75th International Astronautical Congress (IAC), Milan, Italy, 14-18 October 2024.

IAC-24-A6IP

Optimal active debris removal sequence identification through combined debris index analysis and long-term projection of the orbital environment

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Abstract

Current projections of the in-orbit objects' population show that even an effective implementation of mitigation measures may not be sufficient to counteract the proliferation of space debris. Hence, remediation actions are also under consideration and various Active Debris Removal (ADR) techniques and mission scenarios are currently investigated. This work aims at providing scientific support in the identification of the temporal sequence of derelict objects to remove, which ensures the greatest beneficial effect for the orbital environment. The optimal ADR candidates are determined through the synergistic use of the long-term debris evolutionary model COMETA, developed by the authors, and of sustainability metrics for the evaluation of the risk posed by an orbiting object or mission. The software COMETA is employed to project the objects' population into the future, under the effect of objects' sources and sinks, and implemented control actions. Defined a static or dynamic ADR rate, the model determines the best ADR candidates at discretised time epochs, by evaluating the risk posed by each in-orbit object to the whole spacecraft's population. The classical formulation of risk as probability×severity is employed, i.e., as the product between the probability of the object's breakup and the impact such fragmentation would have onto the space environment. The developed methodology is applied to the analysis of the long-term impact of different ADR rate profiles on the orbital environment.

Keywords: Space debris evolutionary model, Space debris index, Active debris removal

Nomenclature

a	=	Semi-major axis, km
A_c	=	Cross-sectional area, m^2
A/M	=	Area-to-mass ratio, m^2/kg
c_D	=	Drag coefficient, -
e	=	Eccentricity, -
F	=	Flux, 1/m^{2}s
H	=	Scale height, m
M	=	Mass, kg
N	=	Number of fragments, -
P_c	=	Collision probability, -
t_L	=	Lifetime, s
T	=	Orbital period, s
v_{rel}	=	Impact velocity, m/s
η	=	Number of impacts, -
$\dot{\eta}$	=	Impact rate, 1/s
ρ	=	Atmospheric density, kg/m^3

Acronyms/Abbreviations

COMETA	=	Continuum Mechanics for space debris EnvironmenT Analysis
DISCOS	=	Database and Information System Characterising Objects in Space
ESA	=	European Space Agency
EMR	=	Energy-to-Mass Ratio
MRO	=	Mission Related Object
SBM	=	Standard Breakup Model

1. Introduction

Large derelict objects pose a constant threat for safe in-orbit operations. Several studies have highlighted how such abandoned spacecraft will shape the future evolution of the orbital environment, if no action is taken. Their permanence in orbit is so detrimental that even under the most optimistic mitigation scenario, with all future missions causing zero net debris release, the growth of orbiting fragments may not stop [1]. For this reason, the space community has started investigating the feasibility of performing missions to remove these hazardous objects from space [2][3][4]. An ADR mission represents a challenge for multiple reasons [5]: the development of the needed hardware for the removal; the design of the guidance, navigation and control system of the chaser satellite, which has to grab an uncooperative target object, whose attitude dynamics may be uncertain; the complex de-orbiting of the chaser-target couple; the implementation of a mission with no direct revenue; etc. Because of the high cost and the intrinsic risk associated with such missions, it is also of crucial importance the identification of the derelict objects, whose removal ensures the maximum long-term beneficial effect. Furthermore, the quantification of this positive impact, in terms of decrease in the expected number of objects in the future orbital environment, as well as of risk reduction for operational satellites, is required to define an optimal remediation plan, and to acquire consensus on the need of its implementation. Similarly to other works in the literature [6][7][8], the present paper aims at providing scientific support on this delicate task. It is worth commenting that this study only looks at the problem from the perspective of effectiveness of the considered remediation plan on the space environment and does not discuss the feasibility of its actuation from an economic point of view.

Several studies have been carried out with objective of ranking derelict objects based on their likelihood to contribute to Kessler's syndrome. In particular, different formulations of a so-called space debris index have been pursued to quantify the current risk posed by an orbiting object on the whole satellites' population [9][10][11]. Such metrics define the risk as the probability that the analysed object fragments multiplied by the consequences such breakup would have in terms of orbital pollution. With the objective of determining the optimal sequence of derelict objects to remove, so that to quantify the potential long-term impact of ADR missions, a space debris index formulation is here used within the debris evolutionary model COMETA [12], developed in previous works by the authors. Defined a static or dynamic ADR rate, the model determines the best ADR candidates at discretised time epochs, by evaluating the risk posed by each in-orbit object to the whole satellites' population. The decrease in number of debris and collision rate caused by their removal is monitored and discussed.

