Long-term environment simulations and risk characterisation in support of a Zero Debris Policy

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Abstract
Following ESA's Director General call to stop the generation of debris in valuable orbits by 2030, ESA's Zero Debris Approach has been developed. A concurrent design facility study was held at the end of 2022 to draft a preliminary set of technical recommendations. Such recommendations were based on an extensive simulation campaign, mostly based on the analysis of the long-term evolution of the debris environment through different metrics and under different policy options. The paper discusses the rationale for such analyses, their outcome, and their connection to the Zero Debris Approach.

1 Introduction
The change to the traffic in Low Earth Orbit, with the emergence of the so-called large constellations, has prompted several studies into the assessment of how Space Debris Mitigation standards should evolve to limit the proliferation of debris in orbit, for example by requiring higher success rates for post-mission disposal and by reducing the time allowed for the disposal phase.

ESA aims to lead by example in this field, by putting forward a Zero Debris Approach to be implemented by 2030. A concurrent design facility study (Zero Debris CDF) [1] was held at the end of 2022 to draft a preliminary set of technical recommendations for the policy evolution. The recommendations cover all aspects of a space mission, from design to operations, including proposals to strengthen orbital clearance requirements, recommend design-for-removal for high-risk mission, recognise best practices for collision avoidance, and mitigate the impact of missions on astronomy [2].

Such recommendations were based on an extensive simulation campaign where the long-term evolution of the debris environment was analysed under different policy options, which will be described in the present paper. In 2023, ESA worked on the first translation of such recommendations in a technical standard immediately applicable to its missions [3]. This required a fine tuning of the principles captured in the Zero Debris CDF to ensure the formulation of measurable and verifiable requirements, which were also informed by the analyses presented in this paper.

2 Setup for the long-term simulations of the environment
Long-term (200 years) simulations on the environment are often used in space debris modelling to quantify the sensitivity of the environment to parameters such as launch traffic, explosion rates, disposal approaches. This was the approach used at IADC (Inter-Agency Space Debris Coordination Committee) level to derive the so-called 25-year rule [4], by comparing the outcome to alternative
disposal options. Such outcome is usually presented in terms of number of objects and catastrophic collisions. In the present case, the traditional metrics mentioned above were combined with the representation through a debris risk index and the related definition of orbital capacity [5]. This approach is adopted to assess the risk level associated to the different scenarios and to carry out a more robust assessments of the environment (i.e. not linked to checking a set of guidelines and not assuming specific mission architectures), which can also be used to define reference targets for the space debris environment evolution, similarly to the 2-degree threshold in the climate change sector [6].

The initialisation of the simulations is based on the data available in ESA’s DISCOS database [7], following the approach described in [6] and adopted in the compilation of both ESA’s [8] and IADC’s Space Environment Report [9]. In summary, the launch traffic is derived from historical data for objects not belonging to a constellation, whereas deployment and replenishment model are defined for each constellation that have launched at least one satellite. The explosion rate is defined considering past explosion events that can be classified as not system-related, i.e. not linked to specific design flaws. The disposal rates (i.e. percentage of compliance to the disposal guidelines for non-naturally compliant objects) can be based on historical values or provided as an input to assess the effect of a specific rate of adherence. Different disposal durations and rate can be set for different types of objects i.e. distinguishing between constellation satellites, non-constellation satellites, and upper stages. ESA’s DELTA 3 [10] was used for the generation of the results.

3 Test cases

Tab. 1 reports all the simulation cases analysed during the Zero Debris CDF activity. The year in the label refers to the starting year i.e. the year use to initialise the population and to retrieve historical data. In the traffic column, the number of years refers to the years before the initial epoch used to build the traffic pattern. Where the note “+const” appears, the traffic of constellations and non-constellation objects are treated differently, as explained in Section 1. The cases marked as NFL indicate that No Further Launches are simulated. Columns 3 to 7 define the Post-Mission Disposal (PMD) approach implemented, with the different behaviours for Rocket Bodies (RB) i.e. upper stages, Payloads (PL) i.e. satellites, distinguishing between Constellation (C) and Non-Constellation (NC) objects. The disposal duration ($\Delta t$), i.e. the decay time, is indicated in years. Finally, the last column indicates the smallest object size used for the simulations. For all cases, it is assumed that only Constellation satellites have COLlision Avoidance (COLA) capabilities, with 100% success rate.

