LIFE CYCLE ASSESSMENT INDICATOR FOR SPACE DEBRIS

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ABSTRACT

In the framework of space debris remediation and mitigation and eco-design of space systems, a design indicator is proposed to measure the management of end-of-life options and to compare different design options of a space mission from the perspective of the impacts of space debris. Such an indicator measures the orbital space occupied by missions, seen as a resource used, the risk induced by collisions with operational spacecraft and space debris, the potential of breakup due to non-complete passivation, and the casualty risk on ground. A procedure to include this indicator in the eco-design framework of space missions to be used in preliminary design studies is proposed. This requires the normalisation of each term and their weighting to obtain a single score indicator. Different end-of-life scenarios are considered for selected satellites in low Earth orbit and the single terms of the indicator are calculated and compared.

Keywords: space debris, design indicator, criticality index, risk index

1 INTRODUCTION

The Space surrounding our planet is densely populated by an increasing number of man-made space debris most of which are derived from breakup of operating satellites, abandoned spacecraft or upper stages [1]. Today, the space debris problem is internationally recognised, therefore mitigation measures are being taken and future guidelines discussed. These guidelines can be divided into two classes based on their expected impacts over time as “safety” measures (short-term) or “sustainability” measures (long-term). The avoidance or protection measures include designing satellites to withstand impacts by small debris, or selecting safe procedures for operational spacecraft such as orbits with less debris, specific altitude configurations, or implementing active avoidance manoeuvres to avoid collisions. On the other hand, measures for debris mitigation consist in limiting the creation of new debris, by prevention of in-orbit explosions through passivation, and implementing end-of life disposal manoeuvres to re-enter the Earth’s atmosphere or transfer spacecraft at the end-of-life from operational orbits to graveyard orbits that do not interact with protected regions. If the disposal terminates with the spacecraft re-entry in the Earth’s atmosphere, an analysis of the ground casualty risk caused by the mission has to be performed to determine whether a controlled re-entry is required if the total casualty risk is larger than 10^{-4} [2].

Besides, in the context of a growing public awareness of the urgent need for mitigating the environmental impacts of human activities, the European Space Agency (ESA) considers the environmental concern as a priority in all its activities. To better understand the environmental impacts of the space sector, ESA successfully applied Life Cycle Assessment (LCA) to evaluate the environmental impacts of space projects over their whole life cycle, from resource extraction through manufacture and use to end-of-life, covering spacecraft and launcher-related activities as well as ground segment activities [3]. In a LCA, the emissions and resources consumed (referred to as “elementary flows”), which can be attributed to a specific product, are compiled and documented in a Life Cycle Inventory. An impact assessment is then performed, which aims to evaluate the damage caused by the analysed system on the so-called “areas of protection”, namely human health, the natural environment, and natural resource use [4]. Indicators are quantified based on the Life Cycle Inventory (i.e. the elementary flows) to assess the impact of the system on several environmental impact or damage categories. LCA is then used by ESA in a design perspective to guide the design process towards environmentally conscious space systems: this is the so-called “eco-design” approach.

To better understand and mitigate both the issue of space debris and the environmental impacts of space systems, the Clean Space initiative was implemented as a framework for its activities related to space debris remediation and mitigation and eco-design of space systems. Within this context, a design indicator is proposed to measure the management of End of Life (EOL) options and to compare different design options of a space mission from the perspective of the impacts of space debris, and to define a procedure to include this indicator in the eco-design framework for space missions to be used in preliminary design studies. In this paper a method assessing the space debris issue related to EOL disposal is proposed, considering the following aspects:

- Space occupied as a resource,
- Potential of collision with operational spacecraft and space debris,
- Potential of breakup due to non-complete passivation,
- Casualty risk on ground,
- Pollution on the Earth environment.

The first term is calculated as a function of the spatial density of space objects in each orbital region and the space occupied by the considered mission during its operational and non-operational phase. The potential for collisions or breakups and the following consequences for the space debris environment are from results generated by an extension [5] of the Environmental Consequences of Orbital Breakups (ECOB) index [6]. It assesses the probability of an explosion or collision to happen through the MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) tool [7] and measures their consequences in terms of cumulative collision probability on a set of spacecraft targets caused by the cloud of generated fragments. The software tool DRAMA (Debris Risk Assessment and Mitigation Analysis) [8, 9] is used to compute the potential for casualty risk on ground as function of the entry conditions of the disposal trajectory at the lower layers of the Earth’s atmosphere and a simplified object-based model of the spacecraft design. Finally, the pollution effect of re-entering objects on the Earth environment is instead introduced in the standard LCA indicator for space missions. Different EOL scenarios are considered for selected satellites in Low Earth Orbit (LEO): (1) remain in an operational or protected orbit (due to failure), (2) removal to a graveyard orbit, (3) direct re-entry and (4) re-entry within 25 years. First, the individual terms of the indicator are calculated, then their normalisation is achieved by expressing the indicators with respect to a common reference. In order to achieve a unique indicator, it is necessary to assign distinct quantitative weights (multipliers) to all impact categories expressing their relative importance. Different weighting options are discussed in terms of the objective or subjective evaluation of the process based on the physical meaning or perceived criticality.

2 DEBRIS INDICATOR

The indicator developed in this work is not strictly an “LCA indicator” as it should not be considered as an indicator in line with the general LCA methodological framework but rather as a design indicator to be included in the LCA framework for the eco-design of space missions developed by ESA. The Space Debris Indicator can be defined as:

$$\begin{aligned} I_{\substack{\text{space}\\\text{debris}}} &= I_{\substack{\text{casualty}\\\text{risk}}} \cdot n_{\substack{\text{casualty}\\\text{risk}}} \cdot w_{\substack{\text{casualty}\\\text{risk}}} \\ &+ I_{\substack{\text{orbit}\\\text{resource}}} \cdot n_{\substack{\text{orbit}\\\text{resource}}} \cdot w_{\substack{\text{orbit}\\\text{resource}}} + I_{\substack{\text{debris}\\\text{risk}}} \cdot n_{\substack{\text{debris}\\\text{risk}}} \cdot w_{\substack{\text{debris}\\\text{risk}}} \end{aligned} \tag{1}$$

where I results from the calculation of each individual term of the formula, for each of the identified environmental concerns, n is the normalisation value and w is the weighting factor defined for each term.

