Implementing materials fragmentation in the Life Cycle Assessment of orbital spacecraft

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Abstract

Space debris are a primary environmental concern for the sustainability of space mission activities. When considering terrestrial applications, the Life Cycle Assessment represents a widely standardised technique for estimating the environmental impacts of human activities; however, its implementation in the space-related value chain is still in an early stage. In this study, the implications of two alternative materials in the development of a CubeSat structural bus are investigated with reference to the well-established categories for the Life Cycle Impact Assessment. Moreover, the potential impact of these materials on the orbital environment is quantified by the evaluation of the number of generated fragments upon collision for different significant low Earth orbits. The results of this study allow to quantify the impact of alternative design solutions for space systems on the terrestrial environment as well as the degradation of the orbital resources as a result of the space debris generation.

Keywords: Aerospace structures; CubeSat; Metals and alloys; Space environment; Space debris; Life cycle analysis

1. Introduction

The space around Earth is populated by a multitude of orbiting objects whose only a limited number is represented by operational satellites. The vast majority is composed by fragments formed during collisions and explosions, upper stages of rocket launchers, and abandoned spacecraft (ESA Space Debris Office, 2022; Miraux, 2022). This situation derived partially from the lack of End-of-Life (EoL) management of spacecraft, as no disposal or re-entry procedures were planned for these objects in the beginning of the space era. The presence of a large number of debris in orbit is, furthermore, associated with an increasing cost in the operations of spacecraft. In fact, due to the populated space environment, collision-avoidance maneuvers are nowadays a fundamental measure during the life span of an operating satellite. The tremendous growth of the commercial small satellites segment, in addition, is another key element contributing to the forecasted increasing number of space debris and the associated risk of collision. This is especially relevant in the most crowded orbital regions. More crowding leads to, on one hand, fewer available slots; on the other hand, it leads to a higher probability of collision, consequently causing a runaway production of further space debris as theorized by the Kessler's syndrome (Kessler and Cour-Palais, 1978). As a consequence, the most sought-after orbits gradually become less accessible. Orbits of interest are the geostationary or geosynchronous equatorial orbits (GEO), which are located on the equatorial plane at about 35 786 km altitude, and low Earth orbits (LEO), which extend up to 2000 km altitude. The latter, thanks to an easy access to space environment, is populated by a multitude of

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satellites, including very small ones like CubeSats (California Polytechnic State University, 2014; Toorian et al., 2008). CubeSats are a class of small satellites with typical modular units characterized by a cubic shape with a side length of 10 cm, corresponding to one unit (1U). In recent years, they have become a standard for scientific and commercial missions thanks to their fast development and cost-effectiveness associated to their reduced size. This headway is coupled with the constantly increasing frequency of satellite launches; the extended access to space is marking a turning point in the scalability of satellite constellations, especially very large ones. All these enhanced possibilities have promoted the occupation of certain LEO orbits by a variety of sectors, especially the commercial one, which is particularly active in the 500–600 km range (ESA Space Debris Office, 2022).

Moreover, simulations of possible future scenarios predict an amplified trend. According to the latest estimates by the European Space Agency (ESA Space Debris Office, 2022), the number of space debris objects in LEO is expected to rise even in case spaceflight were interrupted nowadays. For this reason, the Inter-Agency Debris Committee (IADC) has identified two protected safeguard regions, namely LEO (altitude up to 2,000 km), and GEO (altitude from 35,586 km to 35,986 km and inclination $\leq \pm 15°$), against which future missions will have to undergo regulation. The presence of obsolete, worn-out, and no longer-used artificial materials is to be kept to a minimum in these two protected areas.

The application of techniques to evaluate the sustainability of the space sector are still limited, with only few international regulations and general guidelines. Moreover, the scientific literature available on the topic is quite scarce (Maury et al., 2020). The main hindrance is related to the unclear definition and implications that sustainability covers when applied to space activities (Harris and Landis, 2020). Life Cycle Assessment (LCA) has been identified as the main technique to help in estimating the terrestrial environmental implications of space activities, but its implementation in the space-related value-chain is still far from optimal (European Commission, 2003). Indeed, while its use is widespread in several industrial sectors, such as energy production (Barbera et al., 2022), waste treatment (Petrescu et al., 2021), polymers manufacturing (Mio et al., 2021), or transportation (Hawkins et al., 2013), very few cases have been investigated in the space field. For instance, some documents are focused on the evaluation of the sustainability of the overall space sector at present (Wilson et al., 2022) or in the future (Miraux et al., 2022), some other are dedicated to the LCA of peculiar space missions (Wilson et al., 2023), while several publications deal with the ecodesign of space systems using LCA (Harris and Landis, 2020; Wilson and Vasile, 2017). LCA is a well-known methodology for assessing the environmental effects brought on by the production, use, and disposal of items, as well as by natural or artificial systems connected to human activities.

