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Science of the Total Environment, Vol. 667, 2019, p. 780-791
doi:10.1016/j.scitotenv.2019.02.438

Assessing the impact of space debris on orbital resource in Life Cycle Assessment: a proposed method and case study

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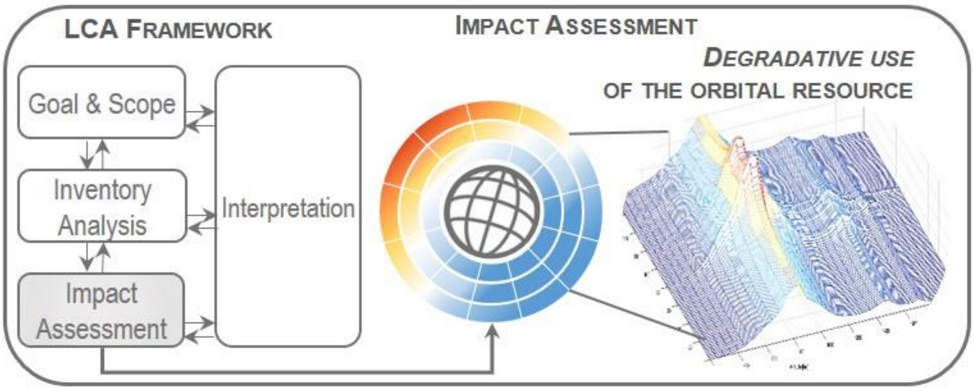
Highlights

- Proposed methodology to include *orbital space use* in the LCA framework
- Development of characterisation factors focusing on space debris related impact
- Design of a midpoint indicator to compare the potential impact of space missions
- Application *via* the analysis of three theoretical post-mission disposal scenarios

Graphical Abstract



Abstract

The space sector is a new area of development for Life Cycle Assessment (LCA) studies. However, it deals with strong particularities which complicate the use of LCA. One of the most important is that the space industry is the only human activity crossing all stages of the atmosphere during the launch event or the atmospheric re-entry. As a result, interactions occur not only with the natural environment but also with the orbital environment during the use phase and the end-of-life of space missions. In this context, there is a lack of indicators and methods to characterise the complete life-cycle of space systems including their impact on the orbital environment. The end-of-life of spacecraft is of particular concern: space debris proliferation is today a concrete threat for all space activities. Therefore, the proposed work aims at characterising the orbital environment in term of space debris crossing the orbital resource. A complete methodology and a set of characterisation factors at midpoint level are provided. They are based on two factors: (i) the exposure to space debris in a given orbit and (ii) the severity of a potential spacecraft break-up leading to the release of new debris in the orbital environment. Then, we demonstrate the feasibility of such approach through three theoretical post-mission disposal scenarios based on the Sentinel-1A mission parameters. The results are discussed against the propellant consumption needed in each case with the purpose of addressing potential 'burden shifting' that could occur between the Earth environment and the orbital one.

Keywords

Orbital environment, Space Debris, Life Cycle Assessment (LCA), Orbital resource use, Low Earth Orbits (LEO), End-of-Life (EoL).

Abbreviations

LCA, Life Cycle Assessment – LCI, Life Cycle Inventory – LCIA, Life Cycle Impact Assessment – AoP, Area-of-Protection – PMD, Post-Mission Disposal – EoL, End-of-Life – LEO, Low Earth Orbits – S/C, spacecraft – ESA, European Space Agency – EF, exposure factor – SF, severity factor

1. Introduction

LCA & Space sector. Several actors of or related to the space industry, such as ArianeGroup and the European Space Agency (ESA), have identified LCA as the most appropriate methodology to measure and minimise their environmental impact (ESA LCA Working Group, 2016; Saint-Amand, 2015). However, space systems deal with a strong particularity related to the use of LCA: space missions are the only human activity that crosses all stages of the atmosphere and stays "out" of the natural environment and ecosystems (Durrieu and Nelson, 2013). LCA could be applied in a holistic way to tackle a set of environmental concerns occurring on the Earth as well as on the orbital environment. In this way, the so-called "burden shifting", which consists of transferring environmental impact from one category to another, could be considered regarding both the Earth and orbital environments.

Integrating space debris issue. A proposal for integrating the orbital space use in LCA has been already analysed in an ESA funded study by Chanoine et al. (2018); Colombo et al. (2017a) and also published by Maury et al. (2017). In the first study, the orbital space use was modelled through a set of indexes indicating the use of space as a resource, the risk due to in-orbit collisions and explosions and their effects onto the active spacecraft environment and the casualty risk on ground during re-entry. The latter one instead suggests to integrate space orbits within the Area-of-Protection (AoP) 'Resources' in the framework published by Dewulf et al. (2015). Adopting a purely anthropocentric view, near-Earth orbits can be considered as an asset of natural resources supporting human activities. The functional value of this resource lies in ensuring a 'safe space' for space activities. This functional approach is widely accepted for assessing resource use in LCA (Dewulf et al., 2015; Sonderegger et al., 2017; Sonnemann et al., 2015; Stewart and Weidema, 2005; Verones et al., 2017).

A parallel between the orbital environment and the Earth environmental deterioration is suggested by Figure 1 which is based on the evolution of a set of environmental stressors proposed by Steffen et al. (2015). According to the Inter-Agency Space Debris Coordination Committee (IADC), space debris is all man-made objects including fragments and elements thereof, in Earth's orbit or re-entering the atmosphere that are non-functional. In this context, the space object population generated by past or present space missions designed without Post-Mission Disposal operations (PMD) (IADC, 2007) is threatening the future access to space reducing the quality of the orbital resource.

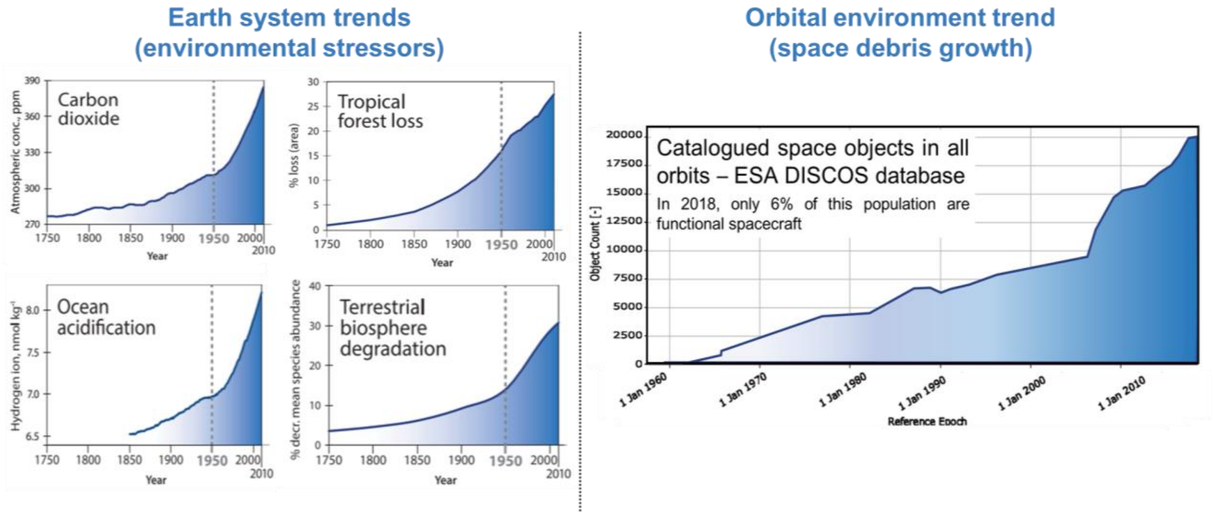


Figure 1 – Several well-known environmental stressors are presented on the left. 1950 is highlighted as the reference year. Space activities are more recent but the trend adopts the same exponential curve than for conventional environmental deterioration. (Freely adapted from Steffen et al., 2015 and ESA Space Debris Office, 2018).

