been to develop, validate with test and in-orbit data and integrate improved reliability approaches enabling a more accurate quantitative risk assessment; as well as to define a concept of operation for the application of RAMS analyses and criteria for the EoL decision.

STUDY ORGANIZATION & ACTIVITIES

In order to achieve these objectives the whole study has been organized in four main phases:

- Task 1: Satellite platform unit reliability models using different approaches whose main activities have been:
  - The identification and description of the wear-out phenomena, main causes/factors, timeframe, observables, recovery/corrective actions and impact on the decision on life extension and disposal for major satellite units
  - the evaluation of the best approaches to model the wear-out phenomena for each of the selected units using Health monitoring, Return of experience and/or Prognostic approaches
- Task 2: Validation of satellite unit reliability models with in-orbit experience and/or testing whose main activities have been:
  - To choose two reference missions: Meteosat Second Generation (MSG) and Sentinel 1;
  - to apply and validate the reliability models derived in Task 1 using test and/or in-orbit experience data for the selected reference missions;
  - to recommend the preferred approaches and models for each of the unit selected for the study
- Task 3: Integration into satellite platform reliability model proof-of-concept whose main activities have been:
  - To develop the functionalities allowing to use operationally the aforementioned RAMS approaches in a proof-of-concept of a whole satellite reliability model
  - To apply the RAMS approaches on the reference cases and to conclude on the improvements in terms of reliability and especially on the recommendations supporting EoL decision process
- Task 4: Concept of operations for reliability based lifetime estimate whose main activities have been to define the data, methods, tools, processes and stakeholders required to update and improve the accuracy of reliability models; and to describe how the outcomes of these RAMS analyses could support decision-making process for EoL

STUDY RESULTS

From the statistics of current Post Mission Disposal success rate, it has been derived that besides those satellites not able by design to perform EoL disposal, not all operators made the necessary efforts to fully comply with SDM standards. In particular, several examples have been highlighted from previous missions in which a too late or wrong decision on when to start the disposal has been taken, especially when the satellite had already experiences several failures.

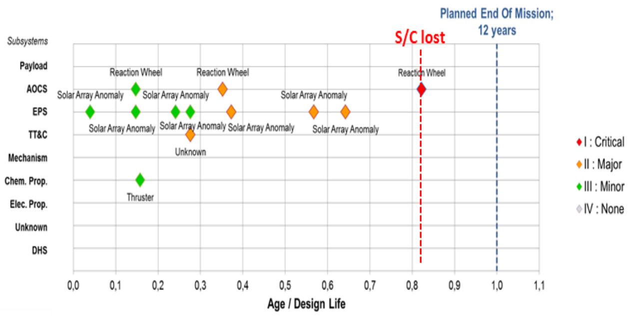

Figure 1: Example of an unsuccessful disposal of a GEO satellite because of failure occurred

Main limitations of the current decision-making process have been then described, especially for what concerns the current RAMS contribution and criteria to the EoL decision. It has been explained why the current approach consisting in reassessing the compliance to the 0.9 requirement over the remaining mission lifetime does not constitute an appropriate criterion. In fact, the 0.9 threshold is reached only after several years even after the occurrence of majors failures and in addition by re-computing this probability later on during the mission, the disposal could be always delayed and, even worse, never started, even in case of a satellite having lost most of its redundancies.

This introduction has allowed to identify several axes of improvements towards a future and ideal approach where more accurate and more appropriate RAMS aspects are taken into account, hopefully leading to a better risk-awareness decision on EoL and thus to a sustainable use of the space environment.

In this sense, the Reliability and Risk awareness estimates proposed by the study team have been seen as very appropriate and useful. Several approaches have been proposed, validated and recommended to more accurately assess the probability of succeeding the EoL disposal. Among others: the consideration of occurred failures (Approach 1), the Return of experience and the Health monitoring on operating temperatures and margins (Approach 2), Prognostic based on stochastic law, engineering models and data trend analysis (Approach 3).