LCA allows practitioners to forecast potential emissions from the system under study to environmental compartments (such as soil, water, and atmosphere) by following the International Standard Organization (ISO) 14,040 and ISO 14044 criteria (International Standards Organisation, 2006; The International Standards Organisation, 2006). The outcomes of life cycle assessments are represented by several impact categories that can encompass the full scope of ecological burdens related to the product system, while preventing impact shifting between environmental compartments. The following four phases are carried on as constitutive parts of the LCA framework: Goal And Scope to declare the characteristics of the assessment, Life Cycle Inventory (LCI) to identify the material and energy balances over the entire life cycle of the product, Life Cycle Impact Assessment (LCIA) to calculate the environmental performance using several impact categories covering different environmental compartments, and Interpretation to analyze the outcomes and derive inferences about the study's findings. The most critical aspects of LCA applied to the space sector are associated with the peculiar materials employed for space-related products and the challenging development of specific metrics for space applications, particularly in relation with the formation of orbiting debris re-entering the terrestrial atmosphere, as shown by Maury et al. (Maury et al., 2019).

In this research, we evaluate the impact of materials constituting the structural bus of a 1U CubeSat. Here, this class of small satellites is taken as a prototypical space system for our analysis, mainly because their standard design allows direct comparison of different options in terms of materials for their structure. It has already been demonstrated how impactful a change in materials for space rockets can be in terms of LCA (Romaniw and Bras, 2014); we aim to evaluate the effect of two prominent aerospace materials in the development of small satellite structures. Beside the well-established categories for the Life Cycle Impact Assessment, our approach relies on the quantification of the number of generated fragments, by introducing a novel metric dependent on the materials properties, to quantify the potential impact on the global environment. In fact, in case of catastrophic collision, a cloud of debris is generated from the impacted spacecraft: the actual number and size of these fragments depends on the nature of the materials being fractured. This novelty provides tremendous advantages in the development of sustainable space systems, as alternative design solutions can be compared in terms of their attitude to exacerbate the space debris situation, a much-needed evaluation that is still absent in the current techniques.

2. Materials and methods

Two different materials are compared along this LCA analysis: (i) 7075 aluminum alloy (the standard for the manufacturing of a CubeSat structural bus) and (ii) a poly(ether ether ketone) (PEEK) structure held together by 24 screws made of Super Invar, a Ni-Fe alloy (Slejko et al., 2021). The latters are both well-known materials for aerospace applications, but quite novel for the development of small satellite structures (Siemaszko et al., 2022). Indeed, using a cut-off allocation method, the spacecraft selected as a functional unit in this research is a CubeSat 1U (corresponding to a 10 cm side length), without propulsion (CubeSat typical features). It is worth noting that, in case of active deorbiting at EoL or collision avoidance, propulsion systems are required. Furthermore, the system boundary does not include the rocket and the propellant burned for the launch of the CubeSat, since it is a common feature shared between the two alternative designs. The main life-cycle phases of a CubeSat are shown in Fig. 1 and include the design phase, the extraction and refining of raw materials, the manufacturing of the CubeSat, testing and transportation of the CubeSat, operations on orbit and its EoL. The CubeSat under investigation are characterized by equivalent weights (92 g) and volumes (10 cm^3). Due to the equivalent emissions related to testing, transportation, operation and EoL between the products, this work adopts a cradle-to-gate approach, including the design, extraction and refining of raw materials, and the manufacture of the CubeSat. Additionally, as Operation and EoL are space-related activities, the emissions from these activities shouldn't be included in a typical LCA because the characterization factors used during LCIA might not be appropriate for the space zone.

Secondary data have been retrieved within ESA database (ESA LCA Working Group, 2016), which is tailored for the space industry, in combination with ecoinvent v3.8. The manufacturing processes include section bar extrusion, sheet rolling and metal working for aluminum, 3D printing for PEEK (63.3 g), and section bar rolling and metal working for Super Invar (28.7 g).