Literature review. In the present paper, we will focus on space debris related impacts which is today widely discussed within the aerospace engineering community. Letizia et al., (2017) underline several indices have already been developed in recent years aiming at assessing the criticality of a spacecraft against the current or future debris population. Moreover, these indices can be used to target the best candidates for a future active debris removal campaign (Pardini and Anselmo, 2018) but also during the design phase of a space mission to identify the optimal strategy in term of end-of-life scenarios (Colombo et al., 2017a). Numerical and analytical approaches have already been proposed and discussed by several authors, based on the space debris density (Rossi et al., 2015) or the flux of particles (Anselmo and Pardini, 2015; Kebschull et al., 2014; Letizia et al., 2016). However, none of these contributions was developed in line with the Life Cycle Impact Assessment (LCIA) framework since they do not follow a clear impact pathway linking inventory and impact and/or damages through "characterisation factors".

Objectives of the paper. Therefore, the objective of this paper is to provide a new midpoint indicator adapted from the current literature and representing the potential impact of a space mission on the orbital environment. A comparison with the previously proposed indexes is carried out. This indicator should follow the framework proposed by Maury et al. (2017) which is based on an impact pathway in compliance with the LCA standards (ISO, 2006a, 2006b). Consequently, a complete set of *characterisation factors* (CFs) covering the overall circular Low Earth Orbits (LEO) is proposed hereafter to capture into LCA studies the potential contribution of a space mission to the space debris population. The goal is to ensure a more sustainable design for present and future space missions. Finally, the methodology is applied to a case study to prove its applicability. The impacts of a theoretical space mission based on the Sentinel-1A mission parameters occurring during the on-orbit lifetime (use phase and end-of-life) will be addressed through the comparison of three theoretical disposal scenarios as also done in Colombo et al. (2017a). For the first time, these results will be discussed against the propellant consumption needed for the PMD and the associated impact on climate change calculated as a proxy for a global environmental impact.

2. Material and methods

2.1 Proposal of impact pathways

In our understanding, two physical phenomena occur within the orbital environment. One deals with the exposure of space debris which increases the risk of a potential failure or loss of mission. In case of break-up, the release of space debris leads to a degradative use of the orbital resource for future space activities. It seems particularly the case for the LEO region, i.e. the spherical shape from the Earth's surface to 2.000km altitude (IADC, 2007), where 77% of the debris is concentrated (Krag et al., 2016).

The second phenomenon is related to space congestion, i.e. the occupation of a narrow orbital area by a certain amount of functional or non-functional spacecraft that can lead to a competition to access the orbital resource. This congestion issue would be analogous to the 'land competition' mentioned in the UNEP/SETAC Land Use framework (Koellner et al., 2013). Such concern involved more geopolitical issues and resource management than conventional environmental degradation. While near-Earth space is particularly wide, attention should be paid to future trends in term of space traffic particularly for special regions of interest. As a single circular orbit above the equator (altitude: 35 787km), the geostationary ring (GEO) encompasses a limited number of orbital "slots" that are available according to the geographic longitudes of the countries (IFRI, 2014). The Sun Synchronous Orbits (SSO) are also strategical: with high inclinations (typically around 98°), they support the majority of Earth's observation satellites thanks to their constant lighting conditions (Liou, 2011). Finally, orbits which are naturally compliant with the Space Debris Mitigation (SDM) requirements (i.e. with an altitude allowing a 25-year re-entry without any end-of-life management) should also be considered in this scope as they could be targeted in priority by future operators of very large groups of spacecraft called mega-constellations. A preliminary attempt on this occupation concern was presented by Colombo et al. (2017a) considering the spatial density of active satellites in fixed orbital bins and the space occupied by the considered mission during its operational and non-operational phase (i.e. 'space occupied as a resource').

The impact pathways related to the orbital space use and their integration into the AoP 'Natural Resources' are proposed in Figure 2. They are based on a cause-effect chain as recommended by Jolliet et al. (2003) and consider orbital resource as a final socio-economic asset (Verones et al., 2017) damaged by the presence of space debris (degradative use) or by the occupation of objects with limited functional value (consumptive use). Both are seen as a stressor of the orbital environment that could lead in a short term to a potential *orbital scarcity* for future activities. This paper focuses on *orbital occupation*, *exposure to debris* and *severity* in case of break-up for orbital systems as mentioned in Figure 2. The *orbital resource competition* describes through the *consumptive use pathway* is out of the scope.

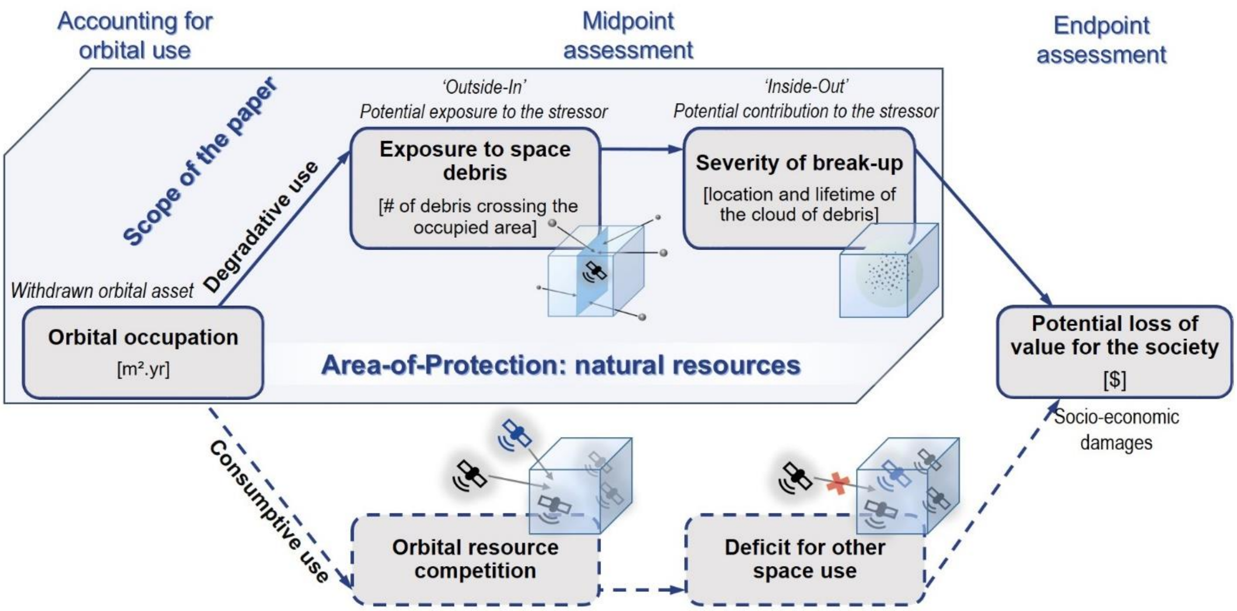


Figure 2 - Impact pathways proposal - only *degradative use* is further addressed

2.2 *Definition of life cycle inventory variables*

The impact pathway starts with the results of the life cycle inventory (LCI) step. The change in the asset of resource shall be evaluated with physical accounting. The use of space is depicted through the *orbital occupation* (see Figure 2). The latter corresponds to the orbital surface withdrawn by the studied objects multiplied by their respective on-orbit lifetime, expressed in m^2·*years* (see Eq.1). In the case of a spacecraft, the withdrawn surface depends on its design.

$$Orbital\ occupation = A_c \cdot \sum_{Orbits} t_i \qquad [m^2.yrs] \qquad \text{(Eq. 1)}$$

A_c is the average cross-sectional area of the S/C which is the product system under study in the case of the LCA of a space mission. According to ISO 27 8520 (2010), this design parameter is obtained by integrating the cross-sectional area across a uniform distribution of attitude of the spacecraft.