The term assessing the potential for pollution was not included in Eq. (1) but directly in the ESA LCA framework, therefore it will be excluded from our discussion. It has to be noted that in LCA the sum of the normalisation factors is not equal to 1 as it depends on the selected reference values and the set of normalisation values used. On the contrary, the sum of weighting factors is necessarily equal to 1. The following sections address the methodology for calculating each term of the formula and discuss the choice of normalisation and weighting.

2.1 POTENTIAL FOR CASUALTY RISK ON GROUND

The ESA software suite DRAMA (and its module SARA) [8, 9] was used to perform a re-entry analysis and to calculate the ground casualty risk expectation for the mission to be compared with the limiting threshold of 10^{-4} [2]. The re-entry trajectory conditions at 120 km are here considered as the starting point for propagating with DRAMA the trajectory down to 78 km (assumed as the break-up altitude), applying biases to the atmospheric density. For the propagation below 78 km no further density biases are applied so that one set of initial conditions at 78 km is produced for each atmospheric bias. To assess the risk to the population, a rectangular ground impact corridor is assumed, with a fixed 2σ cross-track extension of ±40 km. The along-track extension is defined by the trailing and leading impact point of each surviving fragment footprint. The trailing edge corresponds to the +20% density bias, whereas the leading edge to the -20% density bias, or the first trajectory that reaches the ground without demising. For every surviving object the casualty area and the geodetic impact coordinates are provided as a function of the applied density biases. The ground risk computation can be computed by DRAMA using the biased re-entry simulation and the population density which is defined on a latitude, λ and longitude, ϕ grid with a resolution of 15’. An exponential growth of the population in time t (expressed in years) is assumed since 1994.

$$\rho_p(\lambda,\phi,t) = \rho_p(\lambda,\phi,1994)\exp\left(\frac{t-1994.5}{59.63}\right)$$

The ground risk computation depends on the re-entry forecast of the mission (i.e. short-term or long-term prediction). For long-term predictions, as the re-entry location on the orbit is unknown, a uniform impact probability is assumed for a given orbit inclination $(P_i)_k = (\Delta s_x)_k / (2\pi R_E)$, where R_E is the Earth's radius, Δs_x is the along-track extension of the rectangular ground impact corridor, and k is the number of bins in which the re-entry corridor is subdivided. For the same reason, the population density is averaged in longitude $\bar{\rho}_p(\lambda,\mathrm{t})$. In addition, due to the symmetry of the problem, a single orbit is used as the analysis interval. The expression for the corresponding casualty risk is then

$$E_c = 1 - \prod_{j=1}^{J}\left(1 - E_{c,j}\right)$$

where the total casualty risk calculated for j = 1,..,J surviving objects is constructed from each individual contribution $E_{c,j}$

$$E_{c,j} = \sum_{k=1}^{N} (P_i)_k (\bar{\rho}_p)_k \hat{A}_c$$

where $\hat{A}_c$ is a mean casualty area, which is obtained from a weighted average over all possible along-track impact locations, with weights provided by the impact probability density function $(PDF_{2\sigma})_k$ as a function of the impact location:

$$\hat{A}_c = \sum_{k=1}^{N} (PDF_{2\sigma})_k (\Delta s_x)_k (A_c)_k$$

A sensitivity analysis on different re-entry conditions onto the casualty area and the impact masses that reach the ground was performed with several DRAMA simulations. Figure 1 shows a map of the casualty risk as a function of the entry flight path angle and of the orbit inclination for a fixed relative velocity of 7.3 km/s. The impact mass increases moving from direct to retrograde orbits, and gets lower for flight path angles around -0.5°. The casualty risk follows more closely the population distribution on the Earth, where the highest concentrations can be found at intermediate latitudes (±45°). The inclination thus influences the casualty risk the most, whereas the flight path angle produces less significant effects, as the casualty risk analysis performed uses a longitude averaged population density.

Figure 2 and Figure 3 show the variation of the casualty risk as a function of the entry velocity and flight path angle for two specific values of the orbit inclination. It is evident that for moderate velocities the higher the entry velocity the better is the demise, as the heat load on the spacecraft will be greater. However, the higher the relative velocity the greater the chance the spacecraft will not re-enter (dark grey areas), especially for direct orbits. The flight path angle influence seems instead related to the orbit inclination. For the 30° inclination orbit the demise of the spacecraft is greater for steeper re-entries, whereas for the 120° orbit the demise is greater for shallow entries.

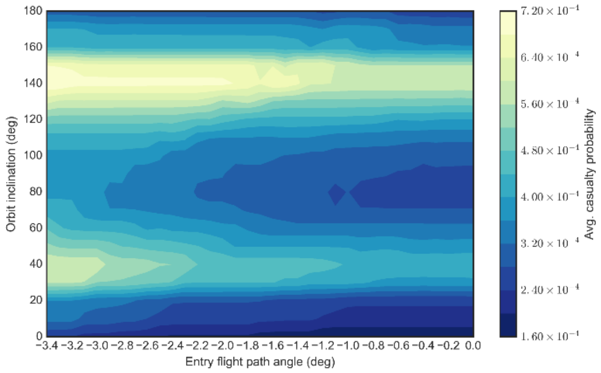


Figure 1. Casualty risk as function of orbit inclination and entry flight path angle for a 7.3 km entry velocity.

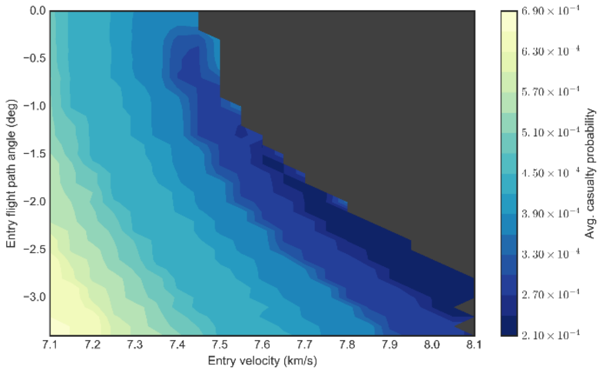


Figure 2. Casualty risk as function of entry velocity and flight path angle for a 30 inclination orbit.

