LEVERAGING SPACE DEBRIS SIMULATION RESULTS: REVISITING GUIDELINE VALUES FOR EXPLOSION AND CUMULATIVE COLLISION RATE

V. Schaus[(1)], F. Letizia[(1)], B. Bastida Virgili[(1)], and S. Lemmens[(2)]

[(1)] *IMS Space Consultancy GmbH @ ESA/ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany, Email: {Volker.Schaus, Francesca.Letizia, Benjamin.Bastida.Virgili}@esa.int*

[(2)] *ESA/ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany, Email: Stijn.Lemmens@esa.int*

ABSTRACT

Space debris mitigation requirements in-place today define thresholds for the probability of accidental on-orbit break-up and, sometimes, cumulative collision probability over the residual orbital lifetime of a spacecraft. For both cases, the postulated probability limit is set to 1/1000. The caveat of having fixed design target values is that their justification has to be revisited from time to time. This is especially true when previous assumptions and initial considerations are not applicable anymore. In fact, the recent years have revealed several new trends and tendencies in the way space launches and operations are nowadays performed. These developments were not considered in long-term space debris environment models which underlie current space debris mitigation requirements. This ranges from multi-spacecraft launches and the increase in smaller spacecraft (mini, micro satellites and CubeSats) to introduction of large constellations to pursuing active debris removal concepts.

These behavioural changes have been analysed in long-term space debris environment simulations in the recent past. The paper taps into the results and the scenario descriptions of over 400 simulation setups either conducted by partners in joint simulation campaigns or at ESOC/Space Debris Office directly. It derives best estimates for collision rates and explosion rates originating from the various different simulation scenarios. The findings are presented in multidimensional views linking important simulation parameters such as the post mission disposal rate, constellation and active debris removal rate to the overall growth in the number of space (debris) objects at the end of the simulation period.

Besides the direct application for challenging the design guideline values for collision and explosion rate, this enables us to further exploit the many long-term simulation results performed over several years. The analysis helps to gain further inside in the effectiveness of certain debris mitigation strategies. It can be used to identify gaps in the previous simulation scenario setups, which can be closed in future simulation campaigns and is a pre-requisite for training a surrogate model of the space debris environment. Moreover, we demonstrate how these simulations and aggregated results can be used to calibrate the values obtained from estimators for the space environment capacity and hence future is implied by sustainable behaviour.

Keywords: space debris simulation; collision probability threshold; accidental on-orbit breakup; environmmental capacity index.

1. INTRODUCTION

In the recent years, the Space Debris Office took part in a variety of long-term simulation campaigns of the space debris environment. Some activities were coordinated internationally via the Inter-agency Space Debris Coordination Committee (IADC) working group 2; others were performed as contracted simulation studies. The Space Debris Office can be regarded as hub for those activities, sometimes actively participating, sometimes as contracting body. This lead to the presence of a divers set of space debris simulation scenario results which are now available for further analysis. At the top-level, they can be divided into two categories, (1) complete simulation run results performed with ESA-DELTA[1] and (2) aggregated results from the ESA-funded study focussing on the "Impact risk in LEO as a result of the increase of nano and micro-satellites"[2]. Both of them will be further described in the next section.

The scenarios of these analysis cover a broad range of parameter variations. The results are of statistical nature and are used to examine overall trends, tipping points and the (relative) effect of mitigation measures. The conclusions derived from such long-term simulations are typically addressing the space debris environment as a whole. The analysis presented in this paper makes use of over 400 results of the long-term simulations and puts them in context with the guidelines and threshold values for single spacecraft. In particular two values are of importance, namely the accidental break-up probability P_{ab} and the cumulated, accidental collision risk P_{ac} of a spacecraft throughout its orbital lifetime. For both parameters,

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

there are established thresholds in space debris guideline documents as of today. The goals is to see whether the long-term simulation results justify the thresholds or if reconsiderations might be necessary.

ISO24113:2019 [3, Section 6.2.2] gives a value of 1e−3 for the accidental break-up probability caused by an onboard source of energy until its end-of-life. The document also mentions the case of accidental breakup caused by a collision, but does not assign a threshold value for this case.

The NASA Technical Standard 8719.14B [4, Requirement 4.5-1] defines a threshold for the cumulative collision risk of any spacecraft in low Earth orbit (LEO) throughout its orbital lifetime to not exceed 1e−3 considering orbital debris larger than 10 cm. In Requirement 4.4-1, the Standard also mentions the probability for self-induced explosions during deployment and operations to not exceed 1e−3.