4 Long-term simulation results

The results of the simulations for the main analysed cases are reported in Fig. 1, which shows the evolution of the number of objects (in Low Earth Orbit, LEO) and catastrophic collisions. Among the scenarios, the red one (Extrapolation) is taken as representative of the current use of space, the yellow one (PMD90(25y)) represents the adherence to current mitigation standards. The grey one (No further launches) is taken as benchmark: ideally the mitigation approach is such that the effect of space activity is neutral i.e. equivalent to the case where no additional launches are performed. By looking at the results in Fig. 1, one can observe how the extrapolation scenario results in a population growth equal to 21 times over 200 years with respect to the initial population, with an increase of the growth rate over time, which signals that such a scenario is not sustainable. Even the scenario with adherence to current mitigation standards and the one with no further launches result in a population growth of respectively 7.11 and 2.84 times over 200 years.
Tab. 1. Full set of simulations analysed during the study. Acronyms defined in the text.

<table>
<thead>
<tr>
<th>Label</th>
<th>Traffic</th>
<th>PMD rate RB</th>
<th>PMD rate PL (NC)</th>
<th>PMD rate PL (C)</th>
<th>PMD Δt [y] PL (NC)</th>
<th>PMD Δt [y] PL (C)</th>
<th>Min Size [m]</th>
</tr>
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<tr>
<td>2005,Extrapolation</td>
<td>5-year</td>
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<td>0.05</td>
<td>N/A</td>
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<td>25</td>
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<td>2005,NFL</td>
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<td>0.05</td>
<td>N/A</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>2005,PMD90</td>
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<td>N/A</td>
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</tr>
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<td>2014,Extrapolation</td>
<td>5-year</td>
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<td>N/A</td>
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<tr>
<td>2014,NFL</td>
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<td>0.1</td>
<td>N/A</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>2014,PMD90</td>
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<td>0.9</td>
<td>N/A</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>2021,Extrapolation</td>
<td>5-year + const</td>
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<td>0.3</td>
<td>0.9</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
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<td>0.3</td>
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<td>25</td>
<td>25</td>
<td>0.1</td>
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<tr>
<td>2021,PMD90</td>
<td>5-year + const</td>
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<td>0.9</td>
<td>0.9</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>2021,PMD90, Const99.5(1y)</td>
<td>5-year + const</td>
<td>0.9</td>
<td>0.9</td>
<td>0.995</td>
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<td>1</td>
<td>0.1</td>
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<td>0.9</td>
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<td>25</td>
<td>0.1</td>
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<td>0.9</td>
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<tr>
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<td>2022,PMD90, Const99.5(1y)</td>
<td>5-year + const</td>
<td>0.9</td>
<td>0.9</td>
<td>0.995</td>
<td>25</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>2022,PMD99.5(5y)</td>
<td>5-year + const</td>
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<td>0.995</td>
<td>0.995</td>
<td>5</td>
<td>5</td>
<td>0.1</td>
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<tr>
<td>2022,PMD99.5(25y)</td>
<td>5-year + const</td>
<td>0.995</td>
<td>0.995</td>
<td>0.995</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
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<tr>
<td>2022,PMD99.5(1y)(1cm)</td>
<td>5-year + const</td>
<td>0.995</td>
<td>0.995</td>
<td>0.995</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
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<tr>
<td>2022,PMD90(25y), 2019traffic</td>
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<td>0.9</td>
<td>0.9</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>2022,PMD90(5y)</td>
<td>5-year + const</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>5</td>
<td>5</td>
<td>0.1</td>
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<tr>
<td>2022,PMD90(5y)(1cm)</td>
<td>5-year + const</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>5</td>
<td>5</td>
<td>0.01</td>
</tr>
<tr>
<td>2022,PMD90(25y)(1cm)</td>
<td>5-year + const</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>25</td>
<td>25</td>
<td>0.01</td>
</tr>
</tbody>
</table>
One way to act on the population growth is to limit the duration of the disposal phase. Some results for different disposal durations (1, 5, and 25 years) are shown in Fig. 2, where almost complete adherence to the guidelines is assumed. (99.5% success rate). From the results we can see how following the 25-year guideline was and is a fundamental prerequisite for space sustainability. Going lower than 25 years leads to a 25% (5y) - 35% (1y) reduction in the amount of debris, but a nearly 50% (5y) - 75% (1y) reduction in amount of catastrophic collisions. This is because fragments created are mainly in lower orbits and hence decay faster and have less time to collide with other objects.

The results above were presented in terms of number of objects and collisions: these are global metrics useful to compare different scenarios, but which hide differences related to where the objects are located (i.e. short- or long-lived), their activity status, etc. For this reason, some complementary analyses were performed and are described in the following.
5 Analysis of debris growth for target missions

As outcome of the DELTA simulations, it is possible to extract the debris density for a given epoch in the simulated scenario. The density is expressed as a function of altitude and inclination to highlight how the growth rate can be different depending on the orbital region. The debris density at the beginning and at the end of the simulation was retrieved for several scenarios; their ratio, indicated as debris density growth rate, is shown in Fig. 3. One can see how only the selection of a very short disposal duration (1 year) avoids the creation of high density regions due to the concentration of disposed objects. As expected, regions at high altitude are the most exposed to debris accumulation. In none of the simulated a case a reduction of the debris density is observed.