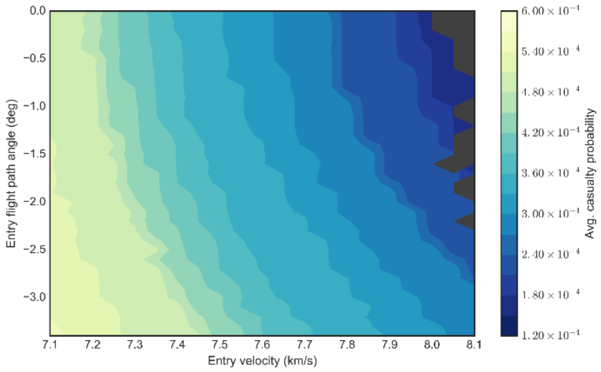


Figure 3. Casualty risk as function of entry velocity and flight path angle for a 120 inclination orbit.

2.2 ORBIT RESOURCE USE

To set the general calculation methodology and input parameters required for the term *orbital resource use* of the debris indicator, we draw an analogy with resource indicators already used in LCA, namely the land use indicator or occupation impact [10]:

$$I_{\mathrm{occ}} = \frac{A \cdot t_{\mathrm{occ}} \cdot Q}{S_i} \quad [\mathrm{m}^2 \cdot \mathrm{year}]$$

where A is the surface occupied in m², t_{occup} is the time of occupation in years, Q a dimensionless qualitative indicator of the quality of the soil, S_i is a dimensionless slope factor that reflects the time of restoration.

Using this analogy for the orbit space resource use, A would refer to the cross-sectional area of the single spacecraft, which is not considered here as usually the cross-sectional area of the spacecraft does not enter in the requirements for s/c operations such as collision avoidance manoeuvre, apart the case of the International Space Station. S_i is also not applicable in the case of orbit resource use, or has default value equal to 1, t_{occup} retains the same meaning, while Q should be adapted to the *value* of the orbit. The value of the orbit could be measured in two ways, or both can be used. The first approach is the *revenue grid*, or financial revenue of the missions using the orbit in terms of services to humankind. The second approach measures how an orbit is valuable based on the *number of operational spacecraft* in the given orbit slot.

Use of Space

As a measure of the use of space (use of given orbital region for a given class of missions) we consider the number of operational spacecraft per orbit bin. This is achieved using data from the Union of Concerned Scientist (UCS) Database [11], which provides a picture of the current use of space; as an extension, the future use of space may be extrapolated from the same data.

Space mission revenue

For assessing the space mission revenue, The Space Report 2011 by the Space Foundation was used, which provides a guide to global space activity in 2011 [12] (more up-to-date data should be ideally used). The revenue for the commercial space products and services sector was considered (reported in Table 1) as this remains the largest component of the space economy (total revenue in 2010 was $102 billion).

- Satellite broadcasting: $79.22 billion in sales for direct-to-home television;
- Satellite communications: $17.92 billion in revenues for fixed satellite services (FSS) and mobile satellite services (MSS);
- Earth observation products and services.

These three classes represents 98% of the total revenue. In this report geolocation and navigation-related revenues are included in the ground equipment sector due to the fact that the majority of revenue is generated by receiver hardware sales.

Table 1. Revenue for commercial space products and services in 2010 [12].

Category	**Revenue**	**Source**
Direct-to-Home Television	$79.22 B	SIA/Futron analysis
Satellite Communications	$17.92 B	SIA/Futron analysis
Satellite Radio	$2.84 B	SIA/Futron analysis
Earth Observation	$2.01 B	Northern Sky Research
Total	**$102.00 B**	

To provide an idea of how precise data on the revenue of space missions could be used, an example is given in the following section. Note that this is only an example as data were not available for a rigorous analysis. The spacecraft missions in LEO from the UCS database were mapped to a category in the Space Report 2011 [12]. Note that the mapping is not rigorous due to the availability only of the data for the revenue coming from commercial space products and from navigation-related revenues or scientific mission revenues for remote sensing missions.

Orbit resource use indicator

The definition of the value of each orbital bin in LEO for the calculation of the use of space as resource indicator counts the number of spacecraft in a given orbital bin normalised by the total number of spacecraft considered.

$$I_{\mathrm{bin}} = \frac{\sum_{k=1}^{N_{\mathrm{s/c}}} \left(k \in \mathrm{bin}_{a,e,i}\right)}{N_{\mathrm{s/c}}} \tag{2}$$

As an alternative, the value of each orbital bin could be assessed based on the total revenue of the missions in that bin, normalised by the total revenue of the missions considered.

$$I_{\mathrm{bin,\ rev}} = \frac{\sum_{k=1}^{N_{\mathrm{s/c}}} \left(k \in \mathrm{bin}_{a,e,i}\right) \cdot Q_k}{\mathrm{Tot\ rev}} \tag{3}$$

The orbit bin value for the calculation of the orbit resource use indicator is shown in Figure 4, based on the spacecraft distribution as in Eq. (2) and Figure 5, based on the revenue of space missions as in Eq. (3). In this analysis the bins are only distributed in semi-major axis and inclination but future work will include the eccentricity. The bin sizing is optimised to cover the data range and reveals the shape of the underlying distribution. As it can be seen in Figure 4 and Figure 5, while the highest value bin is very visible in both maps, considering the revenue (see Figure 5), increases the value of the bins close to the sun-synchronous region, as they are associated to missions with the highest revenue.

