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Thibaut Maury

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POUR OBTENIR LE GRADE DE

**DOCTEUR DE**  
**L'UNIVERSITÉ DE BORDEAUX**

ÉCOLE DOCTORALE DES SCIENCES CHIMIQUES  
SPÉCIALITÉ : GÉNIE DES PROCÉDÉS

**Par Thibaut MAURY**

**Consideration of space debris in the life cycle  
assessment framework**

*Considération des débris spatiaux dans le cadre de l'analyse de cycle de vie*

Sous la direction de : Pr Guido SONNEMANN

*Thèse obtenue avec label Européen - [European Doctorate label]*

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**Membres du jury :**

M. PERRY Nicolas	Professeur, ENSAM Bordeaux (France)	Examineur
M. GARRIGUES Philippe	Directeur de Recherche, CNRS, ISM (France)	Examineur
M. LAURENT Alexis	Associate Pr., DTU, Copenhagen (Denmark)	Rapporteur
M. PETERSEN Johan	Associate Pr., NTNU, Trondheim (Norway)	Rapporteur
Mme COLOMBO Camilla	Associate Pr., Politecnico Di Milano (Italy)	Examineur
M. SONNEMANN Guido	Professeur, Université de Bordeaux-ISM (France)	Directeur de thèse
M. LOUBET Philippe	MCF, Bordeaux INP-ISM, (France)	Invité
Mme INNOCENTI Luisa	Docteur, Agence Spatiale Européenne, (France)	Invité

*Partenariat industriel :*

M. BOUILLY Jean-Marc      ArianeGroup, Issac, (France)



# EXECUTIVE SUMMARY

## **Titre : Considération des débris spatiaux dans le cadre de l'analyse de cycle de vie**

**Résumé :** L'analyse de cycle de vie environnementale (ACV), d'après l'ISO 14040/44, a été identifiée par l'Agence Spatiale Européenne, ArianeGroup et plusieurs acteurs de l'industrie spatiale européenne comme la méthodologie la mieux adaptée pour réaliser l'évaluation environnementale des missions spatiales. Cependant, le secteur spatial est un domaine d'activité dont la particularité est de s'étendre au-delà des limites de l'environnement terrestre. Ainsi, s'il est possible d'évaluer les impacts sur l'environnement classique *via* la méthodologie ACV, les impacts générés sur l'environnement orbital ne sont aujourd'hui pas considérés dans son cadre de référence.

Par conséquent, il s'agit ici d'étendre le champ des études ACV dans le domaine du spatial afin de caractériser les étapes du cycle de vie ayant lieu en orbite, c'est-à-dire la phase d'usage pendant la mission spatiale et la phase de fin de vie (ou *Post-Mission Disposal*). L'anticipation de cette dernière est devenue une étape cruciale dans la conception des missions spatiales du fait des réglementations visant à limiter la prolifération des débris spatiaux. En effet, seulement 6% de la population en orbite autour de la Terre sont des satellites actifs, le reste étant considéré comme des débris, résultat des missions et activités spatiales passées. Etant donné cet enjeu de durabilité majeur pour l'industrie spatiale, les études environnementales se doivent de mettre en évidence les transferts de pollution potentiels non seulement entre les impacts environnementaux classiques tels que Changement Climatique ou la Toxicité mais aussi ceux relatifs à l'environnement orbital, au premier rang desquels figurent les débris spatiaux.

Afin de caractériser cet impact sur l'environnement orbital, nous proposons de définir une nouvelle catégorie d'impact en ACV dénommée '*Orbital Space Use*'. La conformité avec le cadre de référence de l'ACV est assurée au travers de la construction de chaînes de cause-à-effet (ou *impact pathways*) reliant les flux élémentaires du système d'étude aux mécanismes environnementaux (indicateur midpoint) et au dommage final (indicateur endpoint) au sein de l'Aire de Protection 'Ressources Naturelles'. En effet, les orbites proches de la Terre qui supportent les activités spatiales sont considérées à ce titre comme une ressource pouvant être impactée par des 'stresseurs'. Les débris spatiaux sont aujourd'hui identifiés comme les principaux 'stresseurs' vis-à-vis de l'accès et de la pleine utilisation de la ressource orbitale. Ainsi, le développement d'un modèle de caractérisation a été entrepris. Il permet d'évaluer l'impact potentiel d'une mission spatiale sur la population des débris déjà présente en orbite. Les facteurs de caractérisation obtenus sont appliqués à un cas d'étude comparant trois scénarios de fin de vie différents dans le but de prouver l'applicabilité du modèle. En outre, une première approche s'intéressant à la quantification des externalités économiques négatives engendrées par la prolifération des débris est développée. Elle constitue une étape préliminaire en vue d'un développement d'une catégorie de dommage dite 'endpoint'. Enfin, les challenges méthodologiques restants et les potentiels développements complémentaires sont abordés.

**Mots clés :** Analyse du Cycle de Vie, Débris spatiaux, Fin de vie, Impact environnemental

## **Title: Consideration of space debris in the life cycle assessment framework**

**Abstract:** Several actors of or related to the European space industry, such as ArianeGroup and the European Space Agency (ESA), have identified life cycle assessment (according to ISO14040/44) as the most appropriate methodology to measure and minimise their environmental impact. Nevertheless, space systems deal with a strong particularity which adds new aspects considering the scope of the LCA framework. Space missions are the only human activity that crosses all segments of the atmosphere and stays “out” of the natural environment and ecosystems. Regarding space systems with a holistic approach, environmental impacts could occur not only in the conventional *ecosphere* (Hofstetter et al., 2000) but also in the outer space, referred to as the *orbital environment*.

Consequently, the current scope of LCA studies should be broadened to take into account the on-orbit lifetime as well as the end-of-life disposal of the spacecraft. Yet, it is becoming a crucial point of the space mission design due to the future increase of the orbital population composed in a major part by space debris. In this way, LCA studies of space missions could indicate trade-offs not only between typical impact categories (toxicity and climate change for example) but also with regard to impacts generated in the *orbital environment* with a particular focus on space debris related impacts.

Hence, the priority has been given to the integration of a new impact category called *orbital space use* in the life cycle impact assessment framework. To address the environmental burdens comprehensively in this new category, impact pathways linking elementary flows to environmental mechanisms (midpoint) and damages (endpoint) are developed within the Area-of-Protection ‘Natural resources’. Space debris is identified as the main stressor of the orbital environment. Thus, ‘characterisation factors’ are defined and calculated at midpoint level to assess the potential impact of a space mission on the orbital environment. The methodology is applied to a case study to prove its applicability: the potential impact of a theoretical space mission is addressed through the comparison of three disposal scenarios. Also, a first attempt regarding the characterisation of the endpoint damage is provided taking into account the economic externalities caused by space debris. Finally, remaining methodological challenges and perspectives for future work are provided.

**Keywords:** Life cycle assessment, Environmental impact, Space debris, Orbital space use, Post-Mission Disposal

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**Institut des sciences moléculaire – Groupe CyVi**

Université de Bordeaux

CNRS UMR 5255 - Bâtiment A12, 351 cours de la libération, 33405 TALENCE cedex

# DEDICATION

*A ma famille,*

*A mon grand-père Paul, homme savant  
qui toute sa vie durant a cultivé le jardin des Hommes,*

« Chaque génération, sans doute, se croit vouée à refaire le monde. La mienne sait pourtant qu'elle ne le refera pas. Mais sa tâche est peut-être plus grande. Elle consiste à empêcher que le monde ne se défasse. »

Albert Camus, 1957

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# ACRONYMS & ABBREVIATIONS

AoP: Area-of-protection

ASD: European aerospace and defence industries

BAU: Business as Usual

CAD: Computer-aided design

CDF: Concurrent Design Facility

CFs: Characterisation factors

CNES: French space agency (Centre national d'études spatiales)

CRM: critical raw materials

DALY: Disability-adjusted life years

ECSS: European cooperation for space standardization

EF: Effect factor

EO: earth observation

EoL: end of life

ESA: European Space Agency

EU: European Union

FF: Fate factor

GEO: Geostationary Earth orbit

GR: Growth rate

GTO: Geostationary transfer orbits

IADC: Inter-Agency Space Debris Coordination Committee

IPAT: Impact, Population, Affluence per capita, Technology

$I_{sp}$ : Specific impulse

JRC: Joint research center

LCA: Life cycle assessment

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

LCSA: Life Cycle Sustainability Assessment

LEO: Low Earth orbits

LMRO: Launch and Mission Related Objects

LOS: Loi sur les operations spatiales (French space act)

LV: launch vehicle

M€: Millions of euros

MASTER: Meteoroid and Space Debris Terrestrial Environment Reference (ESA's reference space debris model)

MEO: Medium Earth orbits  
MLI: Multi-layer insulation  
MROs: Mission-related objects  
NaK: Sodium-Potassium (droplets)  
PDF: Potentially disappeared fraction of species  
PLM: Product life cycle management  
PMD: Post-Mission Disposal  
REACH: Registration, Evaluation, Authorization and Restriction of Chemicals  
S/C: spacecraft  
SDM: Space debris mitigation  
SETAC: Society of environmental toxicology and chemistry  
SF: Severity factor  
SRM: Solid Rocket Motor  
SSO: Sun synchronous orbits  
STM: Space traffic management  
TLE: Two-line elements  
TRL: Technology readiness level  
UCS: Union of concerned scientists  
UN COPUOS: United Nations committee on the peaceful uses of outer space  
UNEP: United Nations environmental program  
w/i: within  
WMO: World meteorological database  
XF: Exposure factor

# PREFACE

**PhD director:** Pr. Guido Sonnemann (Université de Bordeaux),

**Supervisors:** Philippe Loubet (Bordeaux INP), Aurélie Gallice (ArianeGroup), Camilla Colombo (Politecnico Di Milano)

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## Context of the thesis:

ArianeGroup is lead contractor for Europe's Ariane 5 and Ariane 6 launcher families and design authority on Ariane 6. Via its internal R&T project 'Eco-space' dealing with eco-design and Life Cycle Assessment (LCA), ArianeGroup wished to carry on a PhD project in partnership with the CyVi group of the University of Bordeaux. The CyVi group is a specialised research department which has gained recognition for its expertise in Life Cycle Assessment methodologies and sustainable assessment studies. The thesis was supported for a 3-year period by a 'CIFRE convention' (Grant agreement No 2015/1269 – Industrial Agreements for Training through Research) from the French National Association for Technical Research (ANRT).

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- T. Maury, P. Loubet, J. Ouziel, M. Saint-Amand, L. Dariol, G. Sonnemann, Towards the integration of orbital space use in Life Cycle Impact Assessment, *Sci. Total Environ.* 595 (2017) 642–650. doi:doi.org/10.1016/j.scitotenv.2017.04.008.
- T. Maury, P. Loubet, M. Trisolini, A. Gallice, G. Sonnemann, C. Colombo, Assessing the impact of space debris on orbital resource in Life Cycle Assessment: a proposed method and case study. *Sci. Total Environ.* doi:10.1016/j.scitotenv.2019.02.438
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- Thibaut Maury, Camilla Colombo, Philippe Loubet, Mirko Trisolini, Aurélie Gallice, Guido Sonnemann (2018) Integrating space debris modelling to environmental impact studies via the LCA Framework, 5th European Workshop on Space Debris Modelling and Remediation, CNES HQ, Paris
- Thibaut Maury, Philippe Loubet, Camilla Colombo, Mirko Trisolini, Aurélie Gallice, Guido Sonnemann (2018) Considering Space Debris related impacts into the LCIA framework, SETAC Europe 28th Annual Meeting, Roma
- Thibaut Maury, Philippe Loubet, Ludovic Dariol, Guido Sonnemann (2017) Considering Space Debris within the LCA Framework, ESA Clean Space Industrial days  
<http://blogs.esa.int/cleanspace/2018/03/27/how-to-evaluate-the-environmental-impacts-of-space-debris/>
- Thibaut Maury, Loubet Philippe, Ludovic Dariol, Guido Sonnemann (2017) From PhD to Apps: Considering Space Debris within the LCA Framework, LCM Conference. Luxembourg (Awarded best PhD oral presentation – First prize, Springer Award).
- Thibaut Maury, Jonathan Ouziel, Philippe Loubet, Guido Sonnemann (2017) How to integrate Space Debris into the Environmental Assessment of Space Missions? 7th European Conference on Space Debris, [url](#)
- Thibaut Maury, Philippe Loubet, Jonathan Ouziel, Guido Sonnemann (2016) Considering operating orbits of the outer space into a new LCIA resource framework, 22nd SETAC Europe LCA Case Study Symposium. Montpellier

# 1

## INTRODUCTION



Atlante Farnese (Atlas), 2<sup>nd</sup> century AD – Museo Archeologico Nazionale, Napoli

*“Two things fill the mind with ever new and increasing admiration and awe: the starry sky above and the moral law within”*

– Immanuel Kant

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## 1. Current space activities

Satellites orbiting Earth are used in many areas and disciplines, including space science, Earth observation, meteorology, climate research, telecommunication, navigation and human space exploration. Space applications provide unique and essential data collection service dealing with Earth observation and climate monitoring (Yang et al., 2013). As highlighted during the COP21 in Paris, of the 50 essential variables used to assess Earth's climate, 26 are monitored from satellite observations (CEOS and ESA, 2015).

In 2018, the total number of successful launches since the first artificial Earth-orbiting satellite, Sputnik, in 1957, exceeded 5.400 (ESA's Space Debris Office, 2019). Since 2010, the average number of launches has been approximately 80 per year according to NASA (Liou, 2016). In January 2019, the total number of satellites operating in space orbits reached 1.957 units as mentioned by the UCS satellite database (UCS, 2019). Figure 1.1 depicts the constant increase in the operating population of satellites (i.e. active satellites) since 2010. This increase is mainly driven by the nano-satellite launches (e.g. CubeSat) that grew up rapidly in recent years. For instance, more than 250 nanosats per year were launched in 2017 and 2018 (Kulu, 2018).

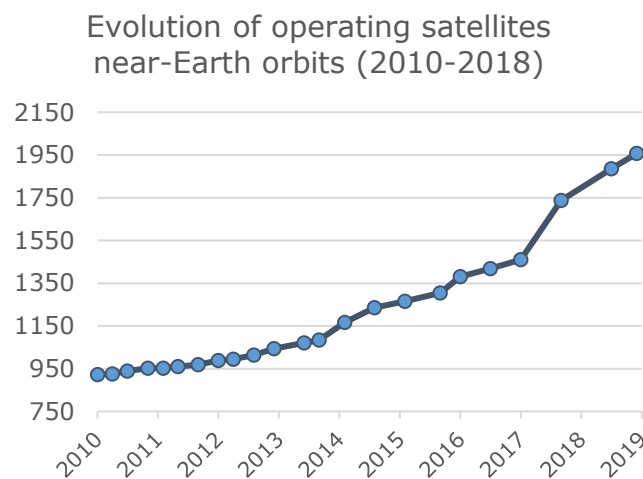


Figure 1.1 - Active population of satellites in near-Earth orbits. Data retrieved from the UCS satellite database (UCS, 2019)

Space has always been considered as a stake of power by nations. From only three space-launching countries (USSR, USA and France) and three additional countries owning satellites (Canada, United Kingdom and Italy) in 1966, we reach today around 65 countries involved in space among which ten entities with space-launching capacities (i.e. USA, Russia, Western Europe, Japan, China, India, Ukraine, Iran, South and North Korea). The distribution of uses is reported by the UCS database as follows: commercial purposes 44%; governmental use 28%; identified military use 22%; civil applications 8% (e.g. Universities or research centres).

The majority of operating satellites (63%) are in the low Earth orbit (LEO) region. This spherical region extends from the lowest altitude that a spacecraft must achieve to orbit the Earth (160 km) to 2.000km (IADC, 2007). In these orbits, a spacecraft circles our planet once every 88 min at the lowest altitude to approximately 127 min at the highest altitude. The LEO region is the simplest and cheapest location for satellite placement. The distribution of the 1230 LEO satellites according to their main mission is given as follows (UCS, 2019): *Earth observation*, 56%; *communications*, 22%; *technology development*, 17%; *space observation and science*, 5%. The International Space Station and the Hubble Space Telescope are also located in the LEO.

The second most important area supporting human space activities is the geostationary Earth orbit (GEO)



region, with 28% of the current operating satellite population. The GEO is composed of only one circular orbit, which is 35.786 km above the Earth's equator and follows the direction of the Earth's rotation. The orbital period is the same as the Earth's rotational period (i.e. 24 h). In this way, communication, broadcasting and weather geosynchronous satellites have the advantage of remaining permanently in the same area of the sky, as viewed as a fixed object from a given ground station. A volume of +/- 200 km in altitude and +/- 15 degrees in latitude encompasses the unique GEO orbit and forms the GEO region (IADC, 2007). The distribution of the 558 GEO satellites according to their main mission is given as follows (UCS, 2019): *Communications, 90%; Earth observation, 8%; Technology development, 1%; Space observation and science, 1%.*

Between the LEO and GEO, the medium Earth orbit (MEO) region extends from 2,000 to 35,586 km and accounts for more than 95% of the volume (Johnson, 2010). MEO supports the global navigation satellite networks but it represents only 10% of the global orbiting satellites' population. The MEO region also holds the geostationary transfer orbits (GTOs) which allow the placement of payloads into the GEO orbit.

Figure 1.2 shows the main orbital regions. The volume encompassed by these three regions (i.e. LEO, MEO and GEO) is defined as the 'useful orbital volume' for near-Earth space activities.

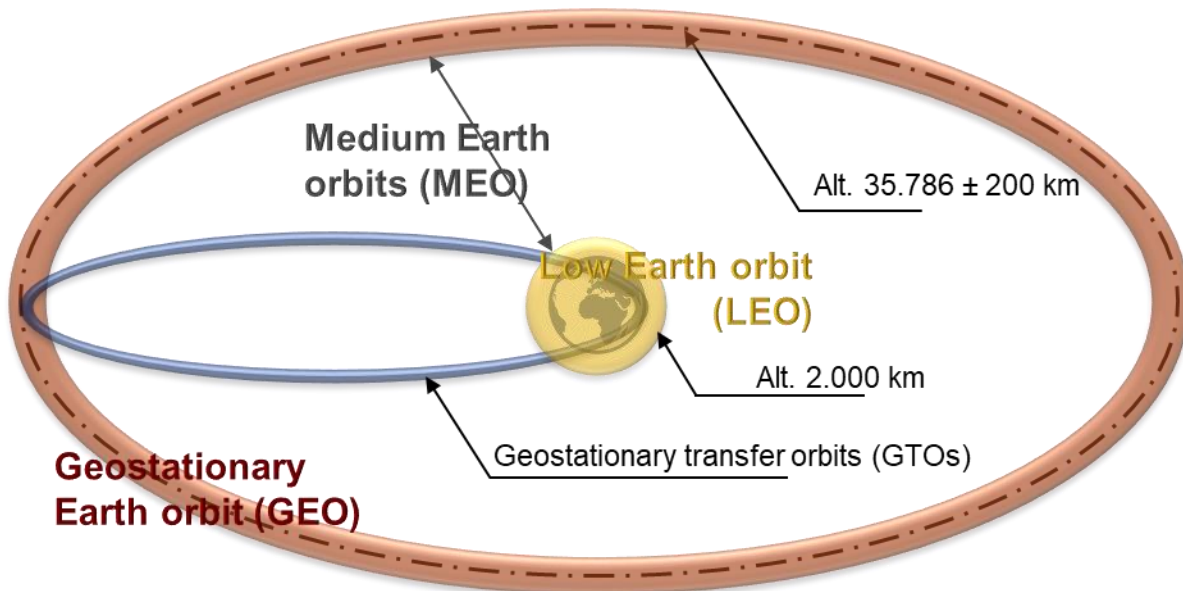


Figure 1.2 - Main orbital regions encompassing Earth's orbits

## 2. The challenge of space sustainability

Like any industry, the space industry generates pressures on the environment and strives towards more sustainable activities. For the first time in 2016, the member states of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) reached an agreement, adopting the first set of guidelines for the long-term sustainability of outer space activities. Guideline 27 refers to the development and promotion of technologies that minimise the environmental impact of manufacturing and launching space assets with maximising the use of renewable resources to enhance the long-term sustainability of space activities (UN COPUOS, 2017a).

Going further, France is currently the only state possessing a binding national legislative framework. The French Space Operations Act has provided a national legislative framework concerning all the space

operations launched from the French territory (i.e. Guiana Space Centre). With a full entry into force in 2020, the act aims to make operators responsible for the prevention of risks to people, property, public health and the environment (Legifrance, 2011). Its article 8 mentions that impacts on the public health and environment related to a potential operation shall be addressed within a dedicated impact study.

Finally, within the European Union, industrial stakeholders and agencies in the space sector are affected by a set of non-specific environmental directives or regulations. One of the most important is the so-called European Commission regulation concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). The RoHS directive, short for *Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment* can also be mentioned. It restricts the use of ten substances mainly heavy metals like lead or mercury. In parallel, particular attention should be paid to the use of critical raw materials (CRMs) targeted by the European Commission (European Commission-JRC, 2017; European Commission, 2017).

Regarding the production rates, the space industry is small in comparison to other industrial sectors. While a major part of the materials is highly specific, space sector is a minor customer in term of volume. That situation could lead to a lack of anticipation in term of vulnerability and substitution of materials. There is a high concern from European space manufacturing industry to manage and mitigate those long-term risks of 'obsolescence' and supply risk disruption (ASD-Eurospace, 2017). This was particularly the case when REACH regulation came into force in 2007.

Space sector industries sometimes claim to develop "green" or "eco-friendly" technologies when fulfilling specific regulations (such as avoiding substances from the candidate list of REACH), which is typically the case for the so-called "green propellants" (Gohardani et al., 2014). However, the environmental compliance does not capture the full environmental footprint because the technologies are not assessed holistically.

Several kinds of environmental aspects need to be considered when assessing the impacts of the space sector. Industrial activities related to space sector require energy, fossil and mineral resources that lead to impacts on *climate change* and *abiotic resource depletion*. *Human toxicity* and *ecotoxicity* related impacts are also generated during the energy production, the manufacturing operations and the launch event including propellant burning. *Acidification of soil or aquatic ecosystems* can also result in the propellant burning. Due to the particular nature of the space industry, launch-related activity is the only human activity responsible for direct emissions of aerosols and gases in the stratosphere. The latter can be major contributors to the *ozone layer depletion* and, to a lesser extent, *climate change*.

The end of life (EoL) of space missions also generates emissions in the environment during the atmospheric re-entry: the thermal degradation by fusion (i.e. ablation) and oxidation causes a partial or total demisability of materials according to its thermos-mechanical properties. These specific emissions generate atmospheric-related impacts. In addition, about 70% of the reentering elements impact sea or coastal water and other 18% of them hit the soil according to the French Space Agency (CNES) (Combes, 2013). These objects, as well as the fall down of the launcher stages into oceans, have a local impact on ecosystems due to the *ecotoxicity* of the materials and the remaining part of propellants into vessels. Also, the European operators shall respect a quantitative requirement regarding the re-entry of a spacecraft fragment hitting the ground after the end of operations. The *casualty risk*, i.e. the probability that a person is killed or seriously injured due to the re-entry, shall not exceed 1 in 10,000 for any re-entry event, controlled or uncontrolled (ECSS, 2012a).

Another sustainability concern is occurring in the space sector: 34,000 human-made objects larger than 10cm (~8400 tonnes), are orbiting the Earth but only 6% are operational spacecraft. The remaining objects (94%) are uncontrolled space debris which is today a significant and constant danger for all space missions (ESA's

Space Debris Office, 2019). A parallel between the orbital and the Earth environmental deterioration is suggested by Figure 1.3 which shows the temporal evolution of a set of environmental stressors (Steffen et al. 2015). According to the Inter-Agency Space Debris Coordination Committee (IADC), space debris is all human-made objects including fragments and elements thereof, in Earth's orbit or re-entering the atmosphere that is 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.

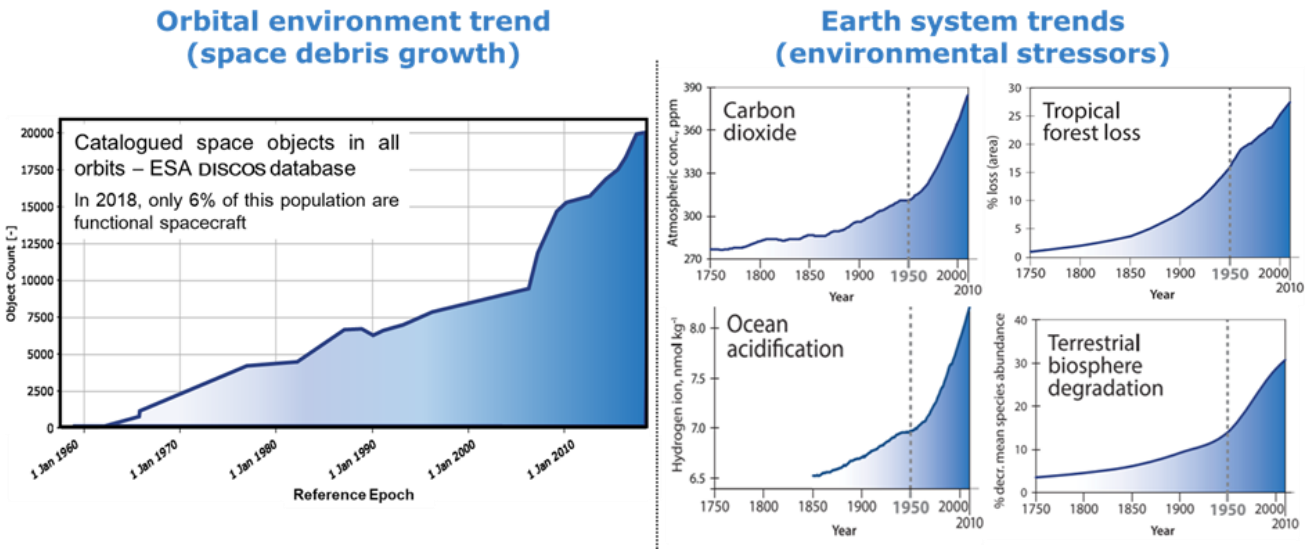


Figure 1.3 - (i) The catalogued population of space objects is presented on the left. It should be noted that the debris population grows faster than the number of active satellites representing in 2018 only 6% of this catalogued population. (ii) Several of well-known environmental stressors are presented on the right. For the latter, 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).

### 3. LCA methodology: an appropriate tool for space sustainability?

In the early '70s, Holdren and Ehrlich (1974) first attempted to determine the global drivers leading to environmental deterioration. They proposed the so-called 'I=PAT equation', where (I) is the overall environmental impact, (P) is the population, (A) is the per capita affluence expressed in material affluence per person and (T) is the technology's environmental intensity factor measured in environmental impact per material affluence.

As the space activities are continuously growing and more and more actors want to have access to space (Henry, 2018; Peterson et al., 2018), it seems that their overall impact could only be reduced through the technology's environmental intensity factor (T) of the IPAT equation. In this way, two main parameters are identified to decrease the environmental burden:

- i. the *dematerialisation* concept which implies the total material and energy reduction of raw materials at the production stage, of energy and material inputs at the use stage, and of waste at the disposal stage to fulfil a given function (UNEP, 2001);
- ii. the *transmaterialisation* concept which refers to the substitution of old materials by newer, technologically and environmentally more advanced (Labys, 2004).

The definition of *dematerialisation* provided by UNEP as well as the *transmaterialisation* foster a life cycle thinking perspective. Since the last three decades, the environmental life cycle assessment (LCA) methodology according to ISO 14040/44 (2006) is considered as a relevant methodology to support decision makers in the evaluation of the environmental impacts linked to the design, manufacturing, transporting, and disposing of the goods and services (Guinée et al., 2011). It compiles and evaluates the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. As a multi-criteria methodology, LCA studies avoid the ‘burden shifting pollution’ which consists in transferring impact from an environmental impact category to another, or from a life cycle stage to another. According to Moltesen & Bjorn (2017), LCA shows how a specific functionality can be achieved in the most environmentally friendly way among a predefined list of alternatives, or in which parts of the life cycle it is particularly important to improve a product to reduce its environmental impacts. Consequently, LCA may be considered as an appropriate methodology towards improving the last dimension of the ‘IPAT’ equation, i.e. the technology’s environmental intensity factor.

The space sector is a new area for applying LCA methodology. Several actors of or related to the European space industry, such as ArianeGroup or and the European Space Agency (ESA) have identified the LCA as the most appropriate methodology to measure and minimise their environmental impact. In 2016, the ESA LCA Working Group released a first set of guidelines in a space-specific handbook entitled: *Space system Life Cycle Assessment (LCA) guidelines*. The objective of this document is to establish the methodological rules on how to correctly perform space-specific LCA.

#### 4. Problem setting and research question

Space systems deal with a strong particularity which adds new aspects regarding the scope of the LCA framework (see Figure 1.4). Rocket launches are the only human activity that crosses all segments of the atmosphere and stays “out” of the natural environment (Durrieu and Nelson, 2013). Environmental impacts of space systems could occur not only in the conventional *ecosphere* (Hofstetter et al., 2000) but also in the outer space, further referred to as the *orbital environment*. Consequently, the current LCA faces current methodological gaps when applied to space systems.

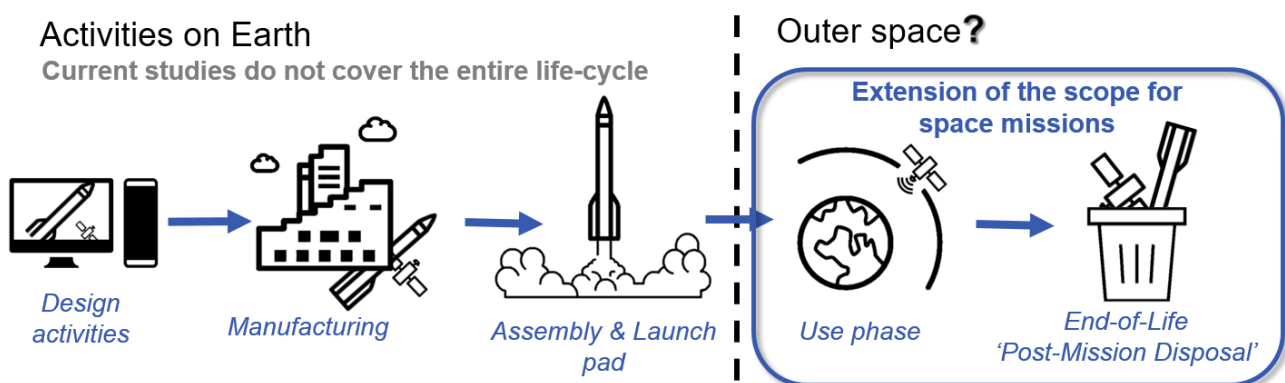


Figure 1.4 - Life cycle of a space mission

The scope of space missions should be extended to cover the phases dealing with in-orbit operations, i.e. the use phase and the EoL including post-mission disposal of the space missions. In this way, the impacts occurring in the orbital environmental would be assessed and provide a holistic analysis of space missions. Since the interactions between space system and the orbital environment take place out of the *ecosphere*, there are no damages on the ‘Areas-of-Protection’ (AoP) *human health* and *ecosystems*. However, orbital

environmental provides functions to the human societies. Therefore, it can be considered as a natural resource and its deterioration could be assessed within the AoP '*natural resources*' which is commonly taken into account in LCA. Hence, burden shifting between the Earth and the outer space could be avoided while minimising the resource intensity factor (T). In such case, the resource intensity would refer not only to conventional natural resources but also to the *orbital environment* aiming to reduce the in-orbit environmental burden of space systems.

Based on the concerns above, we define the research question of the thesis:

*How to consider orbital space use and, in particular, the impact and damage due to space debris population, in the life cycle assessment framework aiming at designing more sustainable space missions?*

## 5. Hypotheses, objectives and thesis outline

We formulate the following hypotheses to answer this research question:

- **Hypothesis 1:** LCA is an appropriate methodology to measure the environmental impact of space mission extending the conventional scope to cover in-orbit operations during the use phase and end-of-life.
- **Hypothesis 2:** Impact(s) occurring in the orbital environment can be integrated into the LCA framework to identify potential burden shifting between the Earth and the orbital environment.
- **Hypothesis 3:** The characterisation of new environmental impact(s) would bring ways of improvements to ensure more sustainable space missions.

These hypotheses represent the starting point of the thesis and set the direction of the research. The latter is approached through the main objective of this thesis, which is: **to define an impact category indicator with its associated methodology regarding the integration of the orbital space use in the LCA framework and assessing the space debris related impact in particular.**

The following sub-objectives serve to achieve the main objective of the thesis:

- a) Give a detailed state-of-the-art of the LCA applications in the space sector while identifying the main methodological challenges for assessing the full scope of space missions' life cycle
- b) Define impact pathways related to orbital space use that are compliant with the LCA framework according to ISO 14044 and covering in particular space debris related impact
- c) Characterise the space debris population in the orbital environment
- d) Develop a new impact category with associated characterisation factors based on the impact pathways previously defined
- e) Demonstrate the added value of applying this/these indicator(s) on a pilot case study highlighting a potential 'burden shifting' between conventional impacts on the Earth and space debris related impact on the orbital environment
- f) Explore the possibility of a specific damage category for space debris considering economic externalities

The present thesis manuscript covers the completion of the main objective and associated sub-objectives. The structure of the thesis is described in Figure 1.5 and detailed hereafter.

After the introduction (**Chapter 1**), **Chapter 2** is a state-of-the-art which aims at compiling papers related to (i) the implementation of a space-specific good practice for LCA studies; (ii) LCA studies of space systems. Research needs and methodological challenges are identified and discussed. The need for a specific impact category related to the space debris concern is highlighted.

From this review and first analysis, **Chapter 3** proposes an original approach aiming to integrate the *orbital space use* in the LCA framework. After a critical review of the 'resource use' characterisation in LCA, this chapter presents impact pathways linking orbital space use to resource-oriented impacts and damages. Those pathway(s) are a first step towards the elaboration of a dedicated indicator fitting in the AoP '*natural resources*'.

**Chapter 4** depicts the current situation regarding space debris proliferation and the associated legislative framework. The ESA's reference model MASTER-2009 (Technische Universität Braunschweig, 2011) is described and used to compute the flux of debris crossing circular orbits of the LEO region.