Their benefits and improvements with respect to current and classical use of CDR models have been highlighted, especially for those units experiencing wear out and/or whose operating conditions are different from the ones assumed/expected during the development phase.

In addition, a Short term reliability criterion has been proposed with the aim of re-evaluating during the mission, after the occurrence of each new major failure or after a given timeframe (e.g. at least once per year), the probability of succeeding the EoL disposal in a short timeframe.

Its outcome is a recommendation to anticipate the disposal when a too low probability is computed (red zone). On the other hand, if the reliability figure is still high (green zone) one could more easily decide to pursue the mission. Finally in an intermediate case (orange zone) a special attention has to be paid, especially for those units that, if failed, could prevent a successful disposal.

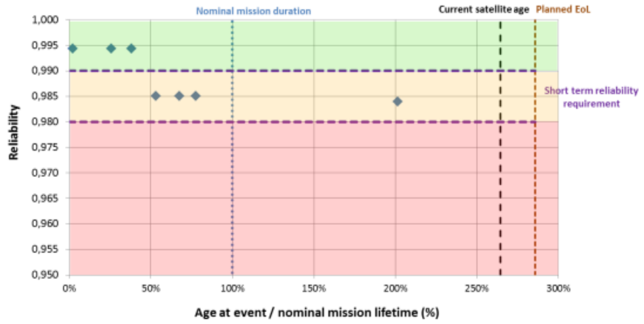

Figure 2: Overview of the Short term reliability criterion (probability computed over one year)

This reliability criterion and the different reliability approaches have been applied also to the two reference cases selected for this study: Meteosat Second Generation in GEO and Sentinel 3 in LEO. The proof-of-concept of a generic reliability tool developed in the frame of this study has been used for this activity. In both cases it has been concluded that the proposed approaches and tool allow for a better risk-awareness decision on the End of Life and could ideally lead to a high Post Mission Disposal success rate in the future.

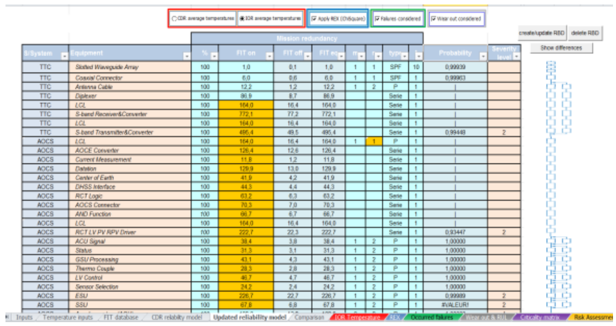

Figure 3: Overview of the generic reliability tool supporting the different approaches.

In addition to these quantitative RAMS analyses, Risk Assessment analyses have been proposed for an improved decision making process since they can provide a clear picture of the current and future capability of performing the EoL disposal operations via a nominal, contingency or emergency strategy. Here, in addition to the classical risk analyses (e.g. critical SPF list, list of Operation Life limited Items or those experiencing wear out, FEA, PRA, etc.) a Two failure matrix and an Enhanced risk assessment have been proposed and promoted by the study team in order to support decision-making process for the EoL.

They allow to analyse combinations of failures that could lead to the loss of disposal capability, assessing the related risk and identifying potential corrective/compensatory means, already since the early phases of the satellite development process. They can be then reassessed at any point in time of the satellite nominal life in case of faults/anomalies that change the satellite configuration, expected life or operation. They are therefore particularly useful for satellites with enhanced lifetime and/or that are in non-specified conditions and prone to multiple failures due to "aging".