The paper is, next to the introduction, organised in three sections. Section 2 first gives a brief description of the COMETA model and then explains the latest extension implemented for the modelling of ADR. Section 3 presents the results of some performed simulations, comparing the effects of different removal profiles against the reference scenario without ADR. Finally, Section 4 draws the conclusions of the work and discusses future developments.

2. Method

2.1 COMETA Software overview

The software COMETA has been developed at Politecnico di Milano in collaboration with ESA's Space Debris Office, with the objective of leveraging on the efficiency of density-based debris models, developed by the authors [12], to reduce the computational burden associated to long-term simulations of the space debris environment. A brief technical overview of the model is provided in this section.

COMETA retrieves the information on the initial objects' population from the Database and Information System Characterising Objects in Space (DISCOS) [13], maintained by ESA. In particular, orbital data, launch epoch and physical properties are queried for all catalogued objects. The whole population is processed by the model and divided into two categories: fragments and intact objects. This latter category is further classified into multiple species, i.e., payloads, rocket bodies, Mission Related Objects (MROs), and constellations, with each constellation considered as a separate species.

The fragments' population, which includes both the background distribution (i.e., fragments already in-orbit at the reference epoch) and simulated fragmentation clouds, is modelled through a density-based approach. The particles are not treated as single pieces but as a continuum, whose density is varied by the effect of orbital perturbations. This makes the simulation time independent of the number of modelled objects, allowing the extension of long-term analyses of the debris environment to any objects' size. On the contrary, an individual characterisation of the orbital evolution of the intact objects is performed. For each of them, a simplified mission profile is assumed, possibly accounting for operational and Post-Mission Disposal (PMD) phases, whose duration is specified independently for each considered species.

The method accounts for three sources of objects:

1. Spacecraft's launches: current implementation considers the repetition of the launch traffic pattern of the five years prior the reference epoch for spacecraft not belonging to a constellation. A continuous replenishment of the constellation satellites is instead foreseen.
2. Fragment-intact object collisions: the collision probability for each intact object is evaluated at discretised time epochs from the evolving debris' flux. In case of a collision event, the model discerns between catastrophic/non-catastrophic event through the evaluation of the Energy-to-Mass Ratio (EMR). Following the approach of the NASA Standard Breakup Model (SBM), if

EMR > 40 J/g a complete destruction of the object is assumed.

3. Intact object explosions: survival functions for each objects' species are computed from the history of explosion events (retrieved from DISCOS). Such curves allows estimating the explosion probability given the time spent in orbit by a payload/rocket body.

Within this work, three sinks of objects are considered:

1. Natural decay: atmospheric drag is modelled through the superimposed King-Hele formulation developed by Frey et al. [14]. Atmospheric density varies over time under the effect of a time-varying sinusoidal solar flux profile.
2. Post-mission disposal: the tool allows specifying a PMD duration and strategy (i.e., circular or eccentric disposal orbit) independently for each considered species. Under the assumptions of the King-Hele's drag theory, the method computes the disposal orbit that guarantees re-entry in the given PMD duration.
3. Active debris removal: details on the adopted approach for ADR are provided in Section 2.2.

2.2 Extension for ADR

To ensure the capability of studying any ADR profile, the number of objects to remove is specified for each simulated year within an input file passed to the software COMETA. The ADR candidates are selected based on the risk they pose to safe in-orbit operations and to the long-term sustainability of the space environment. The in-orbit risk has been historically assessed as probability×severity [9][10][11][12], i.e., as the product between the probability of the object's breakup and the impact such fragmentation would have onto the space environment. The same approach is adopted within this work.

The probability term P_c is computed from the number of impacts η over a time range through a Poisson distribution. The number of impacts is the result of the time integral of the impact rate $\dot{\eta}$, which linearly depends on the time-varying fragments' flux $F(t)$, as follows:

$$\dot{\eta} = A_c \times F(t) \tag{1}$$

with A_c spacecraft's cross-sectional area.

Two main approaches can be found in the literature for the evaluation of the severity component. The first approach does not involve any simulation and aims to obtain an immediate assessment of the consequences of the potential breakup based on relevant factors, such as the properties and location of the fragmentation, or derivatives of these. Examples of this methodology are the Criticality of Spacecraft Index (CSI) proposed by Rossi et al. [9] and the Collisional Debris Cloud Decay of 50% (CDCD50) developed by Anselmo and Pardini [10]. A second approach involves the characterisation and propagation of the potential breakup. The effect of the fragmentation is formulated as the impact it would cause on the spacecraft operations in the same region, monitoring the cumulative collision probability. Example of this second approach is the Environmental Consequences of Orbital Breakups (ECOB) index formulated by Letizia et al. [11], which has been later extended within the THEMIS software [12], currently in use at ESA.