$\sum_{Orbits}(t_i)$ expresses the sum of the dwelling time into each orbital area i crossed by the trajectory of the spacecraft. This on-orbit lifetime covers the nominal time of the mission (use phase) plus the post-mission disposal duration representing the End-of-Life (EoL) phase. The trajectories for the nominal mission lifetime and the post-mission disposal are here propagated thanks to the Planetary Orbital Dynamics (PlanODyn) suite (Colombo, 2016). Supporting Information (§1.Keplerian orbital elements and orbit propagation) provides a further detailed description.

The *launch mass* of the spacecraft (in kg) is also considered as an inventory parameter: the dwelling time in orbit t_i is mainly dependent to the area-to-mass ratio which allows quantifying the effect of orbital mecanics perturbations (e.g. solar radiation pressure, atmospheric drag). Going further, the mass of the spacecraft is also the main parameter involved in the calculation of the number of debris generated when a break-up occur.

2.3 Exposure factor (Outside-in perspective)

Space debris is the main *stressor* affecting the functional value of the orbital resource. The interaction between the presence of this stressor in the orbital environment and any other space object under study follows an '*outside-in'* perspective. This concept was firstly addressed by Porter and Kramer (2006) and further defined as the potential impact of external environment on the product system by Cimprich et al. (2017). In this case, we can make a parallel with the supply risk of mineral resources in the frame of criticality assessment (Achzet and Helbig, 2013;

Drielsma et al., 2016b, 2016a; Mancini et al., 2016; Schneider et al., 2014; Sonderegger et al., 2019; Sonnemann et al., 2015).

The orbital *stress* caused by space debris should be assessed for the LEO region to obtain spatially differentiated factors since each orbit presents a different state which allows to classify and differentiate them accordingly. It is done by computing the flux of the catalogued objects in each LEO operational orbits as done in previous studies (Anselmo and Pardini, 2015; Kebschull et al., 2014; Letizia et al., 2016). It represents the background population (i.e. explosion and collision fragments, rocket bodies, dead and active spacecraft *etc*.). It does not represent debris that is potentially caused by the space mission under study.

Therefore, we define the *exposure factor* (XF_i) in Eq.2 as the average flux of space debris passing through a targeted circular orbit *i* of the LEO region for a period of one year.

$$XF_i = \overline{\phi}_{h,inc,t} \qquad [\#. m^{-2}. yr^{-1}] \qquad \text{(Eq.2)}$$

where XF is the exposure factor for a particular circular orbit *i*; $\overline{\phi}$ is the relative flux of catalogued particles provided by the ESA's reference model MASTER-2009 (Technische Universität Braunschweig, 2011) at a given altitude *(h)*, inclination *(inc)* and interval of time *(t)* averaged on a 35-year period based on a 'business-as-usual' perspective. Independent from the defined time interval (here 35years), the program output (flux) is always normalized to a period of one year. The 35-year period has been chosen with the aim of covering the orbital lifetime of a satellite completing a 10-year mission and a 25-year Post-Mission Disposal as required by the international standard (IADC, 2007). All debris which size is higher than 1 cm are accounted for in the population and all the sources for debris (apart from 'multi-layer insulation and 'clouds'). The detailed flux calculation method is provided in Supporting Information (§2. MASTER-2009: flux calculation).

We computed the relative flux of debris for all orbits in the range of altitude [200; 2000 km] with a 50 km-interval and the range of inclination [0;178°] with a 2° inclination interval. It led to the characterisation of 3330 orbits, and consequently 3330 runs of the MASTER-2009 program.

The product between orbital occupation (Eq 1) and exposure factors (Eq 2) gives the Eq.3. The latter formula can be used as a stand-alone risk indicator complementary to the LCA results (Sonnemann et al., 2018).

$$c = A_c \times \sum_{i=orbit} (t_i \times \bar{\Phi}_i) \qquad \text{(Eq.3)}$$

Where c is the mean number of collision occurring in a given orbit and during a certain period.

2.4 Severity factor (Inside-out perspective)

The second element taking into account to characterise the degradative use of space orbits is the severity of a potential break-up in the case of a collision between a space object and a space debris. It adopts an inside-out perspective which focuses on the contribution of the product system to the *stressor*.

The contribution to the *stressor* we define follows the approach developed by Krag et al. (2018, 2017a). Their model first quantifies the number of debris emitted in the orbital environment in case of catastrophic collision through the NASA Break-Up model presented in Eq.4 (Johnson et al., 2001; Krisko, 2011). This number of debris is derived from NASA empirical dataset: collision debris observations from both on-orbit and ground-test events are used. In the frame of the LCA framework, the quantity of debris released only depends on the mass of the product system and so is considered in the inventory phase.

Second, the model quantifies the temporal survivability of the cloud in the orbital environment with respect to its initial altitude of emission. It is based on the propagation of 10-cm debris until their complete decay taking into account a temporal cut-off rule of 200 years. In this way, the temporal fate of the cloud is characterised.

Number of fragments released into the orbital environment. The term ‘Fragments’ is defined by the IADC (2014) as the debris coming exclusively from a break-up or a collision and is further used in this paper. In the case of a catastrophic break-up (i.e. energy-to-mass ratio > 40 J/g), the following equation (Eq.4) is considered:

$$N(L_C) = 0.1(M)^{0.75} \cdot L_c^{-1.71} \quad \text{[fragments]} \qquad \text{(Eq. 4)}$$

Where N is the number of released fragments of size Lc, in meter. The value *M* is defined as the mass in kg of all objects generated in a catastrophic collision. As a proxy, we use the mass of the studied spacecraft as already done by Anselmo and Pardini (2015). The calculation of N follows two assumptions:

i. *Worst case scenario*: we consider a systematic catastrophic collision for all cases, i.e. the spacecraft is destroyed after the collision. It is not necessarily the case since debris smaller than 10 cm may only provoke the mission termination while generating a limited number of debris. Usually, only debris with a size around 10 cm or higher reaches the required energy (40 J/g) that provokes a catastrophic collision.

ii. *Size of the debris released:* we choose 10 cm as a lower cut-off (i.e. Lc = 0.1 m) in order to be in the range of the equation provided by Krag et al. (2017a). It means that only the generation of fragments larger than 10 cm is accounted for.

Survivability of the debris over time. According to Krag et al. (2018, 2017), the percentage of fragments > 10 cm released at an altitude *h (km)* and still on orbit after a given time *t* (yrs) follows the Eq.5:

$$P(t,h) = e^{-\frac{t}{128.3 - 0.585892 \cdot h + 0.00067 \cdot h^2}} \quad [\%] \qquad \text{(Eq. 5)}$$

Where P is the percentage of fragments (in %) still in orbit after a period t (in years) and h is the initial altitude of release (in km).

The cumulative residence time of debris into orbits is obtained by the integral of $P(t, h)$ over a given interval of time. Here, we choose the following time interval: [0:200] yrs. The polynomial part of the Eq. 5 is later expressed as ρ and can be considered as a constant in the integral which is only time-dependent. Thus, the *severity factor* (SF_i) for a break-up occurring in a given orbit *i*, is given in Eq.6. It represents the cumulative survivability of one fragment with respect to its altitude of emission expressed in years.

$$SF_{i,200\,yrs} = \int_{0\,yr}^{200yrs} e^{-\frac{t}{\rho}} = \left[-\boldsymbol{\rho}\cdot\boldsymbol{e}^{-\frac{t}{\rho}}\right]_{\mathbf{0}\,\boldsymbol{yrs}}^{\mathbf{200}\,\boldsymbol{yrs}} \quad \text{[years]} \qquad \text{(Eq. 6)}$$

The calculation procedure for the SFs is further detailed in Supporting Information (§3.Calculation of the severity factors (SFs)).