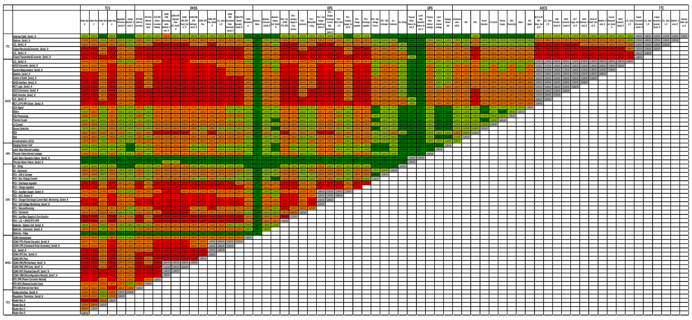

Figure 4: Example of two failure matrix

In addition, some decision criteria have been suggested (e.g. Risk Index, probability of disposal via nominal or degraded strategies) and implemented in the proof-of-concept of tool supporting these approaches. A very recent and preliminary application of the multi-disciplinary Enhanced Risk Assessment Technique on a real satellite has demonstrated its feasibility and interest for a better risk-awareness decision on EoL.

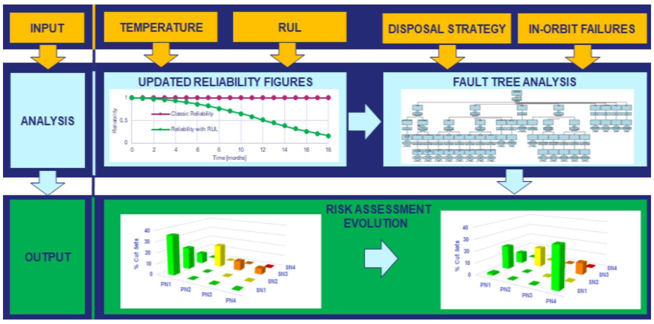

Figure 5: Enhanced Risk Assessment technique working logic and outcomes

CONCLUSION AND PERSPECTIVE

To conclude, all the activities expected in the frame of this study have been performed. Quantitative and qualitative RAMS analyses and criteria, supported by a generic reliability tool, have been proposed in order to more accurately assess the probability of succeeding the disposal and especially to support the decision-making process on when and how the EoL operations should be performed.

A simplified overview on how these EoL criteria could be used operationally to support the decision-making process for the EoL of satellites is provided below: the classical propellant mass criterion, as well as two additional quantitative and qualitative criteria, will be computed before the launch (see **Figure 6**) and reassessed during the whole mission (see **Figure 7**) by taking into account the functions needed for the disposal, the failures occurred in orbit and the current status of the satellite units and their Remaining Useful Lifetime (RUL).

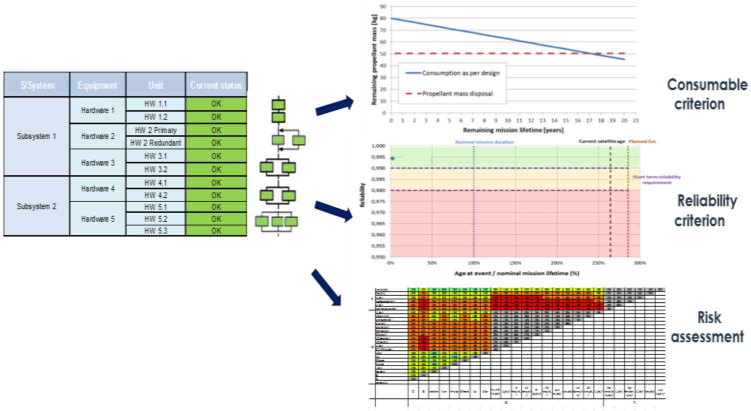

Figure 6 : Outputs of the generic tool for a satellite at the beginning of its mission

