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Mission-based and environment-based approaches for assessing the severity of a space debris evolution scenario from a sustainability perspective

Francesca Letizia[a]*, Camilla Colombo[b], Alessandro Rossi[c], Andrea Muciaccia[b], Lorenzo Giudici[b], Ryusuke Harada[d], Satomi Kawamoto [d], Lorenz Böttcher [e] , Vincent Ruch[f], Christophe Taillan[f]

[a] *European Space Agency (ESA), Keplerlaan 1, 2201 AZ, Noordwijk, The Netherlands,* francesca.letizia@esa.int
[b] *Politecnico di Milano, Via Giuseppe La Masa 34, 20156, Milan, Italy*, camilla.colombo@polimi.it, andrea.muciaccia@polimi.it, lorenzo1.giudci@polimi.it
[c] *IFAC-CNR, Via Madonna del Piano 10, 50019, Sesto Fiorentino, Italy*, a.rossi@ifac.cnr.it
[d] *Japan Aerospace Exploration Agency (JAXA), 7-44-1 Jindaiji-Higashi-Machi, Chofu, Tokyo, 182-8522, Japan*, {harada.ryuusuke, kawamoto.satomi}@jaxa.jp
[e] *TU Braunschweig, Institute of Space Systems, Hermann-Blenk Str. 23, 38108 Braunschweig, Germany*, l.boettcher@tu-braunschweig.de
[f] *Centre National d'Études Spatiales (CNES), 18 Avenue Edouard Belin 31400 Toulouse, France*, {Vincent.Ruch,Christophe.Taillan}@cnes.fr
* Corresponding Author

Abstract

As the number of space missions in orbit is increasing, the amount of space debris in orbit is set to rise, even if with a stricter adherence to space debris mitigation rules are advocated for. The dynamic change in the space object environment is calling an international effort in defining indicators that can be used to assess the severity of the current space debris environment and to characterise its future possible evolutions. It is important to define what those indicators should measure, what their input are and how a shared methodology can be achieved to push for an international consensus around the concept of the space carrying capacity. In this paper, two approaches are followed, a mission-based approach and environmental-based approach. For the mission-based approach, a comparative analysis of the different formulations of a space debris index present in literature is performed, with the aim of identifying common underlying input parameters, dependencies from space debris populations characteristics, and assumptions among the different proposed formulations. Then, some of these formulations are selected to compute the space debris index on all the objects present in a long-term simulation of the space debris environment, under different future traffic and mitigation scenarios to understand whether, by properly normalising the indicators, different space debris formulations can give a consistent picture of how the global space debris environment is evolving. On the other side, an environment-based approach is also followed where a single parameter summarises the overall status of the debris environment. Using the same long-term simulation, different proxies that can be used to indicate the severity of the space environment in terms of orbital carrying capacity are investigated. We target at linking an environment-based metric to a mission-based space debris metric, aggregated on all the space missions to have a unique evaluation on how a given evolution scenario is performing.

Keywords: space debris index, orbital capacity, space sustainability

Acronyms/Abbreviations

ADR	Active Debris Removal
AOP	Argument Of Perigee
CCM	Collision Criticality Metric
CSI	Criticality of Spacecraft Index
DISCOS	Database and Information System Characterising Objects in Space
ECOB	Environment Consequences of On-orbit Break-ups
GEO	Geostationary Earth Orbit
GTO	GEO Transfer Orbit
LEED	Leadership in Energy and Environmental Design
LEO	Low Earth Orbit
LCA	Life-Cycle Assessment
MASTER	Meteoroid And Space Debris Terrestrial Environment Reference
MEO	Medium Earth Orbit
PMD	Post-Mission Disposal
RAAN	Right Ascension of the Ascending Node
SDM	Space Debris Mitigation
SSO	Sun-Synchronous Orbits
STELA	Semi-analytic Tool for End-of-Life Analysis
THEMIS	Tracking the Health of the Environment and Missions In Space
TLE	Two Line Elements

1. Introduction

Since more than 20 years different metrics have been proposed to characterise the status of the debris environment or the criticality of a mission based on its main characteristics.

Kessler and Anz-Meador [1] were probably the first to propose a simple indicator (i.e. the number of intact objects) to define whether the space debris environment can be considered stable or not, using an analytical approach that combined the effect of atmospheric drag and the production of fragments able to trigger catastrophic collisions, also based on empirical observations of break-ups. This type of approach is what we define an *environmental-based* approach i.e. a single parameter summarises the overall status of the debris environment.

An alternative approach is to look at how single missions contribute to the space debris issue, and this is what we classify as *mission-based* approaches. One of the first formulations in this category is the one by Yasaka [2] in 2011, where a so-called *debris index* is computed considering parameters such as the mass of the object, its cross-sectional area, the flux of debris at the altitude of operations. Already in this initial paper, it suggested that such an index could be used as a licensing tool for spacecraft and upper stages to limit the creation of new debris, comparing the index with a threshold value.

Over the years, several other formulations were proposed, initially with main purpose of selecting suitable candidates for Active Debris Removal (ADR) missions [3]-[8], and later on with a wider possible scope of applications e.g. in terms of assessing the compliance with space debris mitigation measures [9]-[12].