2.5 Midpoint characterisation model and impact score related to degradative use

Characterisation factors (CFs). Combining Eq.2 and Eq.6 we obtain the CFs calculated for a given circular orbit *i* as the product of the *exposure factor* and the *severity factor*:

$$CF_i = XF_i \cdot SF_i \qquad \text{[potential fragment.years]} \qquad \text{(Eq. 7)}$$

The result is given in *potential fragment·years* which represents the cumulative time survivability of a unique fragment in the orbital environment after a potential break-up. Applying the Eq.7 to a specific spacecraft (i.e. product system) which occupies one orbit *i* during a period *t* in years we obtained:

$$IS_i = A_c \cdot t \cdot k \cdot (M)^{0.75} \cdot CF_i \qquad \text{[potential fragments.years]} \qquad \text{(Eq. 8)}$$

Where IS is the impact score of a space mission in one orbit expressed in *potential fragments·years*. $[A_c \cdot t]$ is the orbital occupation defined in Eq.1, while $[k \cdot (M)^{0.75}]$ is the number of debris generated considering $k = 0.1 \cdot L_c^{-1.71} = 5.13$ if the lower size chosen is 10 cm. A space object crosses several orbits during its 'post-launch lifetime'. In such case, the impact score (IS) of the spacecraft considering its whole lifetime in orbit is:

$$IS_{mission} = A_c \cdot k \cdot (M)^{0.75} \cdot \sum_{i}^{orbits} t_i \cdot CF_i \qquad \text{(Eq. 9)}$$

2.6 Applicative case study

Theoretical space mission. The proposed CFs developed above were applied to characterise the potential impact of a spacecraft assuming equivalent characteristics than the Sentinel-1A satellite (Panetti et al., 2014). The same test case and EOL scenarios were proposed in Colombo et al. (2017a), allowing the results to be compared. The three PMD scenarios defined are the following:

1. *direct deorbiting*: the atmospheric re-entry occurs in less than one year after the end of the mission thanks to engine re-ignition and deorbiting;
2. *delayed re-entry*: a manoeuver is performed to reorbit the S/C with a lower perigee aiming at ensuring an atmospheric re-entry within the 25-years PMD threshold (IADC, 2007);
3. *no disposal management*: a natural decay due to the atmospheric drag can occur, mainly dependent on the atmospheric density and the initial altitude h of the spacecraft's operational orbit. Hence, in case of no disposal, the remaining time in orbit can vary between less than a decade for lowest orbit altitudes (<500 km) to several centuries for orbits above 800 km.

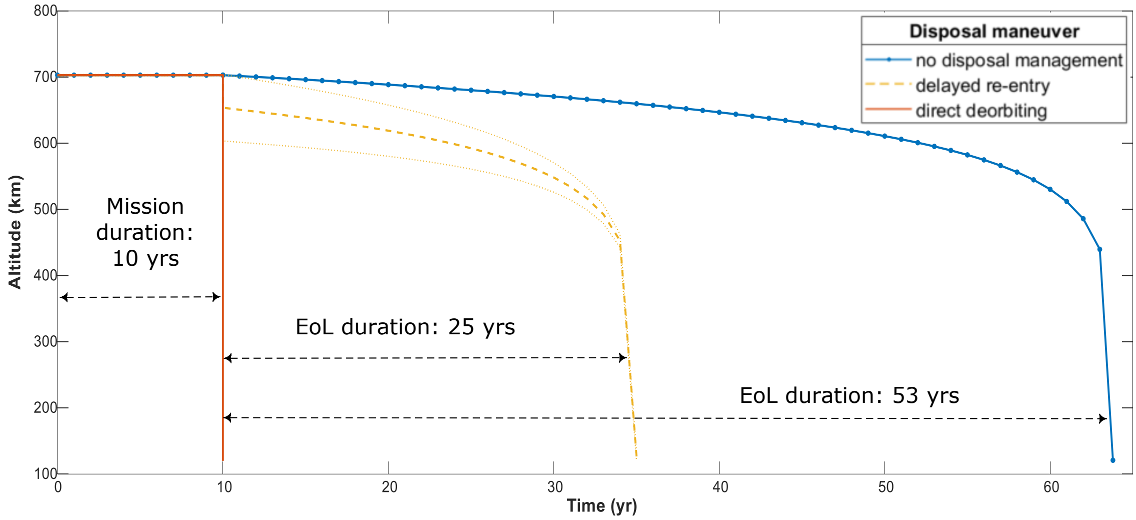


Figure 3 - Semi-major axis of the spacecraft during the operational time of the mission and its Post-Mission Disposal. The average cross-section area is similar to Sentinel-1A and was estimated at 23 m^2 according to ESA DISCOS database (ESA's Space Debris Office, n.d.)

The latter EoL scenarios are depicted in Figure 3. The impact score is calculated according to the Eq. 9 for each EoL scenarios. The launch mass of the spacecraft equals to 2157 kg and its average cross-sectional area is 23 m^2. With the considered drag model for the orbit propagation, the nominal operational lifetime for Sentinel-1A is expected for 7,5 years. However, the amount of embedded propellant reaches 154 kg of hydrazine and can cover an extended timespan, ensuring on-orbit operation for 12 years (Panetti et al., 2014). According to this data, we assume an operational lifetime of 10 years (i.e. use phase).

Propellant consumption. A simplified study addressing the potential 'burden shifting' between orbital and environmental impacts related to EoL management is proposed. The goal is to analyse the environmental impact of the additional Hydrazine budget allocated for the disposal manoeuvre (*deorbiting* or *reorbiting*) against the impact score obtained for each mission profile (see **Error! Reference source not found.**). We propose to calculate a theoretical amount of propellant needed for the mission and the chosen PMD scenarios and then add them. The procedure is detailed in Supporting Information (§4.Propellant consumption).

To compare the three theoretical EoL scenarios the following functional unit were chosen: *"Complete a 10-year mission followed by its removal from the operational orbit (inc=98°, h=703 km) until its atmospheric re-entry (h=120 km)"*. Further details related to the calculation of the theoretical amount of hydrazine, the associated product system description and its characterisation in terms of environmental impacts are given in Supporting Information (§4.Propellant consumption). We consider that the combustion of hydrazine occurring during the mission and PMD do not generate emissions since they do not generate impacts in the outer space. To get an overview of the environmental impact we chose to present climate change impact related of propellant manufacturing based on the greenhouse gas quantification method proposed by the Intergovernmental Panel on Climate Change (IPCC, 2007). In this way, we can assess the burden shifting between the potential generation of debris related to a mission and the environmental impact related to the manufacturing hydrazine propellant.

3. <u>Results</u>

3.1 Characterisation factors for the LEO region

Complete result data are provided in Supporting Information (excel sheet § 5.Complete set of exposure, severity and characterisation factors (CFs)). It gives the values of the XF_i, SF_i, and CF_i which characterise the *degradative use* of the orbital resource at the midpoint level.

Exposure factors. Figure 4 shows the mapping of the exposure factors *(i.e. the outside-in* perspective) covering the LEO region from 200 to 2000 km with 2°×50 km interval bins obtained from MASTER-2009 model (Technische Universität Braunschweig, 2011).