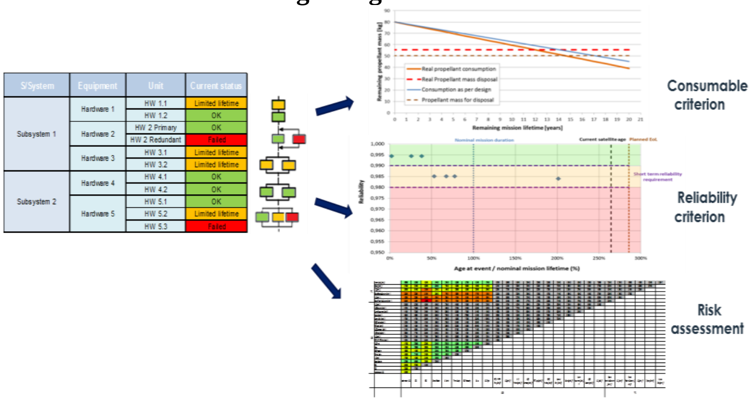

Figure 7 : Outputs of the generic tool for a satellite during its mission

The proposed approaches and tool allow for a better risk-awareness decision on the End of Life and could ideally lead to a high Post Mission Disposal success rate in the future. This has been demonstrated also via the practical and operational use of these RAMS approaches for the End of Life review of two on-going missions.

In addition, a preliminary application to previous missions, both in LEO and GEO, has shown that, if correctly defined, the aforementioned RAMS criteria could have helped in succeeding their EoL disposal, thus avoiding to leave/loose several satellites in orbit.

The generic tool developed as a support of the future approach to EoL and the new criteria will be even more important and useful for future missions since:

- It will be anyway required by the updated ISO 24113 standard to define a specific criterion for initiating the disposal of a spacecraft, to evaluate it during the mission and to execute consequent actions if it is no longer met;
- A high PMD success rate is indispensable for the sustainability of the space, especially for large constellations, in order to limit the proliferation of space debris in already crowded LEO orbits;
- with future in-orbit refueling missions the propellant mass criterion could become less useful / adequate to decide when to dispose the satellite. In fact, if refueled, the propellant mass

threshold would be reached always later or never ever. Therefore the reliability criterion would be the 'only one' to be able to recommend the disposal when the risk of not being able to succeed the disposal will be too high.

This criterion could be also used in the future not only for the EoL disposal decision but also for other applications. For instance:

- to select the launch date or the constellation replenishment strategy;
- to assess the interest of a refueling mission for an already too 'old' satellite and to answer to the question: Does it make sense to refuel and already old (less reliable) satellite?
- to derive the need of a maintenance mission to replace the failed units or those showing a significant degradation of performance. Thus answering to these questions: Which are the HW more likely to be replaced in orbit? And when should we replace them?

Future activities are needed and critical for solving the identified gaps within this study. Such as to apply these RAMS approaches on current and future novel satellites, to finalize the selection of the RAMS criteria, including their validation on previous/on-going missions; to further evaluate appropriate approaches for 'New Space' missions and constellations; and to further evaluate the prognostic approaches, and especially those based on data trend analysis which has been seen as very promising for EoL decision. These aspects are recommended for future studies.

REFERENCE

[1] Final Report of the study: Reliability Model Enabling Satellite Life Extension and Safe Disposal 0005-0010209307

[2] D1: Satellite platform unit reliability models using stochastic, model-based, and/or data trend analyses 0005-0011949245

[3] D2: Validation of satellite unit reliability models 0005-0013045142

[4] D3: Satellite platform reliability model proof-of-concept 0005-0013782102

[5] D4: CONOPS and preliminary requirements for reliability driven design, health monitoring and operations 0005-0014737130

[6] ISO 24113 standard - Space systems — Space debris mitigation requirements (2019)

[7] Loi N° 2008-518 du 3 juin 2008 relative aux opérations spatiales version consolidée du 24 juin 2016. ESRX0700048L

[8] Risk to space sustainability from large constellations of satellites.

[9] ESA's annual space environment report GEN-DB-LOG-00288-OPS-SD

[10] Tri-Agency Reliability Engineering Guidance: Post Mission Disposal and Extension Assessment

ACRONYMS

EoL	End of Life
FMEA	Failure Mode Effect Analysis
FTA	Fault Tree Analysis
GEO	Geostationary Earth Orbit
IOR	In Orbit Return
ISO	International Organization for Standardization
LEO	Low Earth Orbit
PMD	Post Mission Disposal
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram
RUL	Remaining Useful Lifetime
TAS	Thales Alenia Space