**Chapter 5** focuses on the development of a dedicated midpoint indicator to address space debris related impacts in the frame of LCA of space missions. Following the impact pathway, a set of characterisation factors (CFs) for the circular low Earth orbits is provided considering the flux of debris previously obtained as the main stressor of the orbital environment. Those CFs are applied through a dedicated case study: the comparison of the impacts of three theoretical post-mission disposal scenarios based on a similar mission and orbital parameters than Sentinel-1A satellite.

**Chapter 6** presents a first step in addressing potential socio-economic damages related to space debris release. A preliminary study is proposed with the aim of computing the actualised value of potential negative externality caused by debris in the current operating satellite population.

Finally, the hypotheses are tested and the research question is answered in **Chapter 7**. A general conclusion about the main outcomes of the thesis is engaged, while perspectives for future work are provided.

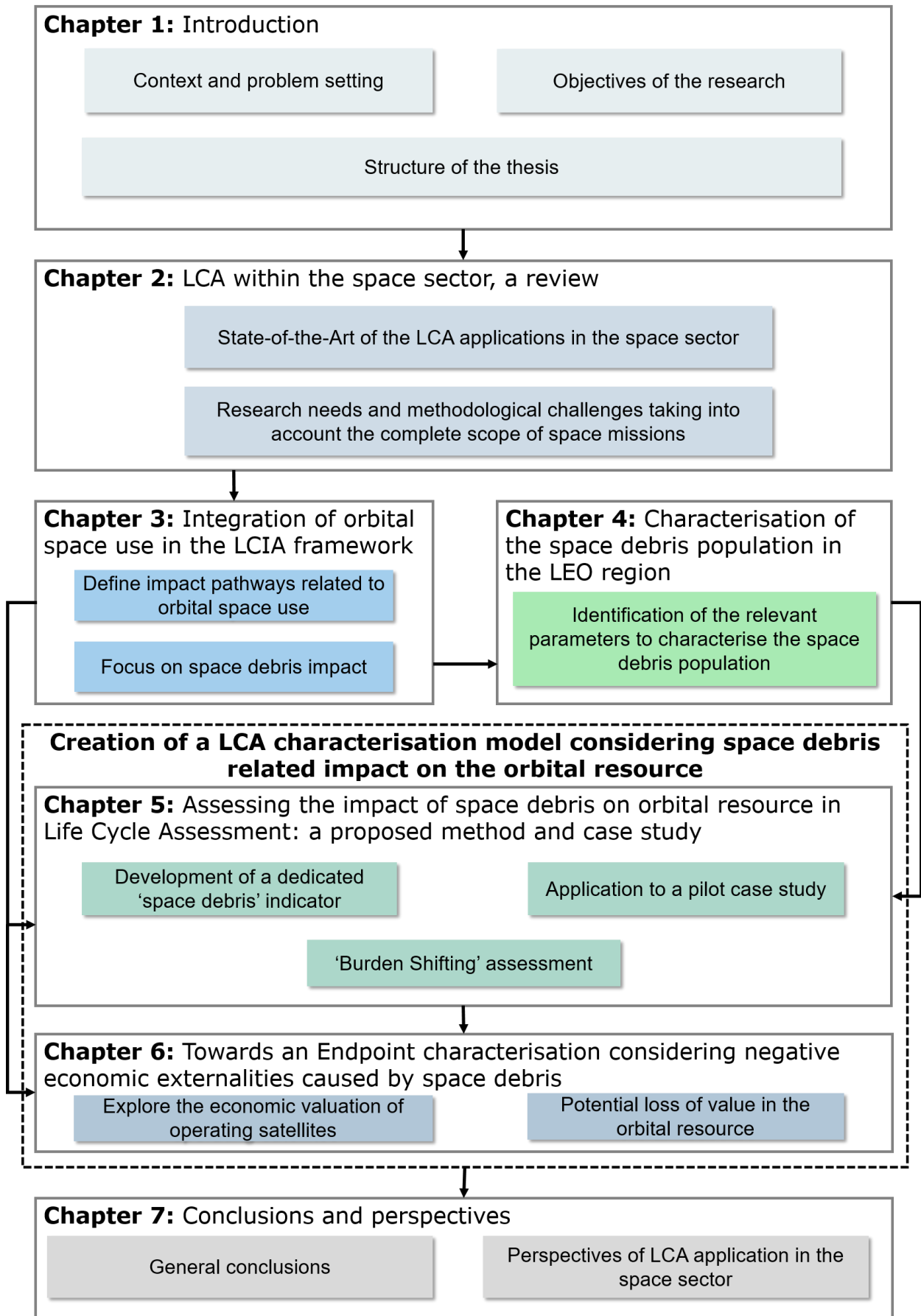


Figure 1.5 - Structure of the thesis

Content of this chapter will be submitted to the journal *Acta Astronautica* (Ed. Elsevier) as follows:

*T. Maury, P. Loubet, A. Gallice, S. Morales, G. Sonnemann, Application of environmental Life Cycle Assessment (LCA) within the space sector: a review. (in preparation)*

# 2

## ENVIRONMENTAL LIFE CYCLE ASSESSMENT (LCA) WITHIN THE SPACE SECTOR



Pierre Soulages (1961), *Brou de noix sur papier*  
Musée Soulages, Rodez

*“Il ne sert de rien à l’homme de gagner la Lune s’il vient à perdre la Terre”*

*“There is no point for man to reach the Moon if he loses the Earth”*

– François Mauriac, écrivain bordelais,  
Prix Nobel de Littérature 1952



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## 1. Introduction: the LCA structure

Since the development of the LCA methodology during the 1990s, strong efforts have been made to increase the robustness and the maturity of the practice. In addition to the standards ISO 14040/44 (2006), international initiatives carried under the umbrella of UNEP/SETAC, e.g. Life Cycle Initiative (2002), have been conducted in order to build a global consensus on the Life Cycle Assessment Framework (Sonnemann and Valdivia, 2014). Also, the European Commission provides recommendations for harmonising quality and consistency of life cycle data, methods and assessments (JRC European Commission, 2011).

LCA is carried out in four distinct phases as defined in ISO (Figure 2.1). It starts with an explicit description of the goal and scope of the study before providing an inventory of flows from and to the environment for a product system during the life cycle inventory (LCI) phase. Inventory analysis is followed by impact assessment during the life cycle impact assessment phase (LCIA). This phase of LCA aims at evaluating the significance of potential impacts based on LCI flow results. Finally, the interpretation phase is based on the identification of the significant issues, limitations, and recommendations and shall be integrated systematically at each step of the LCA study.

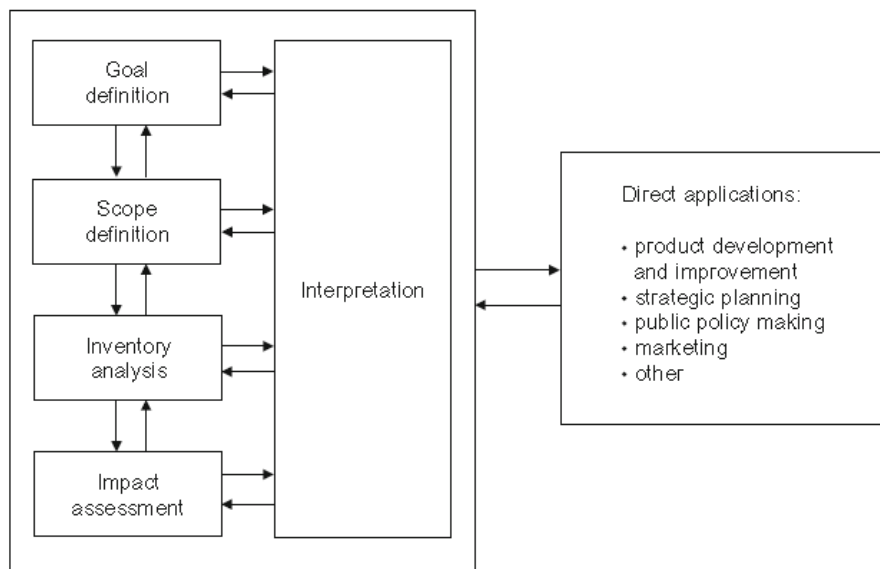


Figure 2.1– Framework of LCA according to the ISO 14040 standard

Today, an LCA community involved in space activities is emerging, as it can be noticed by the presence of LCA and eco-design sessions within aerospace conferences, particularly the CEAS Conferences (CEAS 2013; CEAS 2015), or the participation of Airbus Defence & Space within the Organizing Committee of the LCM conference 2015, in Bordeaux (LCM Conference Series, 2015). The Clean Space Industrial Days (2018, 2017), now includes a specific eco-design theme with dedicated sessions on LCA.

While life cycle thinking is setting up within the sector, a limited number of peer-reviewed publications is today available. Most of the documents released by the stakeholders can be considered as grey literature fostering the idea of confidentiality and lack of maturity of this sector in comparison others industries (e.g. automotive, chemical or building). As the topic is not properly discussed in the literature, we think there is an opportunity to put in the public domain the initiatives carried by the space sector in recent years.

Thus, this chapter aims to provide a comprehensive overview of past and present studies following the

standardised LCA framework (ISO 14040/44, 2006). After mapping the LCA initiatives in the space sector, a detailed state of the art is proposed. Case studies are selected and analysed using criteria from the 4 phases described in LCA international standards, goal and scope definition, LCI, LCIA and interpretation. Finally, ways of improvement, challenges and opportunities are exposed and discussed.

## 2. Methods

### 2.1. Selection of LCA papers dealing with space activity

The present review aims at compiling papers presenting a special interest in the application of LCA related to space sector. According to ISO 14040 (2006), Life cycle assessment (LCA) compiles and evaluates the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. As a multi-criteria methodology, LCA studies avoid the ‘burden shifting pollution’ which consists in transferring impact from an environmental impact category to another, or from a life cycle stage to another.

We chose to select papers, conferences proceedings or technical reports dealing with at least one step of the methodology: (i) definition of goal and scope, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretations of the results. Eventually, the present review compiled relevant publications defining a framework or a methodological development linked to sustainability for space activities as it could be a good starting point in the harmonisation of the LCA practice within the space sector.

The papers, proceedings and technical reports come from various channels: (i) Scopus database with the following query: *[TITLE-ABS-KEY("Launcher<sup>sci</sup>") OR TITLE-ABS-KEY("satellite<sup>sci</sup>") OR TITLE-ABS-KEY("spacecraft") OR TITLE-ABS-KEY("rocket") OR TITLE-ABS-KEY("space mission<sup>sci</sup>") OR TITLE-ABS-KEY("space sector")] AND (TITLE-ABS-KEY("LCA") OR TITLE-ABS-KEY("life cycle assessment") OR TITLE-ABS KEY("ecodesign"))*, (ii) The NASA’s Technical Library Public search Engine ‘TechDoc’ (<https://tdglobal.ksc.nasa.gov/>), (iii) several conference proceeding publications which are directly available on the conference website (CEAS, LCM and IAC conferences, ESA Clean Space Industrial Days) and (iv) elements collected within the space industry from different sources (final reports of environmental studies *etc.*).

### 2.2. Analysis grid of the selected papers

We define two separated grids of analysis to cover the overall scope of the review: a- Framework and good practices related papers; b- LCA studies. For each grid, a set of qualitative criteria has been established allowing a classification and an analysis of the papers. The criteria are described in the followings sections.

#### 2.2.1. Criteria for ‘Framework & Good practices’ analysis grid

Papers taken into account within this grid are generic publications discussing the relevancy of applying LCA to space activities. Here, the analysis deals with the goal of the selected papers. The following questions were used as qualitative criteria: Does the paper -(i) provide a complete framework and/or good practices for concrete LCA application within the sector? -(ii) discuss the possible integration of LCA studies during the design phase of new material, product or process? -(iii) consider a broader scope than environmental LCA with the aim to integrate other sustainability concerns? -(iv) present a coupling solution between LCA and design tools/methodologies for space systems?

## 2.2.2. Criteria for ‘LCA studies’ analysis grid

Table 2.1 - Description of criteria for LCA studies

Type of papers	LCA phase	Qualitative Criteria
<b>LCA studies</b>	Goal & Scope	<i>Goal of the study</i>
		<i>System boundaries</i>
		<i>Functional unit</i>
	LCI	<i>Source of foreground data</i>
		<i>Source of background data</i>
LCIA	<i>Mono or multi-criteria analysis</i> <i>Selected LCIA methodology/indicators</i> <i>Weighting and normalisation (yes/no?)</i>	
Interpretation	<i>Environmental hotspots</i> <i>Conclusions: added value of the study</i>	

Case studies are selected and analysed using criteria from the 4 phases described in LCA international standards (see Table 2.1).

- i. First, we focus on the *Goal & Scope* of the space LCA studies, analysing the goal of each LCA studies. The methodological framework provided by the ESA LCA Working Group (2016) in the ESA LCA Handbook proposes to adapt the life cycle phases of the European-standardized space project management system (ECSS, 2009) to describe better the life-cycle steps of a large-scale system. The results are presented in Table 2.2 for each specific segment of a space mission (e.g. Space segment, Launch segment, Ground segment) which are defined as a set of elements or combination of systems that fulfils a major, self-contained, subset of the space mission objectives (ECSS, 2012b). Based on this framework, we discuss the system boundaries of each study (§3.3.1). Then, the functional unit is detailed in a dedicated subsection (§3.3.2).
- ii. For each targeted study, the analysis of the *life cycle inventory* (LCI) *phase* addresses the issue of the source of the data and its quality, differentiating the data coming from the foreground and background systems (§3.3.3). As explained by Bjorn et al. (2018), on the one hand the data coming from the foreground system, i.e. all the specific processes that are under control, should be directly collected by the practitioners. On the other hand, LCI databases can be used to source data for the background system, i.e. not under direct control of the decision makers involved in the study, and also for the parts of the foreground system where more specific data cannot be obtained.
- iii. Then, *life cycle impact assessment* (LCIA) proceeds through two mandatory steps: selection of impact categories and characterisation of the impacts. In this review, we identify the selection of a mono (e.g. carbon footprint) or a multi-criteria approach for the assessment of a system under study. Concerning multi-criteria analysis, the chosen LCIA methods with associated indicators at midpoint and/or endpoint level are described (§3.3.4). The presence of normalisation and weighting which are optional elements (ISO) based on value choices (i.e. not science-based) is also discussed.
- iv. Considering the *interpretation phase*, the environmental hotspots are identified thanks to the analysis of the relative contributions of the sub-systems. In addition, the added value of the studies is discussed focusing on its conclusions (§3.3.5).

Table 2.2 – *Goal & Scope*: system boundaries according to the specific segments of a space mission as presented in the ESA’s Handbook (ESA LCA Working Group, 2016) for a large-scale space system.

	<b>Space Segment</b>	<b>Launch Segment</b>	<b>Ground Segment</b>	<b>Support segment (Infrastructures)</b>
<b>Phase A - Feasibility Phase B - Preliminary Definition</b>	<i>Office work and travelling Qualification and testing</i>			<i>Design facilities</i>
<b>Phase C - Detailed Definition  Phase D - Qualification and Production</b>	<i>Production and development testing of critical elements and engineering models  Production of spacecraft components and propellants  Qualification, testing and verification  Spacecraft assembly</i>	<i>Production of launcher components and propellants   Stage assembly</i>		<i>Production &amp; Testing facilities</i>
<b>Phase E –Utilisation</b>	<i>Launch campaign</i>	<i>Launch campaign  Launch event (launch pad operations and lift-off)</i>	<i>Launch and early operation phase + Commissioning  Mission control</i>	<i>Spaceport  Telemetry, Tracking and Command Ground Station(s)  Flight Operation Control center(s)  Payload Datacenter</i>
<b>Phase F – Disposal</b>	<i>Disposal of the spacecraft</i>	<i>Disposal of the launcher stages</i>	<i>Ground operations for the end of life of the spacecraft</i>	

### 3. Results of the review

#### 3.1. Analysis of the selected documents

Fifty-two documents were collected. After a first screening within the document list, a substantial part (13 documents) were considered out of the scope and disregarded. It is the case for papers discussing the benefits of applying eco-design in the space sector without a concrete reference to LCA applications or addressing a limited scope. Publications referring to “life cycle assessment” or “analysis” without including an environmental dimension were removed. It is the case especially for several of NASA’s LCA studies that do not match with the standardised LCIA methodology (ISO 14040/44). Finally, we selected eleven papers dealing with “framework and good practices” aspects (11) and twenty-seven papers regarding LCA studies (27) having a total of thirty-eight papers (38). Table 2.3 shows the complete list of the selected documents.

On the thirty-eight remaining documents, 84% comes from conference proceedings (32) while only 8% are peer-reviewed papers (3) and 8% technical reports or dissertations (3). Those figures show the confidential nature of the LCA practice in the space sector. The geographical distribution shows that Europe is by far the leader in applying LCA within the space sector with 87% of the selected documents. The European Space Agency is the major actor in this field, associated with 74% (28) of the whole selected documents (38). The temporal distribution of the publications is addressed in the following section (§3.2).

Table 2.3 – Key points of the analysis of the selected documents.

(P.rev: peer-reviewed; ConfP: conference proceedings; Report: Technical report or dissertation. Inf & GS: Infrastructures & Ground stations; Launch seg: launch segment; S.mission: space mission; Mat: materials; Integ. w/i design: integration within the design phase)

Reference	Year	Europe/ESA	Europe	N. America	Type	LCA study	Framework	Clusters	Topics
1	Castiglioni, A.G. <i>et al.</i>	2015	x		P.rev	x		Inf & GS (III)	<i>Facility management</i>
2	Chanoine, A.	2017	x		ConfP	x		Launch seg. (IV) & S.mission (VI)	<i>European launchers &amp; mission (Earth observation, Communication)</i>
3	De Santis, M.	2018	x		ConfP	x		Inf & GS (III)	<i>Ground stations</i>
4	De Santis, M. <i>et al.</i>	2013	x		ConfP	x		S. mission (VI)	<i>Missions (Astra 1N and MetOp-A)</i>
5	Gallice, A., <i>et al.</i>	2018	x		ConfP	x		Launch Seg. (IV)	<i>Ariane 6</i>
6	Geerken, T. <i>et al.</i>	2018	x		ConfP	x		S. mission (VI)	<i>Greensat ecodesign (Proba V)</i>
7	Geerken, T. <i>et al.</i>	2013	x		ConfP	x		S. mission (VI)	<i>Mission (Proba II)</i>
8	Izagirre, U. <i>et al.</i>	2017	x		ConfP	x		Mat. & process (I)	<i>Passivation process</i>
9	Kurstjens, R. <i>et al.</i>	2018	x		ConfP	x		Mat. & process (I)	<i>Germanium use in space sector</i>
10	Meusy, N.	2009	x		ConfP	x		S. mission (VI)	<i>CDF ecosat mission</i>
11	Neumann, S.	2018		x	Report	x		Launch Seg. (IV)	<i>Expendable/Reusable launchers</i>
12	Pettersen, J.B. <i>et al.</i>	2018	x		ConfP	x		Mat. & process (I)	<i>ESA Space LCI database</i>
13	Pettersen, J.B. <i>et al.</i>	2015	x		Report	x		Mat. & process (I)	<i>ESA Space LCI database</i>
14	Pettersen, J.B. <i>et al.</i>	2015	x		ConfP	x		Mat. & process (I)	<i>ESA Space LCI database</i>
15	Pettersen, J.B. <i>et al.</i>	2017	x		ConfP	x		Mat. & process (I)	<i>ESA Space LCI database</i>
16	Pettersen, J.B. <i>et al.</i>	2016	x		Report	x		Propellants (II)	<i>ESA Space LCI database</i>
17	Pettersen, J.B. <i>et al.</i>	2017	x		ConfP	x		Propellants (II)	<i>ESA Space LCI database</i>
18	Pourzahedi, L. <i>et al.</i>	2017		x	P.rev	x		Mat. & process (I)	<i>Material replacement</i>
19	Remy, B. <i>et al.</i>	2018	x		ConfP	x		S. mission (VI)	<i>Greensat ecodesign (Proba V)</i>
20	Romaniw, Y. <i>et al.</i>	2013		x	ConfP	x		Mat. & process (I)	<i>Material replacement</i>
21	Saint-Amand, M. <i>et al.</i>	2013		x	ConfP	x		Mat. & process (I)	<i>Solid rocket motorcase (materials)</i>
22	Silva, E.J.	2015	x		ConfP	x		Mat. & process (I)	<i>Photovoltaic system</i>
23	Soares, T. <i>et al.</i>	2012	x		ConfP	x		Launch Seg. (IV)	<i>Ariane 5</i>
24	Sydnor, C. <i>et al.</i>	2011		x	ConfP	x		Inf & GS (III)	<i>Facility management</i>
25	Thiry, N. <i>et al.</i>	2017	x		ConfP	x		S. mission (VI)	<i>Greensat ecodesign (Sentinel 3)</i>
26	Thiry, N. <i>et al.</i>	2018	x		ConfP	x		S. mission (VI)	<i>Greensat ecodesign (Sentinel 3)</i>
27	Vercalsteren, A. <i>et al.</i>	2017	x		ConfP	x		S. mission (VI)	<i>Greensat ecodesign (Proba II &amp; V)</i>
28	Austin, J.	2015	x		ConfP		x	Harmonization	<i>Guidelines for space sector</i>
29	Chanoine, A.	2015	x		ConfP		x	Integ. w/i design	<i>ESA CDF design</i>
30	Chanoine, A.	2017	x		ConfP		x	Integ. w/i design	<i>ESA CDF design</i>
31	Durrieu, S. <i>et al.</i>	2013		x	P.rev	x		Position paper	<i>Possibility of LCA use in space sector</i>
32	Huesing, J.	2015	x		ConfP		x	Harmonization	<i>Guidelines for space sector</i>
33	Morales, S. <i>et al.</i>	2017	x		ConfP		x	Harmonization	<i>ESA LCA framework</i>
34	Ouziel, J. <i>et al.</i>	2015		x	ConfP		x	Integ. w/i design	<i>TRL scale - LCA for new technologies</i>
35	Saint-Amand, M.	2015		x	ConfP		x	Integ. w/i design	<i>TRL scale - LCA for new technologies</i>
36	Soares, T.	2012	x		ConfP		x	Harmonization	<i>ESA LCA framework</i>
37	Wilson, A.R. <i>et al.</i>	2018		x	ConfP		x	Sust. Assessment	<i>Concurrent design</i>
38	Wilson, A.R., <i>et al.</i>	2017		x	ConfP		x	Sust. Assessment	<i>Concurrent design</i>

### 3.2. Framework and development of the LCA practices within the space sector

Figure 2.2 shows the breakdown of the topics addressed in each document.

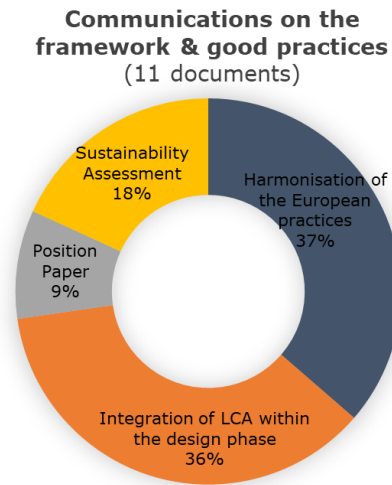


Figure 2.2 - Distribution of the documents related to the LCA framework and good practices applied within the space sector. Eleven documents were selected.

#### 3.2.1. European LCA Framework for space activities

To our knowledge, the first attempt to look at the environmental impacts through a complete LCA study came from an ESA's pilot Concurrent Design Facility (CDF) study called 'Ecosat' (Meusy, 2009). Its conclusions highlighted the need to develop a harmonised LCA framework within the European space sector as well as the development of specific datasets related to the space industry. The European space industry is today well-structured on this topic, mainly due to the strong efforts performed by the ESA in the frame of the eco-design activities of the Clean Space Initiative (ESA Clean Space, n.d.). We have not found any equivalent program in North America or Asia, as underlined by the analysis of the geographical distribution in section 3.1. An important task of the Clean Space Initiative is to raise environmental awareness and establish a complete network among the European space community as explained by the ESA (Huesing, 2015; Soares, 2012). Austin (2015), Huesing (2015) and Pettersen et al. (2015a) highlight the difference between the space sector and a more conventional consumer-oriented industry. They underline the need to adapt the conventional LCA methodology to fit with the specific needs of the Space sector. The priority has been given to the harmonisation of the LCA approach and practices among the European space sector. The main goal is to establish a common framework to be used by national space agencies and industries when performing spacecraft design. This framework is composed of three main pillars (Morales Serrano and Austin, 2017):

- 1) **Guidelines and good practices** helping to perform LCA studies were released by ESA with a dedicated Handbook: *Space System Life Cycle Assessment guidelines* (ESA LCA Working Group, 2016). This handbook aims to establish the methodological rules on how to correctly perform space-specific LCAs at the complete system level (i.e. space mission) or for dedicated space sub-systems, e.g. a specific component, equipment or technology.
- 2) A dedicated **space LCI database** was developed including specific materials and advanced manufacturing processes (Pettersen et al., 2015b) as well as space propellant (Pettersen et al., 2016). Current LCA studies for space relies on this database which covers more than 1.000 space specific datasets (Pettersen et al., 2018).

- 3) An **eco-design platform** called OPERA and coupled with a CDF tool was developed to systematically implement environmental LCA in the early-design phase of the ESA space missions (Chanoine, 2017a, 2015).

### 3.2.2. Integration of the LCA during the design phase

As mentioned by Chanoine (2015), the environmental performance of systems, similarly to cost assessment, is highly driven by design elements which are defined at an early stage in the design process. Consequently, coupling LCA with design tools seems particularly relevant in the case of space missions due to the high complexity of the systems.

The OPERA Platform, cited above, is currently implemented in the frame of the concurrent design process of the ESA. It provides instant feedback to the design team related to the environmental performance of the system under study. At the industrial level, Ouziel and Saint-Amand (2015) and Saint-Amand (2015) discuss the integration of the LCA during the development of new technologies. They recommend adapting the completeness level for a given LCA study based on the Technology Readiness Level (TRL) scale of the studied technology. It should be noticed that systematic integration of LCA information with existing Product life cycle management (PLM) solutions or Computer-aided design (CAD) software has already been successfully applied outside of the aerospace community (Buchert et al., 2019; Ciroth et al., 2013).

### 3.2.3. Sustainability assessment

The ESA mentions the fact that their LCA framework may also help actors of the space sector to address the European environmental legislation, particularly REACH and the RoHS directive, but also to flag the use of critical raw material. According to Huesing (2015), complementary use of the LCA approach lies in the understanding and monitoring of the supply chain to support pro-active and coordinated measures to avoid potential disruptions. This task can be addressed at the inventory level, once the elementary flows are mapped, or *via* the development of dedicated indicators dealing with supply risk during the impact assessment stage (Cimprich et al., 2017a). A preliminary ESA funded study going in this direction was recently presented by Chanoine (2018a, 2018b). In such case, the conventional scope of LCA is broadened with the integration of criticality assessment which is more in line with the Life Cycle Sustainability Assessment (LCSA) framework (Sonnemann et al., 2015; UNEP, 2011).

Moreover, Durrieu and Nelson (2013) suggest the use of the social Life Cycle assessment (UNEP, 2009). An attempt considering economic and social dimensions is currently carried out by Wilson et al., (2018) and Wilson and Vasile (2017). Their work aims at developing an LCSA platform coupled with an internal Concurrent Design Facility tool, to address potential impacts during the early-design of the space missions.

### 3.2.4. Framework development

Figure 2.3 shows the temporal distribution of LCA communications in the space sector. The first range of complete LCA studies was carried out in Europe from 2012 to 2015. Communications in the year 2015 emphasise the efforts made to implement, develop and harmonise the LCA practices in the European space industry. This first phase results in the release of the ESA LCA Handbook for space systems in 2016 and the ESA space LCI database in 2017. From 2017, several new studies are launched by the ESA capitalising on the good practices and knowledge inherited from the previous studies. Today, a new perspective emerges based on this established framework: the scope is broadened aiming at integrating new sustainability concerns while moving forward.



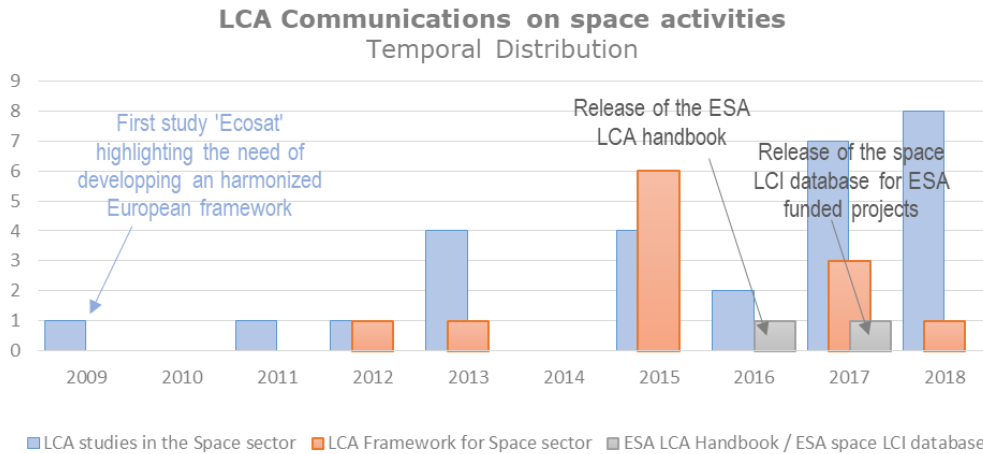


Figure 2.3 - Temporal distribution of LCA communications in the space sector according to specific LCA studies and "framework and good practice" documents; elements composing the European framework (i.e. ESA LCA Handbook and ESA LCI database) are mentioned.

### 3.3. Description of the LCA studies

#### 3.3.1. Goal and system boundaries of the LCA studies

The goal and system boundaries of each LCA study were identified and classified according to six main clusters defined in Figure 2.4: (I) components, materials and manufacturing processes; (II) propellants manufacturing; (III) ground and support segments; (IV) launch segment; (V) space segment; (VI) complete space mission. Figure 2.5 gives the distribution of the LCA studies according to the main cluster covered. For each cluster, a description of the relevant LCA studies is performed through the analysis grid provided in Table 2.1.

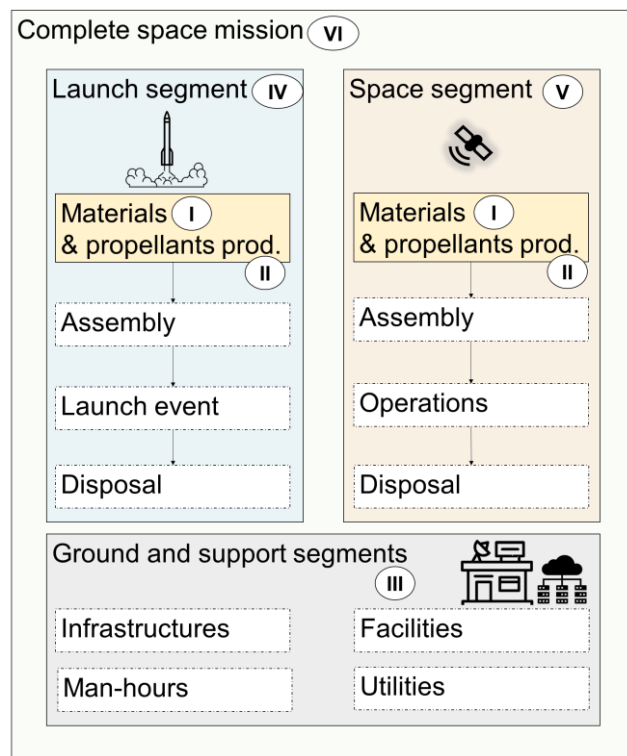


Figure 2.4 - Goal & system boundaries of the selected LCA studies. Six clusters were identified: (I) components, materials and manufacturing processes; (II) propellants manufacturing; (III) ground and support segments; (IV) launch segment; (V) space segment; (VI) complete space mission

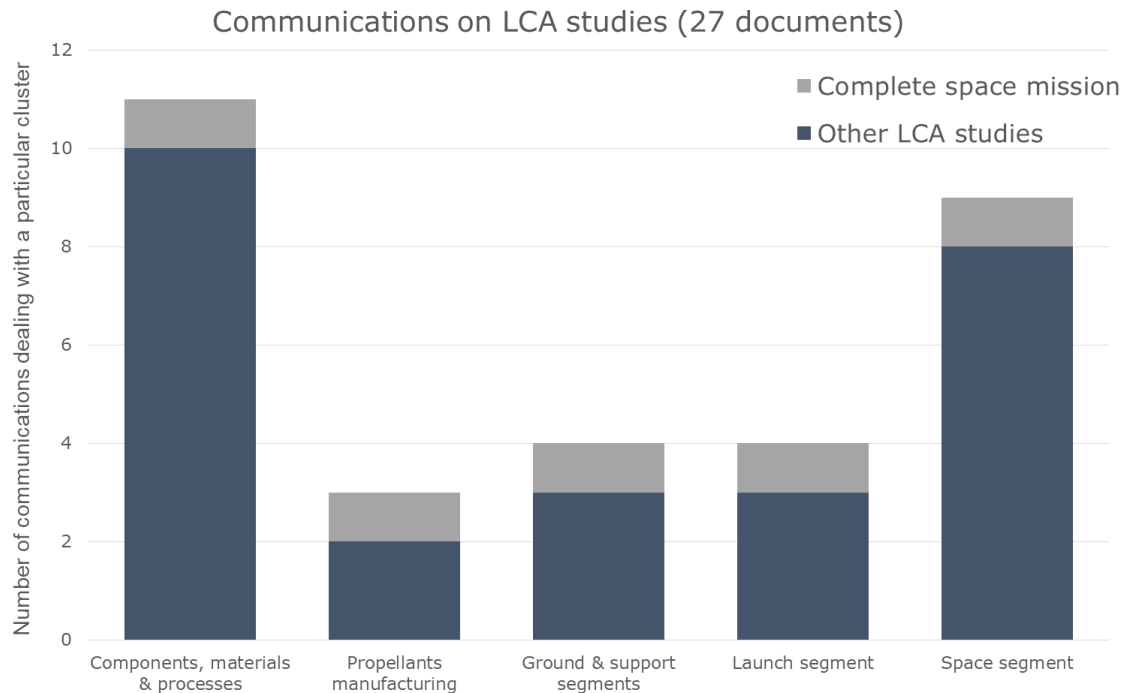


Figure 2.5 – Distribution of the LCA studies according to the six clusters related to the LCA framework and good practices within the space sector. Twenty-seven documents were selected.