For this first implementation of ADR in the software COMETA, the first option has been preferred. The main reason for this choice has been the computational efficiency that these methods guarantee compared to the ones involving the modelling of the fragmentation event, to the detriment of a less accurate assessment. Future developments will investigate the feasibility of performing a two-step selection process, which firstly identifies a subset of optimal candidates and subsequently refines the selection according to the more accurate metric.

Following other works in the literature [9], the severity is conceptually defined as:

$$\text{severity} \propto \text{lifetime} \times \text{N° of fragments} \tag{2}$$

i.e., as the product between the estimated decay time of the ranked object and the number of fragments ejected by its potential breakup. The dependence on the lifetime is included because the longer is the permanence of an inactive object in orbit, the higher is the chance it will be impacted by a fragment. The decay time is approximated through the analytical expressions derived by King-Hele [15]. Given the object's semi-major axis a, eccentricity e, and area-to-mass ratio A/M, the lifetime t_L reads as:

$$t_L = \begin{cases} \dfrac{H\,T(a)\beta(a)}{2\pi\delta\rho_p a^2} & \text{if } z = 0 \\ \dfrac{e^2\left(1 - \frac{11}{6}e + \frac{29}{16}e^2 + \frac{7H}{8a}\right)}{2B(a,e,\delta,\rho_p)} & \text{if } 0 < z \le 3 \\ \dfrac{e^2\left[1 + \frac{H}{2a}\left(1 - \frac{9}{20}z^2\right)\right]}{2B'(a,e,\delta,\rho_p)} & \text{if } 3 < z \le 30 \end{cases}$$

where H is the scale height of the atmospheric density model, $\delta = c_D A/M$ the inverse of the ballistic coefficient, c_D the drag coefficient, T the orbital period, ρ_p the atmospheric density at the orbit perigee, and $z \coloneqq ae/H$.

According to the NASA SBM [17], the number of fragments N ejected by a collision is related to the reference mass M_e as:

$$N \propto {M_e}^{0.75} \tag{3}$$

Within the software COMETA, the reference mass M_e of the collision is evaluated according to the following equation:

$$\begin{cases} M_t + M_f & \text{if EMR} \geq \text{EMR}_{\text{lim}} \\ \left(M_t + M_f\right)\dfrac{\text{EMR}}{\text{EMR}_{\text{lim}}} & \text{if EMR} < \text{EMR}_{\text{lim}} \end{cases} \tag{4}$$

where M_t is the mass of the target object, M_f is the mass of the impinging fragments, EMR is the energy-to-mass ratio, and $\text{EMR}_{\text{lim}} = 40\ \text{J/g}$ is the EMR above which the target object is assumed to be completely destroyed by the collision. EMR is defined as [17]:

$$\text{EMR} = \frac{1}{2}\frac{M_f}{M_t}v_{\text{rel}}^2 \tag{5}$$

with v_{rel} impact velocity. Combining Eq. (3) and Eq. (4), under the reasonable assumption that the fragment's mass is much smaller than the intact object one, it follows that:

$$N \propto \begin{cases} M_t^{0.75} & \text{if EMR} \geq \text{EMR}_{\text{lim}} \\ \left(\dfrac{1}{2}\dfrac{M_f v_{\text{rel}}^2}{\text{EMR}_{\text{lim}}}\right)^{0.75} & \text{if EMR} < \text{EMR}_{\text{lim}} \end{cases} \tag{6}$$

Sensitivity analyses proved that setting the severity term adopting the relation number of ejected fragments-mass of non-catastrophic collisions (i.e., second expression in Eq. (6)) results into a higher beneficial effect. Indeed, if the first expression in Eq. (6) were used, the algorithm would point towards the removal of heavy objects which, however, are unlikely to fall apart, due to a small average EMR. Note that removing the objects with the highest velocity relative to the fragments population not only is expected to reduce the fragments ejected by non-catastrophic collisions, but also those generated by catastrophic events, as it implies taking out spacecraft which are more likely to overcome the energy limit EMR_{lim}, despite being very massive. Lastly, even though a non-catastrophic collision pollutes the orbital environment less, given the same fragmented mass, its occurrence is significantly more probable than that of a catastrophic collision and, moreover, the latter generally involves smaller objects.