A second order motivation for the work presented in this paper was the rather simplistic yet commonly applied result evaluation of long-term space debris environment simulations. Often this is limited to examining for example the evolution of the total number of objects and the cumulative number of collisions. The difficulty with these global evolutions is that they do not properly capture the effectiveness of specific mitigation strategies such as the post mission disposal success rate (and the targeted remaining lifetime of end-of-life disposal manoeuvres), the level of collision avoidance and whether active debris removal was considered or not. This makes an assessment of the status of the debris environment and the comparison of the mitigation measures difficult. And in consequence of the shortcomings has lead to the formulation of several indices and metrics to better capture the multi-dimensional nature of the space debris challenge.

Some of the metrics aim at specific purposes such as identifying the most critical defunct space object as target of an active debris removal mission [5–8]. Other formulations target the overall environmental aspects and in general try to pinpoint the tipping point or the beginning of the collisional cascade in certain orbital regimes. There are different nomenclatures for this, e.g. the definition of runaway threshold and unstable threshold in [9], or the environmental capacity index [10, 11]. The latter is also used within this paper as an example to further leverage on the collection of long-term space debris simulation results.

2. DATA ANALYSIS OF THE EXISTING LONG-TERM SIMULATIONS

There are two main sources of simulation result that were used for this evaluation. The first set of data originates from a ESA-lead long-term space debris simulation campaign. The focus of the activity was on modelling the effects of the large constellation and small satellites announced in the recent years. The available data from this study is already very much aggregated. The second batch of simulation results is a collection of internally performed long-term simulations over the past eight years. The simulation used ESA-DELTA code and all the detailed input and output from these scenarios is still available. In total it was possible to process results from 426 scenarios. The tool to parse and prepare the dataset is flexible in the sense that whenever more scenarios are available, the data set can be extended. The next two subsections describe the datasets in more detail.

2.1. Study on constellations and small satellites

A large set of simulations was conducted in the frame of an ESA-lead study named 'Impact Risk in LEO as a result of the Increase of Nano and Micro-Satellites' (GSP-SIM-SOW-00167-HSO-GR). Hereafter these results are identified as GSP study. Its main focus was to do a large parametric study varying both typical mitigation parameters, such as collision avoidance and post mission disposal rates and also study the effects of adding constellations and small satellites to the spacecraft population. [2]

The available results are already very much aggregated and processed. For instance, the results of each individual Monte Carlo run is not available anymore; they are averaged over all runs. The simulations conducted in the study were performed by three different partners. For some of the simulation scenarios, two partners have run the same cases to generate correlation points. The baseline scenario was run by all three partners.

The relevant averaged, annual values for the work presented in this report are:

- Number of intact space objects, non-functional and active: n_{int}
- Number of newly generated fragments originating from collisions and self-induced breakup events: n_{nf}
- Number of old fragments: n_{of}
- Number of total residual space objects: n_{tot}
- Cumulative number of catastrophic and non-catastrophic collisions: n_{ccc} and n_{ncc}

It is important to note that the fragments originating from explosions and from collisions are given as combined value in the output. The sample probability of accidental, self-induced orbital breakup P_{ab} can be estimated by averaging the annual number of explosions n_{exp} by the number of active spacecraft n_{act}.

$$P_{ab} = \frac{n_{exp}}{n_{act}} \tag{1}$$

The number of active objects n_{act} is a subset of all the intact objects n_{int} minus the non-functional (defunct) objects n_{do}: $n_{act} = n_{int} - n_{do}$ The underlying assumption of Eq. 1 is that all missions perform full passivation at their end-of-life. It can be also generalised by normalising to all intact objects n_{int}.

Similarly, the sample probability of accidental collision P_{ac} can be estimated by averaging the number of collisions n_{col} over the number of defunct objects n_{do}.

$$P_{ac} = \frac{n_{col}}{n_{do}} \tag{2}$$

Eq. 2 is only valid for simulation cases that feature a collision avoidance performance rate of 100 %. It is possible to limit this evaluation to simulation definitions which comply to this condition or to generalise again to number of all intact objects n_{int}.

In order to calculate values for the annual evolution of accidental collision rate P_{ac} and the orbital breakups P_{ab} it is necessary to know the number of active spacecraft. Unfortunately, this was not part of the aggregated result files. It was therefore necessary to estimate the number of active objects in each simulation year present in the population. This was done in an iterative manner, from beginning to the end of the simulation: The number of active objects in the i-th year of the simulation can be recalculated from number of active objects in the previous year and the input parameters of the long-term simulation scenario.

$$n_{act,i} = n_{act,i-1} + n_{lr} - n_{eol} - n_{exp} - n_{col} \tag{3}$$

where n_{lr} is the number of newly launched objects (derived from a background launch rate and from constellation built-up and replenishment launches), n_{eol} is the number of missions which reach end-of-life, n_{exp} is the number of explosion, and n_{col} is the number of (catastrophic and non-catastrophic) collisions.