![Fig. 3. Debris density growth rate in four different scenarios over 200 years of simulation.](image1)

![Fig. 4. Debris density growth for some reference missions over 200 years of simulation.](image2)
In the plots in Fig. 3, the location of five missions is also indicated and the debris density growth rate at those orbits was retrieved across several scenarios, as represented in Fig. 4. The debris density growth rate can be seen as a proxy of the debris risk for the missions in the different scenarios and connected to the increase in collision avoidance activities for missions in such regions and, therefore, act as a reminder for operators on how they are directly affected by global mitigation approaches and of the reached level of criticality of the space debris environment.

6 Analysis of conjunction statistics in the simulated scenarios

In order to explore more the impact on collision avoidance operations, for some scenarios, a more detailed analysis was performed to extract yearly conjunction statistics following the approach described in [12]. Fig. 5 shows the number of conjunctions with collision probability higher than $10^{-6}$ and time to close approach smaller than 3 days for a set of representative satellites in Sun-Synchronous Orbits at the year 2040 for the 2022, Extrapolation, optimistic scenario. One can observe how already in the shorter timeframe of the initial 18 years of simulations, the impact on operations is significant, which highlights the need for improved space situational products. This encompasses improved management of space traffic through better coordination of operator plans, and uncertainty reduction, e.g. through better catalogue products and late commanding options. It also shows the importance of covering collision avoidance processes in mitigation approaches and developing designs resilient to the implementation of collision avoidance manoeuvres.

7 Debris index and space capacity

As a final assessment, the debris index defined in [5] was applied to all the scenarios. The idea of such debris index is to measure for each spacecraft its potential to add debris to the environment (e.g. depending on the debris density discussed in Section 5) and the consequences of such event. The index is therefore a risk metric that is computed at single-mission level, but can be aggregated over all the members of a population to obtain an assessment of the global state. In particular, as defined in [6], the aggregated index value for the scenario 2014, PMD90 is used as benchmark: we interpret this scenario as the one implicitly assumed when guidelines such as the 25-year were drafted (i.e. no constellation, high adherence rate). Therefore, the debris risk associated with it constitutes for us the boundaries of what
we mean by “space capacity”. Fig. 6 shows the comparison with such benchmark case by reporting, for different simulation scenarios, the value of the aggregated risk index at the end of the simulations normalised with respect to the benchmark case. The single markers indicate the value for each of the 100 Monte Carlo runs executed for each scenario. As elaborated in [6], the application of the 25-year rule to the current environment (with significantly different launch rates with respect to 20 years ago) results in a final risk level after 200 years around 2.5 times the one in the benchmark case. If one wants to use that risk level as threshold for what’s considered acceptable, then stricter conditions both for the post-mission disposal duration and for its success rate need are required.

8 Evolution of orbital clearance requirements

The results in Fig. 2 clearly show the benefits of a reduction in the disposal duration from 25 to 5 years. The assessment in Fig. 6 summarises that what we really want to limit is the debris risk and the disposal duration is a proxy of it (i.e. the longer an object is inactive in the environment, the highest the chance to be involved in a fragmentation). A way to act on the limitation of the debris risk more directly is to complement the limit on the disposal duration with a threshold for the cumulative collision probability. The rationale for this approach is that this metric considers the different size of the spacecraft and whether it operates in dense regions, without the need for a rigid classification of high-risk regimes or architectures, which risk to quickly become obsolete with the evolution of the space environment and of space technologies. A similar approach is also part of the update of the French Space Operation Act [13].

In particular, a clearance requirement based on a threshold for the disposal time to 5 years and of $10^{-3}$ for the cumulated collision probability was analysed. To explain how the proposed clearance requirements would work, we can take the example of two missions: a large (2000 kg) satellite, and a 3U CubeSat, both operating in LEO. For both missions, the disposal trajectories corresponding to different disposal duration were computed, together with the corresponding cumulative collision probability using DRAMA. For the analysis, the MASTER population in 2030 was used. The results are shown in Fig. 7, where the dashed red line in both plots indicate the threshold for the cumulative collision probability, set at $10^{-3}$ considering the flux of objects larger than 1 cm. This threshold was chosen considering that impacts with objects as large as 1 cm can already be mission-terminating over a large range of impact velocities; in addition, the $10^{-3}$ value is the same as for the breakup probability due to internal causes.
With reference to the results in Fig. 7, in the case of the Large satellite, the threshold on the cumulative collision probability is the one to determine the disposal strategy (resulting in a trajectory with orbital lifetime slightly larger than two years); for the CubeSat satellite, on the other hand, the limitation of 5 years is the decisive one.