Such proliferation of metrics should not be surprising: in several sectors, especially related to the broad concept of sustainability, one can observe different attempts of trying to summarise complex models into actionable information (e.g. EU's Energy Label [*], Nutriscore, LEED certification[†], etc). Moreover, also in other filed of space mission domain risks metrics have been indicated such as the Palermo scale and the Torino scale for asteroid impact threat on the Earth. This is particularly relevant in the assessment of space debris mitigation and remediation measures where the use of single parameter approaches (e.g. mass of the object) may hide relevant information (i.e. altitude of operation, operational status, etc), whereas space debris indices can offer the advantage of modelling several aspects of interest while keeping the ability of comparing objects/scenarios to each other.

Still, the emergence of different metrics is an indication that full maturity on the topic has not been reached. Past works [13][14] have looked at how multiple indices can already be applied to identify the most concerning objects in the space debris population and the present paper, in Section 3, will continue on that path, also providing additional insight on the comparison between the different metrics, having in mind not only the selection of the ADR targets but debris mitigation strategies more in general.

In parallel, and sometimes in symbiosis, to the development of space debris metrics devoted to the assessment of single missions, in the recent years also the topic of space (carrying) capacity has gained momentum. The concept of space (carrying) capacity aims at quantifying the state of the space environment globally, so following more the spirit of approaches such as the abovementioned one by Kessler and Anz-Meador [1]. The concept of space capacity is even in a more infancy phase than space debris indices and different approaches have been put on the table ranging from risk-based formulations [14] to considerations on the maximum number of active satellites that can be safely operated [16]. In the present paper, we do not explicitly address the point of the definition of space capacity, but rather investigate, in Section 4, the potential link between mission-based metrics and environmental-based ones through the use of long-term simulations. We see this as a necessary preliminary step to investigate the feasibility of threshold-based systems where a given health target for the overall environment (e.g. the 1.5-degree in the climate change world) can be translated into actionable limits for single objects/entities/etc. (e.g. carbon/greenhouse gases emissions, if we keep the parallel with climate change).

In the current paper the scope of the investigated indices and formulation is limited to the topic of space debris mitigation and not on sustainability in general as additional elements such as LCA and socio-economic considerations are not modelled by the considered approaches, even if literature on these topics is already available [17]-[19]. However, we think that the issue of the maturation of the space debris indices and space debris capacity approaches (i.e. clarification on assumptions, level of modelling detail, availability of tools) needs to be addressed as a first step to go from theoretical developments to practical tools to support space debris mitigation efforts.

2. Debris index formulations

This section provides a brief overview of the formulations used for the computation in the rest of the paper, highlighting the requested inputs and dependencies from models and assumptions.

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[*] EU Energy Label: https://energy-efficient-products.ec.europa.eu/ecodesign-and-energy-label_en

[†] LEED Certification https://www.usgbc.org/leed

2.1 ECOB

ECOB is a space debris index based on the quantification of the fragmentation risk associated with a space object and for the results in the current paper, only the contribution coming from collisions is considered. The risk value at a given time is obtained as the product between the probability of collision with debris objects able to trigger a catastrophic collision and the severity of the potential collision. The severity is measured by simulating the resulting debris cloud and computing the collision probability induced by the cloud on active spacecraft [10]. The set of active spacecrafts used for the analysis is representative of missions in Sun-Synchronous Orbits (SSO). The so-defined instantaneous risk is integrated over time considering the mission profile (e.g. variation of altitude) to consider the implementation of debris mitigation measures, such as disposal manoeuvres. For this, the expected success rate of the post-mission disposal is factored in the computation, and it is an explicit input to be provided [20]. Other inputs include high-level mission's parameter such as mass, cross-sectional area, operational orbit, and availability of collision avoidance capability. ECOB relies on a model of the space debris environment (e.g. the publicly available ESA's MASTER) and on model of debris clouds propagation [21] (not publicly available). The limitation of the debris cloud propagation model makes ECOB applicable only in LEO.

2.2 The Criticality of Spacecraft Index (CSI)

The Criticality of Spacecraft Index (CSI), Ξ, is a dimensionless quantity originally devised to quantify the risk posed by an abandoned object in LEO. Its formulation is fully described in [7], hence only the main features are recalled here. Given an object with mass M abandoned in space, the index is defined as:

$$\Xi = M/M_0 \; A/A_0 \; \rho/\rho_0 \; L/L_0 \; f(i) \qquad (1)$$

where:

- M is the mass of the object;
- A is the cross-sectional area of the object;
- ρ is the spatial density associated with the orbital shell where the object is residing in a given year computed by evolving over several decades a reference scenario of the space debris environment with SDM 4.2 [22]
- L is the lifetime of the object at the altitude corresponding to the shell where the object is orbiting, computed through a fit to the lifetime profile of standard objects in LEO;
- $f(i)$ is a function of the orbital inclination i, reflecting the fact that the collision risk is maximum for high inclination orbits.

The terms M_0, A_0, ρ_0, and L_0 are normalising factors for the mass, the area, the spatial density and the lifetime, respectively.

The index Ξ was expressly devised with a simple analytical formulation to allow its reproducibility and is particularly suited to provide a quick indication of the danger to the environment posed by an object with no more manoeuvring capability abandoned in a crowded region of space.