For the above considerations, the severity of an object breakup is evaluated as follows:

$$\text{severity} = \frac{\min(t_L, \bar{t}_L)}{\bar{t}_L}\left(\frac{v_{\text{rel}}}{\bar{v}_{\text{rel}}}\right)^{1.5} \tag{7}$$

where the $\bar{t}_L = 10\ \text{years}$ and $\bar{v}_{\text{rel}} = 10\ \text{km/s}$ are the scaling lifetime and impact velocity, respectively, to pursue an adimensional formulation. Note that the lifetime is bounded at $\bar{t}_L$ to avoid over-weighting objects orbiting at very high altitude.

3. Results

This section presents the results of three different analysed scenarios. The first, referred to as baseline, does not account for ADR; the second and third both include ADR but with different rates, i.e., a linear increase from 1 to 10 removed object per year over the 200 years propagation time and a constant rate of 10 removals/year, respectively. The three analyses only differ for the ADR rate, while they share the same properties in terms of background population (2022 objects population) and objects' species properties, as summarised in Table 1. For the three scenarios, 20 simulations were performed. It is worth highlighting that this number of simulations is most probably not sufficient to guarantee full statistical validity of the results. However, a higher number of runs could not be performed due to time constraints. In the following, the average simulation results are shown.

Table 1. Intact objects number and properties (lifetime, Collision Avoidance (COLA) availability, susceptibility to explosion, Post Mission Disposal (PMD) rate). PMD rates for individual payloads and rocket bodies are set according to historical values retrieved from the analysis in ESA's Space Environment Report [1].

	Objects number	**Lifetime [ys]**	**COLA**	**Explosion**	**PMD rate**
Individual payload	3088	8	yes	yes	40%
Rocket body	951	0	no	yes	55%
MROs	230	0	no	no	/
Large debris	1519	0	no	no	/
Flock	312	3	no	no	90%
Globalstar	72	15	yes	no	90%
Gonets	33	5	no	no	90%
Iridium	106	15	yes	no	90%
OneWeb	634	10	yes	no	90%
Orbcomm	60	5	no	no	90%
SpaceBee	119	2	no	no	90%
Starlink	4263	5	yes	no	90%
Astrocast	16	5	yes	no	90%
Capella	10	3	no	no	90%
Kepler	20	7	no	no	90%

Figure 1 shows the estimated number of fragments over time, both in absolute values and in relative behaviour compared to the baseline scenario, to better understand the difference in magnitude.

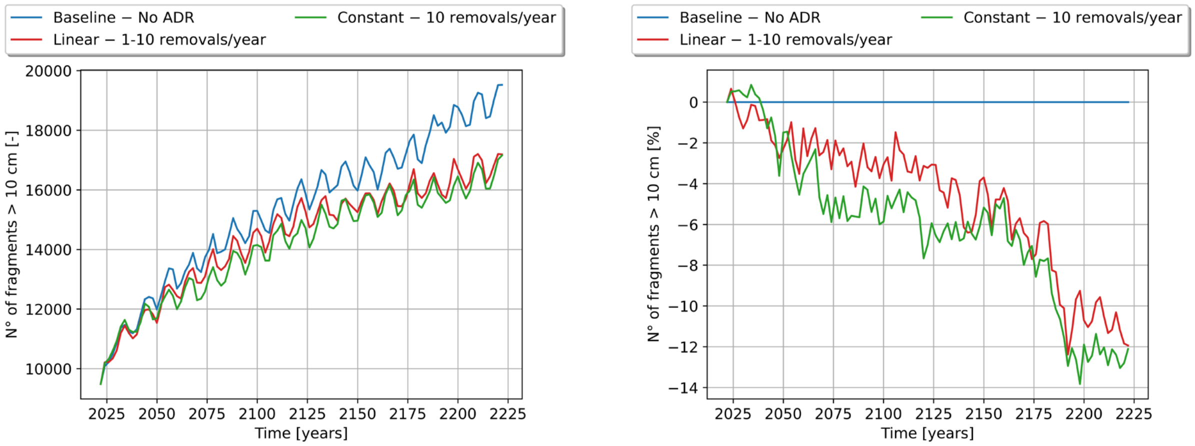

Figure 1. Number of fragments > 10 cm over time for the three analysed scenarios - Absolute value (left) and relative behaviour (right) compared to the baseline case.

Both the ADR rates ensure a reduction of approximately 12% in fragments' number at the end of the 200 years propagation. This result testifies that the removal of objects has a relatively short-term effect. Indeed, when the linearly increasing ADR rate approaches the maximum value of 10 removals/year, the distance between the red and green curves nullifies. In other words, the more congested orbital environment associated to the period with low ADR rate of the linear case does not perpetrate in time. Note that the effect of the objects removal is not so marked due to its almost negligible effect on explosion events, which significantly outnumber collisional ones.