The outcomes of life cycle studies are typically disseminated utilizing ReCiPe, CML, Environmental Footprint (EF), or TRACI, four well-established environmental impact methodologies. In this cradle-to-gate comparative life cycle investigation, the EF impact categories have been

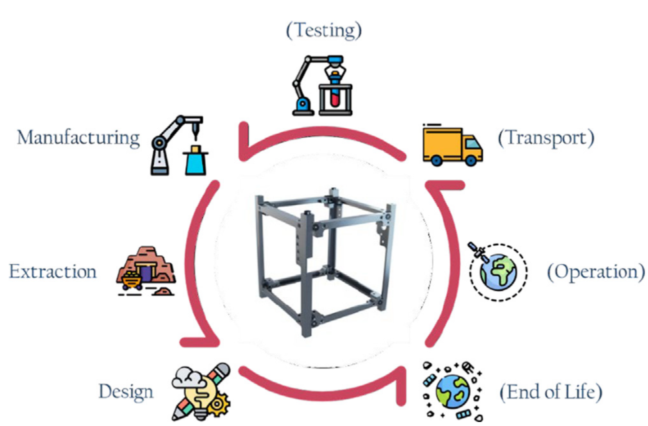

Fig. 1. Life cycle phases of a general CubeSat. The life cycle phases in brackets are not included in the system boundary of this study.

employed (European Commission, 2021): total climate change (CC-T) (Intergovernmental Panel on Climate Change - IPCC, 2013); ecosystem quality, which includes freshwater and terrestrial acidification (EQ-FTA) (Seppälä et al., 2006), freshwater ecotoxicity (EQ-FE) (Saouter et al., 2020), marine eutrophication (EQ-EM) (Huijbregts et al., 2016), eutrophication of freshwater (EQ-EF) (Huijbregts et al., 2016) and terrestrial eutrophication (EQ-ET) (Seppälä et al., 2006); human health, which involves the evaluation of impacts related to carcinogenic (HH-CE) (Saouter et al., 2020) or non-carcinogenic effects (HH-NCE) (Saouter et al., 2020), ionizing radiation (HH-IR) (UNEP Environmental programme, 2016), ozone layer depletion (HH-OD) (World Meteorological Organization - WMO, 2014), photochemical ozone creation (HH-PCOC) (Huijbregts et al., 2016), and particulate matter (HH-PM) (UNEP Environmental programme, 2016); resources depletion concerning the impacts on available raw materials such as dissipated water (RD-W) (Boulay et al., 2018), fossil fuels (RD-F) (van Oers et al., 2002), land (RD-L) (De Laurentiis et al., 2018) and minerals and metals (RD-M) (van Oers et al., 2002).

Even though the downstream processes are not included within the system boundary, the estimation of the impact on the orbital environment has been conducted, too. It was put in place recurring to the indicator proposed by Maury and coworkers (Maury et al., 2019).

On one side, this approach considers the risk –i.e. exposure factor *XF*– on a spacecraft exposed to the orbital debris flux (potentially resulting in catastrophic failure); on the other side, the severity factor *SF* includes to degradation of the orbital environment due to the generation of new debris upon collision of the spacecraft with another orbiting objects. For the equations of the two factors and the detailed calculation please refer to the original contribution (Maury et al., 2019) and the Supporting Information. The exposure and severity factors are determined for every circular orbit that the spacecraft crosses during its lifetime. For this purpose, three altitudes of interest were investigated in order to provide a preliminary LEO mapping as for guidance. The orbits were selected in accordance with to the following arbitrary partitioning:

1. 600 km, a higher orbit, in the range of the commercial ones: this orbital altitudes, at which a few dozens of years are required for free reentry, are becoming more and more attractive given the increasing number of payloads placed here in the last years (ESA Space Debris Office, 2022);
2. 400 km, a medium orbit, where International Space Station (ISS) lies: some CubeSat missions are released from ISS to last approximately 2 years;
3. 200 km, representing a mission surviving only a few days along a very low Earth orbit (VLEO): such orbits have recently been brought to attention for future applications and some critical aspects, including debris collision risk and facilitated end-of-life deorbit (Roberts, 2022).

The different lifetimes have been calculated recurring to the DRAMA software suite developed by ESA; the dwelling time for each orbit has been evaluated considering an interval between consecutive orbits of 10 km (see Table SI1-3).