Building on this original formulation, the shell criticality was developed in [23]. Dividing the LEO environment in M spherical shells of altitude thickness D, using Kepler's equation, the fractional contribution of any object k in an eccentric orbit to the to the criticality index of an altitude shell j is computed as:

$$\Xi_{k,j} = \Phi_{k,j} \, M_k \, A_k \, \rho_j \, L_k \, f_k \qquad (2)$$

where $\Phi_{k,j}$ is the fraction of orbital period that the object k spends inside the shell j. Thus, the overall criticality of an altitude shell can be computed as a result of the individual criticalities of all N relevant objects (possibly including active satellites) transiting through it. I.e., the criticality of the *j-th* shell is given by the sum of the individual criticalities over all the k objects crossing the shell. Finally, the overall criticality for the LEO environment can be estimated as the sum of the Ξ_j over all the M shells in which the LEO region was subdivided.

Recognising the fact that, e.g., active spacecraft can manoeuvre avoiding collisions, in [8] a more complex formulation of the index was adopted by multiplying the CSI of any object by specific weights accounting for the manoeuvring capabilities, the mitigation/de-orbiting policy, the projected failure rates of each spacecraft, etc. This extended formulation was applied to the evaluation of the environmental criticality of the large LEO constellations.

2.3 e-FRG based index

e-FRG based index is a debris index aiming to assess the present environmental impact of a target object's fragmentation (short-term impact) and the continuity of the impacts (long-term impact). This index consists of two indexes: I_{short} and I_{long} which evaluate the short-term and long-term impacts of fragmentation, respectively. The formula of I_{short} is shown below.

$$I_{short} = eFRG \qquad (3)$$

eFRG represents an expected number of fragments when a target object has been collided by another object, multiplying the number of fragments between a target objects and all other objects by each probability of collision. The calculation process of *eFRG* is described in [24]. The long-term index: I_{long} considers the continuity of a fragmentation impact by an orbital lifetime L of a parent object as expressed in Eq. 4.

$$L = \exp (a \times ALT^{b} + c) \times 0.012 / (A/M) \qquad (4)$$

The a, b, and c are constants with values of 14.18, 0.1831, and -42.94, respectively. The original equation in a work of Pardini et al. [25] assumed a fixed object A/M ratio of 0.012, however, I_{long} considers that of each object. The A/M values for each object are obtained from the JAXA database which was developed by JAXA and is updated yearly, based on Two Line Elements (TLE) obtained from the Space Track, optical observations using JAXA telescopes, and the breakup models [26]. The original formula of eFRG-based index simply multiplied Eq. (4) to eFRG [24], but it may let the debris index extremely affected by the lifetime in higher altitudes since the orbital lifetime growths exponentially with altitude. Therefore, I_{long} sets an upper limit on lifetime as 1000 years, i.e., when the calculated orbital lifetime of an object is 1200 years, the orbital lifetime of the object is replaced by 1000 years. The formula of I_{long} is expressed as in Eq. (5)

$$I_{long} = eFRG \times L_{MAX1000yr} \qquad (5)$$

2.4 THEMIS index

Tracking the Health of the Environment and Missions In Space (THEMIS) is a space debris index whose formulation is based on ECOB (Section 2.1), and is therefore defined as a risk metric. However, the THEMIS model was further developed to assess the impact of missions in several orbital regions [34][35], such as LEO, MEO, GEO and GTO, and for different mission architectures (e.g., single satellites, constellations, etc.) [32]. Moreover, the computation of the collision probability is updated with respect to the original ECOB formulation, properly averaging the impact rate over one satellite orbital period. As a result of this change, the effect maps are no longer symmetric around 90-degree inclination. In fact, the fragmentations that cause the greatest detrimental effect are those occurring with an inclination specular to the one where most of the operational satellites orbit, because of a higher average impact velocity. [36].

The formulation is composed of four terms, two for the collision and two for the explosion. Regarding the collision the evaluation considers a probability term focussing on the evaluation of possible catastrophic collision between the spacecraft and the debris background, which relies on the ESA MASTER model for the computation of the collision probability of a mission versus the debris environment. The severity term that accounts for the consequences on the space debris environment of such a collision breakup. The latter is evaluated by simulating fictious breakups, propagating the generated clouds of fragments using the continuum approach implemented in STARLING [33], and evaluating the cumulative collision probability on a set of spacecraft representative of the population of active objects [34]. Differently from ECOB, the set of active spacecraft includes all the active satellite in orbit at a given epoch (allowing the re-computation at different epochs). Then, regarding the explosion terms, the probability of the satellite to explode is based on historical data (from ESA DISCOS database), while the severity term follows the same procedure as the collision but considering explosion-type breakups.

The evaluation can be performed throughout the period in orbit (dividing it into different phases) of the investigated satellite, also assessing the re-entry phase (and its reliability through a wight parameter), by integrating over time the risk indicator.

Although not directly explicit, the formulation internally considers many factors such as the mass and the cross-sectional are of the spacecraft, collision avoidance maneuver capabilities (and their efficacy), evolution of the Keplerian orbital parameters along the mission (and the different phases), type of post-mission disposal (e.g., reentry or graveyard orbits) [32][34].

2.5 CNES index

The CNES index is built upon three pillars: (i) Criticality of Spacecraft Index (CSI) that allows a fast computation and an easy interpretation, (ii) Environmental Consequences of Orbital Break-Up (ECOB) that quantifies the risk induced by a fragmentation on the environment, (iii) extension of the index using mission related parameters.

Based on these existing formulations, the CNES index aims to represent short-term and long-term impact on the environment for a given object.