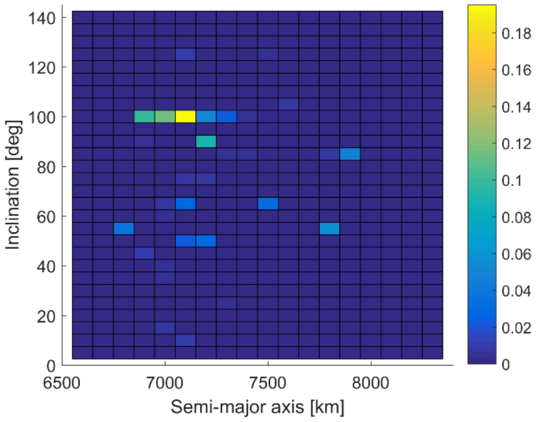


Figure 4. Bin value for the space resource index calculation: number of operational spacecraft in orbit bin normalised by the total number of s/c.

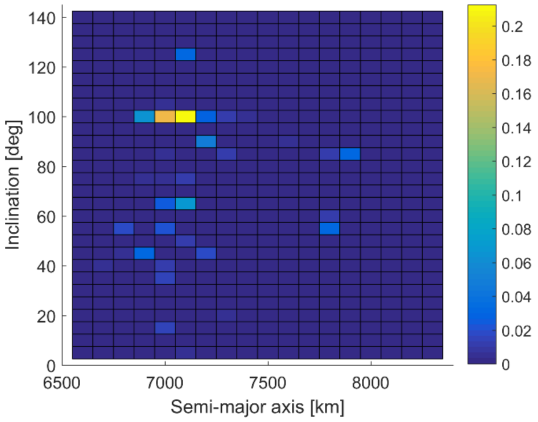


Figure 5. Bin value for the space resource index calculation: total revenue of the missions in each a-i bin, normalised by the total revenue of all the missions considered in LEO.

In the rest of the work, the number of operational spacecraft is used as a proxy for the value of each bin (i.e. Eq. (2)) so the index of space as resource can be calculated as:

$$I_{\substack{\text{orbit}\\ \text{resource}}} = \int_{t_{\text{mission start}}}^{t_{\text{mission end}}} \frac{\sum_{k=1}^{N_{\text{s/c}}} \left(k \in \text{bin}_{a,e,i}\right)}{N_{\text{s/c}}} dt \qquad (4)$$

In other words, the operational orbit and then the disposal trajectory are propagated along the grid and the value of the grid is read at every year to compute the integral of the index during the mission (operational phase plus disposal). This approach gives the same index for two spacecraft having the same operational and disposal trajectory, without measuring the benefit the mission itself gives back to the Earth in terms of services. An alternative to take this into consideration is to include as weight the revenue of the single mission, so that a mission with a higher revenue (used here as a proxy of the benefit to humankind) has a lower index.

$$I_{\substack{\text{orbit}\\ \text{resource}}} = \frac{1}{\text{mission rev}} \int_{t_{\text{mission start}}}^{t_{\text{mission end}}} \frac{\sum_{k=1}^{N_{\text{s/c}}} \left(k \in \text{bin}_{a,e,i}\right)}{N_{\text{s/c}}} dt \qquad (5)$$

However, it has to be noted that it would be very difficult to have a consensus on how to measure the mission revenue considering also the benefits it brings to humankind, therefore in practice it would be difficult to implement the index in Eq. (5).

2.3 RISK ASSOCIATED TO COLLISIONS AND EXPLOSIONS

The interaction of a spacecraft, during its operational or EOL phase, with the space debris environment can be identified by two main aspects. The *probability* of fragmentation caused by the space debris environment on the analysed mission (probability of collision) and from stored energy on-board (probability of explosion). The probability of collision is a function of the flux of space debris, the operational orbit of the object and its trajectory evolution, the capabilities of collision avoidance manoeuvring by the object under analysis (therefore its object type: spacecraft, rocket body, etc.) and its cross-sectional area. The *severity*, instead, measures the consequent effect on the space environment of the analysed mission scenario. As proposed in Letizia et al. [6] we measure the severity as the increased collision risk on the other operational spacecraft in orbit caused by the collision or explosion of the object under analysis. The severity, in case of a a breakup, is function of the mass of the object: the characteristics of the breakup (i.e., collision velocity or energy of the explosion), the orbit where the breakup occurs that determines the following evolution of the cloud of debris fragments.

The index that describes the risk associated to collisions and explosions is based on the assessment of the effect of potential fragmentations on operational satellites and the likelihood of these fragmentations to happen [5, 13].

$$I_{\substack{\text{debris}\\ \text{risk}}} = p_c \cdot e_c + p_e \cdot e_e$$

where p_c is the probability of a collision happening, and e_c measures the effects of the collision on operational satellites, p_e is the probability of an explosion happening, while e_e measures the effects of the explosion on operational satellites. In the debris index there is also the option of taking into account that active spacecraft can perform collision avoidance manoeuvers. In case this is enabled, the collision probability is computed considering only objects smaller than 10 cm (and bigger than the threshold defined by the condition for catastrophic collisions). A thorough presentation of the index is given in [5, 13], in the next paragraphs a summary is given.

Collisions

The probability of collision p_c is computed through the kinetic gas theory, so that the cumulative collision probability is written as

$$p_c = 1 - \exp\left(\rho \Delta v A \Delta t\right) \tag{6}$$

where ρ is the debris density at the spacecraft orbit, Δv is the collision velocity, A the collision area, and Δt is a fixed time interval. For the debris index, an appropriate value of Δt (e.g. one year) should be chosen. The collision velocity of a given spacecraft orbiting through the space debris environment is here calculated from MASTER simulation, building a grid of the most likely impact velocity for a spacecraft at a given semi-major axis and inclination on a circular orbit.

The effect of the collision e_c is assessed by measuring the consequences of a fragmentation of the spacecraft under analysis in terms of the resulting increase in the collision probability for operational satellites [6]. A set of targets representative of the whole population of operational satellites is defined based on the distribution of the cross-sectional area. A grid in semi-major axis and inclination is introduced and a representative target for each cell with the highest cumulative cross-sectional area. This definition of representative targets is done to avoid having to propagate the trajectory of hundreds of satellites. A fragmentation is triggered for each bin in a grid of semi-major axis and inclination and for each event the resulting cloud of fragments is propagated through a density-based approach. The collision probability on each of the representative targets is computed with the same expression as Eq. (6), where now ρ is the spatial density of the fragmentation cloud at the spacecraft altitude, Δv is the relative velocity between the target and the fragments in the cloud, A is the cross-sectional area, and Δt is the time span used for the computation.