Thus, the aforementioned factors have to be integrated over the entire path of the spacecraft in time, resulting in the impact score *IS* of the mission:

$$IS = A_c N \sum_{i}^{orbits} t_i XF_i SF_i \tag{1}$$

In Eq. (1), A_c is the average cross section of the spacecraft, N represents the number of released fragments, t_i indicates the dwelling time in the i-th orbit. The main limitation regarding the analysis of the impact of different materials for space applications is that the determination of the number of fragments under hypersonic ballistic impact is performed by means of an empirical formula, irrespective of the materials constituting the systems of the spacecraft (Colombo et al., 2017; Letizia et al., 2018; Maury et al., 2019). Fracture mechanics indicates that materials behave in a different manner, depending on their capability to dissipate impact energy before breaking. This different response depends on the stress–strain curve of the specific material: the larger the area under the curve, the more energy is dissipated in plastic deformation and less remains for breakage of atomic bonds (i.e. fracture propagation). This characteristic of the material is measured by the fracture toughness (Gupta and Ding, 2002). When the impact energy is enough to break the material, fragments are formed.

In a catastrophic impact, the entire object is fragmented and it is possible to define a distribution of fragments size and shape. Usually, if the material is fragile, a smaller average size of fragments is obtained, resulting in a more densely populated cloud of generated debris (Grady and Kipp, 1993). This indicates that, in case of catastrophic collision, it may be advantageous to choose a material that yields larger average size fragments in order to reduce the amount of debris. There is another aspect to propend for a larger average size of fragments that is associated with the monitoring technological limit. Small debris cannot be detected with ease, therefore a great uncertainty is associated with their position and velocity, increasing the potential risk of collision. It is worth noting that a larger mean size (i.e. less fragments) is not always beneficial, as large debris moving at high speed could represent the condition for a catastrophic collision (conventionally defined at energy densities larger than 40 J/g) with another spacecraft. The precise evaluation of the size and shape of debris can be conducted only by means of statistical analysis, with a precise set of boundary conditions, and it is outside the scope of this contribution. In this research, we focus on the general dependence between fragment generation and materials properties. From fracture mechanics, the average fragments size can be estimated based on Eq. (2) (Grady and Kipp, 1993):

$$s = \left(\frac{\sqrt{24}K_{Ic}}{\rho c \dot{\varepsilon}}\right)^{\frac{2}{3}} \tag{2}$$

In Eq. (2), s is the average fragment size, K_{Ic} indicates the material fracture toughness, ρ represents the density of the material, c is the elastic wave velocity, and $\dot{\varepsilon}$ is the rate of volumetric dilatation, which depends on the specific distribution of stress inside the material upon impact. The elastic wave velocity for a longitudinal propagation is

$$c = \sqrt{\frac{E}{\rho}} \tag{3}$$

The relation between the number of fragments N and the mean size can be expressed as

$$N \propto s^{-3} \tag{4}$$

Combining Eq. (2), 3, and 4 and isolating the materials properties, the Fragment Index *FI* results

$$FI = \frac{\rho E}{{K_{Ic}}^2} \tag{5}$$

The number of generated fragments N due to hypersonic collision is proportional to the fragment index defined in Eq. (5).

Since we are interested in comparing different materials, we can choose a reference and define the index ratio by dividing the fragment index *FI* of one material by the fragment index of the reference FI_{ref}. Therefore, the Fragment Ratio *FR* reads

$$FR = \frac{FI}{FI_{ref}} \tag{6}$$

This ratio is an important parameter, because it allows to directly compare two or more materials based on their relative capacity to generate many small (or few large) fragments. It is worth noting that, since we have isolated all the material properties inside *FI*, the profile of the distribution of fragments generated by the impact, in terms of size and number, is a statistical event depending only on external conditions (e.g. speed of the projectile, angle of incidence, etc.). Therefore, the relative response of each material is well represented by *FR*, irrespective of the actual profile of the distribution of fragments generated. The revised number of fragments, N^*, considering materials response upon fracture, is

$$N^* = N * FR \tag{7}$$

The original number of fragments N as defined in Maury *et al.* has been substituted with N^* in the *IS* formula (Eq. (1)) to quantify the impact of the materials on the orbital environment considering the amount of debris generated upon hypersonic ballistic impact. Applying *FR* to the Impact Score formulation, it is now possible to compare different design solutions (which usually are based on alter-