Through its implementation in the INDIGENE tool [27], it provides a flexible methodology where the emphasis can be placed either on short-term or on long-term effect of an object on a target population.

INDIGENE includes numerous additional data related to how the satellites are built and operated. Each term contributing to the environmental index is normalized to be able to sum up comparable terms. They are then weighed by the user (e.g., certification authority) according to the importance attributed to the different terms.

The index is obtained according to the following calculation:

$$I_{CNES} = w_{ECOB} I_{ECOB} + w_{CSI} I_{CSI} + \Sigma\, w_k\, I_k \qquad (6)$$

where

$$I_{ECOB} = p_{coll}e_{coll} + p_{exp}e_{exp} \qquad (7)$$

p_{coll} and p_{exp} being the probability that a fragmentation (collision and explosion, respectively) occurs, as described in [28].

e_{coll} and e_{exp} : effects of considered fragmentation (collision and explosion, respectively) as described in [28].

I_{CSI} : index described in [7], but with a slight modification of the lifetime calculation to correspond as closely as possible to the lifetimes calculated by the STELA semi-analytical propagator‡.

I_k: other contributors to the index as post-mission disposal rate. In this study, no additional data were used so that $\sum w_k I_k = 0$.

The weights of I_{ECOB} and I_{CSI} are set to $w_{ECOB} = 0.2$ and $w_{CSI} = 0.8$ to accentuate consequences in the long-term.

2.6 Collision Criticality Metric (CCM)

The CCM aims to quantify the criticality for any pair of objects by accounting for their collision probability, their masses and their manoeuvrability. The criticality c_{ij} between an object i and j is computed as

$$c_{ij} = (1 - r_i)(1 - r_j)(m_i + m_j)\int_0^T p_{ij}(t)\ dt \qquad (7)$$

Here, r is the reliability of the respective object, used as proxy for collision avoidance and post mission disposal capabilities of active objects. For non-operational passive objects the reliability is zero. The second term accounts for the mass m of the considered pair of objects and is used as proxy for the severity of a potential fragmentation. The last term represents the collision probability p_{ij} between the two objects integrated over a time span T . The integral in time accounts for the change of orbital elements due to atmospheric drag, geopotential and third body perturbations, as well as solar radiation pressure. Accordingly, the CCM represents the mass-weighted collision probability assuming natural evolution of the objects' orbital elements. Non-natural factors such as the mission profile of active objects are simplified through the reliability factors.

For an initial population snapshot, c_{ij} is computed for all pairs of objects. The environmental criticality is then defined as the sum of all pairwise criticalities. The criticality of a single object is defined as the change in environmental criticality upon removal of that object from the population, which is equivalent to the sum of all adjacent criticalities. A more detailed overview of metric design and characteristics is found in [29]. The environmental characteristics of the metric strongly depend on the choice of reliability (especially when considering constellations), time span and collision probability algorithms. The impact of the mass weighting is small compared to the contribution of the collision probability term. For the highest-ranked objects, the sensitivity of the metric with respect to reliability, time span and collision probability algorithm is less pronounced. The results for this paper have been generated with a reliability $r = 0.9$ for all active objects and a time span $T = 50\ yr$. Collision probabilities have been approximated by the CUBE method accounting for RAAN and AOP [30].

2.7 General observations

The parameters used as inputs to different (21) space debris formulations (available before 2021) § were mapped in terms of Plausibility, Complexity, and Frequency. The three terms refer respectively to

- Plausibility: assessment on a scale from 1 to 5 on how *direct* the input is (high plausibility) or whether it is obtained with assumptions or intermediate modelling (low plausibility);
- Complexity: assessment on a scale from 1 to 5 that considers aspects such as the computational time required to estimate parameter (e.g. very low for parameters that don't require any further elaboration such as inclination), the complexity of the models required to estimate the parameter (e.g. casualty risk estimation) and the availability of free resources to acquire the value of a parameter (e.g. the number of intact objects can be retrieved from space-track.org or ESA's DISCOS);
- Frequency: number of occurrences of the parameter in the set of metrics of analysis.

The results are reported in Fig. 1, where it can be observed how the object mass is the parameter most considered in the analysed formulations, and it can be considered a high plausibility/low complexity parameter. The combination of debris flux and debris spatial density (both with 6 occurrence) corresponds to the second most

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‡ The Semi-analytic Tool for End-of-Life Analysis (STELA) has been procured by CNES (The French Space Agency) to support the French Space Operations Act. https://logiciels.cnes.fr/en/content/stela

§ The 21 metrics with which the parameter mapping was performed do not correspond to the metrics used for the rest of the results of the paper, which are instead the ones for which an explicit definition is provided in Section 2.

frequent input, and it is instead a more complex parameter given the reliance on dedicated models and with a medium plausibility, given the inherent uncertainty on the number of space debris objects, especially when also non-trackable objects are considered. The third most common parameter is the semi-major axis of the studied object. These three parameters (i.e. mass, debris flux/density, semi-major axis) appear also in the subset of formulations used for the results in the following of the paper.