Fig. 7. Cumulative collision probability during the inactive phase for (a) a large satellite and (b) a 3U CubeSat in LEO.

9 Limitations of the assessment and modelling needs

The analysis of the scenarios in Section 3 is affected by some limitations of the assessment. Firstly, for the sake of computational time, most of the simulations were performed considering only objects larger than 10 cm. However, objects down to 1 cm can already trigger catastrophic collisions i.e. collisions able to terminate a mission and produce a significant amount of new debris. Analyses are on-going at IADC level to better characterise the effect of the selection of the size threshold in long-term simulations of the environment. In addition, in DELTA 3, active objects for which collision avoidance is enabled will avoid any object in the simulation, regardless of its size, with an underestimation of the risk coming from the so-called lethal non-trackable objects. The new version of DELTA addresses this issue, with also the planned feature to define different success collision avoidance rate for different classes of objects.

Secondly, the traffic launch for constellations considers only the deployment and maintenance of already existing constellations. This approach was chosen to limit the range of assumptions given the variability of predictions on the actual implementation of the many proposed constellation projects. However, in this way, the number of launched satellites in the period 2023-2030 is around two thirds of the forecast prepared by consulting firms such as Euroconsult [11]. A number of launched satellites in the 2023-2030 period similar to the one in the Euroconsult report could be obtained by dropping the differentiation between constellations and non-constellation objects and simply repeating the launch patterns observed in the years from 2019 onwards (instead of from 2017 as in the results in Section 3). As expected, with this second approach, the traffic pattern is heavily influenced by the Starlink objects and therefore the results are not considered more representative. This is important to keep in mind considering that the objective of the long-term simulations is not to predict how the space environment will look like, but rather to assess its sensitivity to different parameters that can be controlled through mitigation policies. Nevertheless, the exploration of a more integrated modelling of the
interconnections between traffic trends and economic/policy trends, in line with the preliminary attempt in [14], would be an interesting addition for a holistic study of the issue of space sustainability.

Finally, the explosion model used in Section 3 is not linked to the objects in the population. For example, if in a mitigation scenario all upper stages are disposed, still the explosion model would simulate the explosion of rocket bodies based on historical values. While the selection of only non-system-related events goes in the direction of trying to define a background risk for any intact object in space, further developments will likely improve the explosion model in DELTA.

For what concerns the assessment of the cumulative collision probability described in Section 8, it would benefit from regular updates of the reference debris population to ensure the relevance of the risk estimation. For this reason, ESA’s Space Debris Office has been working on a renewed processing framework, based on the data in DISCOS [7], to create MASTER reference populations, with the objective of being able to target annual release cycles. The request for such fast turnaroud time was already identified by the user feedback collected in [16], together with an interest in increased accessibility of long-term evolution simulations. Both topics become particularly relevant in the development of disposal criteria more directly related to the estimated risk conditions in the debris environment. In response to the latter point, the development of alternative methodologies for long-term simulation (e.g. based on particle-in-a-box models [17], continuum approaches [18], graph theory [19]) can be a way to make accessible the generation of long-term evolution scenarios with a contained computational cost.

10 Conclusions

ESA has set the ambitious goal of putting forward a Zero Debris approach for its missions. In 2022 a Concurrent Design Facility study was performed to define a first set of recommendations, which have been the basis for the update of the space debris mitigation requirements applicable to ESA’s missions. The formulation of such recommendations was supported by a series of long-term simulations of the debris environment, where different mitigation options were explored, and different metrics were used in the analysis of the results, with the goal of measuring the sustainability of such options. In particular, the evolution of the number of objects in LEO and of the number of catastrophic collisions shows the benefit of the reduction of the duration of the disposal phase. While such metric can be used only for global assessment, the analysis of the debris density distribution in the different simulated scenarios was used to highlight the different debris risk in different regions of LEO and their sensitivity to the mitigation approach. This shows that, as expected, only a very short disposal duration (i.e. 1 year) avoids the creation of regions with relative risk increase due to deorbiting spacecraft. A debris index was used to further characterise and quantify such debris risk, showing that a neutral space activity (in terms of impact on the space debris environment) can be targeted only with the combination of a reduction in the disposal duration and an increase in the post-mission disposal success rate. As a next step, to more directly act on the debris risk associated with space objects, a disposal criterion based on the cumulative collision probability was presented. Such criterion is meant to complement a more classical one based on the disposal duration. The application to two example missions in LEO was presented, showing how for small missions the disposal duration would still be the criterion that drives the disposal design, whereas for large missions the constraint on the cumulative collision probability may translate into disposal strategies with duration around two years. Finally, the characterisation of the expected conjunctions in the simulated scenarios shows the importance of addressing behaviour and design choices not only at the end of mission, but also during operations to properly manage the collision risk with debris and other operational satellites.
11 References