The effect on each representative target is summed and modified through a weighting factor w_j to take into account that each representative target is associated with a different share of the total spacecraft area distribution. The term e_c is calculated as

$$e_c = \sum_{j}^{N_{tar}} w_j p_{c,j}$$

Note that the sensitivity of the fragmenting mass on the index can be analytically evaluated with a power law [14, 6].

$$\frac{e_c\left(m_{\text{obj}}[kg]\right)}{e_c\left(10000\ kg\right)} = \left(\frac{m_{\text{obj}}[kg]}{10000\ kg}\right)^{0.75} \tag{7}$$

Explosions

An analytical expression for the probability of explosion p_e was derived by analysing statistical data from DISCOS, focussing on fragmentations that have occurred in LEO since 1985. The number of fragmentations are analysed by looking at the time elapsed between the launch of the object and its fragmentation. Two different curves are derived in this way, distinguishing between payloads and rocket bodies [5].

In the case of an explosion, the NASA breakup model gives different equations for the generation of the fragments, as explosions produce larger fragments with lower speed compared to collisions [15]. Even if the mass of the exploding spacecraft does not appear explicitly, a linear relationship was derived between the mass of the object and the mass of the produced fragments [16]:

$$m_{\text{frag}}[kg] = \frac{m_{\text{obj}}[kg]}{10000\ kg}$$

The effect term due to explosions follows the same approach of collisions. An explosion was triggered in each orbit bin of a grid in semi-major axis and inclination, the resulting fragment cloud propagated through a density-based approach and the effect was again measured on the representative targets defined.

For the calculation of the debris risk term $I_{\substack{\text{debris}\\\text{risk}}}$, the spacecraft trajectory is integrated and for each time step (equal to 1 year in this work) and the value of the terms p_c, e_c, p_e, e_e are calculated to give the total value of the indicator over the mission profile.

3 NORMALISATION AND WEIGHTING

Including in the space debris indicator both the risk related to collisions and explosions $I_{\substack{\text{debris}\\\text{risk}}}$ and the orbit resource use $I_{\substack{\text{orbit}\\\text{resource}}}$ may be seen as double counting, as both indices are based (among other factors) on the spatial density of objects in orbit. However, the two indices represent two different physical phenomena.

The orbit resource use indicator represents the use of orbital space as the use of a precious resource, while the risk related to collisions and explosions represents the fact that a particular orbital space being already used by other missions, is more risky for the mission itself; moreover, being a mission in a particular slot, it can create more or less damage to other operational spacecraft. The conceptual difference between the issues these two terms attempt to address can also be explained using the analogy with motorways. The orbit resource use indicator would give a higher value to the highways which are more used (high traffic) as it connect important cities or allow important trading activities. The indicator for risk related to collisions and explosions represents the fact that, as these highways are widely used, the number of accidents is higher and this increases congestion on these routes even more.

As the indicator compares different aspects, an evaluation method that provides multicriteria results should be defined. LCA is a good example of dealing with this. In LCA, the result is essentially a list of the product's contributions to different impact or damage categories, such as climate change, acidification, eutrophication, toxicity, resource depletion. Weighting involves assigning distinct quantitative weights to different impact or damage categories, thereby expressing their relative importance, and makes it possible to derive a single score to ease decision-making. For example, in LCA, the impact category "climate change" may receive a weight of e.g. 30% and the impact category "water depletion" a weight of e.g. 20%, and so on for all included impact categories. The ISO 14044 standard highlights that there is no scientific basis enabling the synthesis of LCA results in a single global score. Nonetheless, a variety of methods have been developed for this 'weighting' step, as illustrated in [17]:

- *Single item*: the focus is put on one single metric among all the environmental indicators quantified,
- *Distance-to-target*: weights are derived from the extent to which actual environmental performance deviates from some goal that is set for each indicator (typically through a regulation). However, no political (or consensus) targets exist yet for space debris (with the exception of casualty risk on ground), which limits the feasibility of this approach.
- *Panel method*: a panel of experts and stakeholders defines a ranking between environmental issues in terms of relative importance, which leads to the definition of a weighting factor per environmental indicator. This method could be applied provided that a relevant panel of stakeholders/experts of space debris issues is created (some already exists such as Inter Agency Debris Committee IADC, the United Nation, ISO). This approach could leverage the knowledge within ESA (a panel method is already used by ESA for its environmental single score, for example).
- *Monetary evaluation* consists in assigning a monetary value to goods that either have no market price (e.g. health), or have a price that does not include externalities. This approach can be applied to environmental effects by evaluating the cost of dealing with consequences of environmental degradation or by estimating the willingness to pay to avoid environmental degradation. In this way, all terms can be summed and normalisation is not required. This method has the advantage of resulting in a score expressed in a monetary unit, which is easily understandable and easy to use by decision-makers. Furthermore, if applied to both the environmental impacts evaluated via LCA and the different terms of the space debris indicator, the approach could make it possible to combine both single scores, and compare these external costs to the internal ("private") costs of a space mission. However, it would be difficult to assess the monetary value related to each individual term of the space debris indicator, in particular the risk related to collisions and explosions. Furthermore, estimating the costs of a space mission would be more complex for certain types of missions: whereas it could be possible to relate the value of a mission to the generated revenue for a commercial satellite, this task would be more difficult for scientific missions or university missions, whose outputs and value are less easily quantifiable. Moreover, it would involve collecting a large volume of (confidential) information, such as the cost of space missions. The approach would still be interesting in the long-term.
- *Meta-models* are combinations of two or more of the other weighting methods. For instance, a meta-weighting method could be the outcome of an average between weighting factors of several existing weighting methods.

Due to the time limitation in this study the weighting approach through the panel method has been taken under consideration. Firstly it is necessary to normalise the single terms of the indicator. While the normalisation of the index for orbit resource has yet to be performed, options for the normalisation of the debris risk index and the casualty risk on ground index have been proposed. Regarding the normalisation, the ideal approach would use the same normalisation case for all the terms of the indicator. This would have the advantage of a similar physical interpretation for all the terms. However, as will be discussed in the next sections, for some terms, in particular the casualty risk, the availability of data and the computational effort for running many simulations is also constraining the choice of the normalisation method. The main challenge here is to define a normalisation strategy that does not favour one components over another and that is robust to different test cases, even the ones not considered in the validation of the indicator. This is still on-going work.