Figure 2 and Figure 3 display the estimated number of catastrophic and non-catastrophic collisions, respectively.

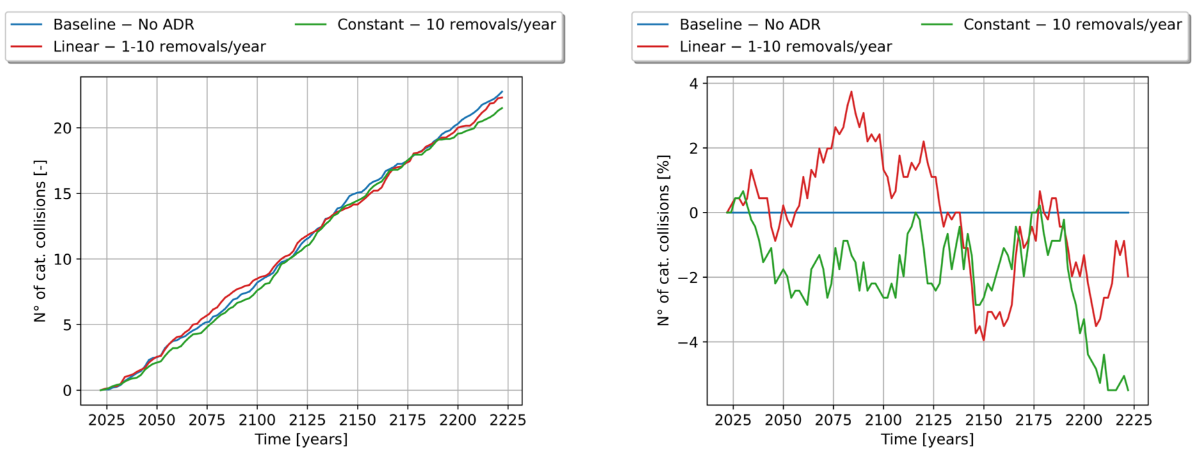

Figure 2. Number of catastrophic collisions over time for the three analysed scenarios - Absolute value (left) and relative behaviour (right) compared to the baseline case.

As it can be observed, the removal of objects considerably reduces the number of non-catastrophic events, while it has no notable effect on catastrophic ones. This result is justifiable by the formulation used for the selection of the derelict objects to remove: the severity component of the index linearly depends on the lifetime, meaning that the algorithm points towards candidates whose residence time in-orbit is longer (i.e., at higher altitudes). Catastrophic collisions, however, requires a greater impact velocity, which implies that their occurrence is more likely at low altitudes. To better understand this point, let us compare the distribution of catastrophic and non-catastrophic collisions as function of altitude for the three analysed scenarios, which are reported in Figure 4 and Figure 5. Note that the figures display the mean results of the 20 simulations performed for each of the studied cases. As it can be noted, the proposed formulation is effective in reducing the number of collisional events in the altitude range 600-1000 km. Only few catastrophic collisions take place on average in this altitude range, which causes their occurrence to be almost unaffected by the proposed ADR formulation. For non-catastrophic collisions, even though the majority of them still occur at 500-600 km, the number of events at 600-1000 km outnumber those at lower altitudes.

