Development of a parsimonious characterisation model to address space debris emission-related damages for the LCA of space systems

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1. Introduction

Satellites orbiting Earth are used in many areas and disciplines, including space science, Earth observation, meteorology, climate research. A rising sustainability concern is occurring in the space sector: 29,000 human-made objects, larger than 10cm, are orbiting the Earth but only 6% are operational spacecraft. The others, considered as space debris, are today a significant and constant danger for all space missions. Life Cycle Assessment (LCA) has been identified as the most appropriate methodology to measure the environmental impact of space activities [1]. However, there is still a need to integrate debris related impacts within the LCIA step to broaden the scope of LCA for space systems. The objective of this presentation is to propose a set of characterisation factors CF to compute the damage *I* caused by the generation of debris N_D on the economic space activities (Equation 1).

$$I = N_D \cdot CF \qquad \textit{Equation 1}$$

2. Material and methods

Following the methodology of emission-related characterisation models [2], the CF of a given substance addressing environmental damages at the endpoint level is expressed as the product of the fate factor (FF), exposure factor (XF), effect factor (EF). Each factor has been adapted to the orbital environment as proposed in Figure 1 and further detailed in the next sections. The orbital environment has been divided into orbital cells *i*, spatially differentiated according to the altitude and inclination parameter. It is to noted that the emissions of debris (N_D) related to space system (as shown in inventory and emissions of Figure 1) has already been investigated by Maury et al [3].

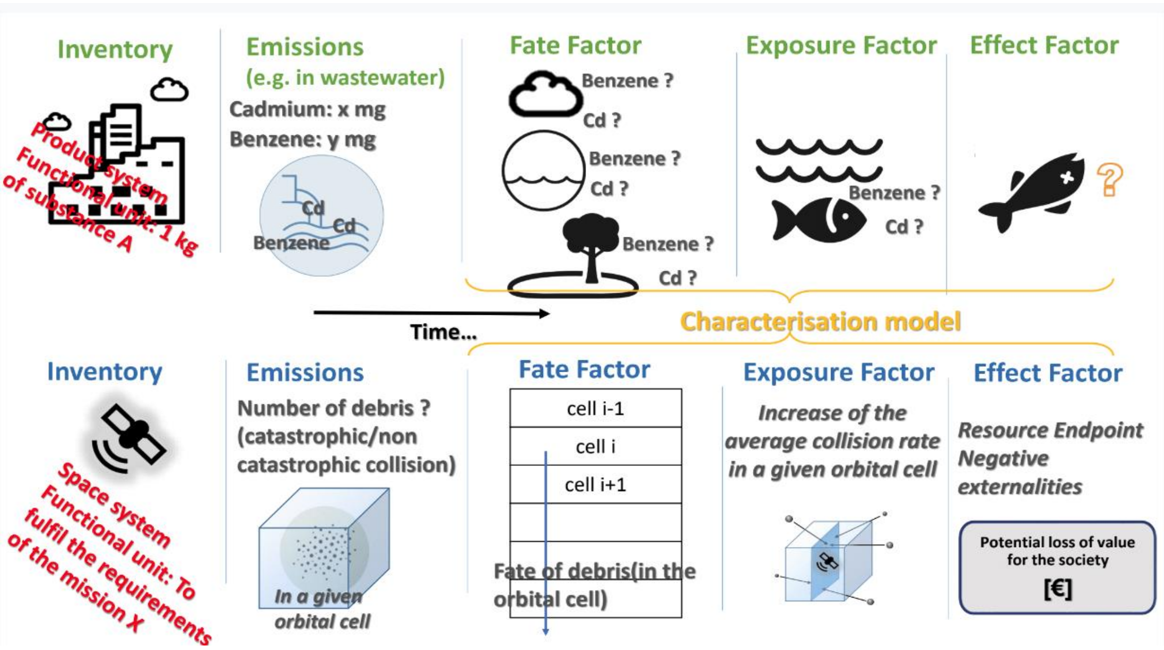

Figure 1. Impact pathway for emission-related characterisation models

2.1. Fate Factor

Survivability of the debris over time can be described by Equation 2 [4], where α, β and γ are empirically-determined coefficients and coefficient k_h represents the removal rate of debris from the orbital cell at altitude h to the sink (atmosphere).

$$FF_h = \frac{dP_{h,t}}{dt} = -\frac{1}{\alpha h^2 + \beta h + \gamma} P_{h,t} = -k_h P_{h,t} \qquad \textit{Equation 2}$$

By assuming that a debris is systematically decaying in a lower altitude compartment, the removal-rate matrix K can be built as an off-diagonal matrix that reflects the debris advection in the orbital environment. The fate matrix describes the residence time of debris in each orbital cell and can be assessed as the transpose of the removal matrix.

2.2. Exposure factor

Any debris emitted by the product system in the orbital environment will potentially generate an additional collision with existing population of space objects (e.g. active or inactive spacecraft). The increase of average probability of collision within an orbital cell can be modelled adopting a marginal impact approach. Exposure factor is expressed as the number of probable collision of the debris with active satellites (Equation 3):

$$XF_j = P = \overline{\Delta v}_{c,j} \cdot \frac{N_j}{V_j} \cdot A_{c,j}$$ ***Equation 3***

Where $\overline{\Delta v}_{c,j}$ (m·s^{-1}) is the average relative velocity of collision in the orbital cell, N_j (*units*) is the number of objects orbiting in the cell, V_j is the volume of the orbital cell (in *m*^{3}), $A_{c,j}$ is the cumulative cross-section area exposed (in m^2)

2.3. Effect factor

The effect factor corresponds to the monetary value loss for society due to the inactivity of a satellite, expressed in dollars. EF will be assessed by the time of the conference.

3. Results

Table 1 shows an extraction of the mapping of interim CFs corresponding to FF*XF for LEO region orbits from 400 to 2000km and inclination between 76 and 82°. Full results (not presented here) cover the LEO region from 400 to 2000km and 0° to 190° with 2°×50km interval bins. These CFs represent the probability of collision between a debris generated in a specific orbit and any active orbiting space object during the residence time of the debris in the orbital environmental.

Table 1. FF*XF: probability of collision between a debris generated in an orbital cell of altitude h and inclination j and active space objects downstream

	76°	*78°*	*80°*	*82°*
400 km	**-**	**-**	**0.0000**	**0.0002**
600 km	**-**	**0.0000**	**0.0022**	**0.0050**
800 km	**-**	**0.0000**	**0.0067**	**0.0123**
1000 km	**-**	**0.0002**	**0.0346**	**0.2458**
1200 km	**-**	**0.0002**	**0.0354**	**0.2793**
1400 km	**-**	**0.0002**	**0.0356**	**0.3032**
1600 km	**-**	**0.0002**	**0.0356**	**0.3469**
1800 km	**-**	**0.0002**	**0.0356**	**0.3503**
2000 km	**-**	**0.0002**	**0.0356**	**0.3503**

For a specific inclination, CFs are increasing with the altitude because debris generated in high altitude cross all orbital cells before their elimination (below 400km) in the atmosphere and therefore are exposed to a higher number of space objects. In addition, CFs are different for each inclination set of cells because of their variable active space objects population. For example, active satellites in the inclination 82° represent a cumulative area of 4124 m^2 whereas only one 4m^2 satellite is orbiting at the inclination 78°.

4. References

[1] ESA LCA Working Group, "Space system Life Cycle Assessment (LCA) guidelines," 2016.

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