3.1 DEBRIS RISK INDEX NORMALISATION

Two options for the normalisation of the debris index have been identified. Both options have the same relative meaning, which is to divide the debris index by a reference value. A first option is to normalise the value of the index with a reference value (taken from a reference epoch) at each time step of the evaluation for the entire mission profile. The second option is to normalise the overall value of the index over the entire mission profile with a reference value (taken from a reference mission profile).

Comparing the two approaches, the advantage of using the first option is the immediate interpretation of the results. In fact, the value obtained is directly related to the criticality defined by the reference value. For example, if the reference value is chosen to be the debris index of Envisat at a reference epoch, the value obtained after the normalisation can be directly interpreted as how many times worse than (a single) Envisat (at a reference epoch) the criticality is, as adopted in the index proposed by Anselmo and Pardini [18]. For the second option, the advantage is to have a resulting index whose value can be expected to be in a limited range, around [0, 1], for all the spacecraft similar to the ones currently in orbit. It is evident that this is dependent upon not just the reference spacecraft selected but also on the reference mission profile. It is thus important to properly select both the spacecraft and the mission profile for this normalisation option. On the other hand, for the first normalisation option, the range of the final value of the index (over the mission profile) would be definitely larger for spacecraft similar to the ones currently in orbit. For example, selecting Envisat as the reference spacecraft, the index would be in the range [0, 100] as Envisat is, in the current population and depending on the rating scheme, one of the more critical spacecraft. Other reference spacecraft choices can of course change the range of the final value of the index. Another option that is currently being discussed is to normalise the debris risk index with respect to a reference value, however no accepted values exist in the literature and requirements, apart from the threshold collision probability used for planning a collision avoidance manoeuvre equal to 10^{-4}, but this could only be used as a reference value for normalising the probability term, while no univocal value exists for the severity term. Future effort will be invested in the definition of a reference case to be used for the normalisation, which can be considered as a threshold between acceptable and unacceptable behaviour of a space mission with respect to the space debris environment.

3.2 CASUALTY RISK INDEX NORMALISATION

In the case of the casualty risk index it was not possible to perform a normalisation with respect to a reference spacecraft. Gathering detailed information for the definition of a spacecraft configuration to be provided to DRAMA is a challenging task. As such, it was decided to present a normalisation with respect to a predefined reference value. The selected value corresponds to the casualty risk limit provided by ESA and IADC guidelines for uncontrolled re-entry, which is equal to 10^{-4} [2].

As DRAMA requires a complete description of the configuration of a satellite, it is practically impossible to provide the satellite configuration for each satellite in the database. Consequently, it was decided to perform a simplified analysis, where the configuration of a selected satellite is obtained by scaling a reference spacecraft configuration, indicated in the following as CompliSat, available at the Space Debris User Portal [19]. With this approach, a satellite configuration is generated replicating the configuration of the reference spacecraft and scaling it with respect to its mass. The materials are maintained the same for the respective components and the dimensions are scaled so that the thickness of the components is held constant. The scaling factor is the ratio between the actual mass of the spacecraft ($m_{\mathrm{s/c}}$) and the mass of CompliSat ($m_{\mathrm{compliSat}}$) as $k = m_{\mathrm{s/c}} / m_{\mathrm{compliSat}}$.

An analysis of the sensitivity of the casualty risk to the spacecraft mass (via scaling with CompliSat), the inclination, the flight path angle and the re-entry velocity was performed. The variation of the casualty risk with the mass follows a closely logarithmic behaviour as already noted by Lemmens et al. [20]. The slope of the curves appears to be constant as a function of the flight path angle and velocity, whereas it changes as a function of the orbit inclination.

However, it has to be noted that the re-entry of a satellite and its demise are strictly correlated to the specific satellite configuration, to the materials and to the design of the components and subsystems, and to the type of payload. As a consequence, a simple linear scaling law from the CompliSat configuration does not provide good results, therefore a more complex scaling would be required, or ideally the detailed configuration to be inputted in DRAMA should be available; this is the case for ESA Concurrent Design Facility studies.

4 APPLICATION OF THE DEBRIS INDICATOR

In the framework of this study some missions onto which to test the indicator are currently being analysed based on their relevance with respect to the objectives of the design indicator:

- Comparison of different technological options (design for demise option)
- Comparison of different EOL scenarios for a given space mission
- Type of object (launcher, space mission, product)
- Sensitivity on orbit
- Sensitivity on mass (different masses considered)
- Sensitivity on cross-sectional area (different areas considered)
- Representativeness with respect to the European space activity (e.g., LEO between 700 and 2000 km altitude).

4.1 METOP-A MISSION

The first test case is the MetOp-A, part of the second generation MetOp satellites developed by EUMETSAT. Although the satellite is not required to perform an end-of-life de-orbit, the possibility to perform a re-entry is currently under study. As different options are being investigated for the disposal of MetOp-A, three possible scenario have been selected: (1) a no-disposal scenario, where the satellite it is not moved from its operational orbit, (2) a second scenario, where the orbit perigee is first lowered to 574 km and then the satellite is left to naturally decay in the atmosphere and re-enters in around 50 years (this solution was proposed in [21] for the disposal of MetOp-A), (3) a third scenario with a direct re-entry, where the disposal is performed with a Hohmann transfer with a target perigee at the Earth's surface. Regarding the spacecraft configuration, the satellite is built around a bus that has been used for many other missions such as Envisat, SPOT 1, 2, 3, and 4, and ERS 1 and 2.

MetOp-A is a 4085 kg spacecraft in a sun-synchronous orbit with a semi-major axis of 827 km and an inclination of 98.72 degrees. The overall size of the spacecraft is 6.2 m x 3.4 m x 3.40 m (launch configuration), with a structural cross section of 2.5 m x 2.5 m, and 17.6 m x 6.7 m x 5.4 m (on-orbit configuration) [22]. The spacecraft cross-section is 37.5 m^2 according to DISCOS.