It was possible to perform this iterative estimation of the number of active objects by using the aggregated results and the input parameters of the definition of the long-term simulation scenario. A total number of 327 cases were analysed with this approach and contribute to the data basis of values for the accidental collision and breakup rate observed in the simulations.The remaining part of this section details further considerations and modelling aspects of the simulations scenarios and how they were treated for the re-calculation of active objects.

The launch rate is in many cases a repeating launch traffic of the past 8 years (period of 2005 f to 2012 for the GSP activity). With fixed eight years of mission lifetime of payloads added to the population, it can be stated that the average number of active payloads remains constant. The development of the number of active payloads was used to judge on the re-calculation results.

On top of the launch rate to form the background population, there are additional launch rates for constellations and small satellites. For the constellations, a similar balance between addition and the retirement of spacecraft is reached during the replenishment phase of the constellation operation. The build-up phase when the constellation is introduced effectively leads to a higher equilibrium of active satellites in orbit. Additional losses to the number of active satellites in the population are the annual rate of explosions and the collision avoidance performance.

The explosion rate is modelled in two ways. Firstly, it can be defined as a fixed number of spacecraft, i.e. two explosions per year. Or secondly, it can be expressed as a ratio of the currently active spacecraft, i.e. 4 % of the active spacecraft explode each year. As for the collision avoidance, the standard approach is also to define it as performance criteria, i.e. 90 % of the collision avoidance attempt are successful. In the simulations, this is implemented by means of Poisson statistics to predict the outcome for each close encounter.

2.2. ESA-DELTA simulation results

The ESA-DELTA [1] result files contain much more information than the results of the GSP study. First of all, the input conditions are available and can be parsed for actual numbers and simulation configuration settings. The same is true for the outputs: The simulations write detailed output files that can be used for recalculation of active payload in each simulation year. For instance, there is a complete launch list and a collision list available. Furthermore, the results from each individual Monte Carlo run are still existent.

The files that were used for extraction the number of active objects and estimating collision rate and explosion rate were the following:

- the general input file for overall configuration of the simulation, e.g. global parameters for mitigation success rate, active debris removal definition, number of Monte Carlos runs, simulation time frame, etc. The file was also used to to determine which modules of the simulation were activated or not (top-level switches), e.g. whether breakup events were allowed or not or whether constellations were in general considered in this scenario.
- the break-up event file to retrieve the annual number of explosions: n_{exp}
- the initial population file to get the number of active payloads at the beginning of the simulation time frame and their respective end-of-life date: $n_{act,0}$ and $n_{eol,init}$. Many scenarios share the same initial population.
- Launch event file to retrieve the number of launched objects and their end-of-life (EOL) year. This covers all launches including constellations, upper stages and rocket bodies (which typically de-orbit within the same year of simulation), CubeSats, and mission

related objects (which are assumed to be be defunct right after start).

- the collision event file to retrieve the number of collisions in each year of simulation: n_{col}
- the annual population history files by aggregating the define binning of the results to extract the total number of intact objects n_{int} and the total number of objects n_{tot}
- the constellation data file for extracting annual number of launched constellation payloads and their corresponding end-of-life year.

Regarding the post mission disposal (PMD) success rate, there was a special parameter variation present in the simulations. Some of the cases analysed the effect of different PMD rates for constellations. As the number of constellation satellites was often large compared to the background traffic, this leads to a shift in the overall with respect to the global PMD success rate value from the general input file. This would lead to an inaccurate categorisation of the simulation case. In order to compensate for this imbalance, it was decide to define a combined PMD rate which is defined as the weighted average of the PMD rates for constellations and for the background population for the number of spacecraft reaching the end-of-life.

$$PMD_{comb} = \frac{PMD_{bgrd} \cdot n_{EOL,bgrd} + PMD_{constl} \cdot n_{eol,constl}}{n_{eol,bgrd} + n_{eol,constl}} \tag{4}$$

This combined PMD rate can be evaluated for each simulation year. As constellations were only introduced for a certain time span (e.g. for 50 years) the value changes throughout the complete simulation. Please note that when no constellation is present, the combined PMD rate is equal to the globally defined value $PMD_{comb} = PMD_{bgrd}$.

2.3. Processing example of single scenarios

This subsection presents an example of the collision rate and explosion rate estimates that became possible after the re-calculation of the split of active, inactive and defunct on-orbit objects.