**Components, Material and Processes (I).** The following section refers to the LCA at materials, equipment or component levels. We identified ten publications dealing with specific materials and processes for space applications. Components for space applications differ from standard applications (Geerken et al., 2018): (i) they are produced in very small quantities thanks to highly advanced processes; (ii) they need to operate in extreme conditions and environments and thus require particular properties control during long testing and qualification steps to comply with the space industry standards.

Given that, half of the documents (5) are related to the creation of datasets for the ESA Space LCI database mentioned in the section above 3.2.1, (Pettersen et al., 2018, 2017b, 2015a, 2015b; Silva, 2015). This database was designed by the ‘Eco-design Alliance for Advanced Technologies’ managed by the consultancy *Asplan Viak* with the industrial support of the ArianeGroup. The dataset covers mostly material and manufacturing processes, with some notable exceptions as manpower and logistics, waste treatments or specific electricity mixes. The system boundaries of each component or sub-system must be addressed separately. Most of the time, the data covers a ‘Cradle to Gate’ focusing on the product chain managed by the manufacturer.

In one of the first LCA study on space sub-systems conducted at the European level, Saint-Amand et al. (2013) compare the environmental impacts of several materials (composites, thermal protection, metal) with the associated assembly phases for a Solid Rocket Motor Case. Another study focuses on the Germanium (Ge) use for photovoltaic (PV) systems (Kurstjens et al., 2018). Another one presented by Izagirre and Zimdars (2017) deals with the comparison of two steel passivation processes (i.e. surface treatment). Finally, two studies explore material substitution of traditional metallic components with polymer composites in the case of electromagnetic interference shielding (Pourzahedi et al., 2017) or with carbon fibre reinforced polymers for structural elements (Romaniw and Bras, 2013).

**Space propellants (II).** The question of the toxicity of space propellants is a highly discussed topic in the space sector under the umbrella of the terms ‘Green propulsion’ or ‘Green propellants’ (Cardiff et al., 2014;

Gohardani et al., 2014; Johnson and Duffey, 2012; Negri et al., 2017). However, the environmental burden of the propellants is most of the time strictly assessed through health risks related to legislation on toxic compounds without matching with an LCA perspective. Only two documents focusing on the LCA of propellants and in line with the ISO 14040/44 were selected (Pettersen et al., 2017a, 2016). They refer to the ESA funded study on the LCA of space propellants that makes a significant contribution in the domain. A large dataset of around thirty (current and potentially future) space propellants is implemented in the ESA space LCI Database with a 'cradle-to-gate' approach for chemicals production and adding processes up to the launch depending on data availability or judgements on the relevance for environmental impacts assessed in LCA studies.

**Ground and support segments (III).** According to ESA Clean Space (2017), a segment that deserves investigations for space missions is the one related to the ground activities. The latter is based on the management of the communications between the in-orbit satellite and the mission control centre as well as the archiving and processing of the mission-specific scientific data collected. Three documents were found: Castiglioni et al., 2015; De Santis, 2018; Sydnor et al., 2011. The ESA funded study (De Santis, 2018) was recently launched with the aim of fully determine the related environmental impacts of those activities. The scope of this study focuses on the characterisation of various "generic families" of ground segment representatives for telecommunication, navigation, scientific, earth observation and CubeSat missions, covering their specific infrastructures and operations. Four major ground segment typologies were identified as follows: a mission operations' centre, a science operation centre, a data processing centre and other ground stations (i.e. optical, radio-frequency or radar terminal). The perimeter of the study includes infrastructure and building construction as well as the operational phase including also transportation phases and facilities. The perimeter of the study includes infrastructure and building construction as well as operational phase including also transportation phases and facilities. Besides, two studies dealing with utility management and infrastructures were previously conducted by Castiglioni et al. (2015) at the European Astronaut Centre and Sydnor et al. (2011) regarding NASA's high-energy ground test facilities. While the first one mainly discusses energy solutions, water and waste management, the second includes in its scope ground test facilities (excluding the construction and the demolition phases).

**Launch segment (IV).** Three studies focusing on launch segment were identified (Gallice et al., 2018; Neumann, 2018; Soares et al., 2012). Also, an additional document (Chanoine, 2017b) that covers the complete scope of space mission is included because a dedicated section of this document focuses on the launch segment.

An ESA LCA study was carried out in 2012 focusing on the European Launchers family (Ariane 5, Vega, Soyuz) (Chanoine, 2017b; Soares et al., 2012). The perimeter of the study follows the 'Launch segment' as detailed in Table 2.2. The study highlights the difficulty to include R&D and testing stages in the perimeter, as well as the infrastructures because their impacts are highly dependent on the number of launches. Consequently, the on-going LCA study of the new Ariane 6 launcher performed by the ArianeGroup (Gallice et al., 2018) disregards the R&D and the feasibility activities, focusing only on the exploitation phase and also excluding the end of life of the launcher. For the first time in the space industry, this LCA study is being performed during the early development of a new launcher system with the goal of providing the complete environmental profile of the launcher at the time of its early production. Another study related to the launcher system was identified: Neumann (2018) compares expendable and reusable launchers.

**Space segment (V).** None of the studies only focuses on the space segment. It is rather included in LCA studies of complete space missions.

**Complete space missions (VI).** Most of the studies dealing with the LCA of complete space missions (6) focus on ‘space segment’ and ‘ground and support segments’ while one (Chanoine, 2017b) gathers ‘space segment’, ‘launch segment’ and ‘ground and support segments’. These studies present the work funded by the ESA Clean Space initiative through a past project called ‘LCA4Space’ (Chanoine, 2017b; Thiry and Chanoine, 2017; De Santis et al., 2013; Geerken et al., 2013) and an on-going ecodesign study entitled ‘Greensat’ (Remy et al., 2018; Thiry et al., 2018; Vercauteren and Holsters, 2017).

### 3.3.2. Functional unit

**Components, Material and Processes (I).** Most of the functional units related to the datasets created in the frame of the Space LCI database are defined to fit with the engineering and eco-design perspective, often mass of materials, mass of materials formed, or mass of material removed. In the case of surface treatment processes, the use of an area unit (e.g. per square meter) seems appropriate while a length unit (e.g. meter) fits well for welding processes.

**Propellants (II).** The propellant data are also expressed following a mass basis as the majority of the LCI data are linked to chemical production and follows a ‘cradle-to-gate’ approach. Nevertheless, the comparison of propellant systems from an LCA perspective is not easy. Each propellant gets specific density and heating value that make the comparison on a mass-oriented basis irrelevant. When comparing two kinds of propellant or propulsion systems, the specific impulse ( $I_{sp}$ ) which measures the efficiency of the propulsion system, has been identified as an appropriate functional unit (Pettersen et al., 2016).

**Ground and support segments (III).** In De Santis (2018), the chosen functional unit is the following: “the fulfilment of requirements of Ground Segment for one year for the following mission types: navigation, Earth observation, science, Telecommunications or CubeSat”. One year of facility operations was also chosen as a functional unit by Castiglioni et al. (2015) and Sydnor et al. (2011).

**Launch segment (IV).** According to the ESA’s Handbook, the functional unit of large-scale systems shall be differentiated between complete space missions and launchers. For the launcher systems, the following functional unit is proposed: “To place a payload of X tons maximum [in single launch configuration and Y tons maximum in dual launch configuration] into orbit Z”. This functional unit allows the comparison of launchers’ environmental performances for the same mission domain. For instance, the comparison between the Ariane 5 and the new Ariane 6 launcher is mentioned in the ESA’s contractual requirement regarding the environmental impact study (Gallice et al., 2018). In such case, the perimeters of the product systems under comparison should be fully compatible and the analysis made under similar assumptions or cut-off rules at the inventory level. When comparing expendable and reusable solution, a temporal dimension must be added related to the launch rates. The yearly equivalent payload mass delivered in orbit may be a good option. Neumann (2018) proposes a launch rate of one launch every two weeks.

**Complete space missions (VI).** Unlike launchers systems, the design of a satellite is highly specific, serving most of the time a unique purpose through a dedicated space mission. Hence, the ESA’s Handbook recommends the following functional unit: “One space mission in fulfilment of its requirements”, but this functional unit can be subject to debate due to the impossible comparison between space missions. An option suggested in the ESA Handbook is to consider the amount of data generated by different space missions to compare the associated environmental impacts of each mission on the same basis. Also, Geerken et al. (2018) highlight that a specific functional unit could be determined for a generic platform design used for instance for multiple missions. This option seems particularly relevant in the case of mass production of satellite platform for mega-constellation systems, e.g. the OneWeb Arrow Platform (Airbus DS, 2018). In this particular case, R&D activities and infrastructures related impacts could be allocated according to the expected

production rate.

### 3.3.3. Inventory

**Source of foreground data.** Over the twenty-seven papers, twenty-one mention that the study is performed or supported by industrial stakeholders. In the case of complex systems including ‘launch segment’, ‘space segment’ or ‘complete space mission’, data collection is a critical part due to the high number of involved industrial partners from suppliers until the final assembly stage in the launch pad. In the frame of the ESA funded studies, industrial contractors are involved in the collection of foreground data specific questionnaires: Deimos for the ground stations (De Santis 2018), Thales Alenia Space for the Sentinel-3B mission (Thiry et al., 2018; Thiry and Chanoine, 2017), and QinetiQ space with the Proba-II and Proba-V missions (Geerken et al., 2018, 2013; Remy et al., 2018; Vercalsteren and Holsters, 2017). The dataset obtained from those studies is expected to be implemented in the ESA space LCI database.

The ESA funded study on the European launchers’ family (Chanoine, 2017b) resulted in the creation of a specific dataset collected from fifteen industrial stakeholders over forty contacted. In the case of the Ariane 6, the data gathered are based on preliminary design status and available information from internal and external partners: more than ten internal focal points and eighteen external focal points among the industrial partners support the data collection step (Gallice et al., 2018). The ESA Handbook mentions that at least two full iterations are necessary for inventory analysis. So, another iteration and an evaluation of the collected data will be completed at the time of the first Ariane 6 launch.

Regarding direct emissions at full system level, the ESA handbook recommends the calculation of flow indicators corresponding to the mass left in space, the mass disposed in the ocean, as well as the atmospheric Al<sub>2</sub>O<sub>3</sub> emissions corresponding to the propellant burning.

For facility management, Sydnor et al. (2011) compile foreground data for each facility involving both facility personnel and the central utilities. For the study, the data for three years of operations are averaged to get a better idea of a typical year for each facility’s usage. In Castiglioni et al. (2015), the data from the European Astronaut Centre are provided or estimated by the ESA for energy, water and waste management.

Several studies point out specific issues related to data collection within the space sector. According to Pettersen et al. (2017a), the specific needs of the space sector lead to the production of materials or chemicals not used elsewhere and with very small production rates. Thus, only very little pre-existing literature for process and precursors can be found. For instance, confidentiality and specificity of the synthesis routes for the chemicals are responsible for major uncertainties during data collection. Those uncertainties are mainly linked with the chemical reactants and associated reaction yields as well as the use of solvents or metal catalysts. Moreover, the highly variable TRL levels hamper the data collection for potential alternatives up-scaled at a potential industrial level.

The study performed by Neumann (2018) emphasises the difficulty of the data collection stage in the space sector. The limitation encountered during the inventory phase, i.e. the exclusive use of generic data coming from a generic database for the materials and propellant parts, prevent from providing a robust conclusion on the comparison between expandable and reusable launcher systems. Besides, the study that focuses on the telecom and meteorological missions (respectively ASTRA 1N and MetOp-A spacecraft) was not directly supported by an industrial stakeholder (De Santis et al., 2013). Its conclusions highlight the difficulties in collecting input data.

**Source of background data.** Ecoinvent database (Ecoinvent Centre, 2013) is used in almost all the studies (23). The US-EI life cycle inventory database (Earthshift, Huntington, VT) is used by Pourzahedi et al. (2017).

For studies dealing with the carbon footprint of materials and propellants (i.e. Pourzahedi et al., 2017; Romaniw and Bras, 2013) the embodied CO<sub>2</sub> are obtained from the Granta Design database (Granta Design Limited, Cambridge, United Kingdom).

Nevertheless, the conventional commercial databases failed in depicting the specificities of the space sector (Saint-Amand et al., 2013). Hence, the ESA space LCI database (gathering ~1000 space specific datasets) should play a major role in the further growth of the LCA applications within the space sector. According to Geerken et al. (2018), a lack of this database lies in the transportation processes for space applications. On the one hand, the high complexity of the supply chain for space activities results in a very broad distance travelled, particularly in Europe where the production, assembly phases and launch event are geographically fragmented. On the other hand, due to the particularity of the space structures and components, the transportation step is most of the time a specific one out of the common logistic circuit. Thus, specifically dedicated transportation datasets should be used instead of conventional ones.

Finally, a hybrid LCA approach with environmentally-extended Input/Output economic data coupled with the foreground data is performed by Geerken et al. (2013). Space applications differ to conventional industrial applications because the price is not mainly driven by the materials but rather by the number of man-hours including energy consumption, travel, buildings but also office equipment and supplies. Consequently, the authors retrieved data for man-hours from the US Input-Output database (Bureau of Economic Analysis, n.d.), taking into account several types of workers: office workers, computer system designers and programmers, scientific researchers.

### 3.3.4. Life cycle impact assessment methods

Among the twenty-seven selected documents, 22 (i.e. 80%) rely on multicriteria analyses while 4 studies just calculate the carbon footprint. One study (Castiglioni et al., 2015) remains at the inventory level, only providing flows of utilities.

The selected LCIA indicators for ESA funded studies are broadly described in the ESA Handbook. They are based on the ILCD 2011 recommended methods (European Commission-JRC, 2011), associated with the Recipe Midpoint *metal resources depletion potential* (Goedkoop et al., 2013b). The latter impact indicator is suggested due to the large number of alloys and metallic components used in the space sector, even if it leads to a “double-counting” issue with the *mineral resources depletion potential* (van Oers et al., 2002). The *ozone depletion potential* (ODP) is a key indicator in the space sector as the space activities are the activities responsible for direct emissions within the ozone layer. ESA also recommends the addition of flow indicators as cumulative energy demand and water consumption of the ecoinvent database v.3 (Ecoinvent Centre, 2013). They can be appropriate when the LCA study covers the perimeter of the facility management system. Furthermore, two flows indicators are designed to account for the use of the substances potentially targeted: on the one hand by the REACH legislation (‘candidate list’ and ‘authorisation list’) and on the other hand the EU critical raw material list (European Commission, 2017). On-going studies are carried out by the ESA about those specific obsolescence or supply risks (Chanoine, 2018a, 2018b).

Dealing with the weighting between the impact categories, an ‘eco-design indicator’ was designed in the frame of the ‘GreenSat’ study (Geerken et al., 2018; Thiry et al., 2018). The eco-design options are chosen based on the score obtained in combining a single environmental score coming from the LCA results and an industrial score based on techno-economic considerations. The topic of weighting indicators through a panel-based approach has been already debated during a ‘round table session’ of the Clean Space Industrial Days 2017. The goal was to make prioritisation to define the most important environmental indicators and to discuss weighting factors between them in order to compute a ‘single score for space’ agreed upon by space

sector actors. However, no consensus was reached because of a potential selection based on 'value choices'.

Finally, current LCIA framework faces methodological limitations to cover the disposal stage and associated end-of-life of both launcher parts and spacecraft systems as underlined by Chanoine (2017) or Geerken et al. (2013). The impacts related to the atmospheric emissions during the launch event need also future investigations (Chanoine, 2017b; Gallice et al., 2018). For instance, aluminium oxide ( $Al_2O_3$ ) which is the main substance emitted during the combustion of solid propellant does not have a characterisation factor regarding toxicity related impacts.

### 3.3.5. Results & Interpretation

**Components, Material and Processes (I).** According to Pettersen et al. (2015b), the environmental impacts of space missions are distributed across a large number of processes and activities, highlighting the complexity of space systems and offering a large range of options for ways of improvement.

First, metal alloys need to include all elements for proper evaluation, especially with the aim of covering the overall *metal depletion* aspects. Only a few quantities of a mineral element can have a great effect on the comparison between metal alloys. Analogous to the alloys, electronic components embedded in the spacecraft contain minor quantities of specific metals (often neglected in technical documents) that may contribute largely to the final LCIA results. It is mainly the case for indicators related to the resource depletion issue. The PV system modelled in the ESA space LCI database by Pettersen et al., 2015a and Silva (2015) is composed by triple junction solar cells of the type gallium indium phosphide/gallium arsenide (GaInP/GaAs) semiconductors on Ge wafer. The gold and silver layers in PV systems and interconnectors are the most important contributors for metal depletion impacts of the whole space segment. The Ge wafer is also an important hotspot for metal depletion and contributes to 75% of the PV score on *global warming potential*. Since germanium is the most important semiconductor material, in weight, of space missions, use of recycled Ge associated with a more efficient industrial processing can generate substantial environmental savings (Kurstjens et al., 2018; Robertz et al., 2015). An alternative to GaAs solar cells is also discussed within the 'Greensat' project by Thiry et al. (2018) considering triple-junction solar cells manufactured thanks to the epitaxial lift-off (ELO) process which results in mass reduction, use of recycled germanium and higher cell efficiency. Perovskite solar cells are also an option but the current low TRL is an issue. Going further, heavy metals, like platinum or rhodium, appear to be important sources for *human toxicity* and *freshwater aquatic ecotoxicity* (Chanoine, 2017b; Remy et al., 2018). However, the metal compounds are not well characterised by any of the existing models (Hauschild et al., 2011). The characterisation factors related to those substances are classified interim by the USEtox consensus model (Rosenbaum et al., 2008) due to the high uncertainties regarding the fate and the exposure of those substances.

Moreover, thermoplastics for space show tendencies to differ from conventional thermoplastics regarding energy-related impacts (e.g. *global warming*) and can contribute to larger toxicity or ozone depletion impacts. Hence, the good representation of chemical precursors used during the synthesis is particularly important to capture the full environmental profile of the material. One specific thermoplastic, the Polytetrafluoroethylene (PTFE), has been identified as responsible for substantial environmental impacts (Remy et al. (2018); Thiry et al. (2018)). This thermoplastic, used as a cable coating in the harness system, represents around 30% of the space segment's *ozone depletion potential* impact. Consequently, its replacement is considered as an eco-design option in the frame of the 'GreenSat' project.

Pettersen et al. (2015a) showed that advanced materials lead to more emissions invested in materials production than conventional ones. Thus material efficiency becomes especially important. Nevertheless, space industry relies on production processes facing a very high buy-to-fly ratio, particularly for tank

production. Hence, recycling of scrap materials could be an interesting way of improvement dealing with resource efficiency. Innovative processes as ‘friction stir welding’ is also a promising option to increase the buy-to-fly ratio (Brassington and Colegrove, 2017). This is also the case of additive layer manufacturing (ALM), for which the potential environmental benefits are widely investigated within the space sector (Ouziel, 2015; Pettersen et al., 2017b; Thiry et al., 2018) and in the aeronautic industry (Ford and Despeisse, 2016; Mami et al., 2017).

Surface treatment processes using chemical baths should be deeply investigated since the chemicals used (e.g. nitric acid or Cr VI) present environmental disadvantages in term of toxicity and can be targeted by specific legislation as the REACH regulation. This topic is discussed by Izagirre and Zimdars (2017) and Pettersen et al. (2015b). However, the heavy qualification procedures represent a limiting factor in finding less impacting alternatives. Besides, the results of the LCA study performed by Izagirre and Zimdars (2017) mentioning a potential environmental gain using citric acid passivation need to be confirmed with full-scale industrial data. If the LCA approach is well suited to evaluate products or processes that are already mature, it faces practical and methodological difficulties when applied to emerging technologies. This topic is currently debated in the LCA community (Arvidsson et al., 2018; Cucurachi et al., 2018; Piccinno et al., 2016).

Finally, mass reduction thanks to technology evolution (e.g. miniaturisation) or linked to the use of lightweight materials was targeted by several space environmental studies. Vercalsteren and Holsters (2017) highlights the mass reduction occurring between two generations of similar scientific instruments: 34 kg for the current embedded Vegetation instrument on PROBA-V mission against 150 kg for the previous instrument on SPOT5 mission. Mass and associated environmental savings are also studied in exploring material substitution of traditional metallic components with composites as carbon nanotube composites in the case of electromagnetic interference shielding (Pourzahedi et al., 2017) or with carbon fibre reinforced polymers for structural elements (Romaniw and Bras, 2013). By reducing the mass of the components, substantial propellant savings may be expected. According to the Tsiolkovsky rocket equation, the delta-V parameter (which determines how much propellant is required for a vehicle of a given mass and propulsion system) increases exponentially with respect to the mass ratio of the wet and dry mass.

**Space propellants (II).** The trade-off between the lightening of the mass and the reduction of propellant consumption is a key element regarding the eco-design for space activities. The mass of propellant represents the majority of the mass breakdown (e.g. around 87% of the lift-off mass for Ariane 5 ECA), and its production is a major contributor regarding the environmental profile of the launcher-related segment (Gallice et al., 2018; Pettersen et al., 2018).

In the case of propellants deriving from generic chemicals, the importance of the environmental impacts can sometimes differ. For instance, space-grade liquid hydrogen produced for launches in Kourou (French Guyana) generates one order of magnitude more impacts than conventional liquid hydrogen (Pettersen et al., 2017a). Furthermore, several purification steps are necessary to guarantee a high purity grade of the propellants (> 99%). It results in additional use of solvent and electricity: a similar quantity of energy is used in the purification step to obtain pure hydrazine (99%) from conventional hydrazine (64%) and to obtain an ultrapure Hydrazine (99.9%) from pure hydrazine (99%). As the majority of propellants faces toxic risks, the decontamination and waste treatment steps (such as purges with helium or nitrogen and solvent flush) lead to environmental hotspots on the overall impact categories. The end of life of contaminated solvent is a critical issue regarding LCA modelling.

In Pettersen et al. (2016), three propulsion systems are compared: monopropellant hydrazine; bi-propulsion mixed oxides of nitrogen (MON)/monomethyl hydrazine (MMH), and chemical-electric propulsion



hydrazine/xenon. The chemical-electric propulsion system with xenon/hydrazine has the highest environmental impact for all impact categories in comparison with the two other systems except for *freshwater ecotoxicity potential*. It is mainly due to the production of xenon that requires 1400 kWh per kilo when extracted with the cryogenic air separation process (according to the ecoinvent database). However, it should be noted that electric propellants have higher  $I_{sp}$  values (by approximately 4-8 times) than the other propellant types and thus require lower weight and volume storage that should modify the propulsion system.

**Ground and support segments (III).** As the specific ESA funded study on Ground Segment is not completed (De Santis, 2018), the available results are yet very limited. For the NASA's ground test facilities, most of the impacts on *global warming potential* stem from electricity and natural gas consumption. Almost half of the contribution to the *global warming* impact is driven by coal-fired electricity alone. Therefore, the use of renewable energy coupled with an optimised facility management seems today a key element in decreasing the impact of space activities on *climate change*. This way of improvement has been identified in the frame of the 'GreenSat' project (Thiry et al., 2018; Thiry and Chanoine, 2017).

Besides, Sydnor et al. (2011) emphasise the carbon footprint of specialised facilities using refrigerant (e.g. R-134 or R-14) due to the high global warming potentials (GWP) of these gas. In facilities that use refrigerants, loss of refrigerant gas by leakage usually dominates the carbon footprint of the facility. Gallice et al. (2018) also mention the issue of refrigerant fluid for air conditioning. It should be investigated in the next iteration of the Ariane 6 LCA study.

**Launch segment (IV).** Regarding the Ariane 5 study provided by Chanoine (2017), electricity and heat consumption from the propellant production, the stage production, and launcher integration are the three main contributors for the global warming potential. The activities that take place in the Guiana Space Centre (spaceport), mainly the propellant production, are less contributing to global warming potential than primary energy consumption thanks to the Guianese electricity mix composed by 47% of renewable energy. Transport stage is also a non-negligible contributor to global warming potential, specifically maritime transport which is also an important contributor to terrestrial acidification, marine eutrophication and photochemical oxidation potential.

The production of the stages, driven by the structure of two boosters and the main cryogenic stage, are identified as the main contributor for the categories metal depletion, human toxicity and freshwater ecotoxicity mainly due to the use of stainless steel. The impact on ozone depletion potential is dominated by the 'launch event' due to the direct emissions of alumina and chlorine occurring in the high atmosphere. Hydrogen chloride is also emitted during the 'launch event' and is responsible for one-third of the terrestrial acidification impact.

Regarding only the overall propellants production, environmental impacts are mainly generated by the solid propellant which represents more than 70% of the propellant loaded mass. The solid propellant contributes to 65% of the impact regarding the overall propellant production for global warming potential impact and around 90% of the impact for toxicity and freshwater ecotoxicity due to CrVI emissions as well as metal depletion due to platinum use. Considering the mass of propellant loaded, liquid H<sub>2</sub> (~5% of the propellant mass) represents around 15% of the impact on global warming potential for the propellant part.

The interim results for Ariane 6 presented by Gallice et al. (2018) at the ESA Clean space industrial days, may confirm that 'production and assembly stages' and 'propellant manufacturing' are the main contributors for both Ariane 5-ECA and the future Ariane 6. However, the contributions of the R&D and preliminary testing phases were not taken into account in both cases while they should influence the energy-driven impact

categories. According to Soares et al. (2012), the allocation of the impact of these phases presents several difficulties mainly linked with the ‘Technology heritage’ issue, i.e. the identification of which parts or components are inherited from a previous launcher design.

**Complete space missions (VI).** The launcher represents 99% and the spacecraft 1% of the mass of a complete space mission. Therefore, the environmental impacts related to the launcher (production, launch campaign, launch event) is a major hotspot on all the impact categories, e.g. between 50% to 70% of the *global warming potential* depending on the launcher’s dry mass (Chanoine, 2017b). The use phase (control centres and ground stations) contributes to most of the impact categories *via* the energy consumption for operations particularly the *toxicity/ecotoxicity potentials* (~50%) and to a lesser extent *global warming potential* (~25%). The ‘Launch event’ (propellant burning) is the most impacting phase regarding *ozone depletion potential*: near 100% of the impact. The production of the PV system (for solar cells) also generates 100% of the impact on *mineral resource depletion potential*.

When the launch segment is not considered within the scope, the utilisation phase of the spacecraft (see Table 2.2) contributes to 40 to 60% of the environmental impacts for the overall categories in the particular case of the Proba-V mission (Remy et al., 2018). During this use phase, electricity consumption of the data centre and servers are majors contributors as shown by Remy et al. (2018) and Thiry and Chanoine (2017). Regarding the design and the production phase of the spacecraft, it accounts for more than 30% of the overall environmental impacts (Remy et al., 2018).

Within the design and production phase, the office work is by far the major contributor (>50% for all the impact categories) with the exception of for the *mineral resource depletion* driven by the materials used for satellites (Remy et al., 2018; Thiry and Chanoine, 2017). During the production stage, the scores related to the *toxicity/ecotoxicity* categories are also driven by the production of the electronic components embedded in the payload that account for around 30% (Chanoine, 2017b). These results are in line with the conclusions of Geerken et al. (2013) also mentioned by Vercauteren and Holsters (2017) that highlight the environmental importance of the phases with a lot of man-hours. The production and testing of satellites gather most of the working time, so the corresponding phases are responsible for a large portion of the environmental impacts. The R&D man-hours have a major contribution to the environmental impact of the satellite mission. Their impacts are mainly generated by the consumption of energy and the infrastructure.

## 4. Discussions & perspectives

### 4.1. Extending the goal and scope for LCA studies in the space sector

The space industry is today experiencing an innovation-driven paradigm shift, leading to the “democratisation” and “industrialisation” of space (OECD, 2016). The emergence of new space systems as large satellites constellations will result in new technological capacities. However, the breakthrough allowed by space applications should also be judged through the scope of the sustainability assessment. Thus, LCA appears as the most relevant tool to holistically address the comparison of the environmental footprint between conventional, Earth/space hybrid and stand-alone space systems.

In a position paper published in 2013, Durrieu and Nelson (2013) explain that LCA methodology is particularly relevant in the field of Earth observation to identify the best option between (i) full series of short-lifetime satellites, (ii) a solution based on a long lifetime observation satellite coupled with airborne systems, (iii) the use of airborne system alone. The communication and internet networks are also a topic of interest as space applications are expected to play a major role in this field. A preliminary work assessing the carbon footprint of a hybrid telecommunication network is proposed by Faulkner et al. (2015). Environmental benefits were

also discussed in the case of space solar power generation through a life-cycle perspective (Gigantino, 2015; Hayami et al., 2005; Weingartner and Blumenberg, 1995). Recently, an attempt to apply the LCA methodology to the emerging topic of 'Asteroid mining' was proposed by Hein et al. (2018). More generally, future applications of LCA in space, following the technological advancements in space exploration and travel, are discussed by Ko et al. 2017. They highlight the need to extend the scope for future LCA in space taking into account the outer space exploration and the potential environmental impacts associated with this activity.

## 4.2. Improving inventory collection

The review of the selected documents highlights the necessity to include the industrial stakeholders to enhance the robustness of the LCA studies within the space sector. The quality and the access to the inventory data remains the major issue regarding the studies. It is mainly due to the complex supply chain for the large-scale systems as well as the confidential nature inherent to the space sector. The lack of a peer-reviewed process is also emphasised through the nature of the retrieved documents with only three scientific peer-reviewed article.

In contrary to the belief that a detailed and accurate data collection would result in punishments compared with a simplified inventory, Pettersen et al. (2018) showed a truncated collection might lead to an overestimation of the impacts. They modelled the same component (i.e. a spacecraft reaction wheel) in two ways: according to a detailed inventory against a simplified one. The simplified LCI leads to higher impacts than the complex one in four of the five selected impact categories. This example should encourage industrial stakeholder to carefully address the inventory stage providing as much as possible foreground data.

Generic good practice regarding data collection are addressed in the ESA Handbook. A cut-off rule based on a mass criterion can be used to ease the completion of the inventory phase. According to the ESA Handbook, material or sub-assembly inputs constituting all together less than 5% of the total mass of the system considered can be neglected. However, particular attention should be paid regarding metals and chemicals: (i) in case of the use of scarce metals only a few quantities can significantly affect the metal depletion scores; (ii) any substance listed as an EU critical raw materials or targeted by the Reach regulation (i.e. REACH Annex XIV) cannot be excluded.

Regarding the end-of-life stage, the ESA Handbook recommends not to provide any environmental benefit due to recycling or due to energy recovery when the material is sent to the recycling plant. If conventional inventory data for the end-of-life shall be collected (e.g. transport to waste management plant, ratio between landfill and incineration processes), the "cut-off at recycling" approach is applied for the recycling and recycled materials. More details in the general allocation rules can be found in Schrijvers et al. (2016).

## 4.3. Towards a better characterisation of the space industry's specific related impacts

When dealing with the comparison of conventional and space applications, a fair characterisation of the environmental impacts shall be performed. However, space systems deal with a strong particularity which complicates 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). As highlighted by the results of the review (see section 3), current gaps in the Life Cycle Impact Assessment framework need to be addressed to cover the full scope of the space activities.

The atmospheric impacts during the launch event are commonly perceived as the major environmental hotspot. However, the specific impacts related to the launch phase need future research efforts to be fully considered in the LCA studies. Gaseous launcher emissions due to propellant burning include CO, N<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, and CO<sub>2</sub>, while solid rocket motors (SRM) generate aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) particles, black carbon (i.e.

soot) and gaseous chlorine species into the atmosphere (Voigt et al., 2013). According to an ESA funded study (Murray et al., 2013), uncertainties affect the characterisation of the launchers' impacts on the atmosphere. The main areas of uncertainties are related to (i) the aerothermodynamics of rocket plumes which include the combustion and expansion process and (ii) the climate modelling including the insertion of small scale plumes into relatively large scale climate models.

A particular focus has been made on the ozone depletion concern, mainly because the emissions associated with the launch are the only human-produced source of ozone-destroying compounds emitted directly into the middle and upper stratosphere (Bekki et al., 2017; Koch et al., 2013; Ross et al., 2009, 2000, 1997; Ross and Vedda, 2018; Voigt et al., 2013). To a lesser extent climate change impacts related to rocket plumes are also discussed (Ross et al., 2009; Ross and Vedda, 2018; Voigt et al., 2013) but often considered in these papers as marginal in comparison with the aircraft's carbon footprint. However, emissions of greenhouse gas in high altitude can have a higher radiative forcing than emissions in low altitude (Jungbluth and Meili, 2018). New propellants are also being proposed by the space industry particularly the liquid oxygen/methane solution. New models of ozone depletion should be adapted to anticipate future environmental impacts. Finally, the question of the toxicity related to chemical compounds should be deeper investigated (Parker, 2009).

With an expected increase of the flight rate of space transportation in the next decades, the burdens on *ozone depletion*, *global warming* or *toxicity* could become critical and change the perception of 'marginality' associated with the contribution of space sector compared to other industries (Larson et al., 2017; Ross and Vedda, 2018). Hence, there is a need to compute the effects of space industry-specific emissions, specifically those occurring in high altitude.

The questions of space debris is also a crucial issue regarding the sustainability of space activities. Colombo et al. (2017) developed a first index while a comprehensive framework was published by Maury et al. (2017). These initial researches lead to the creation of dedicated characterisation factors to include the space debris related impacts within LCA of space missions (Maury et al., 2019). In this way, the burden shifting between the Earth and the orbital environment could be characterised. Going further, the end of life of space missions should also consider the environmental impact due to the atmospheric re-entry in the high atmosphere as well as the presence of non-demised materials or launcher stage in the oceans. An on-going ESA funded study is carried out on the topic of the environmental impact related to the atmospheric re-entry (Bianchi et al., 2018), while work performed for the French Space Agency (INERIS, 2015, 2014) could represent a first step in the elaboration of dedicated characterisation factors covering respectively the atmospheric re-entry and fall of materials on ground or in the oceans.

As LCA is a versatile methodological framework, future investigations on emerging environmental burdens could be implemented in the LCA of space missions as long as new indicators and associated characterisation factors are developed in compliance with the ISO standard (ISO 14040/44, 2006). For instance, if the trend concerning the impacts of acoustic waves on the ionosphere (Chou et al., 2018a, 2018b) is confirmed, the latter impact could be considered in the frame of the LCA of space missions. In this way, the paper published by Cucurachi et al. (2014) provides general guidance for deciding on the inclusion of emerging impacts in life cycle impact assessment.

#### 4.4. Opportunities in developing LCA practices in the European space context

At the European level, the tools and methodologies developed in recent year present a great opportunity to implement and develop the use of LCA within the industry. It allows improving the identification of the environmental hotspots along a company's supply chain of its products, reinforcing the knowledge of the

upstream and downstream activities. Regarding facility management, LCA is a powerful tool to map the flows of utilities (e.g. electricity, water, waste) and identify ways of improvement adopting a so-called *Lean & Green* approach (Garza-Reyes, 2015).