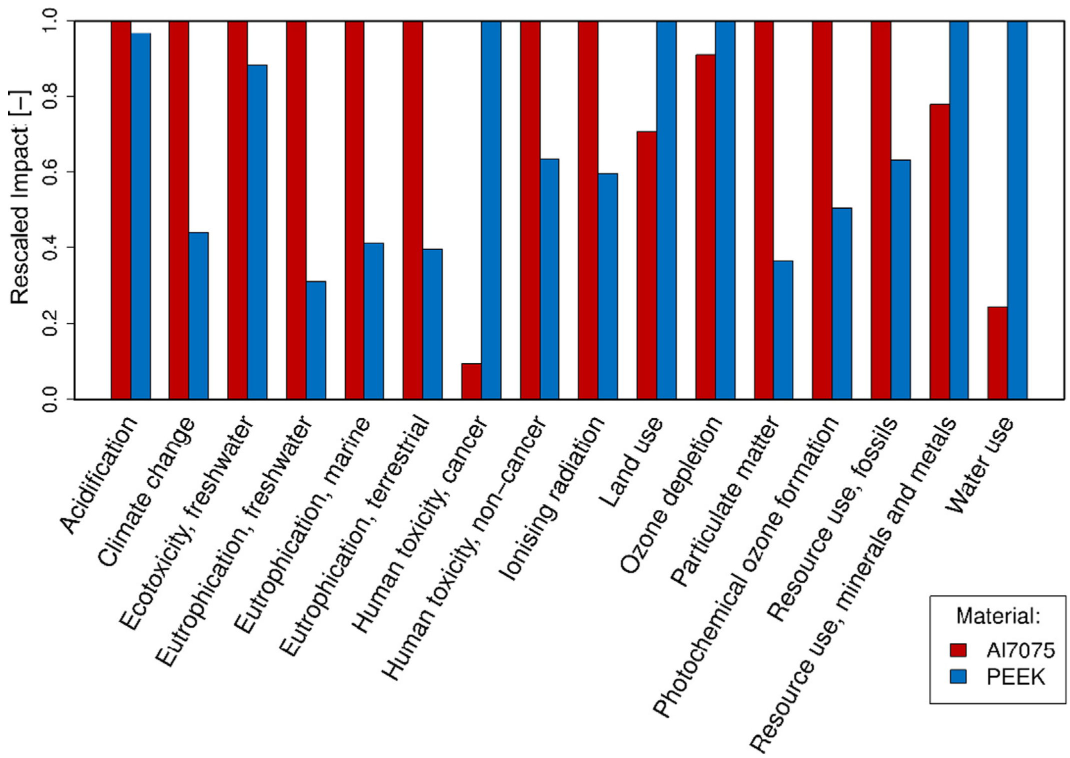

Fig. 2. Rescaled Life Cycle Impact Assessment outcomes for a cradle-to-gate comparison between different manufacturing materials.

native materials) in terms of their impact on the orbital environment, estimated by the number of fragments generated upon collision. In this analysis we will refer specifically to the CubeSat structural bus by comparing different material choices. It is worth noting that CubeSats are complex systems made up of a multitude of components and materials, each one contributing in the fragment generation upon ballistic impact. While the complete assessment of the sustainability of a CubeSat mission, in terms of debris generation by means of the *FR* parameter, is still limited due to the complexity and heterogeneity of the system, we believe this preliminary and prototypical analysis could pave the way for a deeper understanding of the impact of materials on the space environment and foster the development of more refined evaluation tools.

3. Results and discussion

The absolute values of the LCIA scores are reported in Table SI4, while the LCA impact categories scores rescaled to the maximum ones are reported in Fig. 2. In this rescaling process, the score gained by each material for every impact category was divided by the maximum score gained in that particular category. As a result, the greatest score was given a value of 1, while the lowest was rescaled correspondingly. As it clearly appears from Fig. 2, none of the CubeSats outperformed the other in every impact category. Therefore, a trade-off must be identified in order to select the most sustainable material.

According to the results of the impact category analysis, the PEEK-based CubeSat generates less environmental burdens than the traditional aluminum-based one in 11 out of the 16 impact categories that were analyzed, with scores ranging from 30 to 96 % of aluminum's ratings. These outcomes are mainly driven by the extensive usage of aluminum, which is an energy-intensive material responsible for a great portion of CubeSat impacts. In fact, environmental categories such as climate change, marine and terrestrial eutrophication, acidification and photochemical ozone formation are mainly affected by the extensive usage of hard coal for electricity and heat production for aluminum manufacturing. The other impact categories are mainly related to the extraction of bauxite and metals such as cobalt, zinc and magnesium, which are used for the production of AA7075.