Fig. 1 shows the evolution of the number of objects in the simulation. The graph shows the total number of intact objects and the split into active and defunct objects. The case originates from a GSP study scenario and features the presences of a large constellation in the first half of the simulation. This can be easily identified by the step in the number of active objects n_{act}. After the build-up phase at the beginning, the number of active objects is kept constant at higher level (replenishment phase). As also the constellation satellites become inoperative there

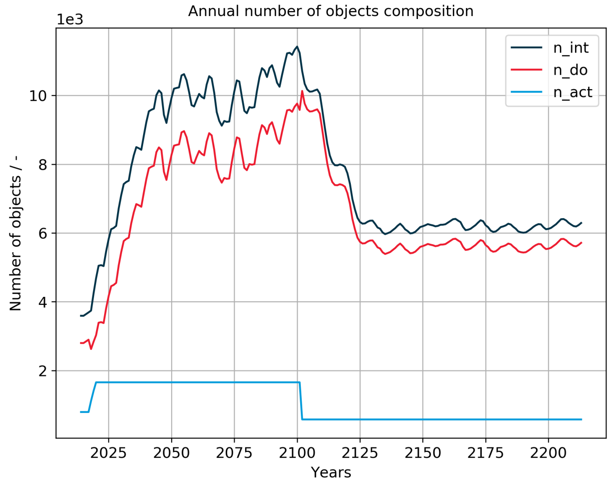


Figure 1. Evolution of the number of intact objects over the time span of 200 years of a simulation scenario with a large constellation. The number of active spacecraft was iteratively re-calculated from the scenario definition.

is a clear rise in number of defunct objects. In this particular case the, the number of objects reduces again once the constellation is no longer present. However, in terms of overall numbers, the case does not return to the levels at the beginning of the simulation.

Fig. 2 and 3 show the estimates of the collision rate and explosion rate respectively. The plots both show directly the extracted values from the simulation results and a least squares linear regression fit. The fit was introduced to have a smother function and to be able to see an overall trend, i.e. the slope of the fit can be used as a simple indicator for an improving or worsening situation of the debris environment. It was saved together with the data and can thus be used at later stages for more elaborate ways to judge on the effect on the space debris environment. Please note that it was not possible to derive the explosion rate evolution for a large number of the simulation scenarios. This is due to the fact that many scenario definitions stated that no explosions would take place at all. The reason for this is that there is the assumption that at a certain point in the future self-induced breakups are becoming more and more unlikely as design changed are introduced in future satellite bus systems. The consequence here is that the dataset for the explosion rates is simply smaller.

3. MULTI-DIMENSIONAL MAPS

With the result database at hand, it is now possible to visualise this information. The goal of this is have a comparative overview and to gain insight in the effectiveness of certain mitigation measures.

A simple metric which was used in this context is the relative growth in the space debris population in a certain

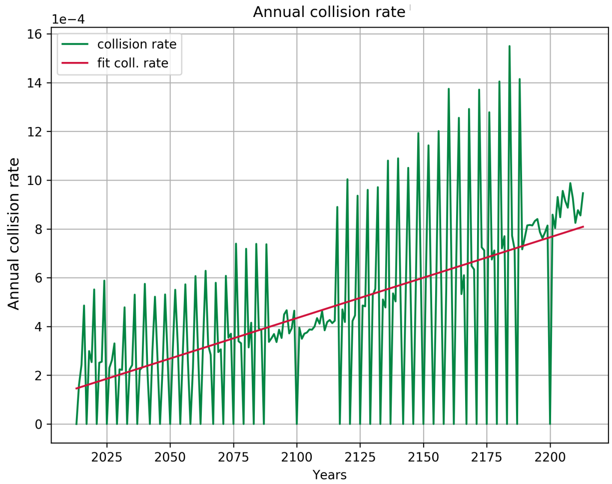


Figure 2. Annual collision rate evolution of a DELTA simulation with a high launch rate of small payload. (ISTS campaign, scenario 27).

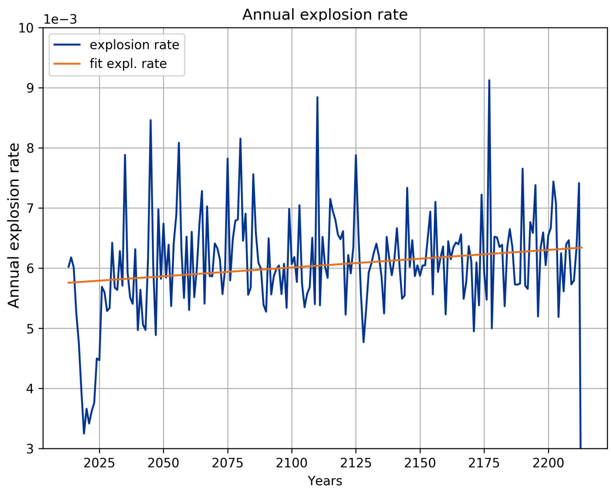


Figure 3. Annual explosion rate evolution extracted from a DELTA simulation.

period.

$$\gamma = \frac{n_{obj,end}}{n_{obj,start}} \cdot (1-\mu) \quad (5)$$

The number of objects in Eq. 5 includes all intact objects and fragments but excludes active objects. The end and start time for the comparison can be freely defined. We experimented with different durations of selecting this growth period, but decided for the last 100 years of the simulation time frame. There are basically two considerations which made us use this period. (1) Due to the nature of the space debris problem and the propagation of the effect, one cannot use a too short time period. (2) The period should see no drastic variations in the input parameters. The long-term simulations usually have such a settling phase in the second half of the simulation time frame. Almost all simulations are covering a 200 year period which means that the range is from the early years 2100s to the early years in 2200s. Additionally, a margin of $\mu = 10\,\%$ was used to be conservative in the assessment of the debris growth.