Moreover, the application of LCA in the space industry can be regarded as a proactive process to anticipate future risks due to public concerns and legislation. The current issue of the plastic marine debris and associated legislative efforts is a good example for this. LCA provides a harmonised response regarding environmental impact assessment along the life-cycle. The communication of the results obtained can be seen as a central element in response to a legislative framework (e.g. the French space act), public concerns expressed by NGOs, or a contractual requirement of a client. Also, as the environmental concern is a new topic in the space community, the environmental life cycle management (LCM) appears as a differentiating factor among the competitors (Sonnemann and Margni, 2015).

The LCA methodology faces currently limitations at low TRL levels as highlighted through the ex-ante LCA concept (Cucurachi et al., 2018). Nevertheless, the integration of LCA as soon as the early design phase seems a promising option to improve the sustainability of the space systems. In this way, a new dimension related to the environmental performance could be included in the concurrent engineering of new projects thanks to the inclusion of LCA-based indicators. This would represent a substantial improvement with regard to the ecodesign procedure of the ISO 14062 (2002) standard dealing with the integration of environmental aspects into product design and development.

Finally, the recognition of LCA as a science-based methodology can also strengthen the environmental reporting in the frame of the corporate social responsibility (CSR). Quantitative environmental disclosures adopting a life cycle perspective could be provided through monitored key performance indicators (KPI). According to Stewart et al. (2018), the LCA stands for an indication of sustainability management practices in the industry among investors or evaluation approaches of external ranking agencies. For example, the sustainable finance action plan launched in 2018 in the European Union requires companies to strengthen their nonfinancial information disclosures.

## 5. Conclusion

This paper reviews the current application of the environmental LCA in the space sector. It shows that existing peer-reviewed literature is scarce. The majority of the work done to use LCA approach in the space sector comes from Europe and particularly the ESA in the frame of its Clean Space initiative. The review highlights the emergence of a common framework regarding LCA practice in Europe.

The analysed LCA case studies show a highly heterogeneous goal and scope definition. While some papers addressed large-scale systems as launch segment or space missions, others focus on space-specific materials or processes. This review highlights the fact that LCA application to the space sector is not straightforward, mainly regarding the completion of the LCI phase where the collection of foreground data is a key element and a current challenge. The access to a space-specific database for the background data is a need considering the particular properties of the materials and chemicals used. At the European level, substantial efforts were made in this sense by the ESA through the achievement of the space LCI database that needs to be maintained and improved by future LCA studies in the sector.

This review also paves the way for future research, with the aim of developing the use of LCA and life cycle management at industrial level while assessing the environmental performance of space missions. However, methodological limitations regarding the LCIA phase remain. They should be tackled to reinforce the credibility and robustness of LCA studies in the space sector. Among others, two topics seem to be of prime

importance. On the one hand, the ozone depletion related impact appears as a major issue, especially since emissions of ozone depleting substances unexpectedly increased in recent years (Fang et al., 2018; Montzka et al., 2018). On the other hand, the impacts occurring in the orbital environment due to the lack of space traffic management and through the space debris proliferation represent a current burning issue that should be fully integrated into the LCA studies, ensuring a more sustainable design of the space systems.



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# 3

## INTEGRATION OF ORBITAL SPACE USE IN LIFE CYCLE IMPACT ASSESSMENT



*“En essayant de copier on voit mieux la chose”*

– Alberto Giacometti

Trois hommes qui marchent (1948), Alberto Giacometti  
Fondation Giacometti



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## 1. Introduction

The outer space is considered by the United Nations' treaties as a 'Global Common' of the humankind such as oceans, the atmosphere or the Antarctic (UN COPUOS, 2017b). Consequently, the topic of space sustainability has gained increasing recognition among States and intergovernmental organisations. The long-term sustainability of the space activities is defined by the UN COPUOS as *'the conduct of space activities in a manner that balances the objectives of access to the exploration and use of outer space by all States and governmental and non-governmental entities only for peaceful purposes with the need to preserve the outer space environment in such a manner that takes into account the needs of current and future generations'*. Regarding the necessity to preserve the orbital environment, a broad consensus is today reached on the need to investigate and consider new measures to manage the space debris population in the long term (UN COPUOS, 2017a). The national delegations of the Inter-Agency Space Debris Coordination Committee (IADC), founded in 1993, published the first "IADC Space Debris Mitigation Guidelines" in October 2002, which were revised in 2007 (IADC, 2007). According to these guidelines, operators of space missions must complete 'Post-Mission Disposal' (PMD) to ensure that the entire spacecraft or parts of a launch vehicle do not become debris. Furthermore, the LEO and GEO areas are recognised as "protected regions" due to their unique nature. It means that orbit retrieval is mandatory for any spacecraft or part of launcher crossing or residing in LEO or GEO regions. In the case where objects are located in the GEO region, they have to be re-orbited far enough away from the original orbit to a graveyard orbit. In the LEO, the 25-year rule must be applied, i.e., space objects must complete a post-mission disposal within 25 years after the end of the mission. A de-orbiting manoeuvre is recommended with the aim of ensuring direct atmospheric re-entry (Bonnal, 2014).

Chapter 2 identified several methodological challenges for the application of LCA within the space sector. One of the most discussed is the need to extend the current scope of the LCA for space missions. In-orbit operations, covering both use phase and EoL of the space mission shall be considered. However, the lack of appropriate impact categories to consider space activities related impact in the orbital environment was highlighted.

Within the aerospace engineering community, Letizia et al. (2017) review several indices that assess the criticality of a spacecraft against the current orbital debris population. 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., 2017b). Numerical and analytical approaches have already been proposed and discussed by several authors, based on the density of debris (Rossi et al., 2015) or the flux of debris (Anselmo and Pardini, 2015; Kerschull et al., 2014; Letizia et al., 2016). For the first time in 2017, Colombo et al. (2017a) proposed an index to be used in a complementary way with LCA for eco-designing space missions. However, none of these contributions was developed in line with the LCIA framework since they do not follow a clear impact pathway linking inventory and impact and/or damages through a consistent characterisation model with associated characterisation factors (CFs).

Given this situation, there is an opportunity to link space activities related impact on the orbital environment and the life cycle impact assessment (LCIA) framework. LCA studies of space missions should indicate trade-offs not only between typical impacts categories (toxicity and climate change for example) but also with regard to potential impacts on the orbital environment (e.g. the release of space debris), as it is an important issue for the sustainability of space activities. Therefore, the primary goal of the present chapter is the development of impact pathways in compliance with the LCIA framework to deal with potential impacts and damages on the orbital environment and occurring during the orbital lifetime of a spacecraft.

For this purpose, we first review the LCIA framework in general and more particularly the characterisation models related to *resource use*. Then, we demonstrate how orbital volume is a valuable resource that should be safeguarded from the threat of space debris and EoL mismanagement. From this review and first analysis, we present impact pathways linking orbital use to resource issues. These pathways are a first step towards the elaboration of a dedicated indicator fitting in the Area-of-Protection (AoP) ‘natural resources’.

## 2. Review of the LCIA framework

### 2.1. General framework description

This paper focuses on the third phase of LCA: the LCIA phase. According to ISO 14040/44 (2006a, 2006b), the purpose of the LCIA phase is to establish a linkage between the inventory of elementary flows in the system under study and their potential environmental impacts and damages related to the induced environmental mechanisms. The description of how the starting points (substance flows and physical changes) are connected to final environmental damages is called an impact pathway (Jolliet et al. 2003). The characterisation steps that shall be considered to build a consistent impact pathway are described in the following subsections.

#### 2.1.1. A starting point for LCIA: the elementary flows

Human activities conduct physical and chemical exchanges with the environment. These exchanges take place between the “ecosphere” (i.e. the whole planetary environment) and the “technosphere” (i.e. sphere of human activity). They are mentioned as “elementary flows” by ISO standards (2006) and may take two forms, as illustrated in Figure 3.1:

- An extraction of resources from the ecosphere to the technosphere;
- A substance emission from the technosphere to the ecosphere.

The substance is emitted either to air, to water bodies, or on the soil. The elementary flows, based on physical and chemical exchanges, can be obtained as a result of the inventory analysis. An estimation of the overall materials and emissions needed through the life cycle of the studied product system. Thereafter any elementary flow is addressed regarding the ‘environmental mechanism’ induced, i.e. the system of physical, chemical and biological processes for a given impact category (ISO, 2006b).

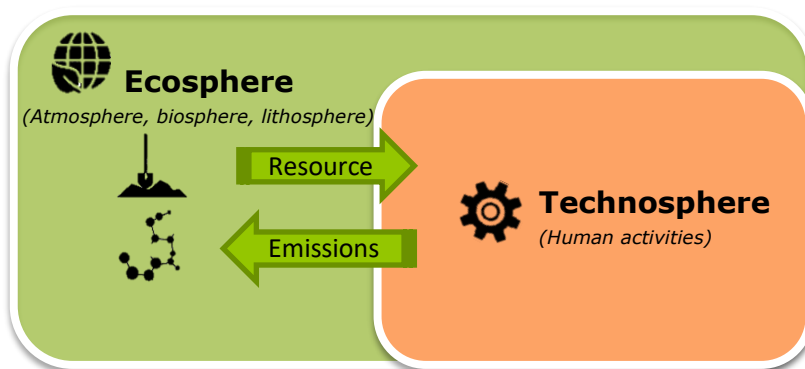


Figure 3.1 – Elementary flows between ecosphere and technosphere

#### 2.1.2. From environmental mechanisms to impacts: the midpoint indicators

Characterisation at the midpoint level allows calculating the environmental impact on the ecosphere taking into account the succession of environmental mechanisms. A point positioned along the environmental mechanisms can be chosen as an indicator, often referred to as the ‘midpoint’, whereas the ultimate environmental damages are referred as endpoints (Hauschild and Huijbregts, 2015; Jolliet et al., 2004).

For each midpoint and endpoint along the impact pathway, ‘characterisation factors’ (CFs) have to be derived from the environmental mechanisms or human interventions. CFs represent the quantitative contribution of a given substance to a specific impact category. It is calculated using scientifically valid and quantitative models of the environmental mechanism representing as realistically as possible the cause-effect chain of events leading to effects (impacts) on the environment for all elementary flows which contribute to this impact (Rosenbaum et al., 2018). For example, regarding climate change, various substances shall be taken into account (e.g. CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>O). For each one, a particular CF, is applied to calculate the substance contribution on the environmental mechanism. In this way, the impact at the midpoint level is Eq. 3.1):

$$IS_c = \sum_i (E_i \cdot CF_i) \quad \text{Eq. 3.1}$$

ere  $IS$  is the impact score for a given environmental impact category  $c$ . The latter is obtained multiplying all the elementary flows  $E$  by their respective characterisation factor  $CF$  and summed over all relevant interventions  $i$  (emissions or resource extractions) (Rosenbaum et al., 2018). The result is expressed in a specific unit equal for all elementary flows within the same impact category.

The CFs associated to a given environmental impact depends on the impact assessment method chosen. The European Commission published in 2011 the ILCD handbook (JRC European Commission, 2011) which contains a list of recommended methods and indicators used for each midpoint impact category. This list was recently updated (Fazio et al., 2018) in the frame of the product environmental footprint (PEF). The recommended methods at midpoint level are presented in Table 3. 1.

Table 3. 1– Recommended methods and their classification at midpoint level (Fazio et al., 2018)

Impact Category	Recommended default LCIA method	Midpoint indicator	Unit
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)	kg CO <sub>2</sub> eq
Ozone depletion	Steady-state ODPs as in (WMO 1999)	Ozone Depletion Potential (ODP)	kg CFC-11 eq
Human Toxicity, cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for humans	CTUh
Particulate matter/ Respiratory inorganics	PM method recommended by UNEP (UNEP 2016)	Human health effects associated with exposure to PM <sub>2.5</sub>	Disease incidences
Ionizing radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al., 2000)	Human exposure efficiency relative to U <sub>235</sub>	kBq U <sub>235</sub>
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	Accumulated Exceedance (AE)	mol H <sup>+</sup> eq
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	Accumulated Exceedance (AE)	mol N eq
Eutrophication, aquatic	EUTREND model (Struijs et al., 2009b) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	kg P eq or kg N eq
Ecotoxicity (freshwater)	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for ecosystems	CTUe

<b>Land use</b>	Soil quality index based on LANCA (Becket al. 2010 and Bos et al. 2016)	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration and groundwater replenishment)	Dimensionless, aggregated index
<b>Water use</b>	Available WAter REmaining (AWARE) in UNEP, 2016	User deprivation potential (deprivation-weighted water consumption)	Kg world eq. deprived
<b>Resource use, minerals and metals</b>	CML 2002 (Guinée et al. 2002) and van Oers et al. (2002).	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ
<b>Resource use, energy carriers</b>	CML 2002 (Guinée et al. 2002) and van Oers et al. (2002).	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq

### 2.1.3. Endpoint characterisation within the ‘Areas of Protection’ (AoP)

The endpoint indicators are related to a damage-oriented approach. According to ISO, the endpoints are classified into three environmental concerns: (i) natural environment, (ii) human health and (iii) natural resources. They are referred to as “Areas-of-Protection” (AoP), i.e., the entities that we want to protect due to their value for society; they were first described by Udo de Haes et al. (1999).

More details are given in Bare *et al.* (2008): the first AoP, human health, relates to the protection of and minimising the potential harm to humans. The second area deals with the quality of the ecosystems that function to support life on Earth. The third, about natural resources, includes both abiotic and biotic and takes into account materials that are extracted, harvested, or otherwise obtained from the environment for the beneficial use of humans.

The latter definition of ‘natural resources’ is in line with the OECD definition (Dewulf et al., 2015): “natural resources are natural assets (raw materials) occurring in nature that can be used for economic production or consumption”. Since this thesis focuses only on the environmental dimension of term *resource* (i.e. not related to the financial or human terminologies), we will further use the term of *resources* which refers to natural resources.

### 2.1.4. Emissions-related impacts

Figure 3.2 illustrates the impact pathways resulting from substance emissions and resource extraction on environmental damage in the three AoP. Regarding the emissions-related impact categories, the characterisation factor of a given substance addressing environmental damages at the endpoint level is expressed as the product of the following factors:

- i. Fate factor (FF) corresponds to environmental processes causing transport, distribution and transformation of the emitted substance.
- ii. Exposure factor (XF) consists of the contact of the substance on sensitive targets in the receiving environment
- iii. Effect factor (EF) represents the observed adverse effect on the sensitive target after exposure to the substance.

Hence, the characterisation factors for emissions-related impacts are expressed as  $CF = FF \cdot XF \cdot EF$  (Hauschild and Huijbregts, 2015; Rosenbaum et al., 2018; Van Zelm, 2010).

The final damage distinguish the severity of observed effects by quantifying the potentially *disappeared fraction of species* in an ecosystem integrated over area and time, or for human health by giving more weight to death and irreversible problems than to reversible temporary problems (e.g. a skin or respiratory irritation) through the concept of *disability-adjusted life years* (DALY – years).

### 2.1.5. Resources-related impacts

Regarding resource extraction, characterisation factors at the midpoint and endpoint levels follow a different layout, as shown in Figure 3.2. Resources are removed from the natural environment by human interventions and transferred into the technosphere, thereby playing a vital role in sustaining the livelihood of human societies.

The first step in the impact pathway is a *change in the asset*, which can be evaluated with resource accounting methods (Swart et al., 2015). It is obtained as a result of the life cycle inventory (LCI). At a midpoint level, the impacts are addressed regarding a reduction in the quantity or the quality of the remaining asset, and consequently, the degradation of the resource after human use leads to decreased potential and functionality (Jolliet et al., 2003).

Environmental damage at the endpoint level is mainly linked to the AoP ‘resources’ (e.g., minerals or fossil fuels) although human health or the natural environment may be targeted in particular cases (e.g., water use or biomass exploitation). The damage on resources can be assessed by increasing the expense of resource extraction due to the decreasing availability of the resource (Goedkoop et al., 2013a; Schneider et al., 2016).

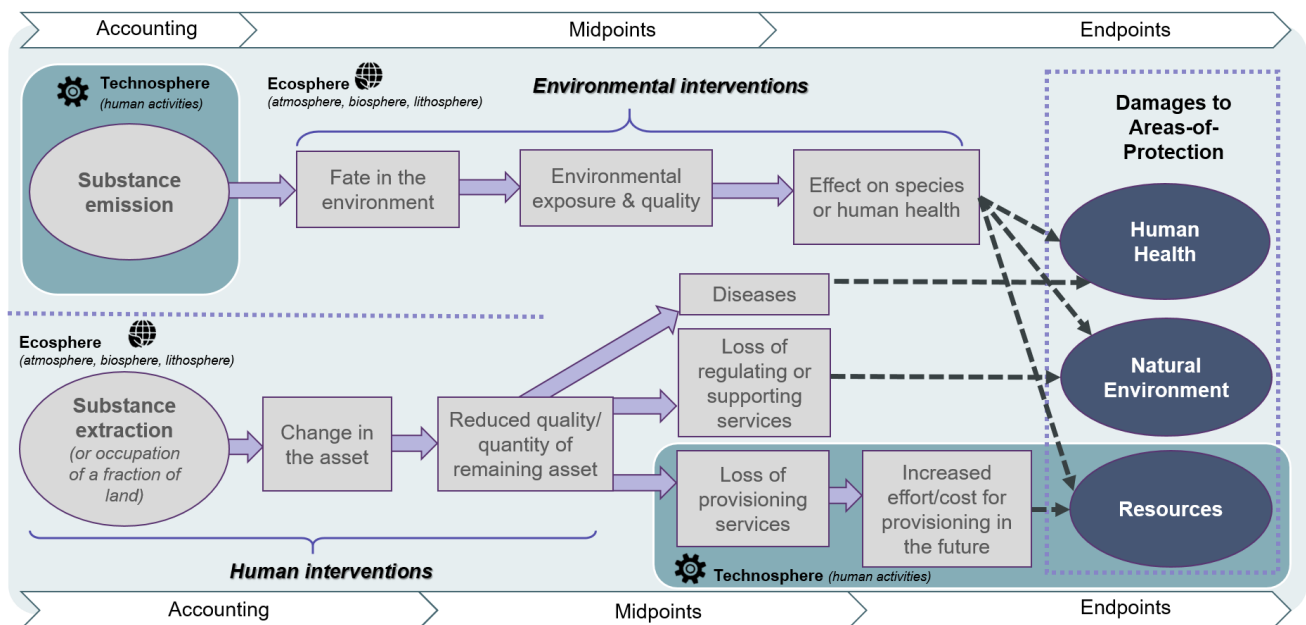


Figure 3.2 - General LCIA framework of environmental impacts and damage to the AoP (freely adapted from Finnveden et al., 2009; Rosenbaum et al., 2018; Sala et al., 2016; Swart et al., 2015; Van Zelm, 2010)

## 2.2. Characterisation of resource use

The evaluation of *resource use* in the LCIA framework depends on an understanding of the resource. A definition of AoP ‘resources’ has not yet been achieved and is still subject to debate (Dewulf et al., 2015; Schneider et al., 2016). Consequently, there is currently no agreement in the scientific community on the most appropriate characterisation models to address resources in LCA (Sonderegger et al., 2017; Zampori and Sala, 2017). A wide variety of LCIA indicators have been developed to assess *resource use*, but there is no recommended method at the endpoint level today due to a lack of clear distinction between impact and damage categories (JRC European Commission, 2011; Sala et al., 2016; Schneider et al., 2016). Mineral resources are subject to special attention. A task force under the umbrella of the UNEP/Life Cycle Initiative (2018) will soon release a set of recommendations on the applicability of current methods and future development needs (Berger et al., 2019; Sonderegger et al., 2019).

In this context, there are currently good opportunities to redefine and adapt the concept of *resource use* in LCA to focus on specific aspects and perceptions of decreased resource availability.

### 2.2.1. Resource classification

Swart et al. (2015) report that available resources may be classified according to the three categories of *stocks*, *funds* and *flows*:

- i. a *stock resource* means the extraction leads to a reduction in the available amount that is not renewed in nature;
- ii. a *fund resource* may be depleted but may also have a renewal rate that allows the resource to recover;
- iii. a *flow resource* cannot be depleted over a consequent time scale but the short-term availability could be constrained.

Furthermore, the use, occupation or transformation of *water* and *land* may also affect their future availability, so these can fit into the AoP 'Resources' (Dewulf et al., 2015). In this way, the allocation of land areas to human-controlled processes is considered *resource use*, particularly in the case of 'land competition', as mentioned in the UNEP/SETAC Land Use framework (Koellner et al., 2013). Moreover, a recent framework based on Dewulf et al. (2015), aiming at addressing impacts of freshwater use to resources for future generations has been published (Pradinaud et al., 2018). It concludes that freshwater exists in the form of three types of resources (flow, fund, or stock) and can be affected by both consumption (source function) and pollution (sink function). It is also the case of the soil in the frame of the land use category.

### 2.2.2. Functionality

Modelling of *resource use* also requires to consider the *functionality* of the resource. In line with Jolliet et al. (2004), a clear distinction must be made between intrinsic and functional values dealing with damage categories. Most abiotic resources only have a functional value from an anthropocentric point of view. This means that the resource is only seen as a way of providing services to the man-made environment and economy (as mentioned in Figure 3.2: 'provisioning services'). Therefore, impacts associated with *resource use* and decreasing availability should be taken into account considering the functionality that they deliver to human society (Finnveden, 2005; Stewart and Weidema, 2005). Verones et al. (2017) describe how damages linked to this functional value can be measured: (i) through damage on the socio-economic assets (e.g. on man-made environment such as built infrastructure, loss of cash crops) and (ii) damage on resources and ecosystem services (e.g. exhaustion of primary mineral resources, loss of availability of crops, wood, loss of water flow regulation potentials).

### 2.2.3. Resource depletion

According to van Oers and Guinée (2016), the depletion of a resource means that its abundance on Earth is reduced. Models assessing the depletion of abiotic resources are mainly based on geological stock and availability with a long-term perspective. The Abiotic Depletion Potential (ADP), included in the CML method and recommended by the JRC European Commission (2011), is the primary approach to dealing with resource depletion (Guinée et al., 2002; van Oers et al., 2002).

To assess the availability of a resource, Goedkoop et al. (2013) propose another approach based on the 'future efforts' in resource extraction, at the midpoint and the endpoint levels using the ReciPe methodology. The marginal cost increase (MCI) was chosen as a part of the characterisation factor and represents an increase in the cost of a commodity, due to an extraction of the resource from the Earth's crust. Therefore, damages to the AoP is evaluated by the additional cost (\$) that society has to pay for future extraction due to lower ore grade for example.

These ‘depletion’ and ‘future efforts’ indicators are based on the current extraction rate from the Earth's crustal content which represents a fixed and finite stock. Nevertheless, Drielsma et al. (2016b) indicate that mineral reserves are defined by what is “economically mineable” at the time of reporting. Therefore, the volatility of raw material prices over the short-term leads to consideration of crustal content abundance as insufficient in order to deal with *resource use* in LCA. To solve the issue of the importance of cost variability of resources, current models are moving towards the use of economic statistics to determine resource availability for human use (Drielsma et al., 2016a, 2016b). The needs of decision-makers are currently based on a short-term approach, which compels the expansion of the scope of a traditional LCA to a ‘resource supply’.

### 2.3. Recent trends in the modelling of impacts related to *resource use*

#### 2.3.1. Resource criticality and ‘outside-in’ approach

Since ‘resource depletion’ has not succeeded in fully covering all aspects of *resource use*, as mentioned above with the supply issue, a wider characterisation of *resource use* dealing with the criticality assessment is currently emerging, as illustrated by the work of Graedel et al. 2012 and Sonnemann et al. 2015. As part of the criticality assessment, scarcity potential offers a more comprehensive and relevant approach. As mentioned by van Oers and Guinée (2016), scarcity of a resource means that the available amount for use is, or will soon be, insufficient, i.e., demand is higher than supply flows. This is based on the short-term approach of resource supply, taking into account the effects on current resource availability for human use (accessibility).

The scarcity aspect is covered by the criticality framework developed by Graedel et al. (2012). While the environmental implications are represented by the damages to human health and the ecosystem (see Fig. 2), supply risk, which includes technological, economic and geopolitical considerations, is addressed to characterise *resource use* sufficiently. Some specific methods and associated indicators assessing ‘supply risk’ have been developed in recent years, mainly the integrated method to assess Resource Efficiency (ESSENZ) (Bach et al., 2016) based on the Economic resource Scarcity Potential (ESP) developed by Schneider et al. (2014) and the Geopolitical Supply Risk method (GeoPolRisk) developed by Gemechu et al. (2015). Cimprich et al. (2017) extend the previously GeoPolRisk indicator by demonstrating the connection of criticality to a functional unit while incorporating measures of material substitutability to reflect the *vulnerability* dimension of criticality.

While the LCIA framework traditionally adopts an *inside-out* approach, i.e. assessment of the impacts generated by the product system under study on the environment, the latter methods attempt to consider supply risk. Thus, they require an *outside-in* approach as firstly mentioned 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 way, the materials used within the production or consumption of the product system is assessed, highlighting the use of critical raw materials (CRMs) (Zampori and Sala, 2017).

#### 2.3.2. Resource dissipation

Another critical aspect restricts the use of the depletion concept in LCIA: once the resource is extracted from the Earth's crust, it is considered as depleted. However, resource stocks can be still available through anthropogenic stocks a long time after being geologically extracted. Thus, the fate of the resource within the technosphere should be considered making the difference between two typologies of resource:

- i. the extracted resource that is not irreversibly lost and can be still recovered (still available at the end of life for another use or potentially recyclable);



- ii. the extracted resource that is dissipated from the technosphere to the ecosphere in a manner that makes their future recovery extremely difficult, if not impossible (Ciacci et al., 2015).

By assessing only the flows of resources extracted from the ecosphere to the technosphere, the full impact related to *resource use* is not captured as the ‘dissipative losses’ occurring along the life-cycle of a product system are not considered. According to the JRC (Zampori and Sala, 2017), the perspective to integrate ‘dissipative use’ of resource within the LCA framework can be defined as additional resources that need to be extracted from the environment, due to dissipative use in the technosphere and associated losses from the technosphere to the environment. In this way, it is relevant to focus on both the LCI and LCIA phases. Nevertheless, the integration of the resource dissipation modelling in the LCA is an emerging topic that will have to be further explored and detailed to be consistently used.

### **2.3.3. Perspectives for *resource use***

Dewulf et al. (2015) propose a complete approach for assessing the impacts of *resource use*, which is currently integrated into the European Commissions' recommendations for LCIA (Sala et al., 2016).

They developed a new framework based on several *perspectives* in order to address damage to redefined AoP ‘resources’ at the endpoint level. These *perspectives* reflect different standpoints of the value of resources, introducing “safeguard subjects” to the AoP (i.e., what is to be protected) from simple resources assets in the natural environment to a full anthropocentric approach dealing with human welfare. In this context, the definition of natural resources should be based on the functional value of the resource, i.e., the beneficial use by humans.

While *Perspective 1* involves a physical accounting of *resource use* and *Perspective 2* matches the current approach to incorporating impacts into a traditional LCA framework, the other *perspectives* go beyond a typical LCA by assessing socio-economic mechanisms. In this way, *Perspective 3* deals with global functions of resources. In other words, all the non-provisioning function for humans which can be the intrinsic (or emblematic) value of the resource or its participation in a global ecosystem mechanism of regulation. *Perspective 4* considers resource as a building block of the supply chain for products and services. This *Perspective* deals with sustainability assessment reflecting geopolitical strategies, labour conditions, or market instabilities induced by the use of the resource. Finally, *Perspective 5* represents the most holistic approach of the role of resource: providing Human welfare through direct or indirect functions of the resource.

### **2.3.4. Broadening the scope using life cycle sustainability assessment (LCSA)**

As illustrated by the criticality assessment and by *Perspective 4* presented above, aspects of sustainability other than environmental or human health concerns are relevant to fully characterising impacts from *resource use*. Following this idea, van Oers and Guinée (2016) mentioned the fact that assessing *resource use* is a problem merging economic and environmental system boundaries. Methods assessing the economic externalities of *resource use* at endpoint level like the LIME2 method (Itsubo and Inaba, 2012) are more and more recommended (Berger et al., 2019).

More generally, recent studies highlight the need for broadening the scope of an LCIA to integrate social and economic aspects, such as Dewulf et al., 2015; Finkbeiner et al., 2010; and Valdivia et al., 2013. A new Life Cycle Sustainability Assessment (LCSA) framework is emerging (Guinée et al., 2011), and the UNEP/SETAC Life Cycle Initiative has already published its recommendations (UNEP, 2011).

### 3. Considering space activities related impacts on the orbital resource

#### 3.1. Inclusion of emerging impacts in the LCIA Framework

With the aim of considering emerging impacts in the field of LCIA, a framework was proposed by Cucurachi et al. (2014). This framework is based on two stages: (i) verifying if sufficient evidence is available for a stressor and (ii) testing its applicability to the LCA computational structure at the LCI and LCIA phases. Both elements of the framework are addressed below focusing on the design of a consistent characterization model and its link with appropriate functional unit and inventory model.

Concerning the first point of the framework, the importance of space debris as a stressor of the orbital environment is described in the introduction (see section 1). Furthermore, peer-reviewed studies based on the data provided by international organisations show that population orbiting the Earth is a growing burden: Kessler (1991); Kessler and Johnson (2010); IADC (2013); Bastida Virgili et al. (2016); Liou et al., (2018).

To integrate emerging impacts into the LCIA framework, a clear mechanistic link, described above as an 'impact pathway' must be established. The key point is to determine which Area-of-Protection is damaged (Cucurachi et al., 2014). According to the review above (i.e., section 2), damage into the AoP 'resources' is considered. This statement is developed in the following paragraphs assessing the environmental impact of space activities on the orbital resource.

The safeguard of operating space orbits is needed to ensure the services on Earth provided by satellites (e.g., communication, GPS, and earth observations). Hence, the functional value of targeted orbits is to support satellite operations that lead to the creation of economic value. As mentioned by experts cited above, the degree of accessibility/usability of some of Earth's orbits will be constrained over time, similarly to the impacts of the extraction of a typical abiotic resource (see Figure 3.2). This is due to the expected growth of satellite launches, the emergence of new mega-constellation systems as well as the increase of the space debris population in the coming decades (IADC, 2013). Bottlenecks emerge linked to the use of highly desirable regions of operation. More particularly, if end-of-life of spacecraft is not managed after a space mission, the orbital occupation generates an additional impact dealing with the deprivation of *orbital resource use*.

The sustainability of space activities is threatened due to a growing demand in access to the orbital resource. The latter aspect contributes to increase the average probability of collision and failure of other (present and future) missions in the same orbital area. In this context, we propose to characterise the impact related to *orbital space use* through an impact pathway so that the potential damage to the AoP 'resources' can be assessed based on the reduction of the resource availability in the future.

#### 3.2. Changes in the orbital asset

The elementary flows induced by *resource use* represent a change in the asset, as mentioned in *Perspective 1* (§2.3.3) and Figure 3.2. This change may be quantified with simple accounting methods: the quantity and/or quality of extracted resources are measured (e.g., mass, area, volume, energy or exergy). In our case, the asset is the orbital resource occupied by a spacecraft.

The occupied resource can be classified into two different categories. Until an altitude of approximately 800km, the orbital resource can be considered as a *fund* with a renewability rate. Indeed, the atmospheric drag will ensure the natural decay of the space object. This atmospheric drag may be considered for only a part of the LEO orbital area. Beyond 800 km, the atmospheric drag forces are absent and thus do not play

any role: the orbital resource can be considered as a *stock* without any renewability rate.

The launch of space systems results in the occupation of the orbits by space objects, e.g. rocket's upper stages, mission-related objects and spacecraft. The overall in-orbit lifetime of those objects is covered by the nominal time of the mission (use phase) plus the time of the end-of-life phase (during which post-mission disposal is performed). This *orbital occupation* leads to a marginal change in the resource asset. It is analogous to the elementary flow related to the 'land use' impact category (Koellner et al., 2013). In this case, the elementary flow is given in  $m^2 \cdot years$  through the product of the occupied area by the occupation time occurring during the whole space mission.

In our understanding, two physical phenomena related to *orbital occupation* occur within the orbital environment:

- On the one hand, the occupation of a narrow orbital area by a certain amount of functional or non-functional spacecraft may lead to space *congestion* and *competition* to access the orbital resource.
- On the other hand, the second phenomenon is related to the *exposure* of space debris population which increases the risk of potential failure or loss of mission and the *release* of additional debris in the orbital environment.

Both approaches are described in the following paragraphs and presented in Figure 3.3.

### 3.3. Consumptive use of the orbital resource

With an increasing launch rate and a democratisation of space, the orbital regions of interest will become more and more congested by active and inactive satellites. If plans about very large groups of spacecraft called mega-constellations materialise (Henry, 2018), the *space traffic management* will become a core issue. According to the Aerospace Corporation (Peterson et al., 2018), new space activities could increase the number of operational satellites by an order of magnitude over the current situation affecting the space environment for generations. In such case, the orbital resource could become scarce, *i.e.* the supply-demand will be higher than the available amount for use, leading to a resource access competition.

While near-Earth space is particularly wide, attention should be paid to future trends in term of space traffic regarding orbital regions with special physical properties:

- 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). Since 1998, the radio-frequencies and the GEO orbit are recognised as 'limiting natural resources' by the International Telecommunication Union (ITU, 1998). Orbital slots and radio frequencies licensing are currently coordinated by the ITU. However, according to Chiu (2018), they only managed to mitigate congestion problem without addressing the overall issue of sustainability. Indeed, the right to use these resources lies in a 'first-come, first-served' basis and begins as soon as the registration is confirmed by the ITU. Therefore multiple actors can 'rush' to ensure access to the scarce slots. In other cases, it is observed that some satellites appear to be procured with the sole purpose of occupying an orbital position (also known as dummy satellite), while their actual functions are still under development (Chiu, 2018). Going further, the same satellite may have been used to maintain the rights of inactive networks at various orbital locations, by "jumping" from one location to another (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. Due to

this unique capability, the SSO region is today the most “crowded” area on space (Liou, 2011), where the threat is not limited to space debris but more broadly to the increasing number of active satellites and particularly the small satellites which are often not manoeuvrable. This region is today a growing concern for insurers who used to focus on the GEO region (Chrystal et al., 2018, 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 mega-constellations. At low altitude, the atmospheric drag ensures an easier removal of dead or non-manoevrable satellites providing systematic compliance with the 25-year rule (IADC, 2007). Even if the renewability rate of the resource is high for the lower part of the LEO region (until around 650 km), we could assist in a congestion phenomenon due to the advantages provided by activities in this region. For instance, a recent statement from the Federal Communications Commission (FCC report, 2018) mentions that Space X seeks to modify its license for the Starlink mega-constellation: the goal is to relocate 1.584 satellites previously authorised to operate at an altitude of 1.150 km to an altitude of 550 km. In this way, the disposal of these satellites and their quick removal due to the drag in case of failure will ensure compliance with the space debris mitigation guidelines (Grush, 2018).