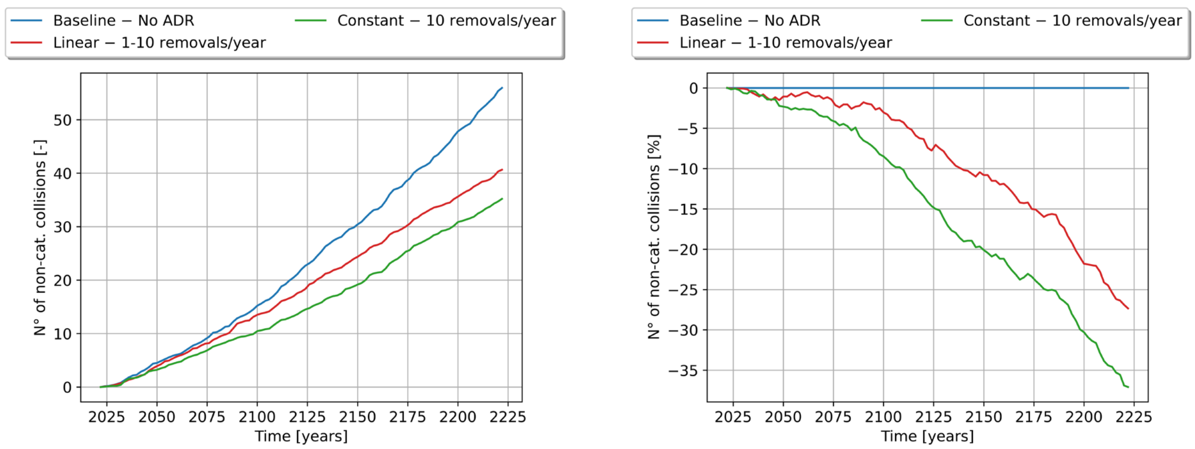

Figure 3. Number of non-catastrophic collisions over time for the three analysed scenarios - Absolute value (left) and relative behaviour (right) compared to the baseline case.

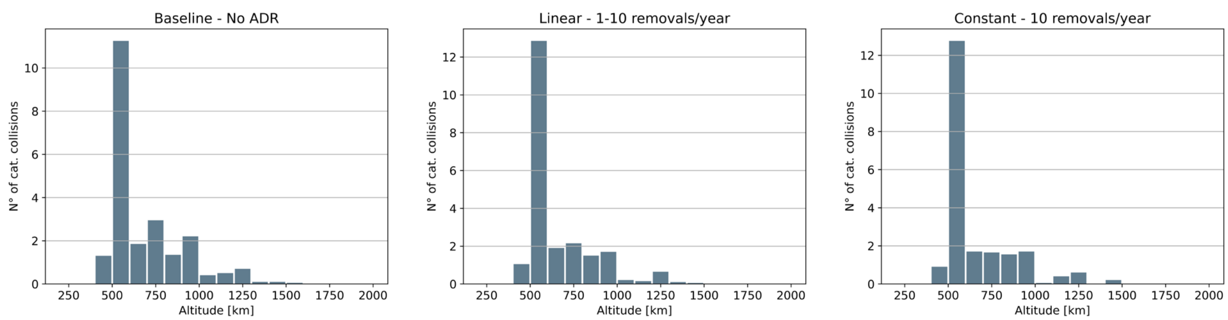

Figure 4. Distribution of catastrophic collisions as function of altitude for the three analysed scenarios.

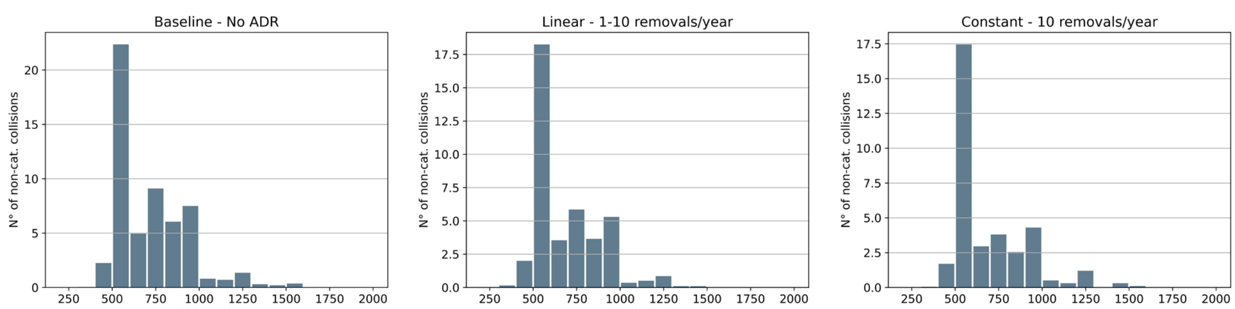

Figure 5. Distribution of non-catastrophic collisions as function of altitude for the three analysed scenarios.

As commented at the end of Section 2.2, even though the adopted ADR strategy does not act on the reduction of the number of catastrophic collisions, it does have an effect on the number of ejected fragments from these events, because of the removal of objects with the highest velocity relative to the background debris population. As a result, less massive objects have on average, sufficient EMR to get completely fragmented by the collision with an orbiting fragment. Figure 6 shows the cumulative number of fragments ejected by catastrophic and non-catastrophic collisions as function of time, in relative behaviour compared to the baseline (no ADR) case. Despite the effect on non-catastrophic events is approximately three times greater, a notable reduction is observable also for catastrophic ones (15% and 22% for the linear and constant ADR rate profiles, respectively).