The scatter plot at the top of Fig. 4 depicts a result map of the mean explosion rate plotted over the relative growth in number of objects in the simulation. In order to allow comparison, the mean explosion rate and the relative growth were evaluated for the same period, e.g. the last 100 year of the simulation. The mean rate was calculated using the linear regression fit saved together with the simulations during the pre-processing step. As a third parameter the colour code adds the combined post mission disposal success rate of the simulation cases to the graph as defined in Eq. 4 and explained thereafter. On top of that the plot introduces four categories with different symbols which aim at adding more context on the specific settings of single simulation cases. Here the chosen categories were

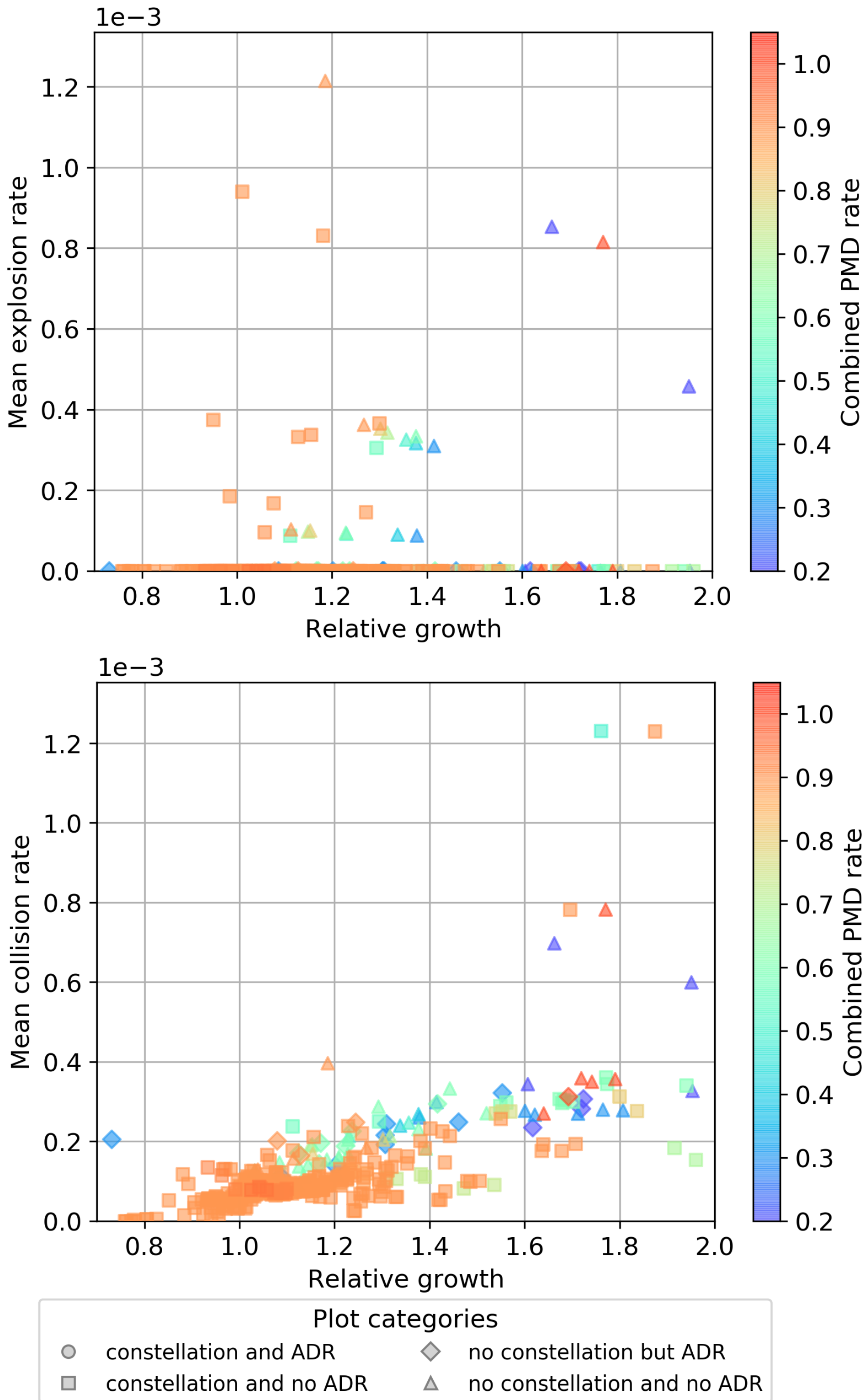
- whether or not large constellations were present and
- whether or not active debris removal (ADR) was used as mitigation measure.