These specific orbital categories strengthen the idea of the orbital resource differentiation according to their functional value and associated quality. In the next decades, competition between operators to have access to this qualitative resource would result in a lack of availability. This issue would be similar to the ‘land competition’ which damages the AoP ‘resources’ in the UNEP/SETAC Land Use framework (Koellner et al., 2013). In the case where the quantity of the available resource would be insufficient, the resource occupied by inactive or low-value satellites will provoke a deficit for other uses. This aspect has been already highlighted for water use in LCA (Bayart et al., 2010). The final damage could be characterised at Endpoint level, as the lack of value generated due to the congestion of the resource. This deprivation of the additional value should be addressed regarding the end-users of the space activities, i.e. the whole society. Such concern involved more geopolitical issues and resource management than a conventional environmental degradation but would be in line with the *Perspective 4* described by Dewulf et al. (2015) and related to socio-economic impacts.

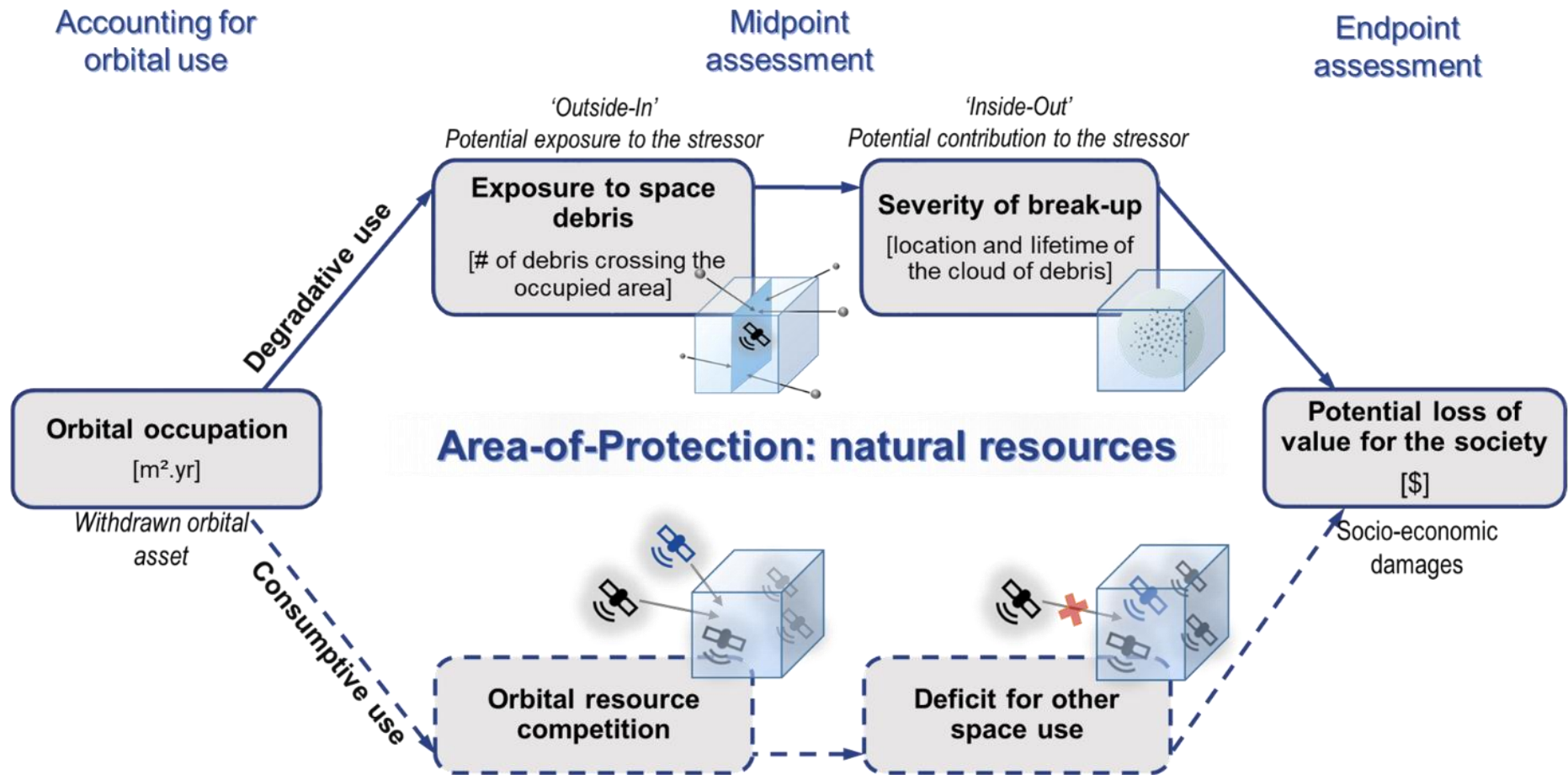


Figure 3.3 - Impact pathways proposal to include *orbital space use* in LCIA - only *Degradative use* is addressed in the following chapters.

### 3.4. Degradative use of the orbital resource

#### 3.4.1. 'Outside-in' perspective: exposure to debris

Space debris is a stressor of the orbital environment which reduces the availability of 'safe space' affecting the functional value of the orbital resource (i.e. supporting the satellite operations). In this way, it leads to a *degradative use* of the orbital resource for space activities. The interaction between the presence of this stressor in the orbital environment and any other space object under study follows an '*outside-in*' relation similar to the case of a mineral resource. It means that we address here the impact of the environment on the product system.

The three main debris categories and their associated causes are presented in Table 3.2.

Table 3.2– Category of typical debris with their associated causes according to IADC, (2014)

Categories	Causes
<b>Mission-related objects (MROs)</b>	<ul style="list-style-type: none"> <li>– Objects released intentionally</li> <li>– Objects released unintentionally</li> </ul>
<b>Fragments</b>	<ul style="list-style-type: none"> <li>– Intentional destruction</li> <li>– Accidental break-ups during operation</li> <li>– Break-ups after mission termination</li> <li>– In-orbit collisions</li> </ul>
<b>Mission-terminated spacecraft and rocket bodies</b>	<ul style="list-style-type: none"> <li>– Inadequate disposal manoeuvre</li> </ul>

Each orbit of the near-Earth environment presents a different state of *debris stress* which allows to classify and differentiate them accordingly. Thus, the orbital environment can be divided into orbital cells, each one with a different level of *debris stress*. Two main physical approaches can be considered to characterise the stress in a local cell (Figure 3.4):

- a) The *spatial density*, which is expressed as the number of space objects in a given orbital cell. The unit is the number of debris per km<sup>3</sup>. It depicts the availability at a given time of the targeted orbital volume. However, even into a 'crowded' orbital region, the order of magnitude of such orbital density is in average less than one object of 10 cm or more in a cube with sides measuring 100 km (i.e. 10<sup>-8</sup> object.km<sup>-3</sup>).
- b) The *flux of space debris*, which represents the number of space debris passing through a targeted orbital cell during a certain period of time. It is expressed as the number of debris divided by the crossed section during a time range (i.e. units.m<sup>-2</sup>.year<sup>-1</sup>).

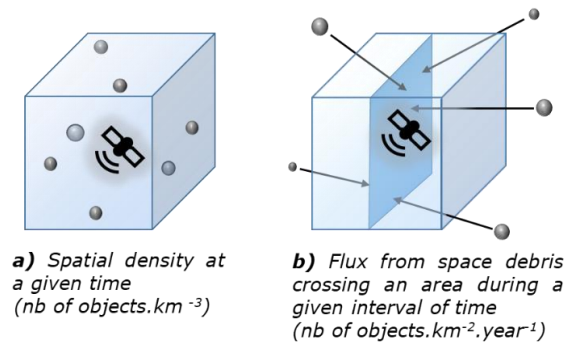


Figure 3.4 - Physical approaches: spatial density versus flux from space debris

Due to the very large distance covered by space debris in a short period of time, typical velocity is around 7 to 8 km/s in the LEO region, the relative flux of debris crossing a targeted orbit (in unit·m<sup>2</sup>·year<sup>-1</sup>) represents a relevant parameter in term of environmental pressure. It seems particularly the case for the LEO region where 77% of the debris is concentrated (Krag et al., 2016).

Consequently, the potential exposure of the spacecraft area to the flux of debris has been identified as a relevant mechanism to take into account within the impact pathway related to the *degradative use* of the orbital resource. This *outside-in* perspective will be further integrated into the characterisation model (see: Chapter 5). In this context, we can make a parallel with other approaches in LCIA that use an *outside-in* perspective:

- Several midpoint indicators assessing the impact of water use are based on “withdrawal-to-availability” or “consumption-to-availability” ratio of water in a given river basin. They represent a level of water scarcity thus depicting the risk of an activity to have limited access to water. (Loubet et al., 2013; Pfister et al., 2009).
- The supply risk of mineral resources in the frame of criticality assessment (Achzet and Helbig, 2013; Berger et al., 2019; Drielsma et al., 2016b, 2016a; Mancini et al., 2016; Schneider et al., 2014; Sonnemann et al. 2015).

### 3.4.2. ‘Inside-out’ perspective: contribution to the space debris population

Following the cause-effect chain established in Figure 3.3, an *inside-out* relation ensures a consistent characterisation of the impact at midpoint level. Here, we focus here on the contribution of the product system to the *stressor*: the number of space debris potentially added to the background population is characterised.

During a given space mission, “fragments” as described in Table 3.2 can be released in the orbital environment. The fragments are the consequence of two distinct break-up events: explosion or collision. Explosion of the spacecraft can be avoided through the passivation process at the EoL of the mission, i.e. the elimination of all stored energy on a spacecraft or orbital stages to reduce the chance of break-up. This requirement refers to the Space Debris Mitigation (SDM) guidelines presented in Annex A.

In-orbit collisions are expected to be the main source of debris in the next decades (IAA, 2017a; Liou, 2010). Such event may occur between the product system under study and debris crossing the area occupied by this space object. While the likelihood of collision is addressed through the *outside-in* perspective detailed above, the severity of the collision is approached by the consequences of a potential break-up on the orbital resource.

The overall impact after a collision could be evaluated through the size and the fate of the cloud generated and its interaction with orbital population. Indeed, the debris emitted could lead to a cascading collision with other spacecraft orbiting in the surrounding areas which would reduce the availability of ‘safe space’ for the future space missions. Regarding the modelling of the debris cloud’s behaviour, previous work has been published by Letizia, 2018; Letizia et al., 2017, 2016; Anselmo and Pardini (2017, 2015); Frey et al., 2019; Krag et al., 2017 and in the case of non-circular orbits by Frey et al. (2018, 2017). A proxy based on one of those models could be defined and then integrated into the LCIA framework.

Given this situation, the proposed characterisation model for *degradative use* merges both *outside-in* and *inside-out* perspectives. A similar structure was previously proposed by Kebschull et al. (2014) defining the criticality on the orbital environment as  $Criticality = Risk \times Impact$ . It should be highlighted that the ‘impact’ (referred in this manuscript as the ‘severity’) differs from conventional *vulnerability* included in the criticality assessment of resources as follows:  $Raw\ material\ criticality = Supply\ risk \times Vulnerability$ . Indeed, the scope of the *vulnerability* dimension, i.e. economic consequences with consideration of substitution potentials (Glöser et al., 2015), varies depending on the organisational level of the assessment: corporate, national or global (Ioannidou and Sonnemann, 2018). In the case of in-orbit collisions, the *severity* must be addressed at a global scale, i.e. for the whole orbital environment. It means that the *inside-out* perspective focuses on the consequences of a break-up for an indiscriminate target that is potentially affected in space.

### 3.5. Socio-economic damages

Within the redefined AoP ‘resources’ proposed by Dewulf et al. (2015), the criticality framework is covered by *Perspective 4* which takes socio-economic mechanisms into account. The orbital resource is seen as a building block in the supply chain for products and services. As a result, the orbital asset provides indirect support to human activities: the orbits host satellites that provide data for commercial and non-commercial uses. If the availability of the targeted orbits becomes constrained, consequences occur in all areas of the supply chain.

‘Future efforts’ methods based on cost externalities are seen today as a promising approach for the endpoint characterisation of the 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 is not easy to perform 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. Consequently, some preliminary studies focus on the economic value of space missions. Colombo et al. (2017a) use the revenues for commercial space products and services with the aim of approximating the economic value of space missions. However, the commercial revenue does not necessarily capture the overall value generated by space activity: it is mainly the case for non-commercial data provided by meteorological or Earth observation satellites, e.g. the European Copernicus constellation (PwC, 2017). 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 is proposed in Chapter 6 to compute the cumulative economic benefits potentially affected by the negative externality (i.e. the release of debris). The approach is based on the ‘use value’ of the orbits 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.*

## 4. Discussions

In this chapter, we integrate the *orbital space use* in the LCIA framework through two different impact pathways that were identified: a first one related to the *consumptive use* of the orbital resource and another one dealing with the *degradative use* (see Figure 3.3). The feasibility of the proposed approaches is discussed hereafter.

### 4.1. Nature of the environmental impact occurring in orbit

Both *consumptive* and *degradative* approaches are responsible for environmental damages in the AoP 'resources'. The analogy can be made with well-known environmental media as *soil* or *water* which face the same duality in being affected by resource consumption (or occupation) and its degradation caused by the emission of environmental stressors. Besides, it is relevant to consider the two types of orbital resource, i.e. fund and stock, when addressing the environmental impact related to *orbital space use* as similarly done in the case of the *freshwater resource* (Pradinaud et al., 2018). The characterisation model should take into account this aspect considering the higher renewability rate of the orbital resource at low altitude where the atmospheric drag operates as a sink mechanism.

The *consumptive use* of the orbital resource appears as an emerging concern regarding future space traffic scenarios. The International Academy of Astronautics (IAA) defined space traffic management as: "the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference." Recent publications highlight the need of an adequate space traffic management (STM) system to tackle emerging concerns in most desirable regions of operations (Gangestad, 2017; Jah et al., 2017; Krag et al., 2017; Peterson et al., 2018). Any effective STM system will have to anticipate the future increase in *orbital space use*. Thus, defining consistent metrics and global guidance is seen as a core issue to ensure the long term sustainability of space activities. The emergence of a common STM system is today a highly debated topic among international organisations, space agencies and operators. However, additional investigation and public debate are needed because of the early phase of the discussions (Gangestad, 2017; Jah et al., 2017).

In this context, the aspect of *consumptive use* will not be further developed in this thesis even if the integration of this impact within the *orbital space use* category would be relevant aiming to strengthen the sustainability assessment of a given space mission. However, in such case, the scope would be beyond environmental LCA and should consider geopolitical and socio-economic impacts.

The priority has been given to the assessment of the space debris related impact through the *degradative* approach because space debris appears today as the major threat for the long-term sustainability of the human activities in the outer space (UN COPUOS, 2017a). As discussed above, the midpoint indicator will have to address both approaches: *outside-in* with the exposure to the space debris population and *inside-out* through the potential release of debris in the orbital environment as a consequence of a potential break-up. Hence, the proposed characterisation model stems from an adapted criticality perspective that is based on the classical risk theory framework (Glöser et al., 2015). In this way, the modelling incorporate a combination of life-cycle and risk assessment methods, i.e. the *integration* of both, instead of merely combining their results in a *complementary use* (Harder et al., 2015; Tsang et al., 2017). It has been already done for other indicators included in the LCA framework, more specifically dealing with toxicity impact categories (Sonnemann et al., 2018). For instance, the framework of the USEtox consensus model (Rosenbaum et al.,

2008) is essentially common with Risk Assessment as reported by Jolliet & Fantke (2015): the characterisation factors developed are based on a modified risk assessment approach considering a steady-state equilibrium.

Furthermore, the characterisation of the Earth's operating orbits involves spatial differentiation. A classification of the orbits could be envisaged in the same way as the bio-geographical differentiation for land use (Koellner et al., 2013) or spatiotemporal framework for water-stress indexes (Boulay et al., 2015). Thus, the set of characterisation factors developed in the next chapters will be spatially differentiated as recommended by the guidance of the UNEP/SETAC life cycle initiative (Verones et al., 2017).

## 4.2. Integration of the *degradative use* impact in the LCA of space missions

According to Cucurachi et al. (2014), the potential emissions of stressors must be scaled on a functional unit and the associated inventory model. This stage is described in the following paragraphs.

### 4.2.1. Link with the functional unit

The quantification of impacts corresponding to the functional unit will represent the additional amount of stressor introduced on top of the background situation, i.e. the overall space debris population which are not related to the mission. The ESA Handbook (ESA LCA Working Group, 2016) recommends the following functional unit for a space mission: *'One space mission in fulfilment of its requirements'*.

The latter requirements are associated with space debris mitigation (SDM) and disposal guidelines which are described in annexe A.1. This functional unit must consider all the post-launch life cycle phases defined by the ISO 24113 (2011) and also presented in annexe A.2. The functional unit should be adapted following the evolution of the binding requirements that will influence the in-orbit life cycle phases of the space system. Since the passivation procedure is mandatory in the ESA's and French law requirements, the generation of fragments caused by the explosion of space objects left in orbit are not considered in our characterisation model. While the explosions from abandoned space objects are today the main source of debris caused by the lack of passivation stage implemented in past missions (ESA's Space Debris Office, 2018), the collisions are expected to be the most contributing source of fragmentation in the next decades due to the increase of the orbital population (Liou, 2010).

Moreover, with the aim of covering the functional unit mentioned above, all elements of the studied space system interacting with the orbital environment shall be taken into account: the launcher upper stage or rocket body (R/B) which places one or more objects in-orbit, one or several operating spacecraft (in case of multiple launches or constellations), but also any objects released as part of normal operations or disposal actions (the so-called mission-related objects or MROs). Each element of the space system gets its proper LCI data with associated trajectory and lifetime in orbit. Thus, the impact score for a complete space mission should be calculated as the sum of the impact calculated for each element.

According to ESA (2014), the *disposal phase* ends when either the space system has performed a direct re-entry or completed its disposal activities (having reached its disposal orbit and having completed its passivation). Nevertheless, the scope covered by the *degradative* characterisation model proposed above is only part of the end-of-life for space missions. The environmental impacts of a space mission should be addressed from a space debris mitigation perspective but also in terms of atmospheric re-entry impacts into the high atmosphere and the impacts of the presence of non-demised materials on Earth. If space mission disposal is managed, we could expect an increase in the relative impacts of the two final life cycle steps (i.e., atmospheric re-entry and on-ground presence) while the score on the 'space debris indicator' would decrease in comparison on a mission with no space debris mitigation concern. This is particularly true because the debris re-entering in the atmosphere and reaching the Earth's surface are today not recovered.

#### 4.2.2. Inventory parameters

Several categories of parameters shall be taken into account in the inventory model related to the space systems:

- *Design parameters.* The average cross-sectional area (in m<sup>2</sup>) of the spacecraft, MROs or the rocket body must be considered. 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. In addition, the mass of the object considered should be known as the number of fragments generated in case of break-up is derived from the mass (in kg) of the space object (Johnson et al., 2001). While the mass parameter of the system varies significantly during the mission, two specific masses are identified: the dry mass and the launch mass which also comprises the embedded mass of propellant. The launch mass can be considered as the proxy at the beginning of the mission and the dry mass can be used once the fuel capacity is exhausted. Lastly, the ratio linking the cross-sectional area and the mass is an important parameter defined as the ‘Area-to-mass’ ratio (ESA Space Debris Mitigation WG, 2015). This factor allows quantifying the effect of several orbital mechanics perturbations on the motion of the space object under-study. Orbital perturbations are mainly composed by the Earth’s oblateness, the solar radiation pressure, the atmospheric drag and the luni-solar perturbations. They are detailed in Annex B.
- *Mission parameters.* The mission parameters give the spatiotemporal characteristics of the product system during the mission, mainly the expected mission duration (in years) which can be extended after the launch. Also, the position over time of the space object must be determined according to its Keplerian coordinates as the characterisation model is spatially differentiated. The complete description of the Keplerian coordinate system is available in Annex B.
- *Space Debris Mitigation parameters.* These parameters are composed by the passivation capacity (avoiding potential break-up after the mission), the expected post-mission disposal scenario (i.e. natural decay, direct or delayed re-entry) and its associated duration. The capacity to realise ‘collision avoidance manoeuvres’ in order to prevent potential loss due to collision with trackable debris could also be considered.

## 5. Conclusion

In this chapter, we show the importance of considering *orbital space use* in LCA. Based on a critical review of different LCIA methods, we demonstrate that the orbital environment can be considered as a resource adopting an anthropocentric point-of-view. Then, we propose a new framework aiming to consider the impact linked to human activities occurring in the near-Earth orbital environment. Two different impact pathways are defined based on mechanistic links: one dealing with the *consumptive use* of the orbital resource and another with the *degradative use*.

The proposed cause-effect chains fit in the AoP ‘resources’ taking into account the three following perspectives: (i) a change in the orbital asset, (ii) associated impact on the provisioning capacity of orbits and (iii) socio-economic damages. This represents a first step in the elaboration of dedicated indicator(s) dealing with the *orbital space use*.

Additional research on the *consumptive use* seems promising. Although it will not be further explored in this thesis, a set of characterisation factors addressing this impact could be developed with the aim of enhancing the sustainable use of the orbits.

The priority is given to the characterisation of the *degradative use* which addresses the space debris related impact on the orbital environment. Both *inside-out* and *outside-in* perspectives are exposed and gathered

proposing an adapted criticality assessment approach. The main parameters that should be included in the characterisation model were identified and discussed. They are further described in Chapter 4. Finally, the link between the characterisation model and the product system under study (i.e. the space mission) is established through a first description of the functional unit and the associated inventory parameters.

In Chapter 5, the equations derived from the impact pathway are further defined and applied in order to calculate a set of characterisation factors. A case study is proposed to prove the applicability of the approach. This development will broaden the scope of a classical LCA for space missions, introducing additional information at a design-phase level. In this way, the environmental impacts of space missions during the in-orbit lifetime can be measured and compared among several post mission disposal scenarios.



# 4

## CHARACTERISATION OF THE LEO ENVIRONMENT IN TERM OF DEBRIS



*“Ocupar un lugar y no tener medida : ¿No será esto el espacio?”*

*“To occupy a place, without measure: isn't that what Space is?”*

– Eduardo Chillida, *El arte y el espacio*

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## 1. Introduction

Since the start of the space in 1957 with Sputnik's launch, more than 5 450 successful launches has occurred placing into Earth's orbits about 8 950 satellites (ESA's Space Debris Office, 2019). ESA estimates about 5 000 the number of these still in space while 1 950 are still functioning. More than 500 unexpected events composed by break-ups, explosions, collisions, or anomalous fragmentation, resulted in the creation of a large population of fragments released over the years in the orbital environment. The total mass in Space of all object reaches 8 400 tonnes in 2019 distributed among 22 300 debris objects regularly tracked by Space Surveillance Networks and maintained in their catalogue. However, the number of debris objects estimated by statistical models is higher depending of the size: (i) 34 000 objects > 10 cm; (ii) 900 000 objects from 1 cm to 10 cm; (iii) 128 million objects from 1 mm to 1 cm.

The goal of the present chapter is to characterise the orbital environment in term of debris. The estimated distribution of debris between the main orbital regions is given in Table 4.1 based on Johnson, (2010) and Krag et al., (2016).

Table 4.1 – Distribution of the catalogued population according to the main orbital regions

Orbital region	% Earth orbital volume	% of catalogued population
<b>LEO (200 – 2 000 km)</b>	<b>0.30%</b>	<b>75%</b>
MEO (2 000 – 35 586 km)	> 95%	~ 17 – 20%
GEO (35 786 ± 200 km)	3%	~ 5 - 8 %

It should be noted that the share of the trackable population is largely dependent on the altitude. It can lead to underestimating the current population in MEO and GEO compared to the trackable population in LEO, where scanning and observing systems are more efficient. Nevertheless, the LEO region is the main zone of interest dealing with space debris population. With only 0,3% of the total earth orbital volume, it concentrates 75% of all catalogued debris. This is because it is the easiest and less expensive orbital region where satellites can be placed.

In this context, we choose to focus our analysis on the LEO region: only orbits from 200 to 2 000 km will be characterised in term of debris. Figure 4.1 depicts the flows of the orbital population associated with the source and the sink mechanisms in LEO. While the previous is directly dependent on the launch rate, potential failure or lack of post-mission disposal management, the latter comes from natural environment perturbations (see Annexe B.2.2) or propulsion manoeuvres. Collision events can occur between the different elements that composed the overall orbital population.

The MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model (Technische Universität Braunschweig, 2014a, 2011) described below, was chosen to compute the orbital distribution of the space debris, as well as the velocity of a collision occurring in LEO. Finally, the flux of debris crossing a set of circular orbits in LEO is obtained as an output of the MASTER program.



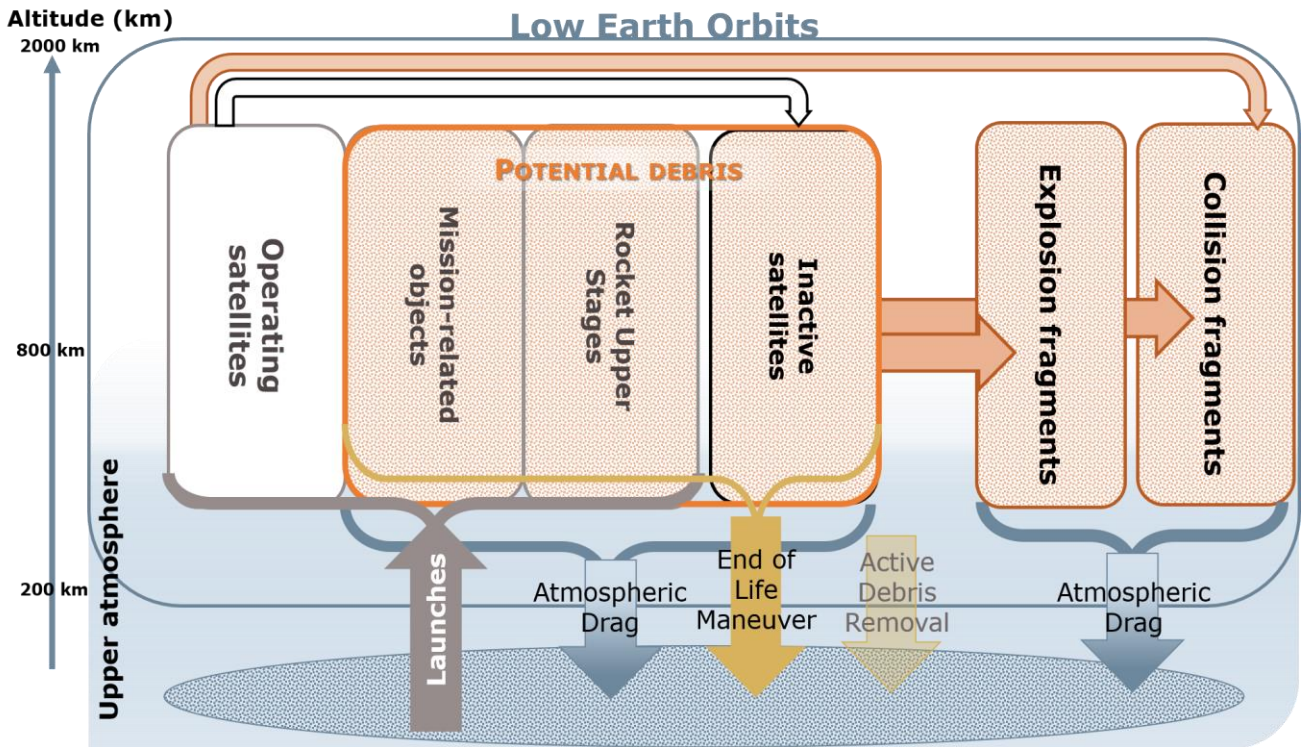


Figure 4.1 – Mapping of the material flows occurring in the LEO region based on source-sink relations. *Active Debris Removal* is not yet a mature technology (freely adapted from Somma et al., 2018)

## 2. Goal & scope of the MASTER-2009 model

The purpose of MASTER is the characterisation of the natural (i.e. micro-meteoroids) and the man-made particulate environment of the Earth. The model and the associated software is developed and updated by the Institute of Aerospace Systems at the TU Braunschweig (Technische Universität Braunschweig, 2014a, 2011). MASTER is the ESA's reference model for space debris and meteoroid environment and has gained international acceptance over the years (IADC, 2013; Krisko et al., 2015).

The MASTER model offers a full three-dimensional description of the debris distribution from (LEO) ( $r > 6,564$  km) up to the Geostationary Earth Orbit (GEO) region ( $r < 43,164$  km). Flux results relative to an orbiting target or an inertial volume can be resolved into source terms, impactor characteristics and orbit, as well as impact velocity and direction. Also, a 3D flux analysis with respect to any two of these parameters simultaneously is possible. Additionally, MASTER offers the analysis of the spatial density of debris objects in a control volume defined by the user.

## 3. Characterisation of the orbital environment using MASTER model

### 3.1. Space debris population

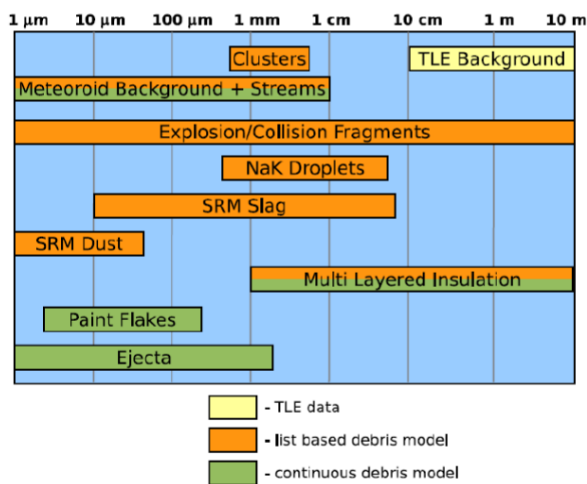
#### 3.1.1. Debris sources

The debris environment on user-defined target orbits is described down to impactor diameters of 2  $\mu\text{m}$ . Predictions for the historic space debris evolution from the start of the space era to a reference epoch (i.e. a given point in time) on May 1<sup>st</sup> 2009 and 50 years into the future are possible. Computer models have been used to simulate the generation of objects due to all known debris sources, and their orbit evolution with time.

The MASTER debris reference population for the epoch 2009/05/01 consists of the following sources:

- Launch/Mission related object (LMRO)
- Explosion and collision fragments
- Coolant releases from nuclear reactors in space (sodium-potassium, NaK)
- Slag and dust particles generated by Solid Rocket Motor firings (SRM)
- Surface degradation particles (paint flakes)
- Ejecta generated by impacts of small man-made objects
- Multi-layer insulation fragment (MLI)

a)



b)

Source	Share
Launch and mission-related objects	1.2%
Explosion fragments	62.4%
Collision fragments	26.4%
Sodium Potassium (NaK) droplets	6.8%
Solid rocket motor slag	2.5%
Multi-layer Insulation fragments	0.7%

Figure 4.2 – a) Sources and size covered by MASTER model. Two lines elements (TLE) catalogue consists of about 14 000 objects larger than about 10 cm at reference epoch (01/05/2009). This accounts only for less than 5% of the population larger than 1 cm assumed to be in orbit. – b) Shares of debris larger than 1 cm in LEO according to Horstmann et al. (2017).

### 3.1.2. MASTER epochs

The historical population in MASTER is a fusion of published object data and simulated objects. For debris sources creating objects larger than 1mm, debris generation events are simulated as follows: 234 fragmentation events, 1 934 SRM firings creating slag, 16 NaK releases. Paint flakes, ejecta and part of the MLI sources are generated through a statistical model (see Figure 4.2).

To estimate future population, three scenarios are available to bound the best and worst implementation of debris mitigation measures by space users (assuming no significant variation in future traffic rates): Business-as-Usual (BAU), intermediate mitigation and full mitigation scenarios.

In the frame of the thesis, the BAU scenario (worst case) was selected adopting a conservative approach. It consists of (i) BAU explosion traffic; (ii) BAU solid rocket motor firing traffic; (iii) No mitigation measures implemented.

The intermediate and full mitigation scenarios consider the implementation of mitigation procedure from 2015 for the MRO, reduction by 5% of explosion traffic by 2020, a drastic reduction of the SRM firing from 2020. In the case of full mitigation, an additional 100% PMD success rate is applied from 2015 for rocket bodies in LEO, and 2020 for payloads in LEO and rocket body in GEO (Technische Universität Braunschweig, 2014a). Taking into account the current global adherence of the SDM guidelines which is around 60% for

payloads in LEO (ESA’s Space Debris Office, 2018; Frey and Lemmens, 2017), we assume that both mitigation scenarios are too ‘optimistic’ and were disregarded.

### 3.1.3. Validation of the population

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.

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 experience lower standard variation.

The ESA’s MASTER model was assessed against NASA’s ORDEM 3.0 (Krisko et al., 2015). The study concludes that: (i) for non-GEO cases, both population match very well considering 1 m debris size; (ii) at 10 cm MASTER-2009 fluxes are all somewhat higher than those of ORDEM 3.0, (iii) within the critical size range at the 1-cm edge, ORDEM 3.0 displays a flux matching that of MASTER-2009. In the important ISS region, ORDEM 3.0 shows a flux reduction of nearly an order of magnitude smaller than that of MASTER-2009.

### 3.2. Volume discretisation

According to Klinkrad et al. (2006), the MASTER model defines a 3-dimensional, time-varying space debris environment from altitudes below 200 km to above the geostationary ring. The spatial resolution of the model is determined in inertial, spherical coordinates. A volume cell centred at **geocentric distance**  $r_i$ , **declination**  $\delta_j$ , and **right ascension**  $\alpha_k$ , shall have the extensions  $\Delta r$  in the radial direction,  $\Delta\alpha$  along the small circle of latitude, and  $\Delta\delta$  along the meridian of right ascension, as shown in Figure 4.3.