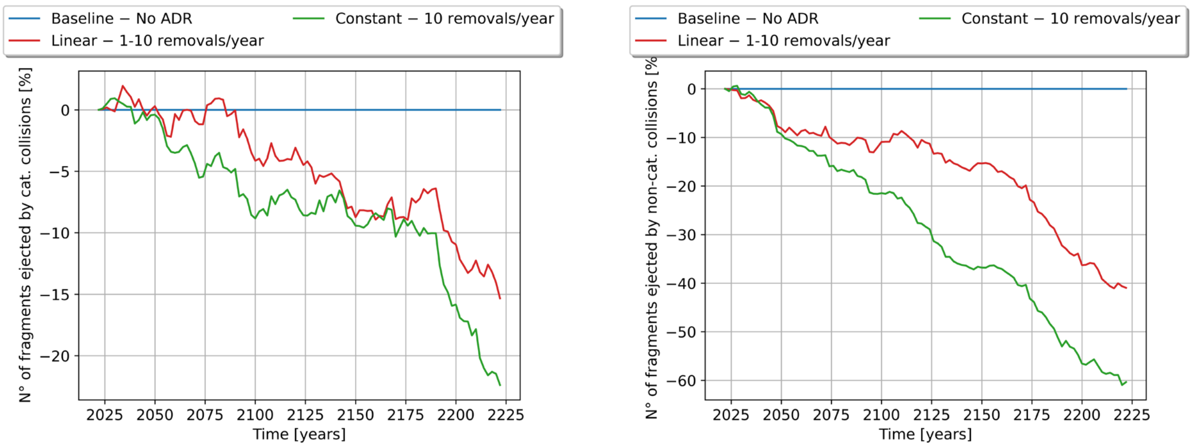

Figure 6. Number of fragments ejected by catastrophic (left) and non-catastrophic collisions (right) over time for the three analysed scenarios. Relative behaviour compared to the baseline case.

Finally, it is of interest to understand where the removals selected by the algorithm are located. Figure 7 and Figure 8 show the cumulative number of de-orbited ADR candidates as function of semi-major axis and inclination through a scatter plot for the two studied ADR rate profiles, after 100 years and 200 years simulation time. The size of each point is scaled based on the number of removed derelict spacecraft in a shell of 50 km in semi-major axis and 5 deg in inclination.

As it can be observed, the vast majority of the objects are removed in the altitude range [500, 800] km. In particular, derelict spacecraft in Sun-synchronous orbits at 98 deg are those that the algorithm found the riskiest for the orbital environment. It is interesting to note that for the constant 10 removals/year case, all orbital slots interested by ADR identified at the end of the simulation were already present after 100 years. This not the case of the other studied scenario with linearly increasing ADR rate, e.g., no removals at 85 deg are monitored within the first 100 years of simulation. For both the analyses, ADR involves only 4 species of objects, with percentage of removals per species with respect to the total as reported in Table 2. As expected, abandon rocket bodies, because of their average larger mass and cross-sectional area compared to payloads, represent the most dangerous species for the long-term sustainability of space activity.

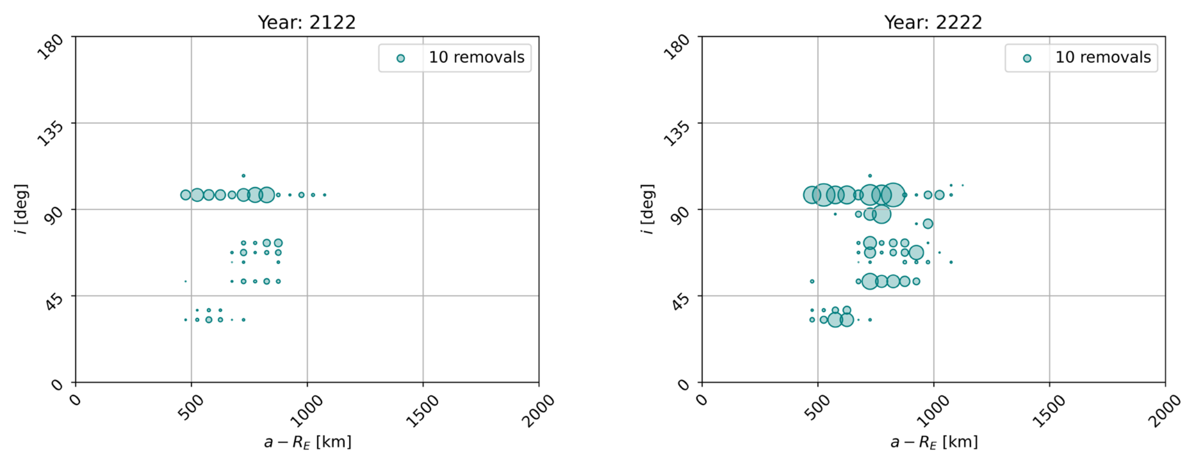

Figure 7. Cumulative number of removed derelict objects as function of semi-major axis and inclination, after 100 and 200 years simulation time – Linear ADR rate profile, 1-10 removals/year.