The impacts of PEEK-based CubeSat are shared between the Super Invar alloy used for the screws and the PEEK used for the structure. The polymeric material is the main source of impacts for resource, land and water use, climate change, ionizing radiation, eutrophication, ozone depletion, particulate matter, and human toxicity impact categories. The other impact categories are mainly caused by screws' impacts, which are strongly related to the presence of a great amount of nickel in the alloy, followed by the impacts generated by the cobalt extraction (Super Invar contains up to 5 % Co).

PEEK-based CubeSat's performed better when compared to the aluminum-based CubeSat in impact categories where metal extraction is the primary cause of impacts, due to its lower alloy requirement. The polymeric material, on the other hand, is more resource- and human-toxicity intensive, mainly due to raw materials procurement and the chemicals involved in the manufacturing process.

The lifetime of the spacecraft, calculated at various altitudes, is reported in Fig. 3a. It derives from the DRAMA-OSCAR software package, which provides an estimation of the orbital decay in time. The dwelling time spent at each orbit is fundamental for the determination of the impact score as defined by Maury and coworkers. The lower altitude can be evaluated only for few days, since the CubeSat deorbits almost immediately; the other two scenarios, instead, present longer dwelling times (in the order of years), Fig. 3c-e. Another important quantity to obtain is the debris flux; it is shown in Fig. 3b as reported by the DRAMA-MASTER package. It represents the total amount of space debris at various semi major axes, thus representing the main source of collision for a spacecraft while in orbit. All these parameters are inserted in Eq. (1) for the determination of the Impact Score. Results for the three orbital scenarios are reported in Table SI5 of the Supporting Information. No difference in the *IS* for the CubeSat made of AA7075 or PEEK is expected by considering the formulation proposed in Maury, since no parameters linked to the materials properties are taken into account. The lowest impact score is associated with the closest orbit, mainly because the time spent before re-entry is only a few days. The opposite reasoning applies to the farthest mission (600 km altitude), for which the time before entering the atmosphere is in the order of tens of years. The calculations of the impact score based on the number of fragments derived from Eq. (6) are reported in Table 1. As can be seen, the Fragment Ratio of PEEK is sensibly smaller than unity (only 45 % of the Fragment Index of 7075 aluminum alloy), meaning that, theoretically, it should generate less than half of the debris of aluminum (see Fig. 4). The values in Table 1 have to be taken with caution as, especially for PEEK, the external conditions could dramatically change the materials properties. For example, when PEEK is stressed at high temperature, its fracture toughness decreases to 1.5 MPa $m^{0.5}$.

Recurring to the Fragment Ratio, we can extend the evaluation of the number of fragments generated upon hypersonic ballistic impact to other structural materials classes. From Fig. 5, it is easily observable the low performance of ceramics in terms of generated debris due to their low fracture toughness; titanium alloys, instead, preset the best behavior. The extension of bars in Fig. 5 is different from one class of material to the other, depending on the variations of the materials properties belonging to that specific class: red bars indicate the best performances (least generated fragments), while white bars represents the worst case within the materials class. From these results, we can appreciate that, when PEEK is stressed in the right conditions, it produces less debris with respect to the reference