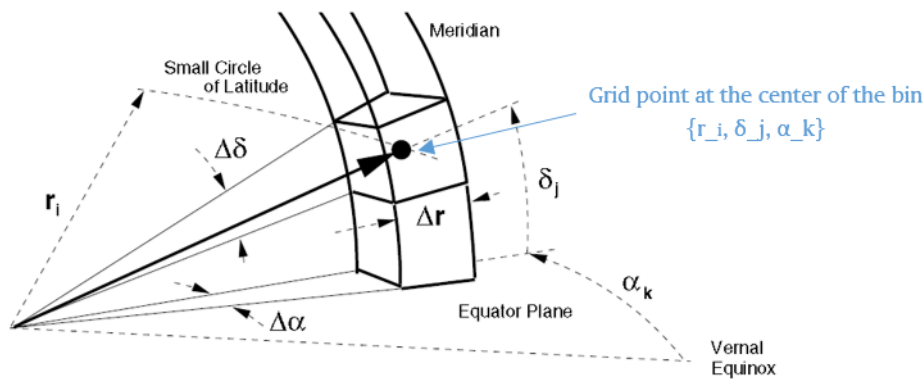


Figure 4.3 – Definition of control volume cells by means spherical coordinates  $(r, \alpha, \delta)$  in the inertial, geocentric reference frame (retrieved from Klinkrad et al., 2006)

Given these parameters, the cell volume  $V_{i,j,k}$  is determined from Eq. 4.1:

$$V_{i,j,k} = \frac{2}{3} (3 \cdot r_i^2 + \frac{1}{4} (\Delta r)^2) \cdot \cos \delta_j \cdot \sin \frac{\Delta \delta}{2} \cdot \Delta \alpha \cdot \Delta r \tag{Eq. 4.1}$$

For the LEO region, 3-dimensional spherical shells are modelled ( $\Delta\delta = \pi$  and  $\Delta\alpha = 2\pi$ ).

### 3.3. Density calculation

#### 3.3.1. Cell passage event

The MASTER program works with the discretised volume elements described above. The basic piece of information used by the tool is **the passage of an object through such an element**. This is, for all sources, handled using so-called Cell Passage Events (CPEs).

Let  $n$  be the counter for a debris object, let  $m$  be the cell passage event (CPE) counter along a single orbit of this debris object, and let  $l$  be the counter for all orbit passes of a given debris population through one particular cell indexed by  $i, j, k$ . Figure 4.4 provides an overview of  $n, m$  and  $l$  parameters.

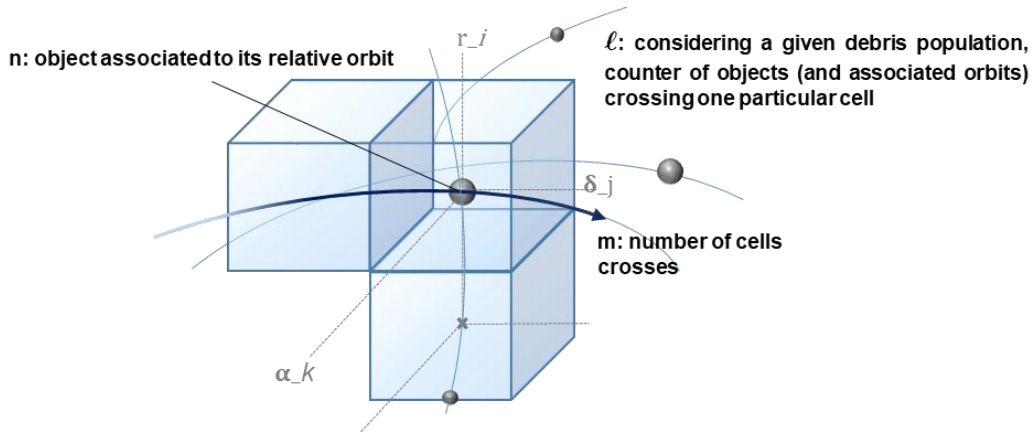


Figure 4.4 – Representation of a cell passage event (CPE)

After sorting the events  $m = 1 \dots M$ , for one particular orbit  $n$ , the dwelling time within the cell  $\Delta t_{l(i,j,k)}$  for the  $l$ -th cell transition is expressed in Eq. 4.2. For an analysis timestep of **one single orbit with a given period  $T_n$** , the **resident probability  $P_{l(i,j,k)}$**  in a given cell (Eq. 4.3), and the resulting contribution  $D_{l(i,j,k)}$  to the **spatial object density** (Eq. 4.4.) in this cell are given as follows:

$$\Delta t_{l(i,j,k)} = t_{n,m+1} - t_{n,m} \quad \text{Eq. 4.2}$$

$$P_{l(i,j,k)} = \frac{\Delta t_{l(i,j,k)}}{T_n} \quad \text{Eq. 4.3}$$

$$D_{l(i,j,k)} = \frac{P_{l(i,j,k)}}{V_{i,j,k}} \quad \text{Eq. 4.4}$$

Finally, **the total object density** for a given cell is obtained through the total CPE count (Eq. 4.5):

$$D_{l(i,j,k)} = \frac{1}{V_{i,j,k}} \sum_{l(i,j,k)=1}^{L(i,j,k)} P_{l(i,j,k)} \quad [\text{units} \cdot \text{m}^{-3}] \quad \text{Eq. 4.5}$$

#### 3.3.2. Density distribution in LEO

The *spatial density mode* of the MASTER-2009 software allows computing the spatial density of debris population as a function of altitude above Earth, geocentric declination, and time. The overall volume to be analysed is given by lower and upper altitude ( $h$ ), declination ( $\delta$ ) and right ascension ( $\alpha$ ) limits. We choose to characterise the LEO region considering the density for all orbital cells in the range of altitude [200; 2000

km] with a 50 km interval, declination [-90; 90°] with a 2° inclination interval, and right ascension [-180; 180°] with a 5° interval.

We compute the density distribution for each 5 years from 1958 to 2027 (which is the last prediction available). It results in 15 runs of the MASTER Software. All the debris sources mentioned above are taken into account considering a lower threshold of 1-cm size.

The outcomes (given in #·km<sup>3</sup>) show the evolution and the distribution of the orbital population over time from the beginning of the space exploitation to an estimated population for the next decade.

### 3.4. Flux modelling

#### 3.4.1. Analogy with gas dynamics

The flux determination software of the MASTER model makes use of an analogy with the theory of gas dynamics (Klinkrad et al., 2006a). The spacecraft, crossing a space environment filled with particles, is seen equivalent to a surface sweeping through a control volume segment (i.e. a volumetric cell) filled with a static gas. All objects being in the path of the surface at the time of its movement are assumed to be collected or, in other words, to impact.

The mean number of collision  $c$  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  $\Delta t$  is given by Eq. 4.6:

$$c = v \cdot D \cdot A_c \cdot \Delta t \quad \text{Eq. 4.6}$$

The collision process is following Poisson statistics. The impact probability  $P_i$  can be approximated with Eq. 4.7:

$$P_{i \geq 1} = 1 - \exp(-c) \approx c \quad \text{when } P_i < 0,1 \quad \text{Eq. 4.7}$$

#### 3.4.2. Flux determination

MASTER software allows the computation of debris flux on a user-defined target orbit, which is defined by a set of five Keplerian orbital elements  $[a, e, i, \Omega, \omega]_{\text{target}}$  at a certain epoch. As we only characterise circular orbits, the Keplerian elements taking into account are detailed in Annex B.1.

Based on the Eq. 4.6, the global flux is calculated in MASTER as the debris density (in units·m<sup>-3</sup>) encompasses in a specific orbital volume Eq. 4.7 multiplied by the relative velocity of collision (m·s<sup>-1</sup>) between the given population and a new in-orbit fictive target (see Eq. 4.8 retrieved from Klinkrad, 2006).

$$\phi_{h,inc,t} = \text{Density} \cdot \Delta v_{\text{col}} \quad [\# \cdot m^{-2} \cdot yr^{-1}] \quad \text{Eq. 4.8}$$

Where  $\Delta v_{\text{col}}$  is the relative velocity between the debris and the object under analysis. We only characterised circular orbits following a regular variation of the altitude ( $h$ ) and the inclination of the orbital plane ( $inc$ ).

For each simulation, a fictive target represented by a spherical shape of 1 m<sup>2</sup> cross-section is located at the position specified by the selected Keplerian coordinates. The model considers an isotropic flux which collides the target with a normal angle. It means that all flux contributions encountered will hit the surface of the fictive sphere with an angle of 90° (Technische Universität Braunschweig, 2014a). Surface-oriented flux computation is also possible in MASTER software but it is not relevant regarding our approach. Indeed, we

seek a generic flux characterisation for a large set of orbits and possible space objects.

We compute the estimated flux of debris in the year 2018 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.

### 3.4.3. Velocity calculation

A specific focus on the velocity of collision is proposed in this section to further detail the characterisation of the orbital environment in term of debris. As mentioned above, we consider a non-oriented flux colliding a fictive sphere with a normal angle for a selected circular orbit.

In such case, the velocity of collision ( $\Delta v_{col}$ ) is only dependent on both velocities: fictive target ( $v_T$ ) and flux particles ( $v_F$ ) because  $\cos\alpha = 0$  for a normal angle. The complete relation is given by Kessler (1981) in Eq. 4.9. The velocity of collision computed corresponds to an intermediate case. The worst case is reached in the case of head-on collision which consider an angle of 180° (*i.e.*  $\cos\alpha = -1$ ).

$$\Delta v_{col}^2 = v_T^2 + v_F^2 - 2v_T v_F \cos\alpha \quad \text{Eq. 4.9}$$

The MASTER model allows us to obtain and discriminate the complete spectrum of the relative velocity of collision for given orbital coordinates. As previously described (Letizia et al., 2018a), the peak in the spectrum showed in Figure 4.5 corresponds to the most probable impact velocity ( $v \sim 14.5$  km/s). Instead of computing the most probable impact velocity, the weighted average velocity could be obtained taking into account the relative contribution of each impact velocity class ( $v \sim 12$  km/s).

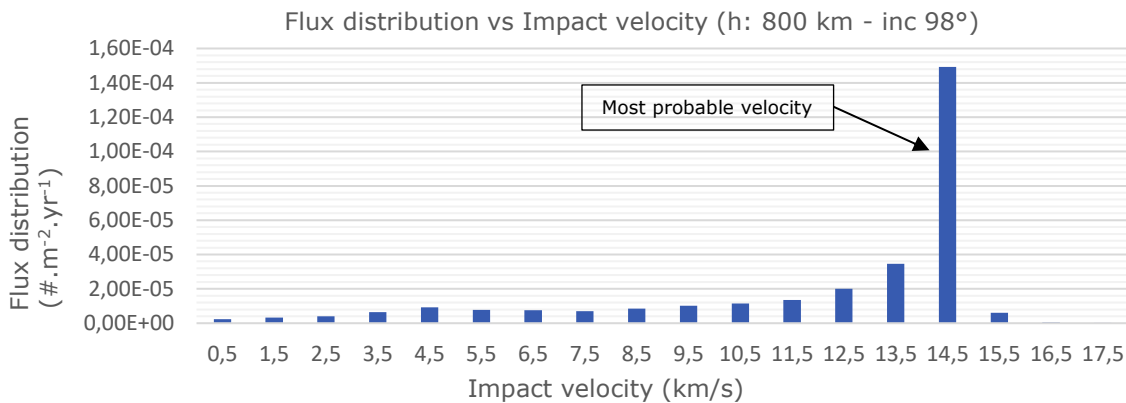


Figure 4.5 – Spectrum of the relative impact velocity calculated with MASTER-2009 model with respect to the flux contribution for a given circular orbit. The peak for each orbit represents the most probable velocity.

The most probable velocity is computed for the 2018 epoch and all the orbits previously defined for the flux calculation: range of altitude [200; 2000 km] with a 50 km-interval and the range of inclination [0; 178°] with a 2° inclination interval.

## 4. Results

### 4.1. Density evolution over time in LEO

The evolution of the averaged LEO density obtained from the MASTER model for fifteen epochs is shown in Figure 4.6. A lower threshold of 1-cm size is considered. It should be noted that this evolution does not represent the regional distribution within the LEO region rather presented in Figure 4. 7.

A rapid and sustained increase in the space density in LEO is observed. The sudden growth of the orbital population from 2008 is attributable to two major events: (i) the Chinese Feng-Yun 1C engagement (anti-satellite system) in January 2007 increased the trackable space object population by around 34% (IAA, 2017b); (ii) the Kosmos/Iridium collision in February 2009 led to the generation of more than 2 200 trackable fragments (Anselmo and Pardini, 2009).

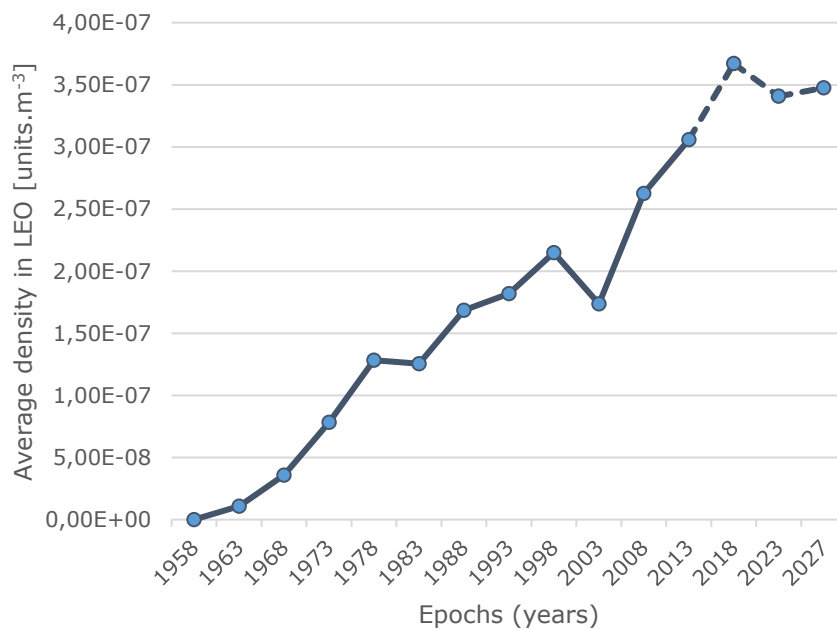


Figure 4.6 – Evolution of the average space debris density (> 1 cm) in the LEO region (200-2000km) retrieved from the MASTER model (1957-2027). The three last values come from predicted evolution while others are historic populations

Figure 4. 7 depicts the density distribution of the space debris population over time. For the year 2018, 2023 and 2027, the orbital density is predicted. The densely populated areas are around 800 and 1 400 km. The highest concentration of debris is at high declination ( $\delta$  around  $+90^\circ$  and  $-90^\circ$ ) as they are crossed by highly-inclined (i.e. near polar) orbits. At this range of declination, the flight path is parallel to the small circle of latitude at the northernmost and southernmost parts of an orbit, leading to a higher residence probability. In lower orbits, the air drag is still such that the life of debris objects is relatively low

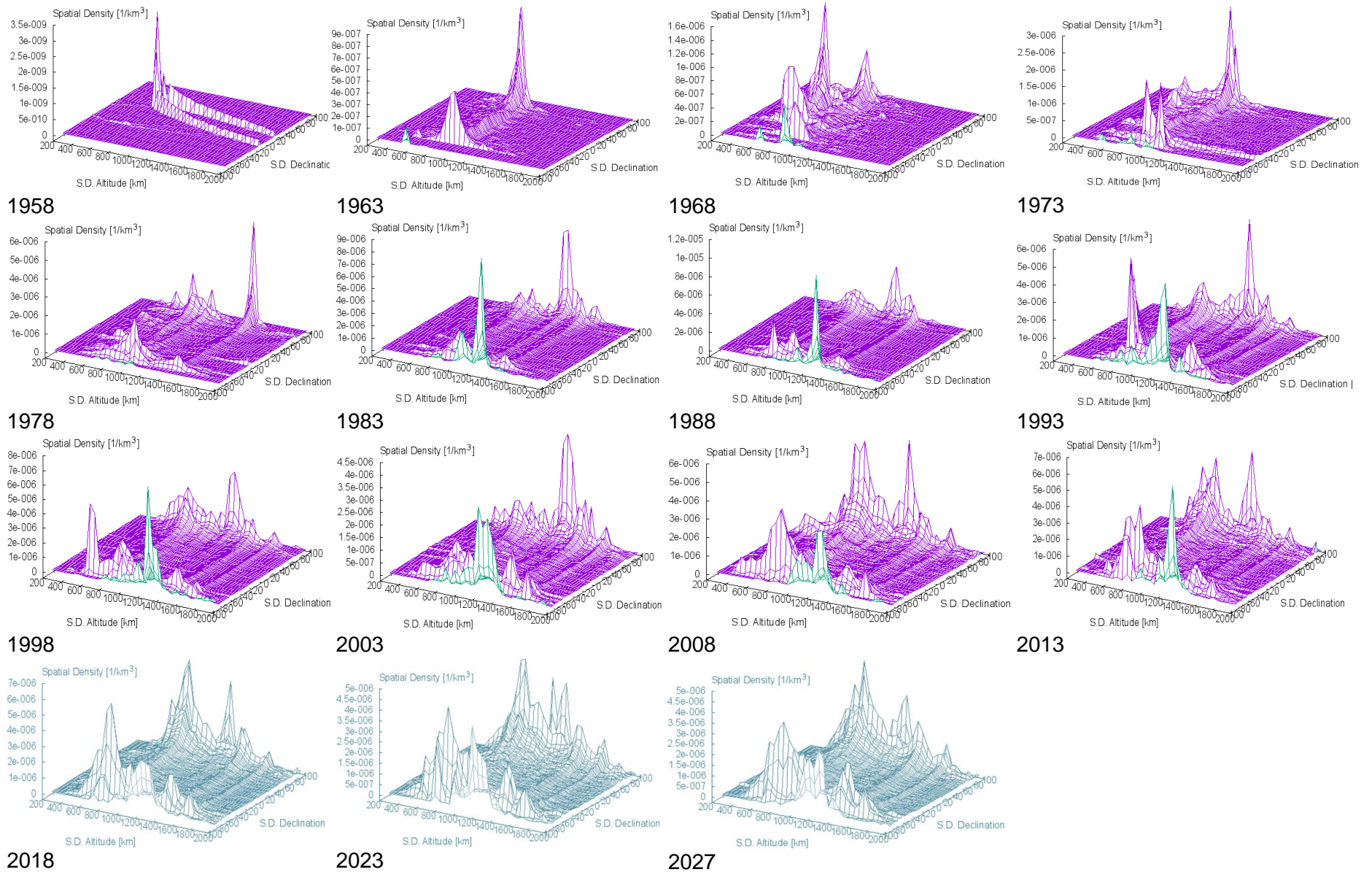


Figure 4. 7 – Space debris density distribution [ $\text{units} \cdot \text{km}^{-3}$ ] vs Altitude [200; 2000 km] and Declination [-90; 90°]. MASTER Model, all sources > 1 cm



## 4.2. Velocity of collision

The MASTER-2009 model allows computing the most probable impact velocity (in  $\text{km}\cdot\text{s}^{-1}$ ) between debris and a fictive spherical target. Figure 4.8 presents a map of the most probable collision velocity. It depicts the distribution of the most probable velocity for the 3330 discretised orbits and the year 2018. The velocities above 14.5km are highlighted because in such case the energy-to-mass ratio for a targeted spacecraft often exceeds 40 J/g which is considered to a ‘catastrophic collision’(Johnson et al., 2001; Krisko, 2011). The outcome of a catastrophic collision is the total fragmentation of the target and therefore the release of a large amount of debris in the orbital environment. The orbits which experience such velocities are located where the spatial density is important, i.e. within the highly inclined region of the orbital band from 400 to 1 000 km.

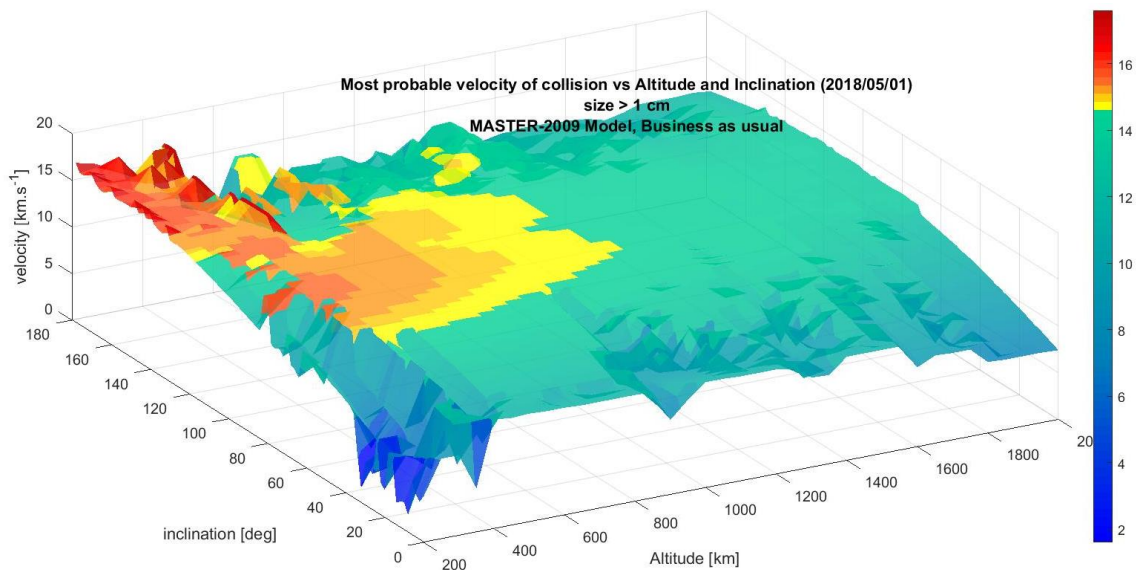


Figure 4.8 – Most probable velocity of collision [ $\text{km}\cdot\text{s}^{-1}$ ] vs Altitude [km] and Inclination [deg] – 2018 epoch – size (m) [0.01-100] – MASTER-2009 Model, Business as Usual perspective.

However, the evaluation of the most probable velocity of collision can lead to overestimating the flux of collision. Thus, the weighted average velocity was also computed. The results are presented in Annexe C.1.

## 4.3. Flux of debris

Figure 4.9 shows the mapping of the average flux of debris covering the LEO region from 200 to 2000 km with  $2^\circ \times 50 \text{ km}$  interval bins obtained from MASTER-2009 model.

We observe an unequal distribution of the flux according to the altitude and the inclination mainly due to the space density distribution (see §4.1). 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 500 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  $120^\circ$  and below  $50^\circ$  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 as shown by Figure 4.8.

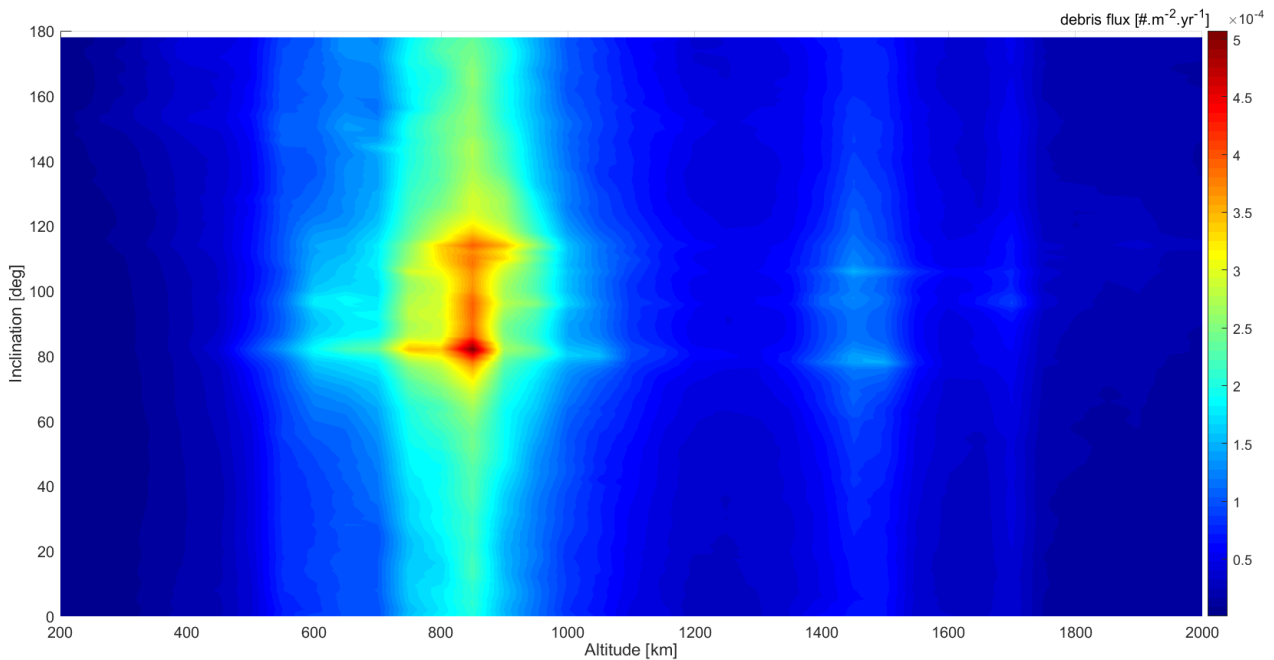


Figure 4.9 – Average relative flux of debris [ $\# \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ ] vs Altitude [km] and Inclination [deg] – 2018 epoch – size (m) [0.01-100] – MASTER-2009 Model, Business as Usual perspective

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, 2017b). 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  $82^\circ$  and  $108^\circ$ , present the most important flux. This is the result of past breakups in near-polar and SSO orbits which is also highlighted by the density distribution (see §4.1). The velocity of collision in this area are also particularly high (see §4.2).

Another region of interest is around 1450 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. The average flux of debris is mapped against the population of active satellites in 2018. The result is presented in Annexe C.2.

## 5. Conclusion

In this chapter, we use ESA's MASTER model to characterise the LEO environment in term of debris. The spatial distribution of the debris population, the most probable velocities of collision and finally the average flux of debris crossing a set of discretised circular orbits are computed. The results show that the main critical region encompasses the highly-inclined orbits of the 750-900 km orbital band. This region experiences the highest spatial density combined with the most probable velocity of collision over 14,5 km/s. The flux of debris was identified in Chapter 3 as a relevant parameter to characterise the *outside-in* perspective defined in the impact pathway. It will be integrated into the characterisation model in the next chapter.



This chapter is based on the following paper:  
T. Maury, P. Loubet, M. Trisolini, A. Gallice, G. Sonnemann, C. Colombo, *Assessing the impact of space debris on orbital resource in life cycle assessment: A proposed method and case study*, *Sci. Total Environ.* (2019).  
doi:10.1016/j.scitotenv.2019.02.438.

# 5

## ASSESSING THE IMPACT OF SPACE DEBRIS ON ORBITAL RESOURCE IN LIFE CYCLE ASSESSMENT: A PROPOSED METHOD AND CASE STUDY



Richard Long, Bilbao Circle (2000),  
Guggenheim Bilbao Museoa

*Pour l'enfant, amoureux de cartes et d'estampes,  
L'univers est égal à son vaste appétit.  
Ah! que le monde est grand à la clarté des lampes!  
Aux yeux du souvenir que le monde est petit!*

– Charles Baudelaire, le voyage

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## 1. Introduction

In Chapter 3, we propose a new framework aiming to consider the impact linked to human activities occurring in the near-Earth orbital environment. Two different impact pathways are defined based on mechanistic links: one dealing with the *consumptive use* of the orbital resource and another with the *degradative use*. The priority is given to the characterisation of the *degradative use* which addresses the space debris related impact on the orbital environment. In parallel, Chapter 4 exposes the current situation in orbit regarding the debris population. It focuses on the LEO region which experiences the highest concentration of space objects. ESA's MASTER model has been identified as an appropriate model to provide the physical parameters required for the design of midpoint characterisation factors (CFs).

Therefore, the objective of this paper is to provide a new midpoint indicator adapted from the current literature and models that represent the potential impact of a space mission on the orbital environment. 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 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 post-mission disposal (PMD) and the associated impact on climate change calculated as a proxy for a global environmental impact.

## 2. Material and methods

The impact pathways related to the orbital space use and their integration into the AoP 'Natural Resources', as defined in Chapter 3 are proposed in Figure 5.1. This chapter focuses on *orbital occupation*, *exposure to debris* and *severity* in case of break-up for orbital systems.

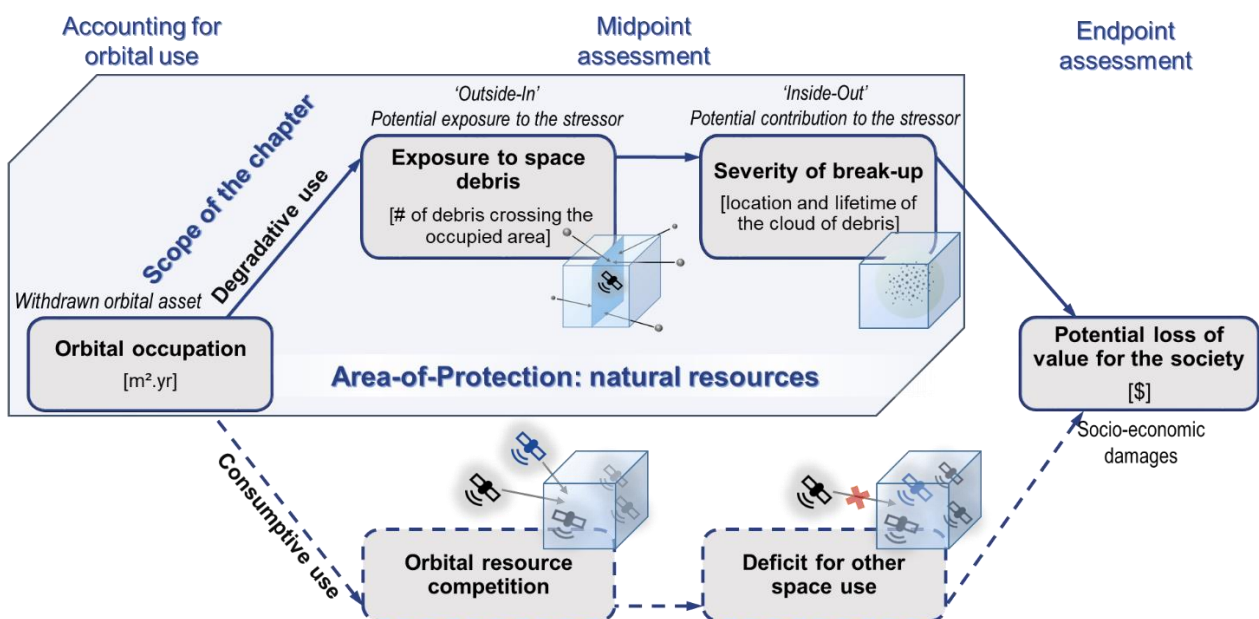


Figure 5.1 - Impact pathways proposal - only *degradative use* is addressed

## 2.1. 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 5.1). It corresponds to the orbital surface withdrawn by the studied objects multiplied by their respective on-orbit lifetime, expressed in  $m^2 \cdot years$ . In addition, the launch mass of the spacecraft shall be considered. The inventory parameters are given by the Eq. 5.1. In the case of a spacecraft, they depends on its design.

$$Inventory = A_c \cdot M \cdot \sum_{Orbits} t_i \quad [m^2 \cdot kg \cdot yrs] \quad \text{Eq. 5.1}$$

$A_c$  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.

$M$  is the *launch mass* of the spacecraft (in kg). The dwelling time in orbit  $t_i$  is mainly dependent to the area-to-mass ratio which allows quantifying the effect of orbital mechanics 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.

$\sum_{Orbits}(t_i)$  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). Annexe B2.1 provides a further detailed description.

## 2.2. 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 as defined in Chapter 3.

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; Keschull 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. 5.2 as the average flux of space debris passing through a targeted circular orbit  $i$  of the LEO region for a period of one year.

$$XF_i = \bar{\phi}_{h,inc,t} \quad [\#.m^{-2}.yr^{-1}] \quad \text{Eq. 5.2}$$

where  $XF$  is the exposure factor for a particular circular orbit  $i$ ;  $\bar{\phi}$  is the relative flux of catalogued particles provided by the ESA's reference model MASTER-2009 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 has been taken into account apart from the multi-layer insulation population, which is not available beyond the year 2009, and the source ‘clouds’ which allows to know the contribution in term of debris cloud of a single event (e.g. the Chinese anti-satellite missile test in 2007) but leads to ‘double counting’ when applied in the same time than the reference population. of explosion and collision fragments.

Similarly to Chapter 4, 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. 5.1) and exposure factors (Eq. 5.2) gives the Eq. 5.3. The latter formula can be used as a stand-alone risk indicator complementary to the LCA results (Sonnemann et al., 2018).

$$c = A_c \times \sum_{i=orbit} (t_i \times \bar{\phi}_i) \quad \text{Eq. 5.3}$$

Where  $c$  is the mean number of collision occurring in a given orbit and during a certain period, as already presented in Chapter 4.

### 2.3. 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.

#### 2.3.1. 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. 5.4) is considered:

$$N(L_c) = 0.1(M)^{0.75} \cdot L_c^{-1.71} \quad \text{[fragments]} \quad \text{Eq. 5.4}$$

Where  $N$  is the number of released fragments of size  $L_c$ , 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.  $L_c = 0.1$  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.

Given the Eq. 5.4, it is possible to express the number of fragments > 10 cm per kg of spacecraft considering the initial *launch mass*. The relation is presented in Figure 5.2. Taking into consideration given class of satellite (e.g. between 1.500 and 2.200 kg), it is possible to determine an  $\alpha$  coefficient that could be seen as a proxy to estimate the number of fragments released per kg (e.g. 0,8 fragments per kg for the class 1.500 - 2.200kg).