The categories are just flags, they do not give any quantitative indication on how large constellations were designed or on how many debris removal missions were allowed.

As stated above, many scenarios did not simulate explosions at all. It is therefore not surprising that in Fig. 4 many data points are distributed along the x-axis with explosion rate of zero. Regarding the cases which have an explosion rate not equal to zero, three data point can be identified for which the is no growth in the population (left of relative growth equals to 1.0). They all have a high PMD rate (of about 90 %) associated to them. Many other cases show growth in the population. It is not straightforward to link mean annual explosion rates to the cumulative threshold for individual spacecraft. Yet we can state that the existing threshold of 1e−3 should remain as the minimum bar to retain when considering a nominal operational lifetime of 7-10 years for a LEO mission, with lower values considerable from the data.

The bottom graph of Fig. 4 focusses on the collision rate and uses a similar multi-dimensional scatter plot than before for the explosion rate. Again the mean rate, now the collision rate, of the last 100 year in the simulations is plotted over the relative growth of the same period. Same as in the previous plot, the PMD rate is represented through colour code and there are the same four categories for constellations and active debris removal. It was possible to calculate a collision rate for all the cases in the simulation data pool. The mean rate exploited again the linear regression fit which was generated for each case. Every data point represents the result of a long-term simulation scenario, the vast majority performing 100 Monte Carlo runs spanning 200 years.

Again linking the annual rate to the cumulative threshold value defined in the NASA Standard [4] is not easily



1e−3
Mean explosion rate
Relative growth
Combined PMD rate
1e−3
Mean collision rate
Relative growth
Combined PMD rate
Plot categories
constellation and ADR
constellation and no ADR
no constellation but ADR
no constellation and no ADR

possible. For a mission in LEO, the cumulative threshold could already easily be reached at the end of the operational lifetime or during the beginning of the disposal phase.

Keeping operational efforts as collision risk mitigation measures in mind, the graph also allows for a different interpretation. If we assume that growth is not tolerated, we can define an area in the plot, which the debris environment should not enter. Here, this covers basically the complete right hand side of the plot with relative growth ≥ 1.0. When we now regard this as a no-go area for the space debris background population, we can identify a maximum annual collision rate which is just about tolerable and does not jeopardize the stability. From the plot, the threshold for this is somewhat close to $1e{-}4$ for the collision rate, with boundary condition of achieving at least 90 % PMD success rates globally. At that level there are no more data points left of the no-growth area with a higher annual collision rate. As a consequence an additional guideline could be defined which reads: The probability of collision for a mission in LEO should be at least below $1e{-}4$ annually for its orbital lifetime in order to remain below the collision rate seen in the background population. This ensures that the newly launched mission will not fuel the collisional cascade.

4. COMBINATION WITH ENVIRONMENTAL INDEX METRICS

A consequent next step in exploiting the result database is the application of additional metric formulations which allow for deeper insight in the data. However, in many cases it is not straight forward to do so as the necessary input data for the metric is not present.

This section presents the results of applying the debris index as defined in [10] to a subset of scenarios for which the required data was available. The necessary inputs are:

- Population snapshot at the beginning and end of the simulation (or at specific intermediate timesteps) with information on the orbital location of the objects and their remaining operational lifetime in case they are still active.
- Spatial density maps of the debris discretised in altitude and declination. Considering these prerequisites, we found that for 18 simulation scenarios each with only 12 Monte Carlo runs it was possible to calculate the debris index.

Fig. 5 shows a boxplot representation of the distribution of environmental capacity index over the post mission disposal success rate. The index was calculated at the last year of the simulation time (after 200 years). Although the box plot and error bars are based only on 12 underlying Monte Carlo runs, it shows a clear separation of the cases with respect to the PMD rate of the cases. There

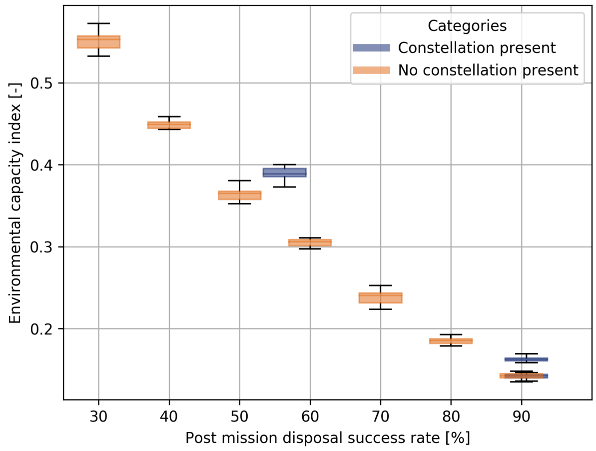


Figure 5. Box plot of the environmental capacity index calculated at the end of the simulation over post mission disposal success rate