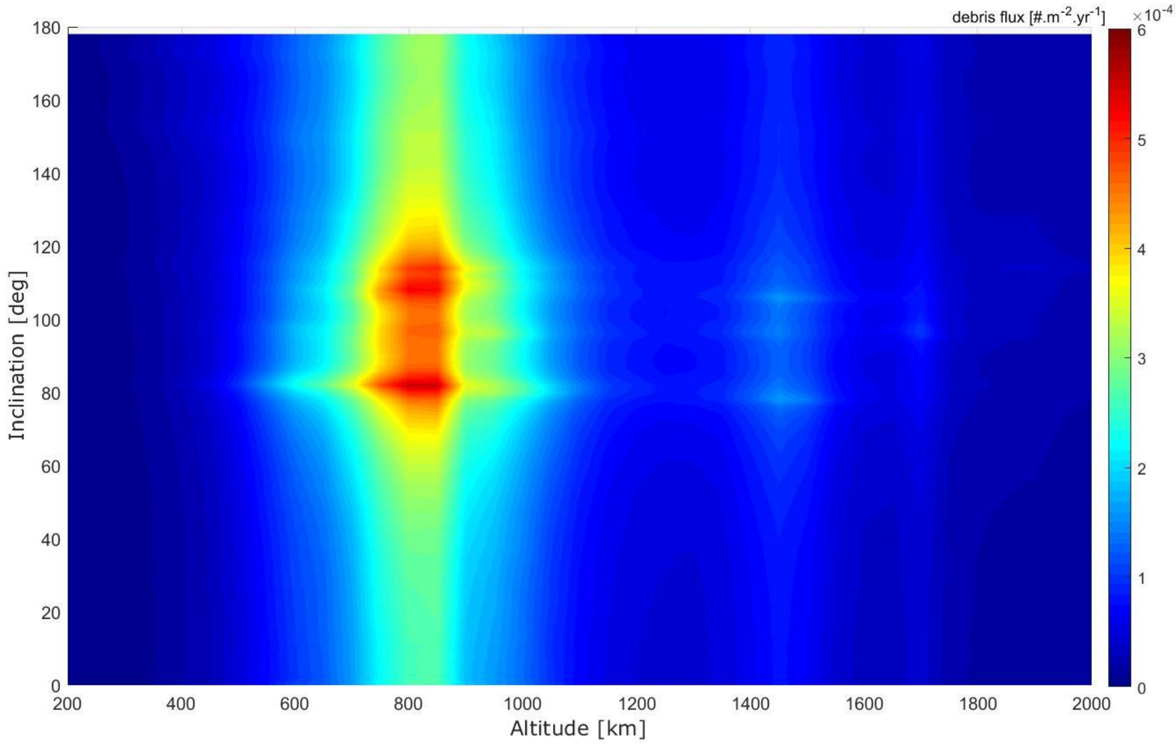


Figure 4 – XFs: Average relative flux of debris [#·m^{-2}·yr^{-1}] vs Altitude [km] and Inclination [deg] – Time range (yr) [2018-2053] – size (m) [0.01-100] – MASTER-2009 Model, Business as Usual perspective. Calculations are made for each of the 3330 discretised circular orbits

We observe an unequal distribution of the flux according to the altitude and the inclination. A statistical range of 2 orders of magnitude can be observed between the minimum and the maximum values in LEO. More precisely, the 20% largest values which cover the main areas of interest for space activities, are seven times higher than the 20% lowest. Some areas present particularly low values: it is the case for the regions below 450 km where the atmospheric decay remove the debris quickly and for the band above 1800 km where very few space activities take place. In general, the orbits with an orbital plan inclination above 120° and below 50° encounter a lower flux of space debris than the rest of orbits. This is mainly due to a more limited potential velocity of collision than for highly inclined orbit: the complete map of the most probable velocity of collision is available in Supporting Information (§2.MASTER-2009: flux calculation).

The highest flux of debris crossed the altitude band from 750 to 950 km where the spatial density above 1-cm size is the most important and distributed between explosion fragments, collision fragments, Sodium-potassium coolant droplets, solid rocket motor slag and to a lesser extent launch and mission-related objects (IAA, 2017). Past events, particularly Fegyun-1C destruction and Cosmos-Iridium collision are the main contributors (Anz-Meador, 2016) even though a narrow orbital decay occurs.

In general, the highly inclined orbits, particularly inclination bins around 82° and 108°, present the most important flux. This is the result of past breakups in near-polar and SSO orbits where the flight path of the debris is parallel to the small circle of latitude at the northernmost and southernmost parts of an orbit leading to a higher residence probability at high inclination. The outputs from the MASTER-2009 model indicate an average impact velocity around 12 km/s between a spacecraft and the flux of debris crossing the region encompassing orbits around 98° within the 750-950 km band. However, in the latter area, the most probable relative velocity is higher than the average and reaches 14.5 km/s contributing to a higher value of the flux (see Supporting Information).

Another region of interest is around 1500 km where explosion fragments are the main stressors (Technische Universität Braunschweig, 2011). It comes from past break-up events particularly, the three Delta second stage breakups in 1973,74 and 77, and other Cosmos rocket body breakups, particularly in 1991 and 99 (Anz-Meador, 2016; Orbital Debris Program Office, 2004). Even if a few numbers of collisions will occur there in the next decades, the generated fragments will stay within the region for centuries due to the absence of a sink effect related to the atmospheric drag. Because several mega-constellations of satellites are expected within the orbital band around 1400 km (Henry, 2018), it could lead to a substantial additional hazard in the future.

Severity factors. Figure 45 shows the mapping of the severity factors for the LEO region *(i.e. the inside-out* perspective) according to Equation 6. The calculation of these SFs is detailed in Supporting Information (§3.Calculation of the severity factors (SFs)). The severity factor increases with the altitude because the survivability time of a fragment also increases with the altitude. This is because the debris decays naturally with the atmospheric drag at low altitude. The inclination of the orbital plane does not influence the value of the SFs.

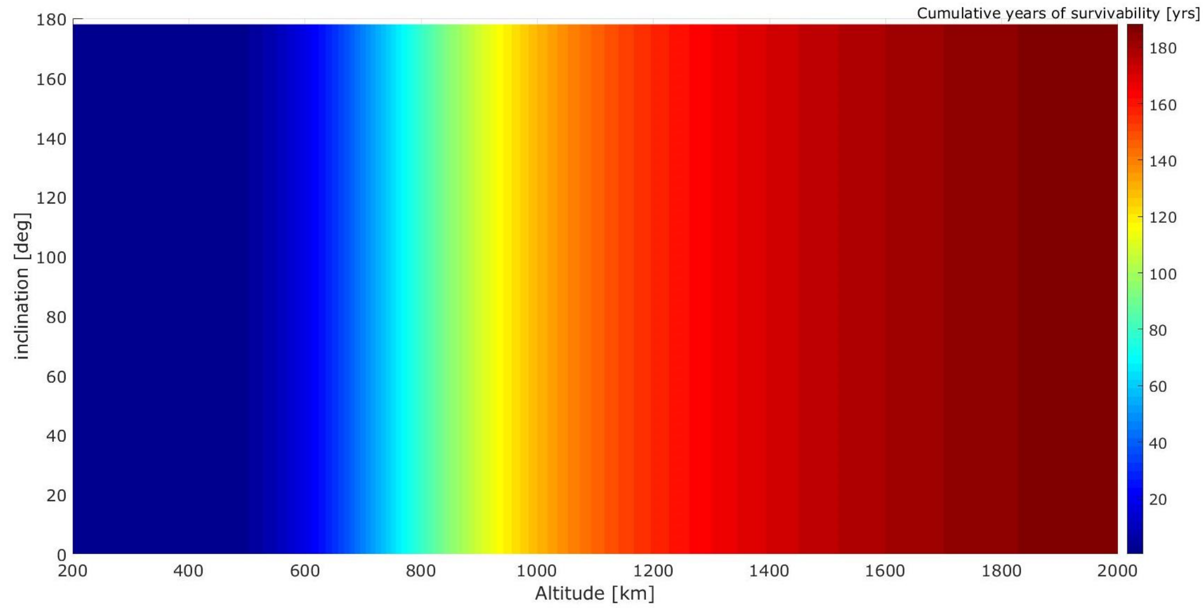


Figure 5 – SFs: Cumulative survivability (in years) of debris in the LEO environment according to its altitude of release and considering a 200 years prospective scenario.