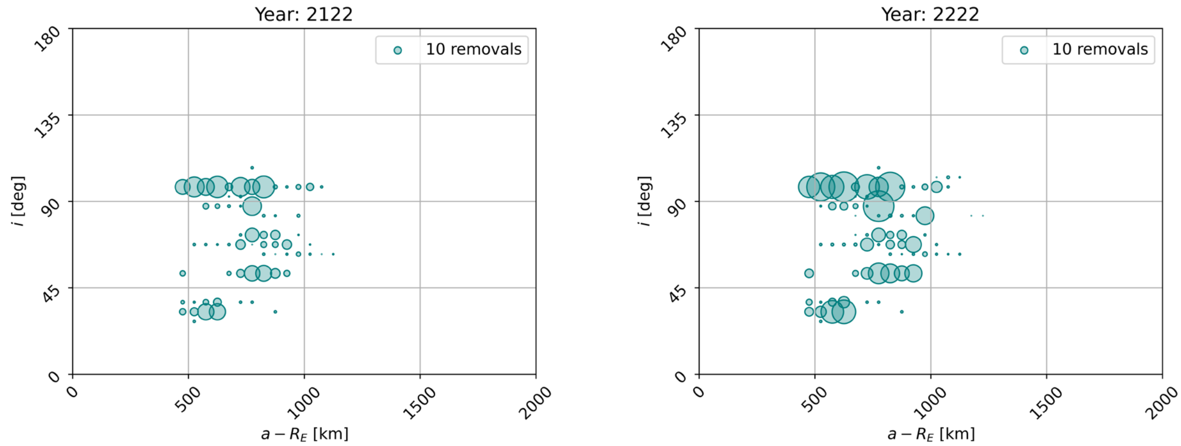

Figure 8. Cumulative number of removed derelict objects as function of semi-major axis and inclination, after 100 and 200 years simulation time – Constant ADR rate profile, 10 removals/year.

Table 2. Percentage of objects removals per species.

Species	Percentage of removals [%]	
	Linear ADR	Constant ADR
Individual payloads	20.9	22.3
Globalstar satellites	12.6	14.3
Iridium satellites	9.2	10.6
Rocket bodies	57.3	52.8

4. Conclusions

This paper presented the extension of the software COMETA to the evaluation of the long-term effect of active debris removal. In particular, the study focused on the selection of the optimal ADR candidates to remove to ensure the greatest beneficial effect for the orbital environment. To achieve this objective, a space debris index formulation is embedded in the debris evolutionary model COMETA to identify the most dangerous objects in the evolving space debris environment. Historically, two different philosophies have been pursued for the formulation of space debris indices: the first approach does not involve any simulations and provides an immediate estimate of the risk posed by an orbiting object, based on its properties and location. The second considers the modelling of its potential breakup and the evaluation of the consequent incremental collision risk for the satellites population. For this first implementation of ADR in COMETA, the first approach was chosen to limit the computational burden. The risk caused by a derelict object is assessed as the product of its probability of collision with orbital debris and the severity of its potential breakup. The severity component accounts for the lifetime of the abandoned spacecraft, to give greater weight to objects whose related fragments would persist longer in orbit, and the average velocity relative to the background debris population, which is a measure of the number of potentially ejected fragments.

Three study cases were analysed: the baseline scenario with no ADR, a linear ADR rate profile from 1 to 10 objects removals per year, and a constant ADR rate of 10 removals/year. The proposed formulation demonstrated to be effective in reducing the average number of fragments ejected by both catastrophic and non-catastrophic events. The results also provided many insights on the effect of ADR. Firstly, from the estimated evolution of the number of fragments over time it can be inferred that remediation actions would not be the solution to the space debris problem, if they are not combined with more stringent mitigation measures, which in first place should point to the reduction of the explosion probability. Second, ADR has a relatively short-term effect, meaning that, considering the high launch rate of recent years, a plan of removals should be put into place to obtain long-term benefits for the orbital environment.

It is worth noticing that the proposed formulation did not include any cost and feasibility analyses on the realisation of the removal of the identified sequence of ADR candidates. Therefore, the results obtained would most probably represent a rather optimistic scenario. Future studies will deal with this additional complexity, as well as with the refinement of the objects selection based on a more accurate space debris index, which evaluates the severity component of the risk as the impact of the object breakup on the in-orbit satellites population.

Acknowledgements

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 101089265 - GREENSPECIES).

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