Table 2 show the debris risk index and the casualty risk index for the MetOp-A mission for the three different disposal scenarios.

The debris index and the casualty risk shows significantly different values. For what concerns the debris index, it is possible to observe that the no re-entry case has a value of the index that is one order of magnitude greater than the other two cases. By remaining in its operational orbit, the satellite has a higher probability of suffering a collision as it stays in an orbital region with high debris density. In addition, if a fragmentation of the spacecraft would occur, it would have a large effect on operational satellites, whose density is also high around the MetOp-A operational altitude. As a consequence its impact on the debris environment is higher. For the remaining two cases, as expected, the lowering + decay strategy has a much reduced debris index than the previous case because it spends a shorter period in orbit and because it is at an altitude where the density of debris and of operational objects is much lower (Figure 6). Clearly, the debris index is still higher than the case of direct re-entry because of the time the satellite spends in the LEO environment during the decay phase. In contrast, the time spent in orbit is very limited, during the direct re-entry scenario. The difference can be explicitly observed looking at the re-entry time for the two cases. On one hand, the decay option takes almost 40 years to re-enter, whereas the direct case re-enters almost immediately. Looking at the casualty risk, the no re-entry scenario corresponds to a casualty risk of zero as no re-entry is actually performed in the considered timeframe. Instead, the difference between the decay and the direct re-entry scenario is mainly due to the difference in the re-entry epoch, which in turn corresponds to a difference in the world population. In fact, although the impacting mass is very similar for the two cases, the decay scenario has an almost doubled casualty risk expectation. As for the decay scenario the spacecraft re-enters almost 40 years later than the direct scenario, and as DRAMA uses an exponential law for the growth of the population, the difference between the world populations in the two cases is considerable.

Table 2. Comparison between three end-of-life scenarios for the MetOp-A mission.

EOL Scenario	$I_{\text{debris risk}}$	$I_{\text{casualty risk}}$	**Impact mass [kg]**	**Re-entry time [year]**
No re-entry	1.025E-02	0	0	n/a
Lowering + decay	1.698E-03	5.60E-04	192.306	39.4258
Direct re-entry	1.188E-03	2.96E-04	190.522	1.07E-04

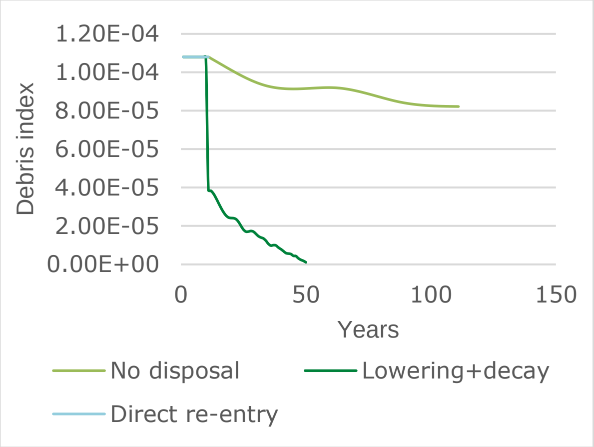
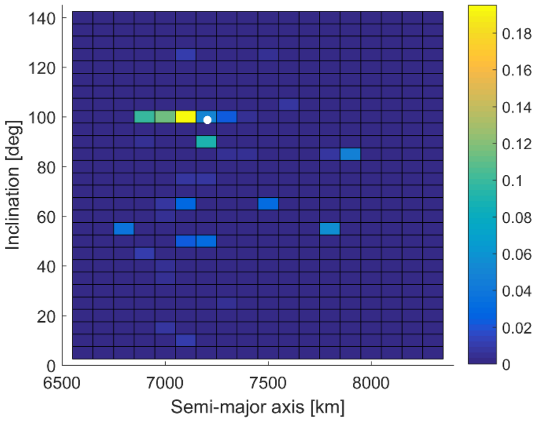


Figure 6. Evolution of the debris risk index over the mission profile for the three analysed EOL scenarios.

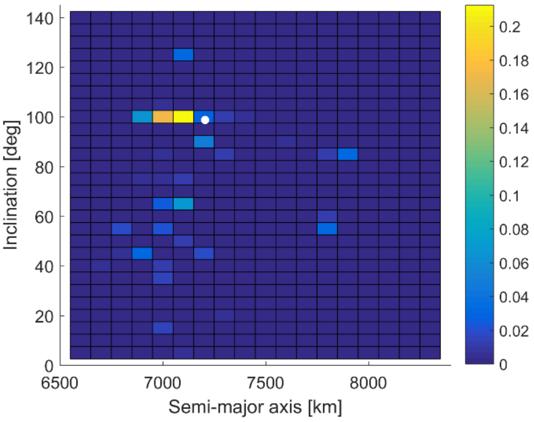
The result of the calculation of the space resource use index is shown in Table 3 in the case of the operational phase of the mission only. The first row shows the value of the bin where the operational orbit is and then the value of the index as calculated as in Eq. (4). The second row, shows the index (instantaneously and over the mission profile) considering also the revenue of the mission as in Eq. (5). In case a mission is considered, having a revenue double of the one of MetOp-A (an ideal mission named here MetOp-A*), the result is shown in the third row. The results are represented in Figure 7. The computation of the index for space reource use for other EOL scenarios has yet to be performed.

Table 3. Index space reource use during the operational phase of MetOp-A (5 year-duration).

EOL Scenario	$I_{\text{orbit resource}}$	Over operational mission profile [year]
Index nun s/c only	0.023107	0.011
Index nun s/c and revenue (MetOp-A)	4.2896	21.448
Index nun s/c and revenue (MetOp-A*)	2.1448	10.724



a)



b)

Figure 7. MetOp-A mission. Bin value for the space resource index calculation (a) Number of operational spacecraft in orbit bin normalised by the total number of s/c, (b) Total revenue of the missions in each a-i bin, normalised by the total revenue of all the missions considered in LEO.