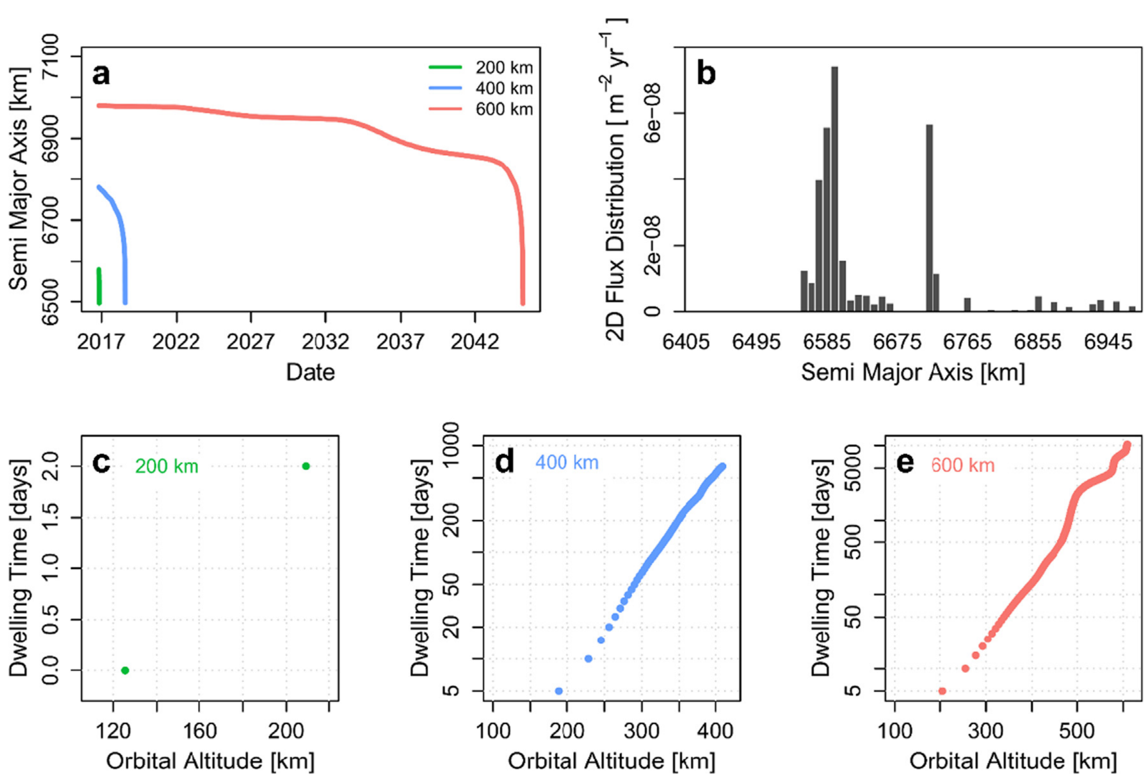

Fig. 3. A) orbital paths in time of spacecraft deployed at 200 km, 400 km, 600 km altitudes. b) Debris flux distribution as a function of the semi major axis, as obtained from ESA DRAMA software. c-e) Dwelling time as a function of orbital altitude for the three orbital paths, reported in Supporting Information.

Table 1
Values of materials properties for the calculation of the numbers of fragments N^* to be used in the impact score formula (Eq. (1)). All material properties are referred to 25 °C.

Material	Fracture toughness, K_{Ic} [MPa·m$^{0.5}$]	Young's Modulus, E [GPa]	Density, ρ [kg·m^3]	Fragment Index, FI [kg·MPa^{-1}·m^{-4}]	Fragment Ratio, FR [-]	N* [fragment]
AA7075	27.5	71.7	2.8	266.4	1.00	5.13
PEEK	6.5	3.9	1.3	120.0	0.45	2.31

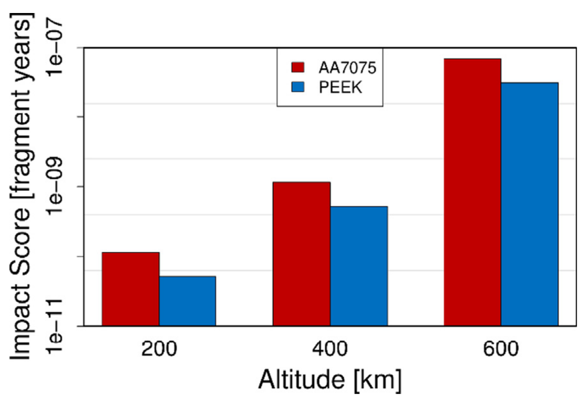

Fig. 4. Impact Score of the three orbital scenarios for AA7075 and PEEK.

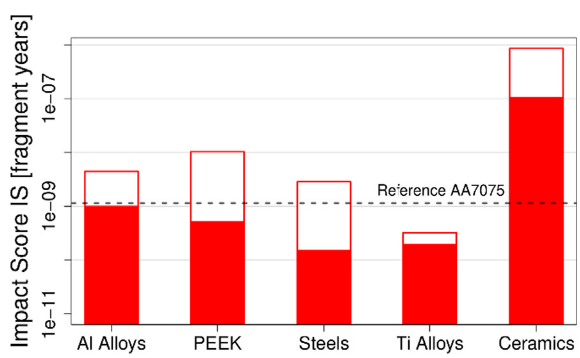

Fig. 5. Impact Score for several structural material classes in the temperature range 0–150 °C for an orbital altitude of 400 km. Dashed line indicates the value of the reference material (aluminum alloy 7075).

Table 2
Fracture toughness of unfilled and short fiber-reinforced PEEK at different temperatures (Roulin-Moloney, 1989). Bracketed numbers indicate the *FR* when compared to AA7075.