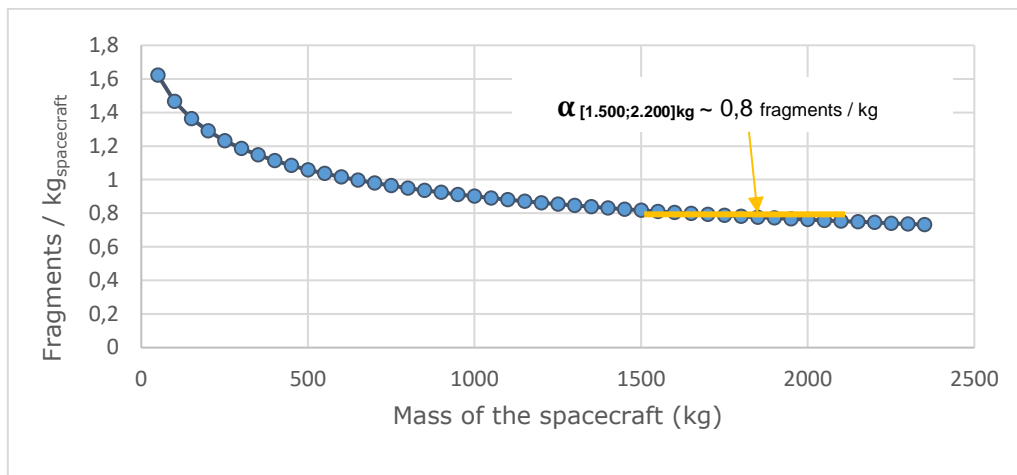


Figure 5.2 – Fragments > 10 cm released per kg of spacecraft according to the mass of the spacecraft.

### 2.3.2. 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. 5.5:

$$P(t, h) = e^{-\frac{t}{128.3 - 0.585892 \cdot h + 0.00067 \cdot h^2}} \quad [\%] \quad \text{Eq. 5.5}$$

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 model is valid for altitudes from 450 km (minimum survivability rates) to 2.000 km (maximum survivability rates). The values computed for 450 km can be applied to altitudes above to extend the characterisation domain until 200 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. 5.5 is later expressed as  $\rho$  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. 5.6. It represents the cumulative survivability of a fragment with respect to its altitude of emission expressed in years.

$$SF_{i,200\text{ yrs}} = \int_{0\text{ yr}}^{200\text{ yrs}} e^{-\frac{t}{\rho}} = \left[ -\rho \cdot e^{-\frac{t}{\rho}} \right]_{0\text{ yrs}}^{200\text{ yrs}} \quad [\text{years}] \quad \text{Eq. 5.6}$$

The calculation procedure for the SFs is further detailed in Annexe D.1.

## 2.4. Midpoint characterisation model and impact score related to degradative use

Combining Eq. 5.2, Eq. 5.6 and the alpha coefficient defined in Figure 5.2, we obtain the CFs calculated for a given circular orbit  $i$  (Eq. 5.7):

$$CF_i = XF_i \cdot \alpha \cdot SF_i \quad [\text{potential fragments} \cdot \text{years} \cdot \text{kg}^{-1}] \quad \text{Eq. 5.7}$$

The result is given in *potential fragment-years per kg* which represents the cumulative time survivability of fragments emitted in the orbital environment after a potential break-up. Applying the Eq. 5.7 to a specific spacecraft (i.e. product system) which occupies one orbit  $i$  during a period  $t$  in years we obtained (Eq. 5.8):

$$IS_i = A_c \cdot t \cdot M \cdot CF_i \quad [\text{potential fragments} \cdot \text{years}] \quad \text{Eq. 5.8}$$

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. 5.1, while the number of fragment over 10 cm generated is given by  $[M \cdot \alpha]$ . 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 (Eq. 5.9):

$$IS_{mission} = A_c \cdot M \cdot \sum_i^{\text{orbits}} t_i \cdot CF_i \quad \text{Eq. 5.9}$$

## 2.5. Applicative case study

### 2.5.1. 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 manoeuvre 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.

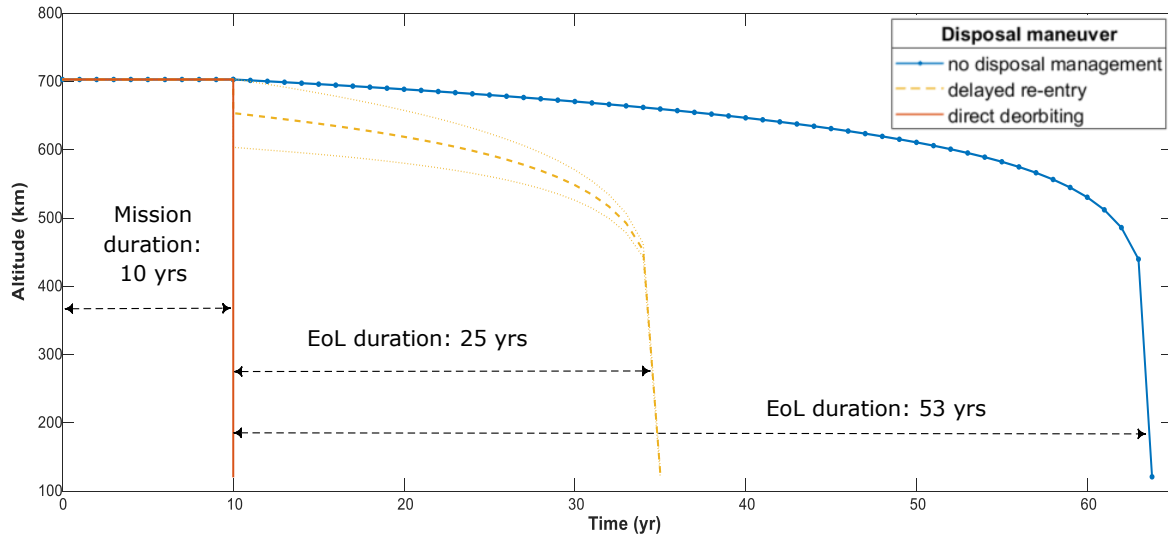


Figure 5.3 - Semi-major axis of the spacecraft during the operational time of the mission and its Post-Mission Disposal. The average cross-section area is similar to Sentinel-1A and was estimated at 23 m<sup>2</sup> according to ESA DISCOS database (ESA’s Space Debris Office, n.d.)

The latter EoL scenarios are depicted in Figure 5.3. The impact score is calculated according to the Eq. 5.9 for each EoL scenarios. The launch mass of the spacecraft equals to 2157 kg and its average cross-sectional area is 23 m<sup>2</sup>. 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).

### 2.5.2. Propellant consumption.

While it seems obvious that a *direct deorbiting* will mitigate the potential EoL related impact on the orbital environment, the feasibility of this option should be discussed regarding the quantity of propellant needed to complete such manoeuvre. Therefore, 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 Figure 5.3). We propose to calculate a theoretical amount of propellant needed for the mission and the chosen PMD scenarios and then add them.

The delta-V budget ( $\Delta v$ ), which measures the impulse needed to perform an orbital manoeuvre, is used to determine the hydrazine mass required for the disposal through the Tsiolkovsky rocket equation described in Annexe E.1.

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 Annexe E.3. 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. Results

#### 3.1. Characterisation factors (CFs) for the LEO region

Complete result data are provided in Annexe D.3. 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.

##### 3.1.1. Exposure factors (XFs)

Figure 5.4 shows the mapping of the exposure factors (*i.e. the outside-in perspective*) covering the LEO region from 200 to 2000 km with  $2^\circ \times 50$  km interval bins. The period covers 35 years from 2018 to 2053. This figure presents a similar pattern than the one previously obtained for the flux of debris in Chapter 4. The comparison between this average flux and the flux of debris previously computed for the year 2018 (see Chapter 4) is proposed in Annex C.3. Both fluxes are obtained following a Business-as-usual perspective (reference year: 2009) to take into account the growth of the orbital population.

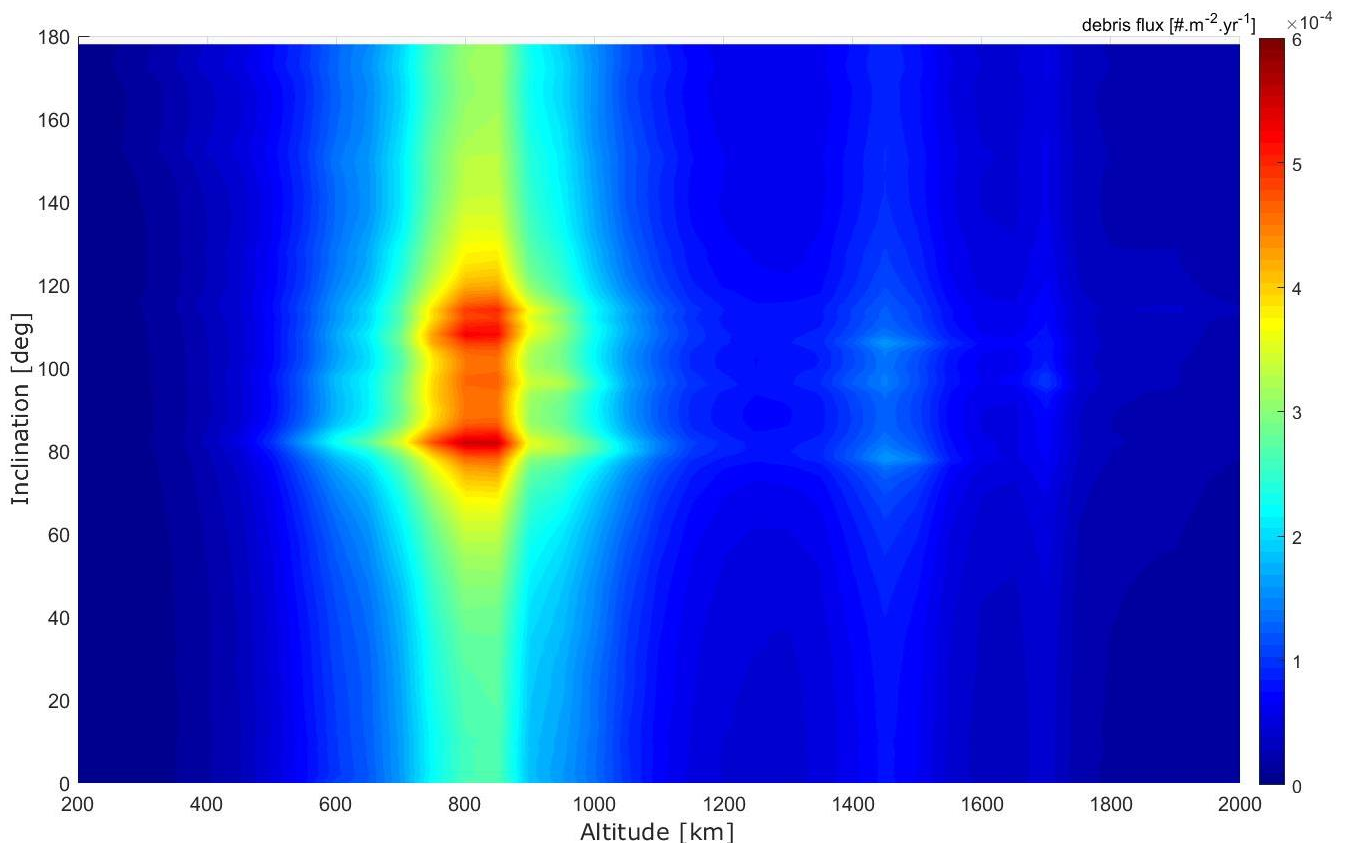


Figure 5.4 – XFs: Average relative flux of debris [ $\# \cdot m^{-2} \cdot yr^{-1}$ ] vs Altitude [km] and Inclination [deg]  
Time range (yr) [2018-2053] – size (m) [0.01-100] – MASTER-2009 Model, Business as Usual perspective.  
Calculations are made for each of the 3330 discretised circular orbits

### 3.1.2. Severity factors (SFs)

Figure 5.5 shows the mapping of the severity factors for the LEO region (*i.e. the inside-out perspective*) according to Eq. 5.6. The calculation of these SFs is detailed in Annexe D.1. 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.

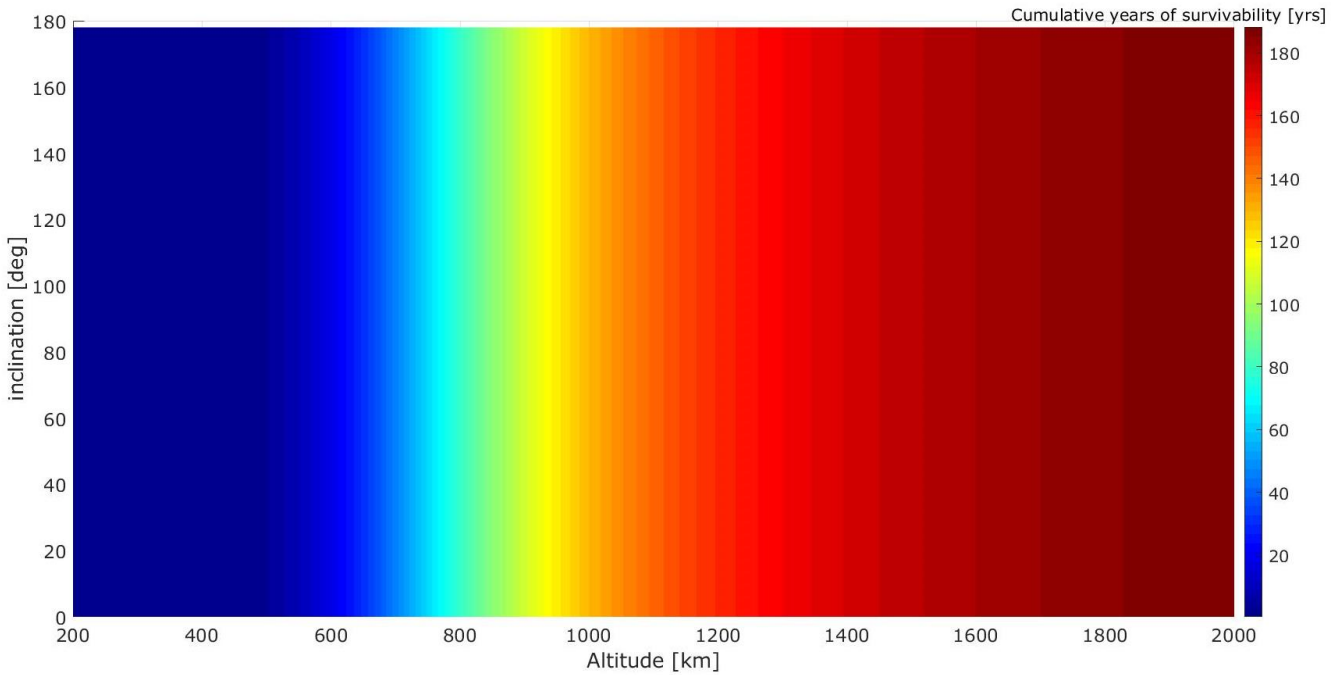


Figure 5.5 – SFs: Cumulative survivability (in years) of debris in the LEO environment according to its altitude of release and considering a 200 years prospective scenario.

### 3.1.3. Characterisation factors

The characterisation model for the *degradative use* at midpoint level is obtained with Eq. 5.7. Figure 5.6 shows the mapping of the CFs which depict the degradative use (*i.e.  $XF_i \cdot \alpha \cdot SF_i$* ) of the orbital resource through the potential emission of debris in the orbital environment.

The variation of the CFs results is mainly influenced by the flux of debris already presented above in Figure 5.4. 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.

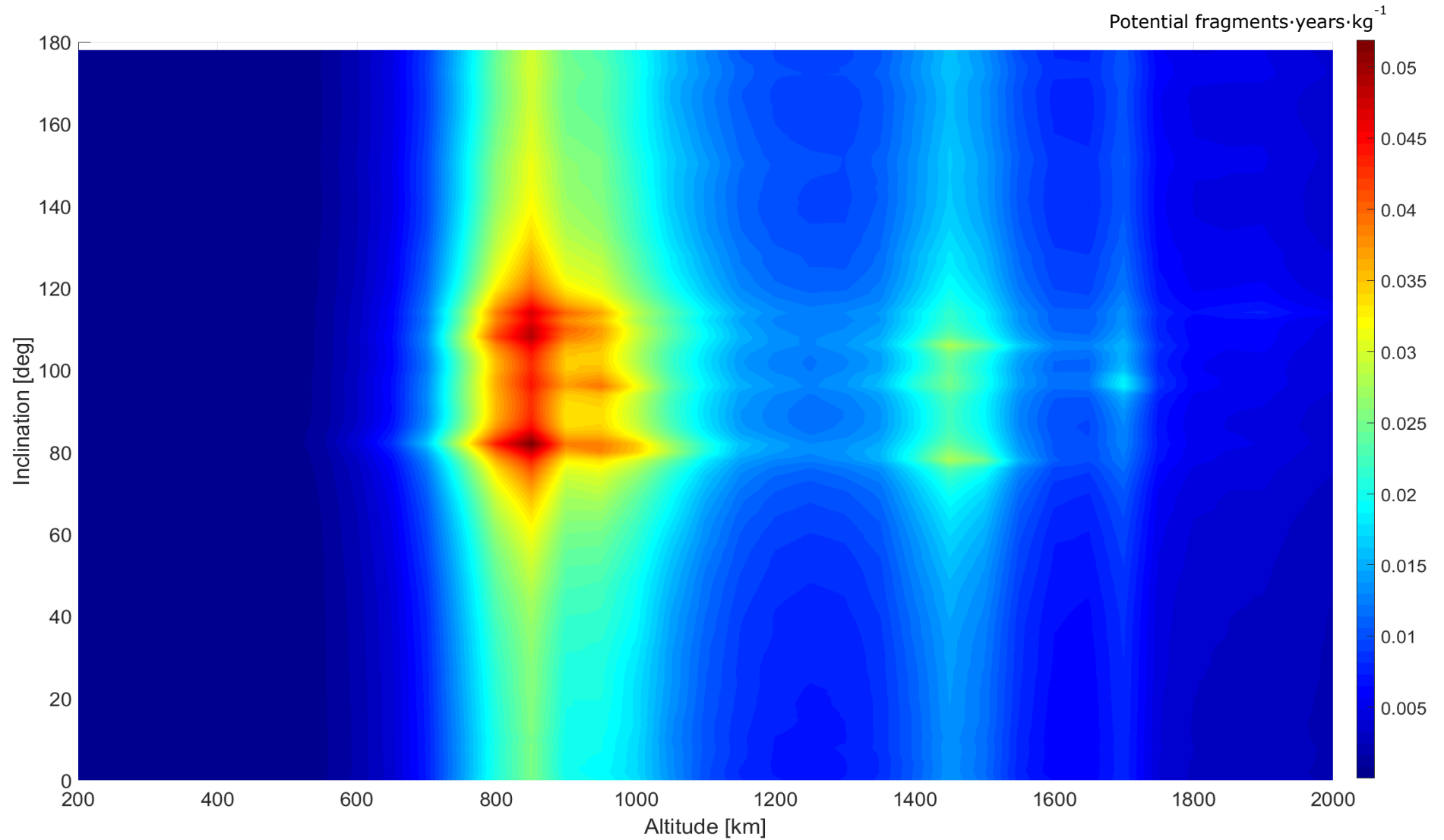


Figure 5.6 – CFs: Potential fragments-year per kg generated as a midpoint characterisation model for the *degradative use* of the orbital resource. The value of  $\alpha$  equals 0,8 fragments·kg<sup>-1</sup> as the interval [1.500-2.200 kg] is considered for the spacecraft.

Calculations are made for each of the 3330 discretised circular orbits

### 3.2. Results for a given space mission

#### 3.2.1. Impact scores for degradative use

Figure 5.7-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.

#### 3.2.2. 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 Annexe E.2 and in Figure 5.7-b. While the mass of hydrazine is estimated to 128 kg for the operating phase, the amount needed for a delayed re-entry and a direct re-entry manoeuvre is respectively 22 kg and 146 kg. When no PMD is performed, the consumption equals to zero.

These propellant consumptions can be used as a proxy for the environmental impact of the PMD phase. 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<sub>2</sub> eq. taking into account all the manufacturing and handling operations until the final fuelling before the launch (see Annexe E.3). 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 5.7-b) for the operating phase and the EoL is presented in Figure 5.7-c and expressed in metric tonnes of carbon dioxide equivalent (t.CO<sub>2</sub> eq.).

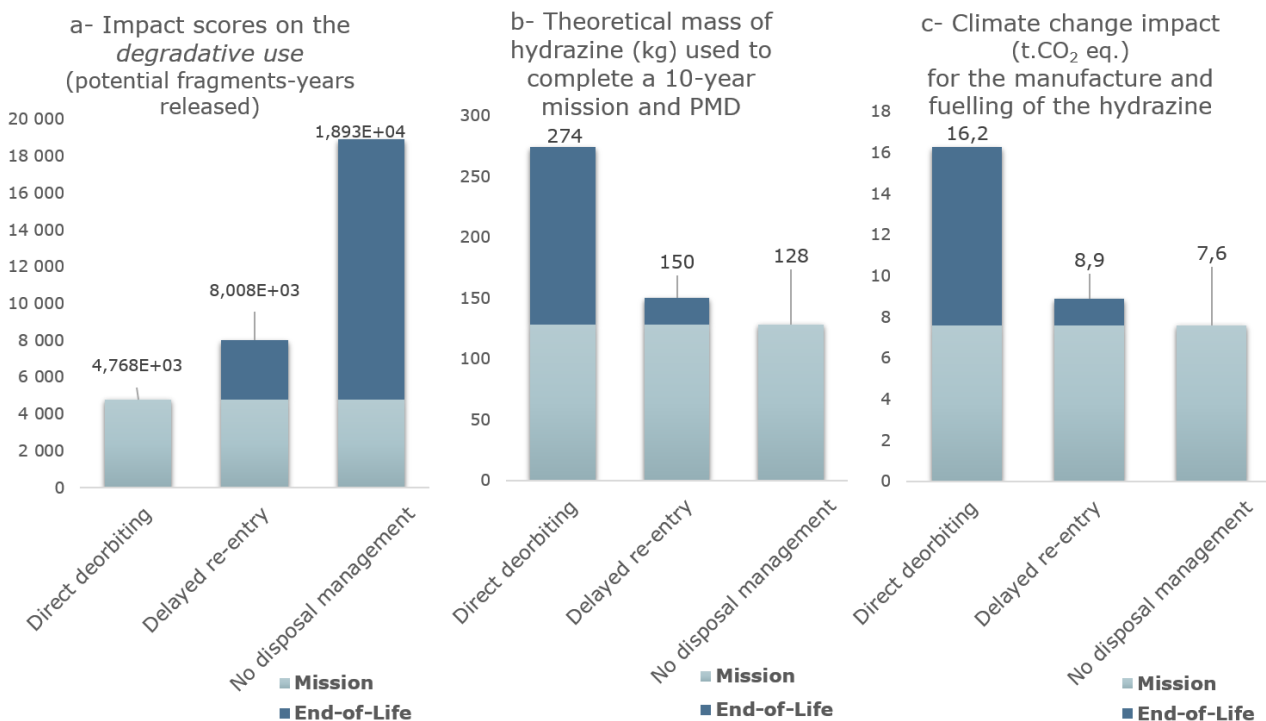


Figure 5.7 – (a) Sentinel-1A impacts related to *degradative use* midpoint against (b) the theoretical mass of hydrazine consumed to complete the mission and (c) the associated climate change of hydrazine manufactured and fuelled into the S/C

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. With a limited capacity of embedded propellant, a trade-off occurs between the propellant budget initially dedicated to the mission and the budget for the end-of-life. The reduction of the environmental impact linked to the propellant consumption appears necessary to adopt an eco-design approach. Alternative processes or propellants with less impact should be studied and more particularly regarding hydrazine which has been targeted by the European's REACH regulation as a substance of very high concern and included in the candidate list for authorisation (ECHA, 2018).

## 4. Discussions

The method proposed in this Chapter 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, 2010b). 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 5.1) 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)

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 manoeuvres that are not included in the scope of our study.

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. A preliminary study is proposed in the next chapter (Chapter 6).

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. 5.3, are based on the law of kinetic

gas theory as presented in Klinkrad et al., (2006a) and given by the Eq. 5.10. The equation was previously defined in Chapter 4.

$$c = v \cdot D \cdot A_c \cdot \Delta t \quad \text{Eq. 5.10}$$

$$P_i = 1 - \exp(-c) \quad \text{Eq. 5.11}$$

$$Criticality_i = P_i \cdot Impact_i \quad \text{Eq. 5.12}$$

where  $c$  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  $\Delta t$ . Eq. 5.3 proposed above stems from this formula. According to Eq. 5.11,  $P_i$  is the impact probability which follows a Poisson distribution. All the indexes mentioned above follow the criticality-based relationship (Eq. 5.12) 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. 5.9, 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 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 5.6). 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. Furthermore, we calculated the probability of collision combining Eq. 5.3 and Eq. 5.11: the  $c$  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 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  $\pm 5\text{km}$  for the altitude and  $\pm 1^\circ$  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 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 Annexe D.3. 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. Further work could be achieved focusing on EoL strategies: passive deorbiting (e.g. solar or drag sails) could be assessed against active deorbiting (e.g. propellant consumption) comparing related impacts on orbital and Earth environment. However, in such case, the *casualty risk*, i.e. the probability that a person is killed or seriously injured due to the re-entry, should be computed to determine which re-entry scenarios is relevant between controlled and uncontrolled re-entry.

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

In this chapter, 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. These 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.



*This chapter is based on the original work carried out by Alexandre Maynard, MSc student in environmental economics, and publicly presented:*

*Maynard, A., Maury, T., Loubet, P., Sonnemann, G., 2018. Assessing the potential loss of value on the orbital resource caused by Space Debris: towards an LCA endpoint characterization, in: ESA Clean Space Industrial Days, ESTEC, The Netherlands.*

# 6

## TOWARDS AN ENDPOINT CHARACTERISATION CONSIDERING NEGATIVE EXTERNALITIES CAUSED BY SPACE DEBRIS



Frantisek Kupka, Autour d'un point (1920/1930)  
Centre Pompidou, Paris

*Ce n'est point dans l'objet que réside le sens des choses,  
mais dans la démarche.*

– Antoine De Saint Exupéry

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## 1. Introduction

The space sector is defined by the OECD Space Forum (2016) as all the public and private actors involved in developing, providing and using space-related products and services, ranging from research and development, the manufacture and use of space infrastructures (e.g. ground stations, launchers and satellites) to space-enabled applications. Although space sector is a high-end niche that represents few revenues compared to its associated market such as the global telecommunications sector, its growth has constantly outperformed worldwide economic growth over the last decade (Oleson, 2016). The overall commercial space economy represented more than EUR 300 billion in revenues in 2013, shared between the space manufacturing supply chain (30%), satellite operators (9%) and downstream consumer services (61%) including actors who rely on satellite capacity for their activities, such as telecommunication, global positioning or Earth observation services providers (PwC, 2018).

The space industry is today experiencing an innovation-driven paradigm shift, leading to the “democratisation” of space (OECD, 2016). The new technical developments and processing efficiencies reduce the production cost. The most significant change in the sector comes from the influence of new private commercial entrants that are currently making strong efforts in increasing the production rates. In the same time, the satellite industry experienced a rapid growth in the development and manufacturing of small and nanosatellites as large satellites constellations (Klinkrad, 2017). Moreover, promising new electric propulsion systems could increase the operational lifetime while substantially reducing the mass of the payload (Henry, 2017; Mazouffre, 2016). Consequently, the access to space is more and more affordable and the applications and uses of satellite are likely to present a subsequent growth in the next decades (European Commission, 2013). This trend, based on a rapid market growth and a diversification of space activities, refers to the so-called ‘NewSpace’ movement.

However, the profitability of space activities is likely to be threatened by the future situation of the orbital environment. As already discussed in this thesis, future spacecraft operators will face an increasing orbital debris population that could limit spacecraft lifetimes drastically (Bastida Virgili et al., 2016; Karacalioglu and Stupl, 2016; Liou et al., 2018; Somma et al., 2018). Economic models have been published to explore potential incentives related to launch regulations and aiming to mitigate space debris. Adilov et al., (2018) suggest that space could become economically unprofitable before it becomes physically unusable due to Kessler syndrome. In a previous study (Adilov et al., 2013), they developed an economic model which describes debris as a negative externality. The socially optimal level of launches is estimated by comparison to a fully competitive market which causes the highest level of debris creation. Then, a set of debris remediation actions are discussed regarding economic incentives. Also, various policy solutions for debris management at short and medium term are proposed by Macauley (2015) which designs a system of launch taxes and rebates. Financial incentives are also studied by Beal et al. (2018). After defining a simplified physical model, they propose an economic model based on three configurations scenarios against the debris proliferation: an “unregulated launches” scenario, a fully regulated launches by an international agency scenario and an intermediate scenario considering launches with a tax. All these models attempt to address the space debris concern holistically. However, none of them could be directly integrated into the LCIA framework because of the need to develop specific characterisation factors included in an impact pathway.

Considering the resource framework in LCA, ‘future efforts’ methods based on cost externalities are currently seen as a promising approach for mineral resource use at the endpoint level (Berger et al., 2019; Sonderegger et al., 2019). In Chapter 3, we defined the orbital resource according to its functional value: *to support satellite operations that lead to the creation of economic value*. Therefore, the externalities could be evaluated through the loss of welfare and/or economic value caused by degraded use of this resource. In this way, the impact



pathway defined in Chapter 3 addresses the potential *loss of value* caused by space debris as a relevant mechanism to be included at endpoint level. In the previous chapter, we developed a set of characterisation factors (CFs) composed of *exposure* and *severity factors*. These CFs focus on the physical aspect of the degradative use of the orbital resource. According to Dewulf et al. (2015), CFs dealing with socio-economic impacts should be derived from resource criticality studies and will have to propose monetisation of the damages to AoP ‘resources’. Resource criticality is defined as the product of the likelihood of supply disruptions and their economic consequences (Glöser et al., 2015; Ioannidou and Sonnemann, 2018).

Hence, we propose in this chapter a first approach towards an orbital resource criticality considering an economic perspective. In this way, we propose to assess the current value of the LEO orbits. We assume that the value of the resource is based on the revenues and potential economic benefits generated by the active satellites’ population in each orbit. In other words, the *use value* of the orbital resource is assessed. Orbital cells are spatially differentiated according to their altitude and inclination as previously done in Chapter 5. The economic value of each orbital cell grid is computed for the year 2018. We compared these economic values against the CF scores obtained in Chapter 5 for the *degradative use*. Therefore, the most critical regions in LEO are highlighted. This is a first step towards creating robust characterisation factors associated with potential losses of value caused by space debris generation.

## 2. Material and methods

### 2.1. Goal and scope of the valuation of orbits

#### 2.1.1. Goal of the study

The development of endpoint characterisation factors should quantify the potential damage (i.e. loss of value) due to the presence of debris in orbit. Thus, the present chapter focuses on the assessment the economic value of the orbits. 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. This assessment is based on the deprivation of the ‘use value’ provided for end-users by each active satellite in orbit according to its specifications, e.g. type of mission, satellite position, embedded scientific instruments, *etc.*

Colombo et al. (2017a) use the revenues for commercial space products and services with the aim of approaching the economic value of space missions. However, commercial revenue does not necessarily capture the overall value generated by space activity. It is particularly the case for open-data services or non-commercial data provided by meteorological or Earth observation satellites, e.g. the European Copernicus constellation. The role of the space sector is not in the data or imagery transmitted through spacecraft, but rather the industries and markets that they enable (PwC, 2018). Thus, the whole value chain of the space sector should be taken into account. The four main segments of the value chain are presented in Figure 6.1 as *upstream*, *midstream*, *downstream* and *end-users*. *Upstream* includes activities that contribute to an operational space system. It includes the manufacture of space infrastructure, related subsystems and components as well as launch services, programme management and additional activities provided by space agencies. *Midstream* is related to satellite operations and the lease or sale of satellite capacity and data. *Downstream* includes activities related to space-infrastructure exploitation and the provision of space-based products and services to *end-users* (PwC, 2018).

According to PwC (2017), “end-users” term refers to final users, either public or private, of applications derived from the use of space activities. End-users can use directly data from the space sector but in most of

the cases they are indirect users, i.e. they are often not even aware of being a space-data user. This segment is very wide as it includes the whole Society which complicates the valuation of the economic benefits generated by space activities. However, in the frame of the LCA, economic value generated at end-users' level must be considered because this value is the most appropriate to depict the potential benefits provided by the Outer space used a resource.

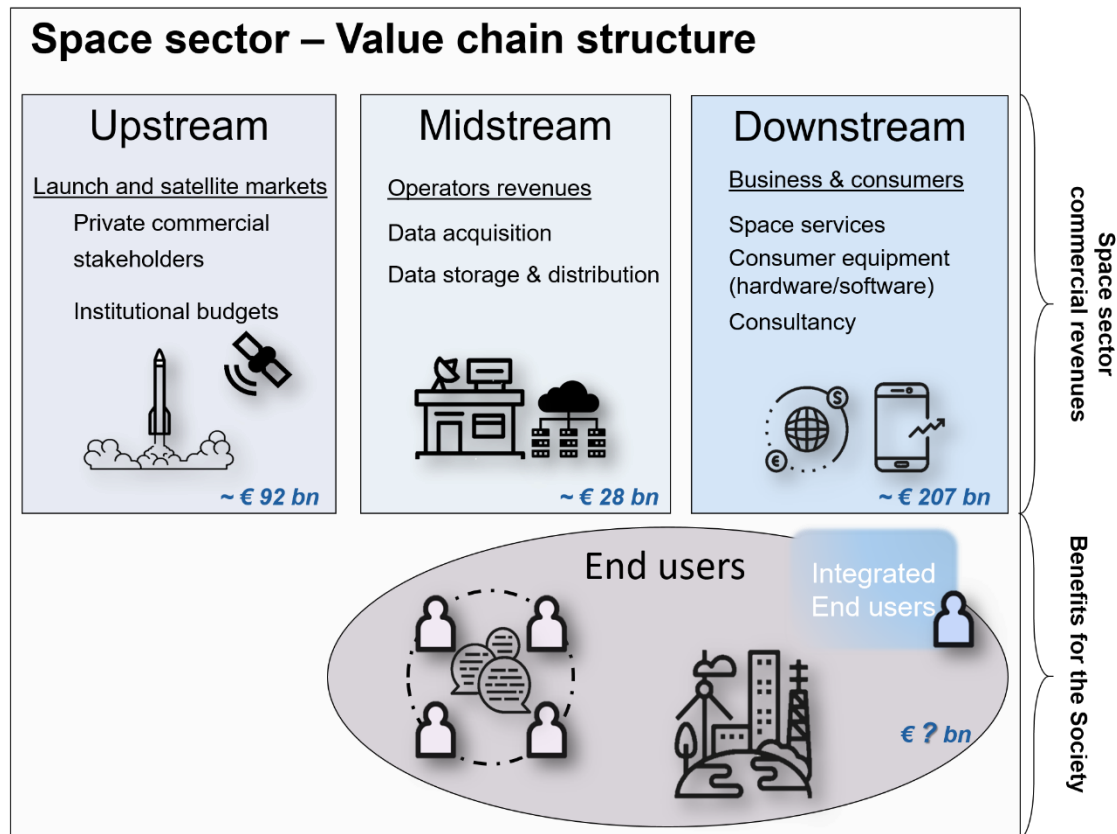


Figure 6.1 – Segmentation of the value chain freely adapted from EARSC (2017); PwC (2018, 2017). Commercial revenue of each segment is estimated by PwC (2018).