Characterisation factors. The characterisation model for the *degradative use* at midpoint level is obtained with Equation 7. Figure 6 shows the mapping of the CFs which depict the degradative use (i.e. $XF_i \cdot SF_i$) of the orbital resource through the potential emission of debris in the orbital environment.

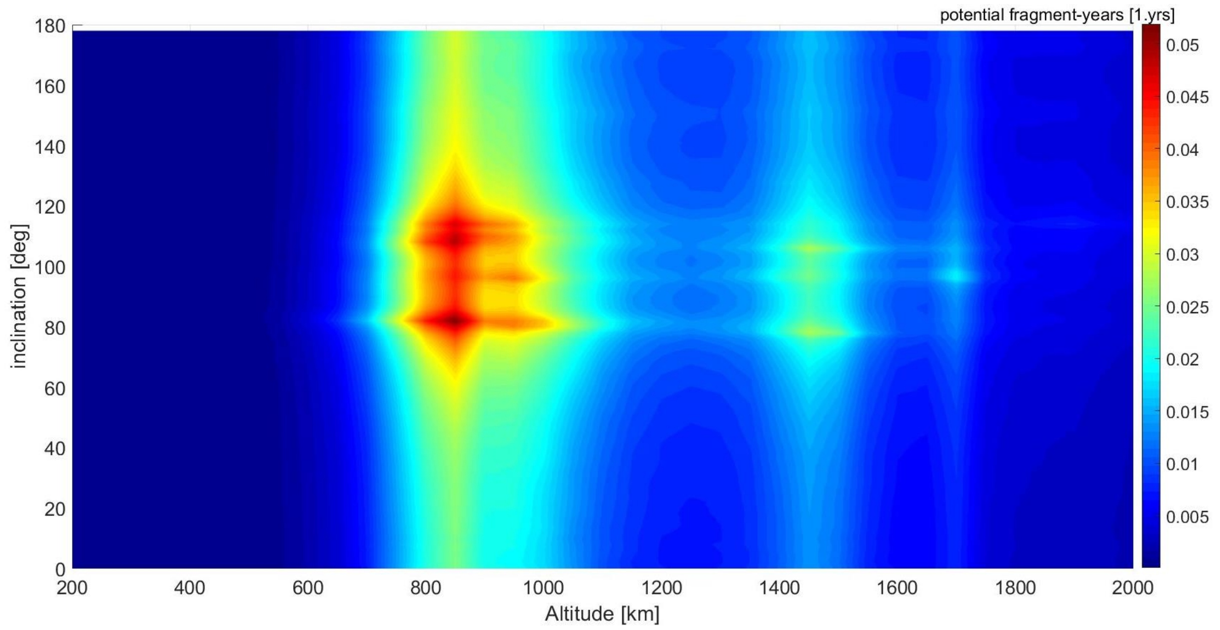


Figure 6 – Potential fragment·year generated as a midpoint characterisation model for the *degradative use* of the orbital resource. Calculations are made for each of the 3330 discretised circular orbits.

The variation of the CFs results is mainly influenced by the flux of debris already presented above in Figure 4. To a lesser extent, the temporal survivability of a fragment in the orbital environment which depends on its altitude of emission contributes to the global impact. It is highlighted by the values around 900 km and for the band at 1450 km that were less noticeable for the exposure factors.

3.2 Results for a given space mission

Impact scores for *degradative use*. Figure 7-a shows the potential number of *fragments·years* generated by each EoL scenarios. We observe that the impact is four times higher when no EoL management is performed (i.e. 53-year EoL duration) than in the case of direct deorbiting for which the contribution of the EoL impact corresponds to zero. The 25-year PMD is an intermediate case reducing the impact by a factor 2.4 compared with the 'no PMD management' option.

Hydrazine consumption and associated environmental impacts. The theoretical use of fuel for a 10-year mission was calculated based on the initial 154 kg of hydrazine fuelled to cover a

12-year period. Also, the theoretical consumption according to the PMD scenarios was calculated. The results are presented in Supporting Information (§4. Propellant consumption) and in Figure 7-b.

These propellant consumptions can be used as a proxy for the environmental impact. We chose to highlight this impact caused by the additional manufactured hydrazine through a mono-criteria assessment representing only the impact on the climate change, expressed in mass of carbon dioxide equivalent. The result shows that 1 kg of Hydrazine at 99% grade causes about 59.3 kg CO_2 eq. taking into account all the manufacturing and handling operations until the final fuelling before the launch (see Supporting Information, §4.Propellant consumption). The emissions of chemicals resulting from the fuel burning in the outer space are not considered. The total impact on climate change related to the mass hydrazine consumed (Figure 7-b) for the operating phase and the EoL is presented in Figure 7-c and expressed in metric tonnes of carbon dioxide equivalent (t.CO_2 eq.).

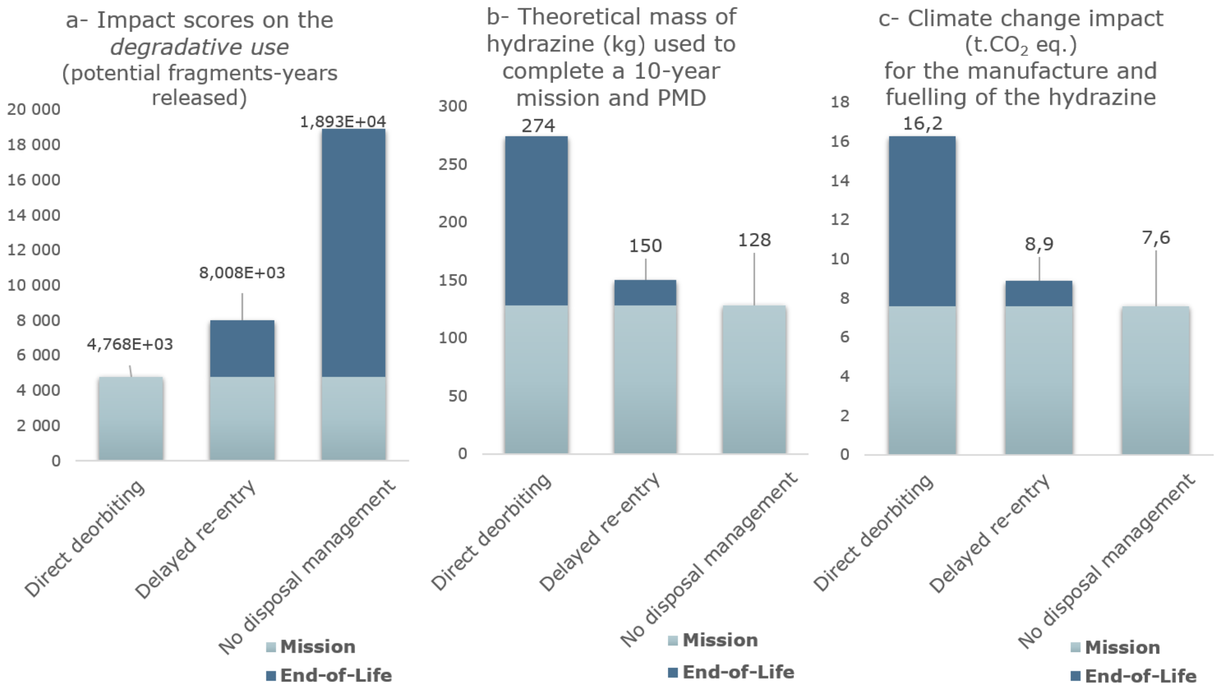


Figure 7 – Sentinel-1A impacts related to *degradative use* midpoint (a) against the theoretical mass of hydrazine consumed to complete the mission (b) and the associated climate change of hydrazine manufactured and fuelled into the S/C (c).