Temperature [°C]	Unfilled PEEK	30 % Carbon Fiber PEEK
25	6.5 (0.45)	6.5 (0.45)
180	1.5 (8.46)	4.0 (1.19)

7075 aluminum alloy. Ideal conditions for PEEK to generate a distribution of few and large fragments are related to low temperatures, for example. A way to improve the fracture behavior of PEEK is represented by creating a composite material: adding 30 % short carbon fiber to PEEK, for example, could improve the fracture toughness even at temperatures as high as 180 °C (see Table 2). Steels and Ti alloys behave better than aluminum, too, thanks to their large fracture toughness. Ideally, this reasoning and the calculation of the Fragment Ratio and the relative Impact Score could be applied to all materials in space components, thus refining the accuracy of LCA studies for the space sector.

3.1. Limitations of the present study

The Fragment Index proposed in this contribution represents a powerful indicator for estimating the debris generation of different materials. It has been derived from a simplified fracture mechanics analysis, thus there are some major limitations worth considering before adopting it. Firstly, there is a strong temperature dependence of the Fragment Index derived from materials properties. This means that the precise evaluation of the potential fragments formed upon collision is hard to perform without any specific input on the thermal environment. Secondly, the fracture toughness of materials depends upon strain rate and thickness, for example. The calculation of the Fragment Index should be performed on specific components and equipment, as the general evaluation of *FR* may be sensibly divergent from the actual value. As already discussed, CubeSats are complex systems made up by a multitude of materials and components. The recursive calculation of the *FR* for each material, aiming to the evaluation of the sustainability of a space mission, may be impractical at the current state. Nevertheless, the *FR* could provide a first indication about the potential impact on the space environment of specific materials during the design and the early stages of spacecraft development. At last, a word of caution when comparing the *FR* of different materials (Fig. 5): the calculation of the modified Impact Score has been conducted considering a fixed mass of the structural bus of the spacecraft. In real space system design, the mass budget is defined by the mechanical requirements and the materials properties, meaning that a CubeSat produced in steel and one produced in 7075 aluminum alloy would have different masses. Unfortunately, at this stage these considerations are not easily implementable in the definition of the Fragment Index. Nevertheless, the *FR* provides a preliminary feedback on the potential environmental impacts to be used for refining the evaluation and comparison of design solutions in LCA studies for the space sector.

4. Conclusion

The choice of materials for the production of a satellite structural bus has an impact on both the terrestrial environment as well as the orbital environment. In particular, two materials for the realization of CubeSats structures were compared in this work: 7075 aluminum alloy frame, and a poly(ether ether ketone) structure held together by Super Invar screws. With reference to the terrestrial environment, a Life Cycle Impact Assessment perspective was adopted to quantify the impact of manufacturing either materials for the development of a 1U CubeSat. According to the results, none of the materials outperforms the other in every impact category: 11 over 16 impact categories, including climate change, marine and terrestrial eutrophication, acidification and photochemical ozone formation, indicate PEEK rather than aluminum as responsible for less environmental burdens. On the other hand, the polymeric material is the main source of impacts for mineral resources, land and water use, ozone depletion, and human toxicity, mainly as a consequence of raw materials procurement and chemicals treatment which are involved during the manufacturing process. LCA has proved itself a valuable tool in the determination of the impact of space activities, but it requires further improvements on available data for the quantitative assessment related to extraction, manufacturing, treatments of space-related materials. Due to the global importance of the topic, it is expected that additional studies will be performed in the next future, consolidating the knowledge and improving the accuracy of space-related investigations, supported not only by the dissemination of ESA life cycle inventory database (ESA LCA Working Group, 2016) to ESA Member States, but also by the Strathclyde Space Systems Database (Wilson, 2019).

On the space side, the orbital resources are degraded due to the space debris generation resulting from in-orbit collisions and explosions. To quantify the potential effect of the number of fragments generated upon hypersonic ballistic impacts, a novel metric (namely the Fragment Ratio) related to the material's properties has been introduced. Accordingly, PEEK has been estimated to generate less debris (but with a larger mean size) than AA7075. The Fragment Ratio provides preliminary feedback on the potential degradation of the orbital resources related to material selection. Since it can be executed for all materials used in space components, it allows substantial refinements in the evaluation and comparison of alternative design solutions, aiming for the determination of the best strategies to limit the environmental impact of space activities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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