is no overlap between the error bars which suggests that certain cases could be clearly identified. The plot also contains two categories: cases with large constellations and cases without. It is worth highlighting that the three entries with high PMD success rate at 90 % are close together. The highest capacity of those three entries is still below the value of the capacity at 80 % PMD success rate. The constellations introduced in these cases had a size of 1080 spacecraft. The PMD rate within the constellation was set at 95 %, leading to a combined rate of 91 %. In essence this would support the assumption that constellations complying to very high debris mitigation standards are indeed tolerable. It is promising to see that the index seems to reflect this and evaluates these cases with a very similar overall capacity value.

This effect is also supported by Fig. 6 and 7. These two graphs show a comparison of the index calculation to the growth in number of objects and the collision rate respectively. The graphs show relative changes which means the ratio between the start and end of the simulation time span. Please note that it was not possible to assess this only for the last 100 years of the simulation. We had to use the full 200 years because the required inputs for the index computation were only available at the very beginning and at the end.

Fig. 6 shows a steeper slope in the data points for the relative change of the index (light blue). The linear fits are are only show as visual aid. This makes the PMD cases more easily distinguishable from each other. This becomes particularly apparent when looking at the relative growth between 50 % to 60 % (purple). There is only a very small difference in the growth whereas the relative change in the index can clearly separate these cases. Furthermore, looking towards the higher values of the PMD rate, the findings described for Fig. 5 are also visible in this relative graph. The relative growth varies between 2.2 and 3.4. The top entry for the growth representing a case with a well-behaving constellation is higher than the

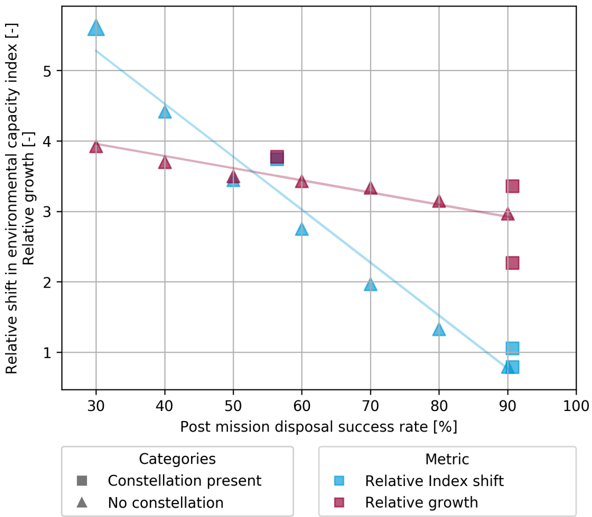


Figure 6. Comparison of relative shift of the index (light blue) and relative growth in number of objects (purple) calculated with respect to the beginning and the end of the the debris simulation. The larger separation of the data points for the index allows for a better discrimination of the different prevalent PMD rates in the simulations.

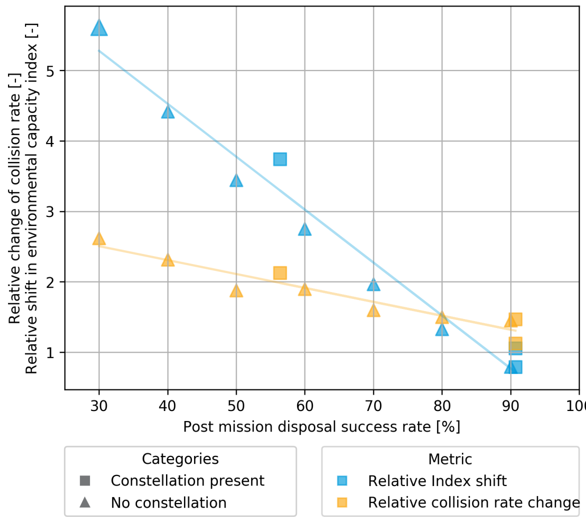


Figure 7. Comparison of relative shift of the index (light blue) and relative change in collision rate (yellow) between the the beginning and the end of the debris simulation.

80 % PMD data point without the constellation. The effect of the PMD is not well captured by looking at the growth or number of objects respectively. In contrast, the relative index data points for the high PMD rates are much closer together thus allowing for a clear distinction between the different PMD rates.

Finally, Fig. 7 comparing the collision rate to the index shows a very similar situation as for the growth. The relative change in index is again steeper which makes the PMD rate as mitigation strategy more differentiable.