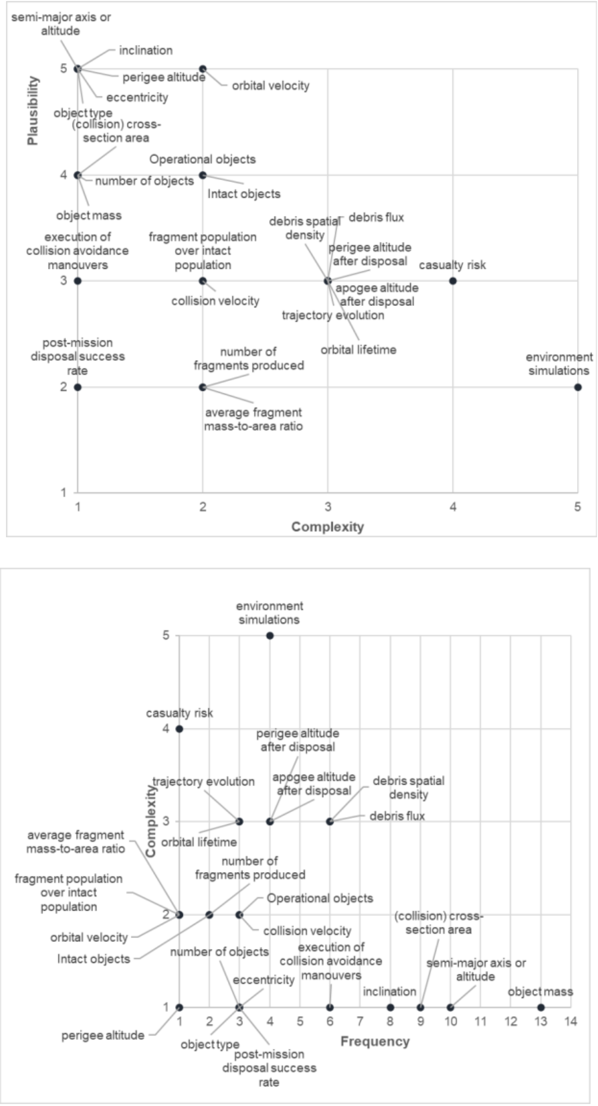


Fig. 1. Mapping of space debris indices' parameters in terms of plausibility, complexity, and frequency of occurrence.

In addition, all the analysed metrics can be reconducted to a risk formulation where the probability term is the probability of collisions (due to the existing environment) and the severity is quantified with different approaches ranging from the expected number of generated fragments in case of fragmentation (lower complexity) to the induced collision probability on other objects (higher complexity). What differs across the formulation is the consideration of operational and disposal behaviours.

Some formulations can include in their assessment also the contribution from the explosion risk, but it was observed how this part is still considered to be at low plausibility and high complexity, given the limited data available to build statistically sound models. On the other hand, fragmentations events are still observed with a frequency of more than 10 events per year [37], so it would be relevant to be able to include this aspect and to link it to the adoption of passivation strategies.

3. Comparative assessment

Similarly to the work in [13], a reference population was generated, in this case using the data available in ESA's DISCOS database and using as reference epoch 2022-01-01T00:00:00. Objects for which no mass value is available in the database or whose perigee altitude is above 2000 km were discarded. For each object, the following parameters were provided: category (e.g. satellite, upper stage, etc.), cross-sectional area, mass, launch epoch, estimated activity status, orbital parameters at the reference epoch, estimated probability of explosion using the methodology in [31]. Each formulation was then applied to the population in order to improve the insight on the available formulations through a quantitative comparison and the characterisation of the results in terms of sensitivity to input parameters.

In order to gauge the similarity between sub-sample sets, the Jaccard index was computed as

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|}, \tag{8}$$

where A and B are two sub-sample sets, defined, for example, by looking at the top 20 objects for each formulation. In addition, correlation graphs were generated for each pair of analysed formulation (Fig. 2). The plots show clearly how the different formulation provide significantly different (i.e. not correlated) assessment of the population overall, they tend to converge on the high-risk objects.

The distribution in terms of mean altitude and inclination of the top-20 objects for each formulation is presented in Fig. 3: a set of 15 objects that features in all the top 20 ranking, in line with similar findings in [13]. This set of objects is composed by Zenit-2 second stages, with mass between 8000 and 9000 km and perigee altitude between 814 and 851 km, at an inclination of around 71 degrees. While the Jaccard index ranges between 0.67 and 0.82 when considering the top-20 objects, the interval is much wider when the subsets are extended to consider the top-100 objects, going from 0.13 to 0.72.