The necessity of removing the spacecraft after the completion of the mission is more and more required by the international guidelines, particularly in Europe with the French Space Act (Legifrance, 2011). Thus, it is not a suitable option to disregard the post-mission disposal (i.e. the case of *no disposal management*) as it could lead to a severe impact on the orbital environment. However, the results show that a substantial amount of propellant is needed to perform a disposal manoeuvre. Therefore, the trade-off between the mitigation of space debris related impact and the increase of propellant budget for PMD shall be taken into account when eco-designing a space mission.

4. Discussions

The method for the creation of the midpoint indicator related to the *degradative use* of the orbital resource caused by the potential release of space debris was evaluated against the specific criteria for midpoint impacts defined in the ILCD handbook (European commission-

JRC, 2010). These guidelines provided in this handbook were used to structure the comparison between our method and other approaches.

4.1 Completeness of the scope

The paper presents a set of CFs addressing the impact of a space mission on the orbital environment. These CFs enable the aggregation of all LCI representing orbital space occupation in the LEO region.

On the one hand, it captures the *geographical* variability of the impact: the LEO region is spatially discretised through 3330 circular orbits. In order to complete the geographical scope of the study, additional CFs could be calculated for other near-Earth regions: the Medium Earth Orbit (MEO) which supports mainly the navigation satellites (GPS services) and for the GEO region. Recent studies focusing on the flux of debris crossing the GEO region (Dongfang et al., 2017; Oltrogge et al., 2018), combined with recent anomalous events (NASA, 2018), suggest that the threat could be greater than it has been assumed until now. In a short-term, the space debris pressure into MEO region seems nonetheless less important (Johnson, 2010). Moreover, the eccentricity parameter should be considered in the characterisation model to integrate non-circular orbits. In this way, Geo Transfer Orbits (GTO) supporting an important share of the orbiting upper stages could be covered. A preliminary result in this direction is presented in Chanoine et al. (2018).

On the other hand, the time variability is taken into account since the flux of debris is computed for the next 35 years in a Business as Usual perspective which is the most conservative approach related to future population scenarios. Dealing with the severity, the cumulative temporal fate is characterised over a 200-year period.

Thanks to this characterisation model, the exposure and potential release of debris of every single object can be calculated considering a systematic catastrophic collision. The midpoint impact indicator allows the comparison with existing or future orbital objects (dead or functional spacecraft, rocket bodies or mission-related objects) as long as the functional unit chosen to make the comparison and the perimeter of the product systems under comparison are fully compatible.

4.2 Environmental relevance

We consider that the full impact pathway (Figure 2) is relevant regarding the definition of natural resources and impacts caused by their use which are currently recommended by the LCA community (Berger et al., 2019; Sonderegger et al., 2019, 2017; Verones et al., 2017). The proposed impact modelling incorporates a combination of life-cycle and risk assessment methods. It involves a complete integration of both in the LCIA framework instead of merely combining their results in a complementary use (Harder et al., 2015; Sonnemann et al., 2018; Tsang et al., 2017)

Both *outside-in* and *inside-out* perspectives are proposed since we assessed the XFs and the SFs of a given object. The consequences of a potential catastrophic break-up are calculated in a *worst case* approach considering a catastrophic collision. In a next step, non-catastrophic and catastrophic collision should be differentiated following the relationships given by Krisko, (2011). In this way, the flux of debris encountered by the satellites could be differentiated between (i) lethal non-trackable debris over 1 cm that may provoke mission-terminating events but a limited release of debris; (ii) debris over 10 cm, that reaches an sufficient energy-to-mass ratio leading to a catastrophic collision associated with the release of a large cloud of debris. Regarding the threat caused by debris over 10 cm, it can be mitigated thanks to collision avoidance manoeuvers that are not included in the scope of our study. Indeed, the indicator represents only potential exposure to debris and its consequences for the orbital environment in the worst case, *i.e.* without any additional intervention from the operators during the use phase.

The potential debris emitted could lead to an additional cascading collision with other spacecraft orbiting in the surrounding areas which would further reduce the availability of 'safe space'. Dealing with the modelling of the debris cloud's behaviour, we proposed a proxy based on work presented by Krag et al. (2017a). The fate of the debris cloud is only approached through the temporal dimension but not according to its geographical distribution. More complete approaches based on a density model of the cloud should be considered in a further development to fully characterised the cloud at any point in space and time (Frey et al., 2019, 2017, Letizia et al., 2017, 2016, 2015).

At the endpoint level, 'future efforts' methods based on cost externalities are seen today as a promising approach for mineral resource use (Berger et al., 2019; Sonderegger et al., 2019). Considering the orbital resource, the externalities could be evaluated through the loss of welfare and/or economic value caused by restricted access to this resource. Nevertheless, it seems complicated to establish the valuation of the orbital resource in itself: orbital use is very distinct from traditional resource use and cannot be estimated using a market price as it is the case for the trade of mineral resources for example. Adopting a fully anthropocentric point of view, the active satellites supported by the orbital resource could be considered as the only economic asset in the Near-Earth space. In this way, the Total Economic Value (TEV) provided by active satellites seems the most appropriate valuation of the orbital resource (Esteve, 2017). In case of a break-up, potential damages on other active satellites will affect the downstream supply chain of services directly. This negative socio-economic externality should be evaluated focusing on the potential loss of value for the society. To that extent, a preliminary statistical study (Maynard et al., 2018) was proposed to compute the actualised value of potential negative externality caused by debris. It is based on the 'use value' generated for end users by each active satellite in orbit according to its specifications, e.g. type of mission, satellite position, embedded scientific instruments, *etc*.

Besides, a further investigation is needed to evaluate the reserve size and the regeneration rate of the orbital asset. The carrying capacity of the orbital environment is a relevant parameter to do so. According to Bjorn and Hauschild (2015), the carrying capacity is defined as the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert. The recent work proposed by Krag et al. (2018, 2017a) assumes a carrying capacity dealing with the potential debris creation into of the space environment. A *distance-to-target* approach could be based on the space environment's capacity estimated *via* the adherence level to space debris mitigation guidelines, mainly the success rate of disposal. It would allow comparing through a normalised use-to-availability ratio the contribution of each product system under study. Also, a physical threshold or boundary could be established based on this approach, beyond which the orbital environment will face an instability or a runaway process, known as the Kessler syndrome (Kessler and Johnson, 2010).

4.3 Scientific robustness

The robustness of the model developed in this paper can be assessed through *(i.)* its comparison to previous models and indicators developed within the space debris scientific community and *(ii.)* the comparison of the result obtained for the case study.

i. The original researches proposed in the field of aerospace engineering by Anselmo and Pardini (2017, 2015); Pardini and Anselmo, (2018), and going further by Letizia et al., (2018, 2017, 2016) are particularly interesting to confirm and strengthen our approach based on the LCIA framework. These previous investigations, as well as the *exposure* we propose in Eq.3, are based on the law of kinetic gas theory as presented in Klinkrad et al., (2006a) and given by the Eq. 10.

$$c = v \cdot D \cdot A_c \cdot \Delta t \tag{Eq.10}$$

$$P_i = 1 - \exp(-c) \tag{Eq. 11}$$

$$Criticality_i = P_i \cdot Impact_i \qquad \text{(Eq. 12)}$$

where $\boldsymbol{c}$ is the mean number of collision encountered by an object of collision cross-section A_c, moving through a stationary medium of uniform particle density D, at a constant velocity v, during a propagation time interval Δt. Eq.3 proposed above stems from this formula. According to Eq.10, P_i is the impact probability which follows a Poisson distribution. All the indexes mentioned above follow the criticality-based relationship (Eq.12) describes by Kebschull et al., (2014) where the criticality of an event *i* is addressed as the product of the *likelihood* P_i by the $Impact_i$. It is also the case of our proposal (Eq.9) which is similar to the formula obtained by Krag et al. (2017a) even if in our case a clear distinction is introduced between inventory parameters (*area, mass, and in-orbit lifetime*) and the CFs which are composed by the XFs and SFs.