5. SUMMARY AND OUTLOOK

Motivated by the lack of a broad and combined collection of long-term space debris simulation results, an effort was made to aggregate existing results of the past decade. Due to format limitations, different origin and non-saved information of the results, it became necessary to re-calculate some of the required variables such as an estimate of the active part of the space object population. With this it was possible to estimate collision rate and explosion rate for over 400 simulation scenarios. It was possible to analyse the results altogether in multi-dimensional plots linking the mitigation effort (i.e. post mission disposal success rate) to the simulated debris situation (i.e. growth and annual collision and explosion rate). The result showed that the commonly seen annual rates are still far from the cumulative threshold for individual spacecraft, but can easily be reached considering the operational (and disposal) lifetime of the missions. Additionally, from the interpretation of the maps it also seems possible to formulate guidelines directly with the annual rates. (Example: The annual collision rate for a mission in LEO should not exceed 1e−4 in order to remain below the collision rate of the background population and to ensure stability of the debris environment). In an attempt to enhance the data with more elaborate metric to judge on the status of the space debris environment, we were able to calculate the environmental capacity debris index for a small subset of the data. When comparing the informative value of the index calculation to the more simple metrics of evolution of number of objects or collisions in the population, we found that different PMD rates can be easier separated by the index formulation. This finding suggests that the effectiveness of mitigation strategies can be better captured and is in agreement with a previous assessment on the capacity index.

Aggregating long-term debris simulations and exploiting them in a larger context is a rather obvious thing to do. However, in practice this exercise proofed to be a diverse and tedious challenge. It required individual solutions for the various origins of data, profound assumptions when data was missing and numerous iterations on re-processing the data and defining (hopefully) insightful visualisations. The potential of more elaborate metrics, such as the environmental index, could clearly be shown. Yet, it must be noted than many of the advanced metrics cannot be re-computed with the information which was recorded for the many long-term simulations. In the future, it should be ensured that the necessary output files are always generated and saved. This would include i.e. for the debris index: information split in active and inactive objects, the location and orbital and remaining operational lifetime (population snapshots), and spatial debris distributions. Other metrics surely depend on different data and this cannot be anticipated beforehand. It is therefore beneficial to transition from a post-processing approach to a direct calculation approach. A consequent next step would be to extend the long-term simulation source code with the functionality to calculate advanced index metrics online, directly when all the necessary information is present.

At last it is worth highlighting that access to a large collection of simulation results is an essential step towards training a surrogate model of the debris environment. This can be used to further visualise the sensitivity of the environment to parameters such as the PMD rate and the implementation of ADR missions. Such representations could, in turn, support the development of space debris mitigation policies by simplifying the evaluation of their robustness with respect to changes in the use of space and operations.

REFERENCES

1. B. Bastida Virgili, "DELTA (Debris Environment Long Term Analysis)," in *6th International Conference on Astrodynamics Tools and Techniques*, (Darmstadt, Germany), 2016.
2. H. Lewis, J. Beck, P. Anderson, M. Oswald, J. Radtke, and A. Rossi, "Impact risk in LEO as a result of the increase of nano and micro-satellites," executive summary, ESA, 2017. Accessed on 26.03.2021.
3. ISO 24113:2019(E), "Space systems - Space debris mitigation requirements," standard, International Organization for Standardization, Geneva, 2019.
4. NASA-STD-8719.14B, "Process for limiting orbital debris," standard, Nasa, Washington, DC, 2019.
5. J. Utzmann and M. Oswald, "Ranking and Characterization of Heavy Debris for Active Removal," *63rd International Astronautical Congress 2012*, no. 2, pp. 1–2, 2012.
6. L. Anselmo and C. Pardini, "An Index for Ranking Active Debris Removal Targets in LEO," in *7th European Conference on Space Debris* (T. Flohrer and F. Schmitz, eds.), (Darmstadt, Germany), ESA Space Debris Office Publishing, 2017.
7. C. Kebschull, J. Radtke, and H. Krag, "Deriving a priority list based on the environmental criticality," *Proceedings of the 65th International Astronautical Congress*, no. September, pp. 1–9, 2014.
8. A. Rossi, G. Valsecchi, and E. Alessi, "The Criticality of Spacecraft Index," *Advances in Space Research*, vol. 56, no. 3, pp. 449–460, 2015.
9. D. J. Kessler and P. D. Anz-Meador, "Critical number of spacecraft in low Earth orbit: using satellite fragmentation data to evaluate the stability of the orbital debris environment," in *Proceedings of the Third European Conference on Space Debris* (H. Sawaya-Lacoste, ed.), (Darmstadt, Germany), pp. 265 – 272, ESA Publications, 2001.
10. F. Letizia, S. Lemmens, B. Bastida Virgili, and H. Krag, "Application of a debris index for global evaluation of mitigation strategies," *Acta Astronautica*, vol. 161, pp. 348–362, 2019.
11. F. Letizia, C. Colombo, H. G. Lewis, and H. Krag, "Assessment of breakup severity on operational satellites," *Advances in Space Research*, vol. 58, no. 7, pp. 1255–1274, 2016.