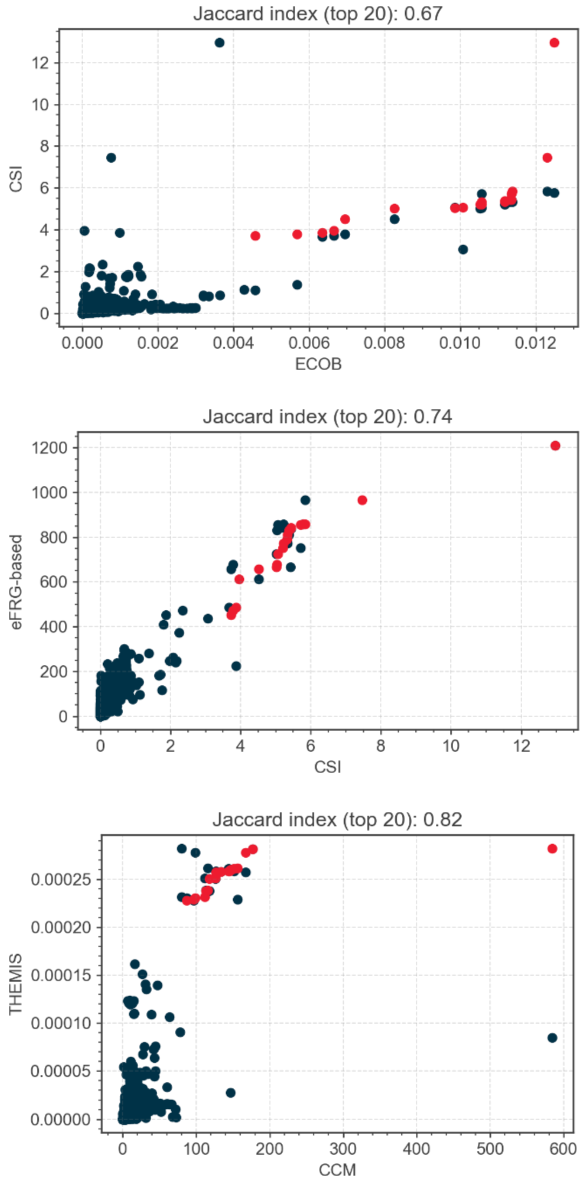


Fig. 2. Correlation graphs between the metrics. The red dots indicate the top-20 objects.

Fig. 4 shows the level of overlap across the top-100 sets by showing the number of distinct objects as function of the number of sets i.e. the value corresponding to $x=2$ indicates the number of objects that are shared between at least two top-100 lists. Interestingly, the 19 objects present in all the analysed six lists are still all Zenit-2 upper stages, with similar characteristics to the ones in the top-20 analysis. Looking at the 25 and 33 objects corresponding respectively to the presence is five and four lists, additional clusters appear, with mean altitude still quite concentrated in the range between 820 km and 850 km, but with a wider range of mass value (down to 4000 kg), as shown in Fig. 5.

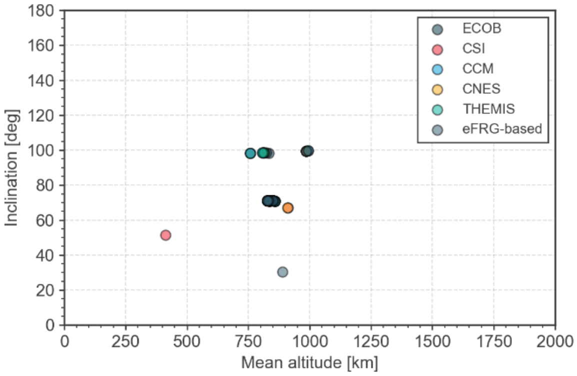


Fig. 3. Distribution of the top-20 objects for each formulation.

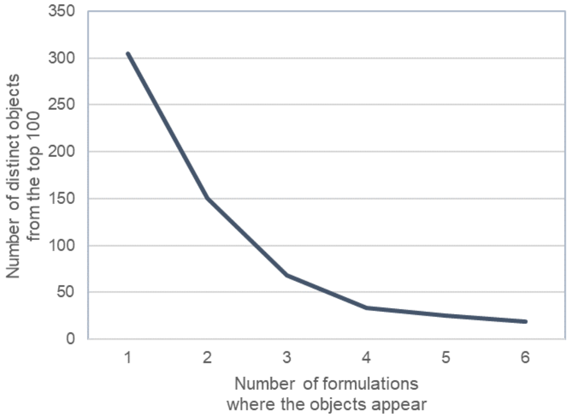
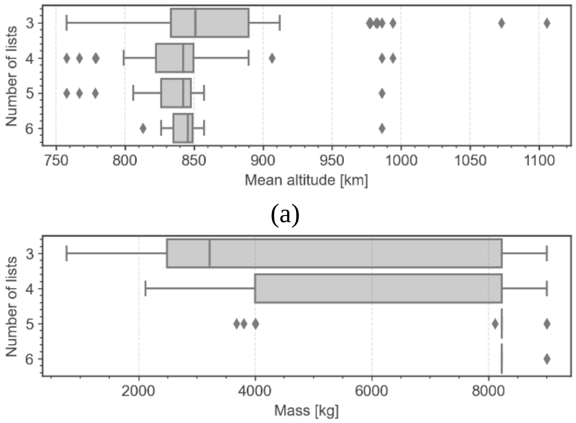


Fig. 4. Number of distinct objects as function of the number of considered formulations.



(a)

(b)

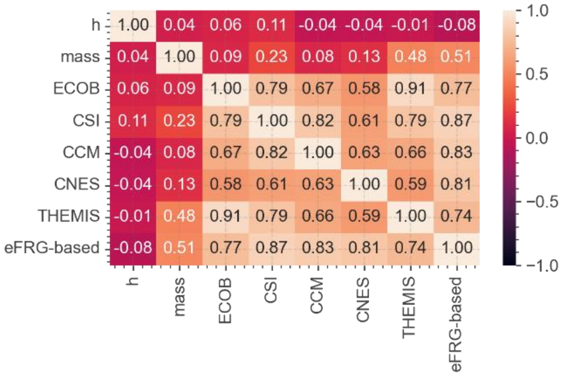
Fig. 5. Distribution of mean altitude and mass for the objects appearing in multiple lists.