The severity aspect is characterised by Anselmo and Pardini (2015) through the concept of collisional debris cloud decay of 50% of the fragments (CDCD50) computed as a function of the breakup altitude and an average solar activity based on past catastrophic events (Pardini and Anselmo, 2014). Thus, the long-term severity is expressed with a time-related parameter which is closed to the percentage of the remaining fragments in orbit after the break-up given by Krag et al. (2017a) and used in our approach. Nevertheless, while Anselmo and Pardini (2015) also consider the interaction of the resulting cloud of fragments with the pre-existing debris distribution through a dedicated factor, we ignore the associated feedback effects with the rest of the environment.

Moreover, Letizia et al., (2018) published an index recently using the MASTER-2009 model. Based on a semi-analytical method, the MASTER software was used to determine the distribution of the space debris density and the most likely impact velocity for different circular orbital regimes. Their work focuses on the characterisation of the LEO orbits regarding the consequence of a potential break-up in term of debris density modelling and its evolution over time as a cloud into the orbits (i.e. *severity* aspect). From our part, we only used the numerical approach proposed by the MASTER-2009 software to obtain a map of the variations of the flux multiplied by the time-related survivability of the potential cloud generated (Figure 6). Even if the physical meaning is different, the MASTER-2009 model gives comparable results in both cases: the computed maps highlight the same orbital areas. The most critical orbits are differentiated in the same way showing the *scarcity* level of ‘safe space’ in the LEO region.

ii. Considering our case study, the results of the impact score (IS) are in line with those presented by Colombo et al. (2017b). The two ‘debris indicators’ are different but in the particular case of Sentinel-1A, we found that the ratio between the scores obtained from one post-mission disposal scenario to another is in close agreement. Also, we calculated the probability of collision combining Eq.3 and Eq.11: the $\boldsymbol{c}$ parameter during the operational phase corresponds to an average of 6,41E-3 debris per year. Assuming a minimum of 7,5 years as nominal lifetime, the cumulative probability of collision P_i reaches 4,7%. Previous analysis on short-term collision risk was led in a very detailed manner by the Sentinel-1A’s designer, subdividing all functions within a general fault tree and analysing the effects of impacts on each critical element of the satellite through a complete physical model. It showed a cumulative probability of 3.2% loss of mission over the 7,5 year lifetime of Sentinel-1 (Bonnal et al., 2013). Both values seem coherent because in our case, the impact of the collision is not differentiated according to the location on the shape: the average geometric cross-section of the S/C is chosen which maximises the exposure. Also, our model overestimates the flux of debris compared with the one used in this specific study. Indeed, we calculated a yearly flux averaged on the next 35 yrs in a Business as Usual perspective.

4.4 Uncertainty

The uncertainties of the characterisation model come firstly from the MASTER-2009 model. Regarding the particles sizes, the MASTER-2009 model has been validated for the 1cm population in LEO based on observation data, which ensures an accurate representation of the reality (Horstmann et al., 2018, 2017). Therefore, the threshold of 1 cm was chosen to cover most of the debris sources, particularly solid rocket motor slag and sodium-potassium droplets which represent together a share of around 10% in the overall population of debris larger than 1cm.

The modelling of future debris evolution is also one of the main sources of uncertainty. Monte Carlo runs were performed by the MASTER model's designers from the 2009-reference year up to 2060 to the analyse the uncertainty linked to the future population growth in the Business-as-Usual scenarios (Technische Universität Braunschweig, 2011). The major sources of uncertainty come from the future number of collisions which raise 14.7 events along the period with a standard deviation of 4.5 and to a lesser extent the number of explosion with a standard deviation of 0.4 for a mean value of 5.6 events. The other sources of debris face lower standard variation.

Another uncertainty is associated with the discretisation of the LEO region following the orbital coordinates. Due to the orbital bin definition, the orbit crossed by the calculated flux of debris is given with an accuracy of ±5km for the altitude and ±1° for the inclination.

Finally, the drag model used for computing the orbit long term evolution as well as the decay of the fragment cloud faces significant uncertainties. Indeed it is known that the modelling of the atmosphere density contains uncertainty due to our poor knowledge of the solar activity and the spacecraft attitude and drag coefficient during re-entry.

4.5 Documentation, transparency and reproducibility

The XFs calculation derives from the MASTER-2009 model (Technische Universität Braunschweig, 2014a, 2011) which is currently the ESA's reference model, freely available and widely accepted by the international community (IADC, 2013; Krisko et al., 2015). The SFs are based on the approach publicly presented by Krag et al. (2018, 2017a).

The values of the CFs supporting the study are openly available through the datasheet provided in the Supporting information (see § 5.Complete set of exposure, severity and characterisation factors (CFs)). Also, the whole CFs can be recalculated thanks to the MASTER software and the equations detailed above ensuring the reproducibility of the results.

Regarding the case study, the orbit trajectories were determined with PlanODyn model (Colombo, 2016). This orbit propagator is an internal tool of the Politecnico Di Milano Aerospace Science and Technology which will be publicly available online in the near future. It should be noted that other semi-analytic orbit propagators as STELA software (CNES, 2017) or the OSCAR tool of the ESA-DRAMA suite (Technische Universität Braunschweig, 2014b) are publicly available.

4.6 Applicability

This methodology is mainly targeted to LCA practitioners studying the environmental impact of space systems. The applicability of the given CFs has been demonstrated through a theoretical case study comparing several EoL scenarios.

In a broader LCA perspective, the inclusion of potential *avoided impacts* dealing with the *orbital space use* category could be envisaged in the frame of the in-orbit servicing and active debris removal (ADR) provided by a 'space tug'. The removal of targeted objects with potential 'high impact' would give an *environmental benefit* computed through a 'negative impact' score. We can make the parallel with recycling processes in LCA that contribute negatively (in term of impacts) to the whole environmental profile of the product system under study.

5. Conclusion and outlook

In this paper, we propose a set of CFs aiming at characterising the exposure of a space mission to space debris (*outside-in approach*) and the temporal fate of the potential fragment cloud released in case of a catastrophic collision (*inside-out approach*). The entire LEO region is characterised through circular orbits. Theses CFs allow covering the post-launch life cycle phases occurring in orbits, resulting in the assessment of space missions' potential impact on the orbital environment. Therefore, the present work extends the scope of the LCA studies for complete space missions. In a further step, the model could be extended to cover other orbital regions than the circular LEO. Also, the characterisation regarding the fate of the cloud could be refined taking into account the density distribution of the cloud over time.

Broadening the scope, this impact category can also be used in the LCA of products and services that need spatial activity in their supply chain: telecommunications, earth observation, *etc*. The current limit to such an application is the integration of satellites' life cycle within these product systems. In this way, the impact on the orbital environment caused by an end-user activity on Earth could be determined. Going further, the amount of data generated by different space activities could be compared regarding the orbital resource intensity required for each activity. An absolute environmental sustainability assessment (Bjørn et al., 2018) based on the physical capacity of the outer space seems currently difficult to reach. Nevertheless, a distance-to-target approach allowing normalisation of each contribution as proposed by Krag et al. (2017a) and based on international political consensus could be a relevant option.

Acknowledgements

The authors acknowledge the support of the French National Association for Technical Research (CIFRE Convention 2015/1269). This research is cofounded by the R&T department of the ArianeGroup in the frame of the Eco-space project.

We also acknowledge the project COMPASS "Control for Orbit Manoeuvering through Perturbations for Application to Space Systems (Grant agreement No 679086) funded by the

European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme.

Finally, we thank the anonymous reviewers that provided valuable comments and helpful suggestions to improve the manuscript.

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