The values of the indicator terms presented so far are not normalised. A preliminary analysis on the option of normalisation for the casualty risk and the debris risk will be shown on the three different mission profiles for MetOp-A, namely, no disposal, direct re-entry, and lowering plus decay re-entry.

For the casualty risk term the normalisation is performed on the threshold for controlled re-entry 10^{-4} and the results are contained in the second column of Table 4.

For the debris risk indicator we consider two different options discussed in Section 3.2. The first case is the normalisation with respect to Envisat, the second case is the normalisation with respect to Sentinel 2. Table 4 (column 3 and 4) show the results of the debris risk index normalised with respect to (1) Envisat at the reference epoch of 2016 and (2) Envisat on its natural orbit over 100 years starting from 2016. Figure 8 shows the evolution of the debris index of MetOp-A over 100 years for the three mission profiles, normalised with respect to Envisat in 2016. In addition, the debris index of Envisat over 100 years is represented. The areas under these curves represent the value of the debris index for the specific mission profile given in Table 4.

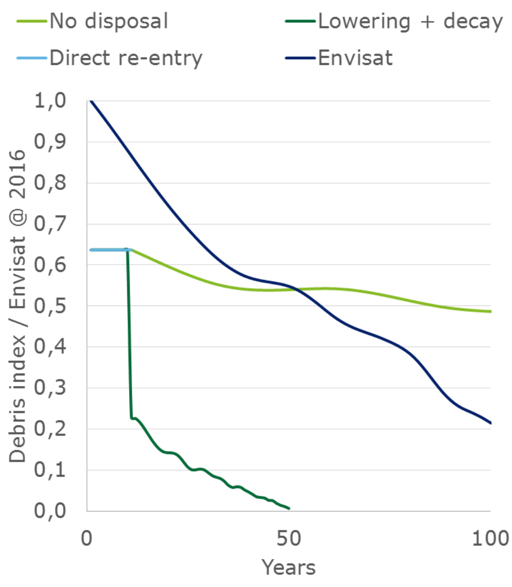


Figure 8. Debris index over time normalised with respect to Envisat at a reference epoch (2016) for MetOp-A over a period of 100 years for three disposal strategies. In addition, the mission profile for Envisat over 100 years is represented (blue line).

As an alternative option, a different satellite (not as critical as Envisat) could be selected for the normalisation. According to the rationale that we want to represents the analysis with respect to an average case and not with respect to one of the most critical spacecraft, the satellite Sentinel 2 can be chosen as the reference spacecraft. Table 4 (column 5 and 6) shows the results of the debris risk index normalised with respect to Sentinel 2 as it represents an average criticality inside the population [6]. Again, (1) the first option is the normalisation with respect to Sentinel at 2016 as reference epoch and (2) the second option is for Sentinel 2 over 100 years. In this case the values obtained are higher with respect to the normalisation with Envisat. With this normalisation, most of spacecraft should have a value of the index around 1 (similar to Sentinel 2), at least at the reference epoch, whereas very critical spacecraft will have a value higher than 1. The variation of the debris index for MetOp-A in 100 years with respect to Sentinel 2 for the three different mission scenarios is shown in Figure 9. The integral below the curves gives the numbers in Table 4.

Table 4. MetOp-A EOL disposal solutions. Casualty risk normalised with respect to casualty risk threshold. Debris risk normalised with respect to Envisat (1) at a reference epoch and (2) for a reference mission profile and Sentinel 2 (1) at a reference epoch and (2) for a reference mission profile.

EOL Scenario	Casualty risk norm.	Debris Index – Envisat norm		Debris Index – Sentinel2 norm	
		(1)	**(2)**	**(1)**	**(2)**
No re-entry	0	60.42	1.09	502.86	37.12
Lowering + decay	5.60	10.25	0.18	85.26	6.29
Direct re-entry	2.96	7.01	0.13	58.28	4.30

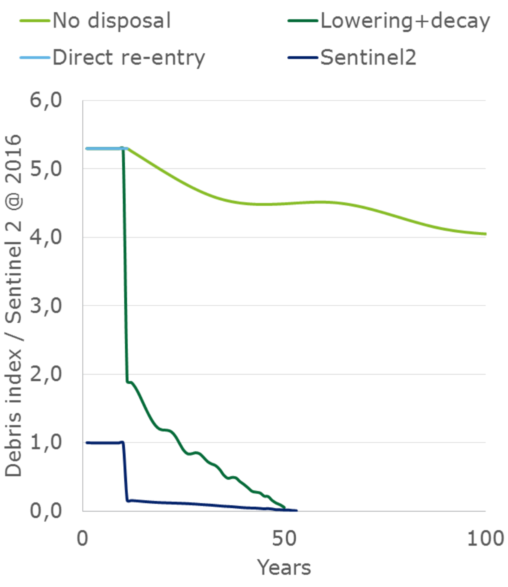


Figure 9. Debris index over time normalised with respect to Sentinel 2 at a reference epoch (2016) for MetOp-A over a period of 100 years for three disposal strategies. In addition, the mission profile for Sentinel 2 over 100 years is represented (blue line).

5 CONCLUSIONS

A design indicator to measure the management of end-of-life options and to compare different design options of a space mission from the perspective of the impacts of space debris has been proposed. Such an indicator could be used in preliminary mission design to optimise the eco-design of the spacecraft considering its demise at the end-of-life, and its interaction with respect to the space debris environment in term of the risk generated via a the collision with other spacecraft or explosion due to non-passivation of the spacecraft, and the casualty risk on ground. Such an indicator can also take into account the use of orbital space as resource measured through the spatial density of objects and/or the revenue of the missions occupying the same (or targeted) orbit. The pollution of the atmosphere, and the Earth's surface can be also considered directly in the Life Cycle Assessment framework. While the calculation of individual terms of the indicator has been completed, this paper represents the first attempt to define a normalisation and weighting that allows reaching a single-score indicator. The application of the approach to more test cases will allow the study of the sensitivity of the indicator and therefore its robustness and the definition of a final choice for the normalisation of the debris risk term and the use of space resource term. Future efforts will be devoted to the weighting process such that a single score indicator is obtained and to the communication of the devised indicator in an easy, accessible and clear way.

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