Past work [20] has already investigated the (non) correlation between metrics and the sensitivity to the inputs. The analysis is repeated here restricting it to the correlation with mean altitude and mass for all formulations. The results of the analysis are shown in Fig. 6: the correlation with simple inputs (i.e. mean altitude, mass) is not enough to explain the different index values and second-order effect of correlation exists. For example, several formulations have a slightly negative correlation with the mean altitude because of the influence of the debris density/flux (that also varies as a function of the altitude) and because for some formulations (i.e. ECOB, THEMIS) the severity term puts more emphasis on the *distance* from operational satellites than on the mean altitude in absolute value.

For this reason, for example, as shown in Fig. 7, a Zenit-2 upper stage at higher altitude (mean altitude around 986 km) scores at the very top for metrics such as CSI, CCM, and eFRG-based, but lower for ECOB (#22) and even lower for THEMIS (#44), given that THEMIS' representative targets were defined at a later date with respect to ECOB and they capture the shift of operations towards lower orbits.

Finally, a check was performed to assess the relative importance of the *top* objects in each formulation. Fig. 8 shows the cumulative share of the aggregated metrics (obtained by simply summing the values for single objects) as a function of the share of objects over the whole population. For reference, also the normalised cumulative distributions of mass and area are added.

THEMIS and ECOB are the most skewed formulations, with 80% of the aggregate index value related to the top-5% objects in the population (i.e. around 400 objects), whereas the e-FRG-based index and the CNES formulation reach the 80% mark respectively with 18% and 59% of the objects in the population. All indices, except for the CNES one, increase the natural skew of the object properties.



	h	mass	ECOB	CSI	CCM	CNES	THEMIS	eFRG-based
h	1.00	0.04	0.06	0.11	-0.04	-0.04	-0.01	-0.08
mass	0.04	1.00	0.09	0.23	0.08	0.13	0.48	0.51
ECOB	0.06	0.09	1.00	0.79	0.67	0.58	0.91	0.77
CSI	0.11	0.23	0.79	1.00	0.82	0.61	0.79	0.87
CCM	-0.04	0.08	0.67	0.82	1.00	0.63	0.66	0.83
CNES	-0.04	0.13	0.58	0.61	0.63	1.00	0.59	0.81
THEMIS	-0.01	0.48	0.91	0.79	0.66	0.59	1.00	0.74
eFRG-based	-0.08	0.51	0.77	0.87	0.83	0.81	0.74	1.00

Fig. 6. Correlation matrix of the analysed metrics with mean altitude and mass.

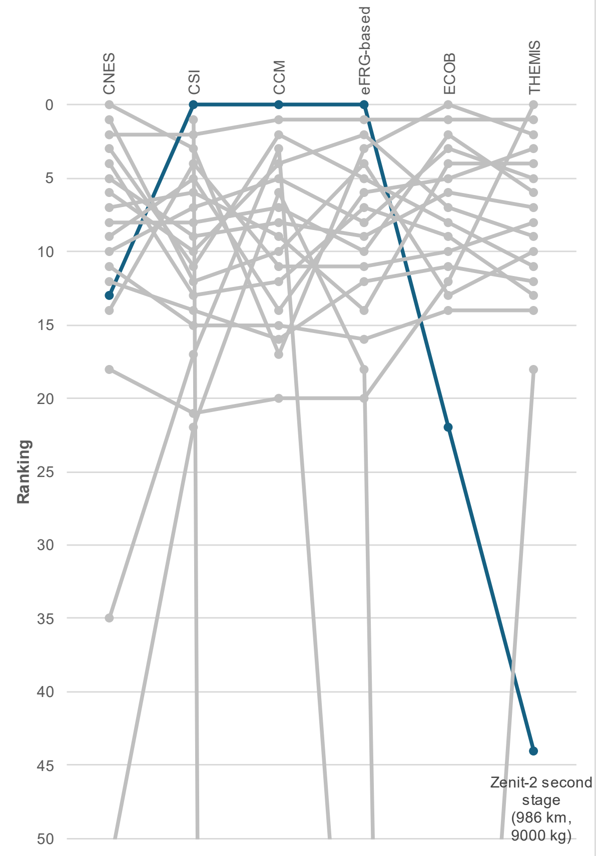


Fig. 7. Bump chart showing the different index rank for the top-20 objects according to eFRG-baesd.

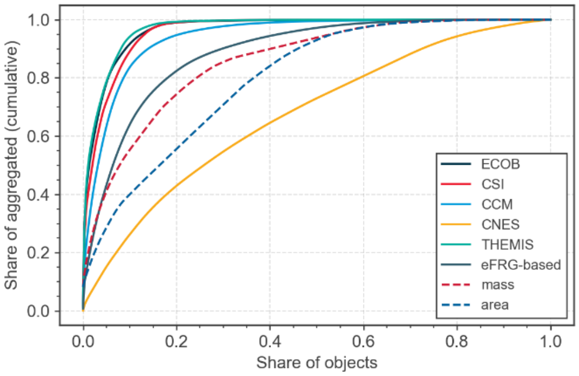


Fig. 8. Share of the aggregated metric value as a function of the share of objects in the population.

None of these relative comparisons can really indicate which of the metric is the most representative or useful, so the next step in the analysis is to test how these metrics related, if at all, with any property of the space debris environment or its evolution.

4. Link with long-term simulations and capacity thresholds

To move forward in the comparison and interpretation of the different metrics, it was decided to investigate the link between object-based assessments and overall environment metrics. The index formulations presented in Section 2 were used to compute the debris index on an entire population of objects and then aggregated on it. This was done by post-processing the results available from long-term debris simulation runs and computing for each timestep the aggregated value of the considered metrics and asses their evolution with time. The aim of this task is to correlate the evolution of the global index to the trend of long-term evolution of the spacecraft object population and to compare it with other indicator that characterise the debris population on the long term.

The considered scenario refers to the evolution of the population of objects larger than 10 cm as of 1st February 2018, propagated into the future (100 years) with the SDM tool [22], considering an 8-year launch cycle, no post-mission disposal actions, no explosions, no collision avoidance capabilities and no active debris removal missions. The settings for this long-term environment model were chosen as simple as possible as the aim of this work is to correlate indicators associated to the overall space debris population with the aggregation of mission-related indexes. Except for the case of CSI, a single population was analysed, whereas for CSI all the available 50 Monte Carlo runs. Past work has already assessed the variability of results across Monte Carlo runs when a debris index is applied [38].

The population is analysed over 100 years and for each year the indexes in Session 2 are aggregated across all population of objects as:

$$I_{tot}(t) = \sum_{j=1}^{N} I(t)_j \tag{9}$$

where for each instant of time t (yearly), the value of index on each object belonging to the population $I(t)_j$ is added up on the whole population to give the aggregated index $I_{tot}(t)$ as proposed in [20]. It must be considered that the proposed indicators have all different formulations and therefore also different units of measures. To overcome this issue, when they are compared, we consider their value normalised to the value they have at time t_0. Fig. 9 shows results if the comparative analysis comparing the different index formulations.

Some further steps were taken to compare the mission-related indexes behaviour to some other classical metrics that are usually used to characterise the overall space object population and are directly extracted from long-term simulations, namely number of objects and (catastrophic) collision rate. Simple variations of those were also considered:

- The catastrophic collision rate
- The non catastrophic collision rate
- The overall collision rate
- The number of objects in the population
- The total number mass of objects

For the collision rates, the exponential fit of the average values across all the Monte Carlo runs were considered, even if the limitations of using mean values when dealing with long-term simulations of the environment are acknowledged [39]. As for the index values, the results are presented in Fig. 9 in relative terms with respect to the initial value as the purpose of the assessment is to compare trends of evolution for the different metrics.

Considering all proxies to characterise the overall trend of a population evolution, it can be noted that, regardless the details of the implementation of each debris indicator, all the indices' formulations c fall into the category of risk metrics, where the probability component has always the meaning of a probability of collision (*pc* in Fig. 9), while the severity component can assume three different interpretations, namely

- Family 1: number of objects generated by the potential collision (as in the case of CCM and eFRG-based I_{short}),
- Family 2: permanence of the objects generated by the potential collision (as in the case of CSI and eFRG-based I_{long}),
- Family 3: induced collision probability on reference targets (as in the case of ECOB and THEMIS).

Each of the three families shows, for the analysed scenario, a correlation with the classical metrics, respectively number/mass of objects (Family 1), catastrophic collision rate (Family 2), overall collision rate (Family 3).

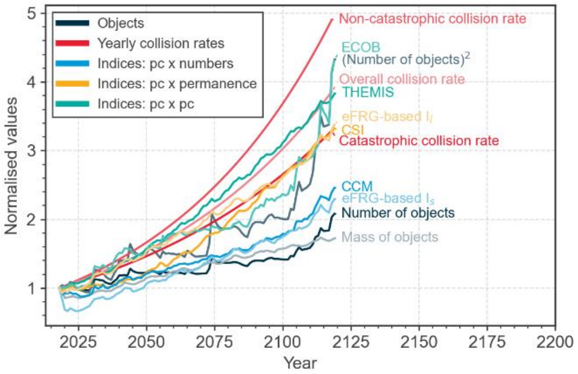


Fig. 9. Trends of the different metrics for the analysed long-term evolution scenario.

This observation, which would need to be confirmed through extending the simulations to additional test cases, present an interesting potential line of applications for such metrics. In particular, the object-based metrics could be used to partition at mission level a desired environment trend. For example, if one wants to control the growth of the catastrophic collision rate, one could decide to use metrics such as CSI or eFRG-based I_{long}. In this sense, one could think of debris mitigation requirements defined not only in terms of lifetime limitation (as in the 5/25-year rule), but also in terms of the discussed risk metrics. It is already observed in the landscape of international space debris mitigation instruments, guidelines and regulations are evolving towards the tailoring of provisions based on the missions' risk profiles [40], so the application of metrics as the ones described in this paper could support such process.

The decision on which environmental trend (or global metric) to regulate and which would be suitable reference targets is not addressed in this paper. None of the proposed debris index formulation provides an *intrinsic* assessment of the status of the environment and therefore they need to rely on an external assessment to define what is acceptable/sustainable.

5. Conclusions

This paper aim at analysing the underlying connections between environment-base metrics inherited from long term debris simulations with mission-related space debris indicators aggregated over the same population. The analysis shows that all the proposed debris indexes follow a trend that are all proportional to the collision risk. Moreover, three families can be identified, which have a further dependence on the number of objects generated by the potential collision, the permanence of the objects generated by the potential collision, or the induce collision probability on other spacecraft in orbit. While none of the analysed metrics provide an intrinsic assessment of the status of the environment, our preliminary results shown that they can be effectively used to flow-down at a single mission level global desired trend for the debris environment.

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