### 2.1.2. Scope of the study

The geographical scope of our study focuses on the LEO orbital region to be consistent with the previous characterisation model developed in Chapter 5. Moreover, 63% of the operating satellites orbit in the LEO region (UCS, 2019) while more than 75% of the debris population is concentrated in this area which represents only 0,3% of the near-Earth orbital volume (Krag et al., 2016).

The distribution of the 1230 active satellites in LEO according to their main mission is given by the UCS database (2019) as follows: *Earth observation*, 56%; *communications*, 22%; *technology development*, 17%; *space observation and science*, 5%. We notice that the share of *Earth observation* and *communication* satellites represents around 80% of the active population. Consequently, our study will focus on the revenue generated by (i) Communication satellites and (ii) Earth Observation satellites.

The first objective is to map different kinds of mission in their respective orbital areas. For both types of mission (communication and Earth observation), the launch masses of the overall active population in 2018 were retrieved from the UCS database and the ESA DISCOS database (ESA's Space Debris Office, n.d.). Launch masses are gathered to obtain cumulative masses which fit within  $2^\circ \times 50$  km orbital cells covering the LEO region from 200 to 2000 km (i.e. same discretisation as the one performed in Chapter 5).

## 2.2. Methodology to assess the revenues of the communication satellites

The methodology for the valuation of communication satellites is presented in Figure 6.3 and described in the next sections.

### 2.2.1. Description of the satellite communication sector

The communication satellites use high-frequency radio waves for telecommunication to allow communication between widely separated geographical points. In 2018, the majority of the active communication satellites (59%) orbit in GEO. Communication satellites represent 37% in LEO, that is to say 294 active satellites. Since satellites orbit faster in LEO than in GEO, they do not remain visible from a fixed point on Earth as it is the case in GEO satellite. To provide continuous communication services, several satellites are required to fully cover the targeted zone called a satellite constellation.

Economic data related to the communication satellites revenues in the LEO region is scarce and not available for all satellites. Only the main private operators provide available economic and financial data. The YCharts database (Chicago, IL), which compiles economic indicators and releases from companies and exchange-traded funds, was used to retrieve the revenues of three satellite-communication companies. Iridium Communications and Globalstar are operators owning major constellations providing satellite phone services, mostly to remote areas. Orbcomm Company operates a satellite constellation which ensures a discontinuous coverage: its satellites store data received by passing over one part of Earth and transmit it later while passing over another part.

The revenues in 2017 for these three majors companies are the following: Iridium Communications, 448 M\$; Orbcomm, 254 M\$ and Globalstar 113M\$. Iridium communication is today the market leader among the communication satellite operators. Its constellation is the largest system in LEO with 66 active communication satellites. A second-generation of 66 satellites, called Iridium-NEXT began to be deployed to substitute the existing constellation in January 2017. This system also includes nine in-orbit spares and six on-ground spares. The ten last Iridium-NEXT satellites were launched in January 2019.

### 2.2.2. Estimation of current and future revenue for communication satellites

The second specific objective is to evaluate the revenue for each communication satellite in the LEO. This work is carried out for the year 2018. The goal is to assess potential benefits for the end-users based on the volume of sales of the midstream operators. In this context, three main assumptions are made:

**(i) Current revenue is only dependent on the mass.** We consider the satellite launch mass as a proxy to evaluate its revenue since (i) this parameter is available for most of the satellites and (ii) the launch mass is one of the main parameters influencing the launch cost. In this way, the mass of the spacecraft is optimized and no useless mass is embedded. Thus, we consider that the mass of the spacecraft is correlated to its performance.

Sixty-six satellites of the 1<sup>st</sup> Iridium generation were needed to ensure a full coverage (spare satellites were available in case of a satellite failure), representing a cumulative launch mass of **45 474 tons** for the active satellites of the constellation. The Iridium Communications company revenue in 2017 was **396,5 M€** (considering an annual average Euro to US-dollar exchange rate of 1.13), leading to a 2017 revenue ( $r_{Iridium/kg}^{2017}$  in €/kg) of **8719 €/kg of satellite**. We assume that the current revenue (i.e. 2017) for each kg of communication satellite in LEO is equal to the revenue per kg of Iridium constellation in 2017 because Iridium is the current leader on the communication market (i.e. conservative approach).

**(ii) The temporal evolution of the revenue is constant and can be based on Iridium growth.** Between 2017 and 2018, we assume a constant increase in all communication revenues. Furthermore, the average annual

revenue growth (RG) of every communication satellites is based on the Iridium revenues from 2007 to 2017. Indeed, the Iridium company experienced a steady state growth in the past ten years thanks to a constant number of operating satellites (1<sup>st</sup> generation constellation). Figure 6.2 shows the yearly growth of revenues per kilogram of Iridium satellite from 2007 to 2017. There is a correlation between the revenue per kg and the year of operation with a correlation coefficient of 0.9275. The annual growth of revenue ( $RG_{Iridium}$ , in €/kg/year) is obtained from the slope of the function  $R=f(\text{year of operation})$ , i.e., **316 €/kg/year**.

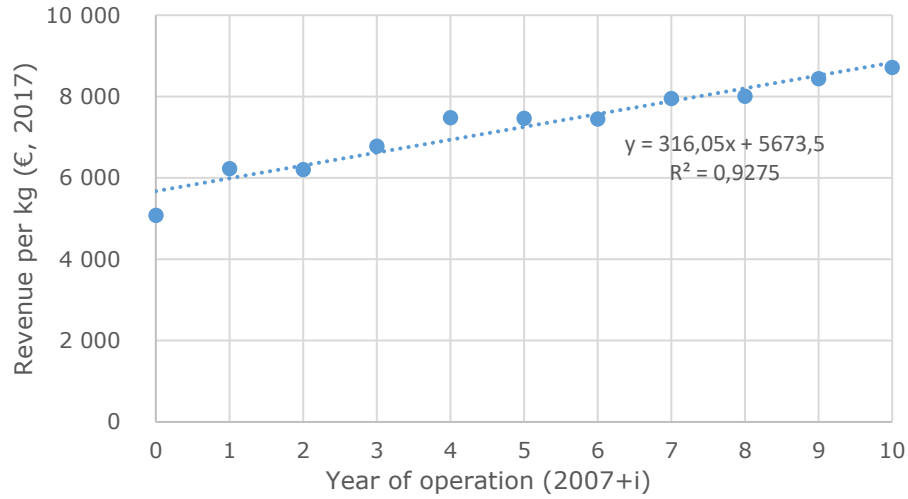


Figure 6.2 – Past annual revenue growth of the Iridium Communications firm from 2007 to 2017

**(iii) The downstream segment accounts for 80% of the revenues generated by communication satellites.** The computed economic revenue represents a potential volume of sales for the midstream segment, i.e. operators' revenues (see Figure 6.1). According to PwC (2018), the downstream segment accounts for 80% of the revenues generated by the satellite communication market.

Based on these three assumptions, we computed the revenue for the downstream segment coming from communications services in LEO in 2018. The following procedure, detailed in Figure 6.3 is applied:

- Collection of masses and coordinates of active communication satellites in the LEO region from the UCS database. It represents 294 active satellites.
- Sum the masses ( $m_{com,sat}$  in kg) of the communication satellites for each LEO orbital cell  $i$  (Eq. 6.1). The discretization of the LEO region according to altitude (alt) and inclination (inc) is the same as the one used in Chapter 5.

$$m_{com,orbit\ i} = \sum_{alt,inc} m_{com,sat} \quad \text{Eq. 6.1}$$

- Computation of the current 2018 revenue ( $R_{com,orbit\ i}^{2018}$  in €) generated in each orbit cell grid  $i$  (Eq. 6.2) from the correlation obtained with assumption (i) and the revenue growth (RG) per kg computed through assumption (ii):

$$R_{(com,orbit\ i)}^{2018} = m_{com,orbit\ i} \cdot \left( \frac{r_{Iridium}^{2017}}{kg} + RG_{Iridium} \right) = m_{com,orbit\ i} \cdot (8719 + 316) \quad \text{Eq. 6.2}$$

- Estimation of the revenue generated in the downstream segment using the assumption (iii). Multiplication by four of the midstream revenue to estimate the potential revenue at the downstream

level. No figure was found to extend the valuation until end-users' segment.

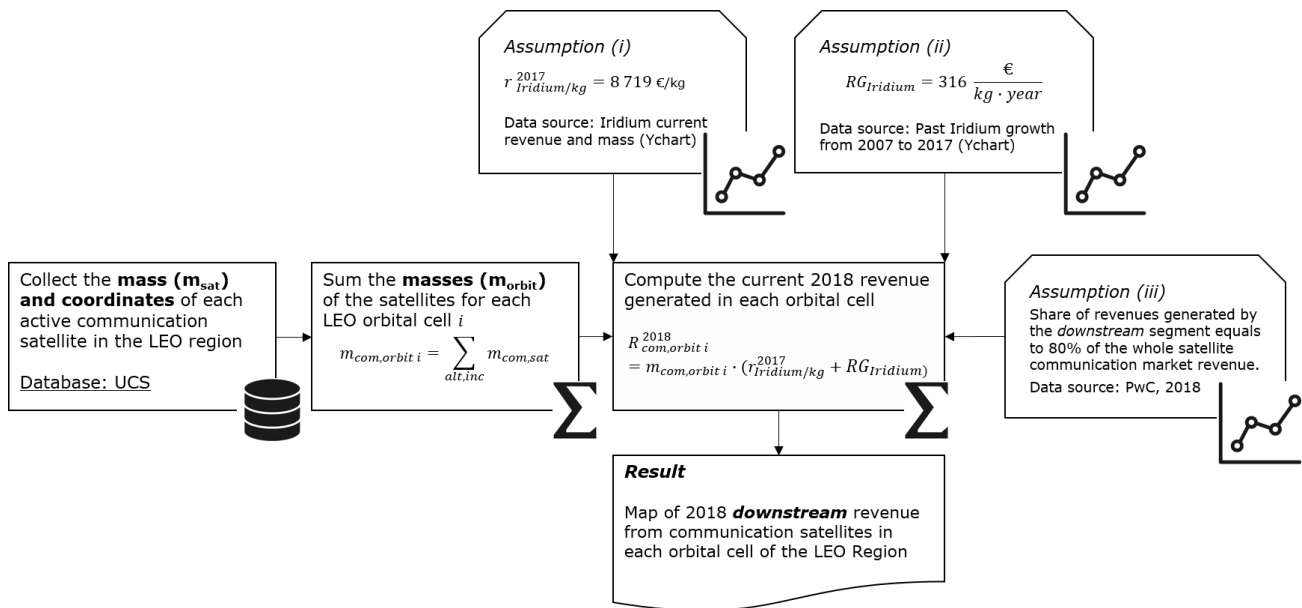


Figure 6.3 – Computation procedure to estimate downstream revenue from communication satellites in LEO. Abbreviations – r: revenue per kg; R: Revenue per orbital cell; RG: revenue growth

## 2.3. Methodology to assess the revenues of the Earth observation satellites

The complete methodology for the valuation of Earth observation (EO) satellites is presented in Figure 6.4.

### 2.3.1. Description of the satellite communication sector

EO satellites are used for environmental monitoring, meteorology or map making. The vast majority of the EO satellites (more than 90% of the 661 active EO satellites) orbit in LEO because the embedded EO instruments operate at a relatively low altitude. EO satellites applications cover a wide range of economic sectors including precision farming, weather forecasting, civil protection, insurance, natural resource monitoring, oil and gas exploration, and urban monitoring.

According to PwC (2018), EO data and added services benefit from the highest annual growth of all the space exploitation markets, with an average annual growth of 15% over 2014-2019. This growth is driven by an increasing focus on analytics from high-resolution and medium-resolution imagery (Werner, 2018). Also, the key role of Big Data reinforces the development potential of commercial activities based on EO.

Because of the high diversity of missions, the economic value from EO satellites is more complex to analyse than communication satellites: they embark different type of scientific, optical or radar instruments which have a variable quality in terms of resolution. Most of the instruments embedded in EO satellites are specifically designed for the mission. For instance, Sentinel-3B which is a European satellite launched in 2018, is primarily used for an ocean mission. However, it is also able to provide atmospheric and land application data. Multiple sensing instruments are embedded on Sentinel-3B: SLSTR (Sea and Land Surface Temperature Radiometer), OLCI (Ocean and Land Colour Instrument), SRAL (Synthetic aperture Radar Altimeter), DORIS (Doppler Orbitography and Radiopositioning Integrated), and MWR (Microwave Radiometer).

Due to this high variability in term of activities and embedded instruments, the revenue of EO satellites cannot only be correlated with their mass as done with communications satellites. Furthermore, governments and institutional stakeholders are more involved in the EO sector than in communications because of the

major role played by EO satellites in the environment monitoring and emergency management. A significant part of the provided data is non-commercial, sometimes in open access. In this context, traditional financial data does not catch the complete value of the EO services for society. It is typically the case of the European EO missions carried out in the frame of the Copernicus programme which is coordinated and managed by the European Commission in partnership with ESA and the EU Agencies. One of the crucial benefits of the Copernicus Programme is that the data are made available on a full, open and free-of-charge basis to all its users allowing many new downstream services to be developed.

### 2.3.2. Estimation of the EO active satellites' performances

A first step to assess the potential benefits of an EO mission for the society is to characterise the satellite and its embedded instruments. We propose to estimate the current value of a satellite according to a “quality score”: the share of revenue of the EO sector that can be attributed to a specific satellite will be dependent of the quality and the number of its embedded instruments.

Our study is based on the Observing Systems Capability Analysis and Review tool (OSCAR) provided by the World Meteorological Organization (WMO, 2019). This tool compiles expert assessments on the relevance of instruments based on pre-defined capabilities and measurement of particular physical variables. A scale from 1 to 5 rates the instruments as follows: 1-Primary; 2-Very high; 3-High; 4-Fair; 5-Marginal.

Five under forty three different instruments are rated in the OSCAR database, covering a wide range of missions (e.g. high-resolution imagery, IR temperature, radar altimetry, spectrometry etc.). For each instrument, the reverse of the score is calculated (1/5-marginal, 1/4-fair, 1/3-high, 1/2-very high, 1-primary) so that the value is high when the capacity of the instrument is good. Then, we propose to sum all the scores corresponding to the instruments embedded in the same satellite. The final score depicts the performance of the EO satellite under study. For example, Sentinel-3B described in the previous section gets a score of 4,78 points. In this way, we are able to characterize 162 satellites, representing around 26% of the active population in LEO.

To extend this parameter to the whole EO population in orbit (i.e. 613 satellites), we carry out a statistical study based on the 162 satellites already evaluated. The goal is to find the parameters available in the UCS database (e.g. the altitude, the mass, the launching year) which could have a significant influence on the quality score. *StataSE 12* software (Stata Corp. LLC, College Station, TX) is used to perform the statistical correlation. The linear correlation is expressed as follows (Eq. 6.3):

$$\begin{aligned} \text{Quality score} = & -1,48 - 0,42 \cdot \text{copernicus} + 0,77 \cdot \text{civil} + 0,82 \cdot \text{meteorology} \\ & + 0.00038 \cdot \text{altitude} + 0.00068 \cdot \text{mass}_{\text{launch}} - 0.060 \cdot \text{age} \end{aligned} \quad \text{Eq. 6.3}$$

Where *Copernicus*, *civil* and *meteorology* are binary variables which equals 1 if correct, and 0 otherwise. This statistical correlation is applied to the 451 EO satellites that were not previously characterised so that a quality score is determined for each satellite.

Finally, the quality score per orbital cell is computed thanks to the values per satellite retrieved from the OSCAR database and the ones obtained by the statistical correlation. It gives a cumulative quality score per orbital cell highlighting the potential value of the area of specific area.

### 2.3.3. Estimation of current and future benefits for end-users using EO data & information

In this section, the estimation of the EO satellites economic benefits on the Copernicus revenues (current and prospective) since they are well documented, which is not the case for other EO systems. A recent report from PwC proposes an ex-ante assessment of Copernicus data and information spillovers, which evaluates

the impacts of the use and exploitation of Copernicus data for the European society (PwC, 2017). The study specifically examines the value created and offered to end-users, with a particular focus on environmental and societal benefits. As highlighted by the report, the assessment of spillovers derived from open data policy (i.e. as it is the case of Copernicus program) is by nature complex and intangible. Nevertheless, this approach is considered as a first step towards the evaluation of the potential benefits of EO services.

The economic valuation is based on the following assumption:

**(i) Current revenue is only dependent on the quality score of each satellite.** The value of revenues per “point” is computed from Copernicus market data. In 2018, Copernicus generated **2 157 M€** for end-users based on the estimation of the PwC (2017) and applying a growth rate of 15% as mentioned above (PwC, 2018). The satellites of the Copernicus program (combining the Sentinel missions and the European contributing missions) have a cumulative quality score of **50.5 points** following the methodology described in section 2.3.2. It results in an economic value (*ev*) of **42,7 M€/point**. Applying this value to each EO satellite according to its quality score enables to map the 2018 economic value for each orbital cell (*EV*) based on the Copernicus 2018 economic value.

The procedure to evaluate the revenues from EO satellites is similar to the procedure developed for communication satellites. The procedure is detailed in Figure 6.4 and hereafter:

- Sum the scores ( $S_{EO,sat}$  in Pts) of the EO satellites for each LEO orbital cell *i*. The discretization of the LEO region according to altitude (alt) and inclination (inc) is the same as the one used in Chapter 5.

$$S_{EO,orbit\ i} = \sum_{alt,inc} S_{sat(alt,inc)} \quad \text{Eq. 6.4}$$

- Computation of the current 2018 economic value ( $EV_{EO,orbit\ i}^{2018}$  in €) generated in each orbital cell *i* from the correlation obtained with assumption (i):

$$EV_{EO,orbit\ i}^{2018} = S_{EO,orbit\ i} \cdot \frac{ev_{Copernicus}^{2018}}{Pts} \quad \text{Eq. 6.5}$$

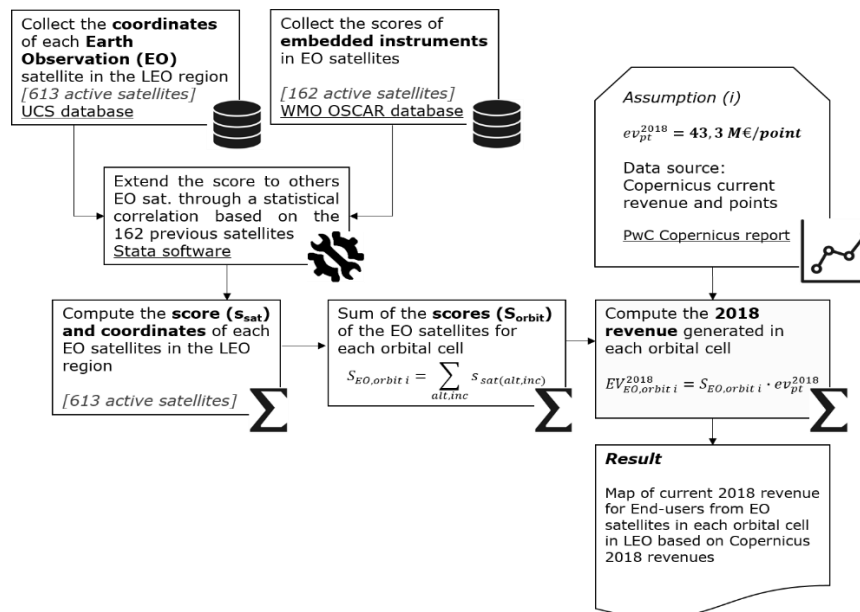


Figure 6.4 – Computation procedure to estimate end-users benefits from EO services in LEO. Abbreviations – S: score per orbital cell; s: score per satellite; EV: economic value per orbital cell; ev: economic value per point

### 3. Results

#### 3.1. Economic value computed for Earth observation and Communication satellites

The cumulative mass of both EO and Communication satellites are compiled for each orbital cell. The result is presented in Figure 6.5 against the flux of debris obtained in Chapter 4. It gives an overview of the orbital situation in LEO for the year 2018 considering only EO and Communication satellites (representing around 80% of the active population in LEO).

We see that the majority of the spacecraft is concentrated in a limited number of orbital cells. The majority of the EO satellites, which represent the main part of the LEO satellites fleet, is concentrated in the altitude band from 500 to 900 km. Their inclinations follow an SSO regime (around  $98^\circ$ ) which ensure constant sunlight conditions. The value of the flux of debris crossing those orbit increases with the altitude in the range comprises between 750 and 900 km. Beyond the SSO regions, the orbital cell which encompasses Yaogan satellites and SB Wass systems (1000 km;  $64^\circ$ ) generates substantial revenue.

A limited number of orbital cells are populated with communication satellites. It concerns constellations as Iridium (800 km;  $86^\circ$ ) and Iridium next (600 km;  $86^\circ$ ), Globalstar (1450 km;  $52^\circ$ ), Gonets and Rodnik (1500 km;  $82^\circ$ ). The flux of debris is particularly high in the area of the Iridium 1<sup>st</sup> generation constellation (due to the past Iridium / Kosmos collision).



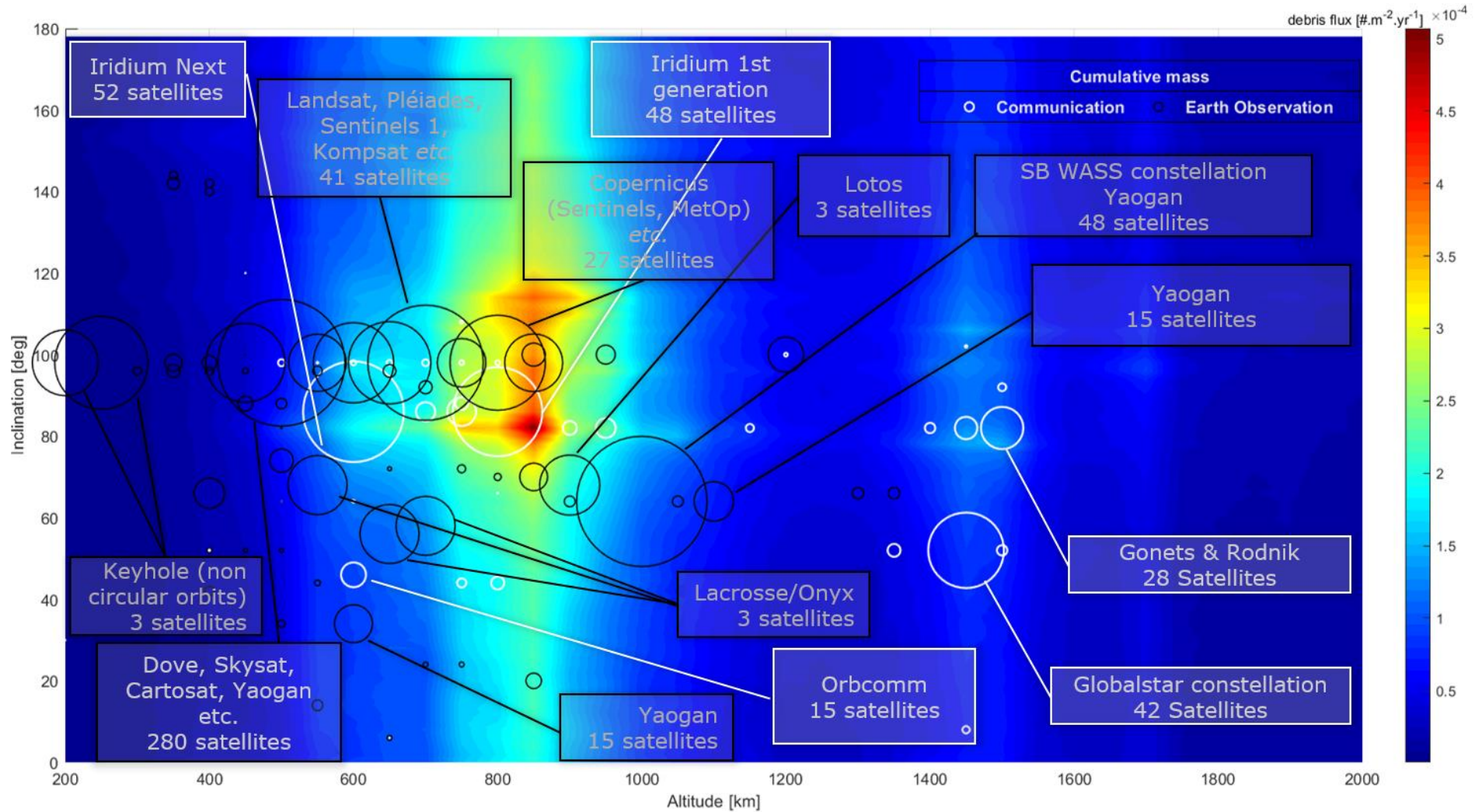


Figure 6.5 – Cumulative mass (Earth observation & Communication) vs Debris Flux in 2018. Debris size > 1cm, MASTER-2009 Model (BAU). Circles represent cumulative launch mass of active satellites per orbital cell

For each orbital cells of the LEO region, we then apply the computation procedures described in Figure 6.3 and Figure 6.4. The resulting revenues  $R_{EO,orbit\ i}^{2018}$  and  $R_{com,orbit\ i}^{2018}$  are obtained. The map of the results is presented in Figure 6.6.

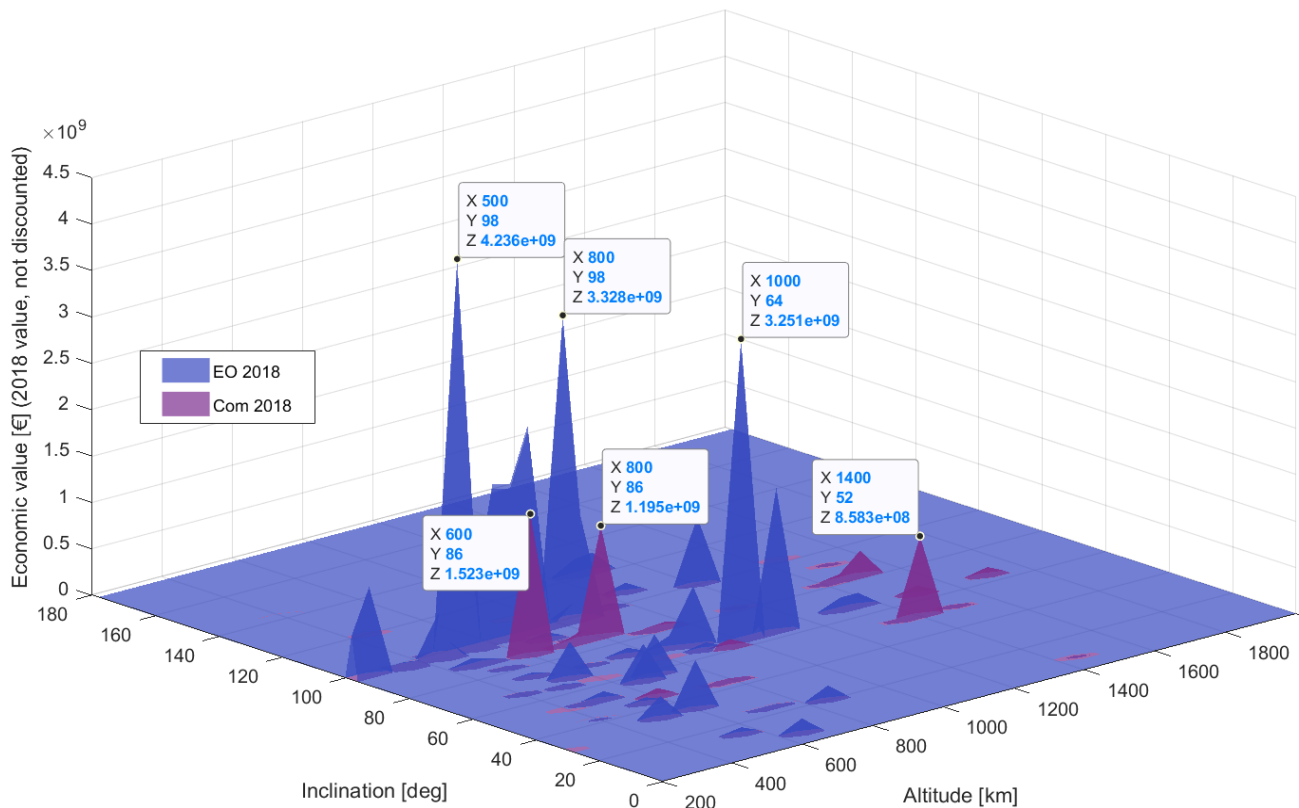


Figure 6.6 – Estimated revenue in 2018 for the EO and communication missions

For the whole LEO region we obtain the following values for the year 2018:

- **4 743 M€** as revenue of the downstream segment related to communication activities
- **27 940 M€** as benefits for the end-users

We notice that Earth Observation generates much more revenue than communication in LEO. First, it is due to the number of satellites orbiting in LEO (613 EO satellites vs 294 communication satellites). Moreover, the EO sector is today the most dynamic market in LEO (PwC, 2018; Werner, 2018) due to data exploitation and value-added services. Lastly, in the case of the EO, the benefits for the end-users (i.e. the whole society) is relevant to calculate because of the important share of non-commercial services provided. It is not the case for the communication satellites for which we consider the revenue of the downstream segment: companies provide communication services on a for-profit and competitive basis.

### 3.2. Communication: economic valuation against degradative use impact

Figure 6.7 shows the most critical areas in LEO, which correspond to the orbital cells combining high *degradative use* potential impact and economic importance.

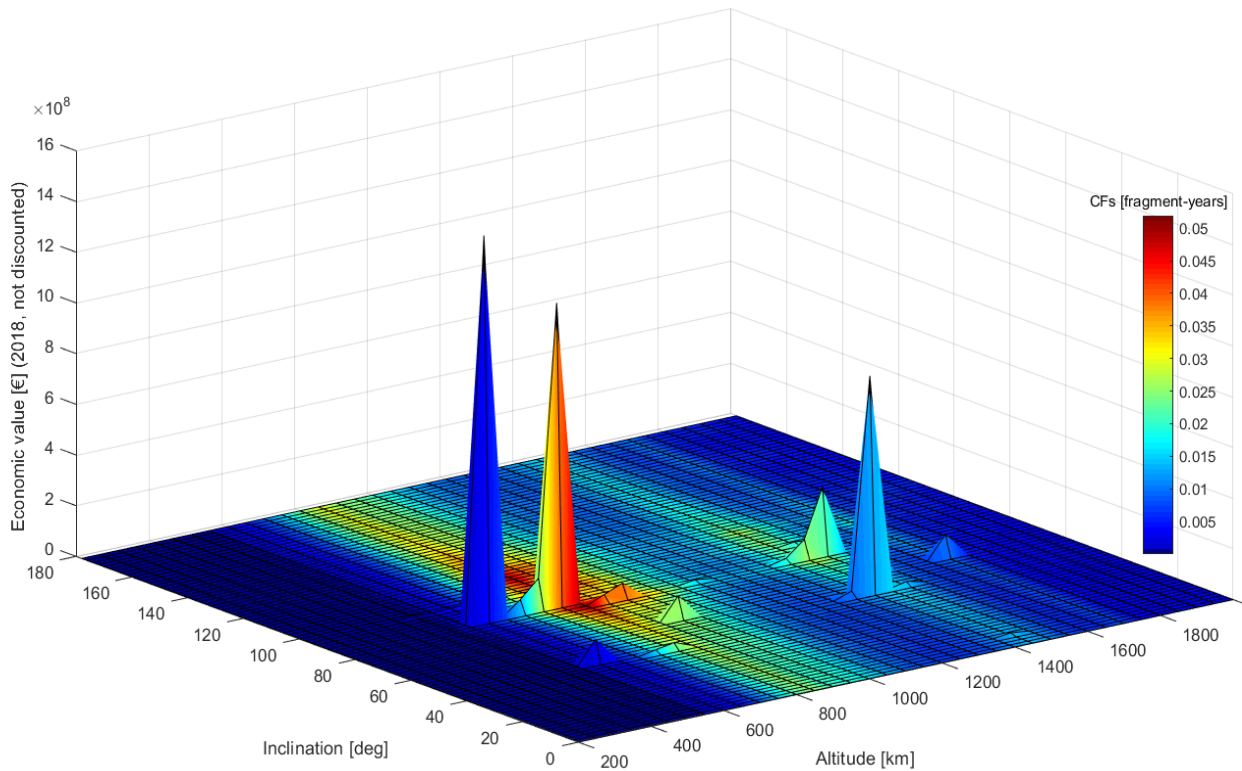


Figure 6.7 – Communication: Downstream segment estimated revenue for 2018 against potential *degradative use* impact. Most critical regions are the ones combining high potential impact and high economic efficiency

We observe a critical area at [800 km; 86°] corresponding to Iridium 1<sup>st</sup> generation. It is not the case for Iridium Next [600; 86°] km. Since the new constellation orbits at lower altitude, the drag compensates the potential degradative use of the resource which explains the low CF value (less than 0.01 fragment-years). However, it generates as much revenue as Iridium 1<sup>st</sup> generation. At high altitude, in the orbital band around 1 400 km, the potential impact generated is higher (CFs value  $\sim 0.02$  fragment-years) as there is no renewability of the resource due to the drag. Nonetheless, the economic importance of those areas is less critical.

### 3.3. Earth observation: economic valuation against degradative use impact

Similarly to communication satellites, Figure 6.8 depicts the critical region for Earth Observation.

The most important region in LEO regarding the economic value generated is the SSO (inc.  $98^\circ$ ). The potential impact is particularly high in the orbital band between 750 and 1 000 km. Thus, critical orbital cells are encompassed in this region particularly at 800, 700 and 850 km where the economic value generated is respectively 3 328, 2 237 and 1 127 M€ while the CF values raise 0,04; 0,02 and 0,045 fragments-year. Also, the orbital cell at [1 000 km;  $64^\circ$ ] is considered as critical with an economic value of 3 251 M€ and a non-negligible CF value around 0,025 fragment-years.

Conversely, the orbital cell at [500 km;  $98^\circ$ ] which generates the highest economic value in LEO (i.e. 4 236 M€) does not seem to expose to a particular impact thanks to its low altitude.

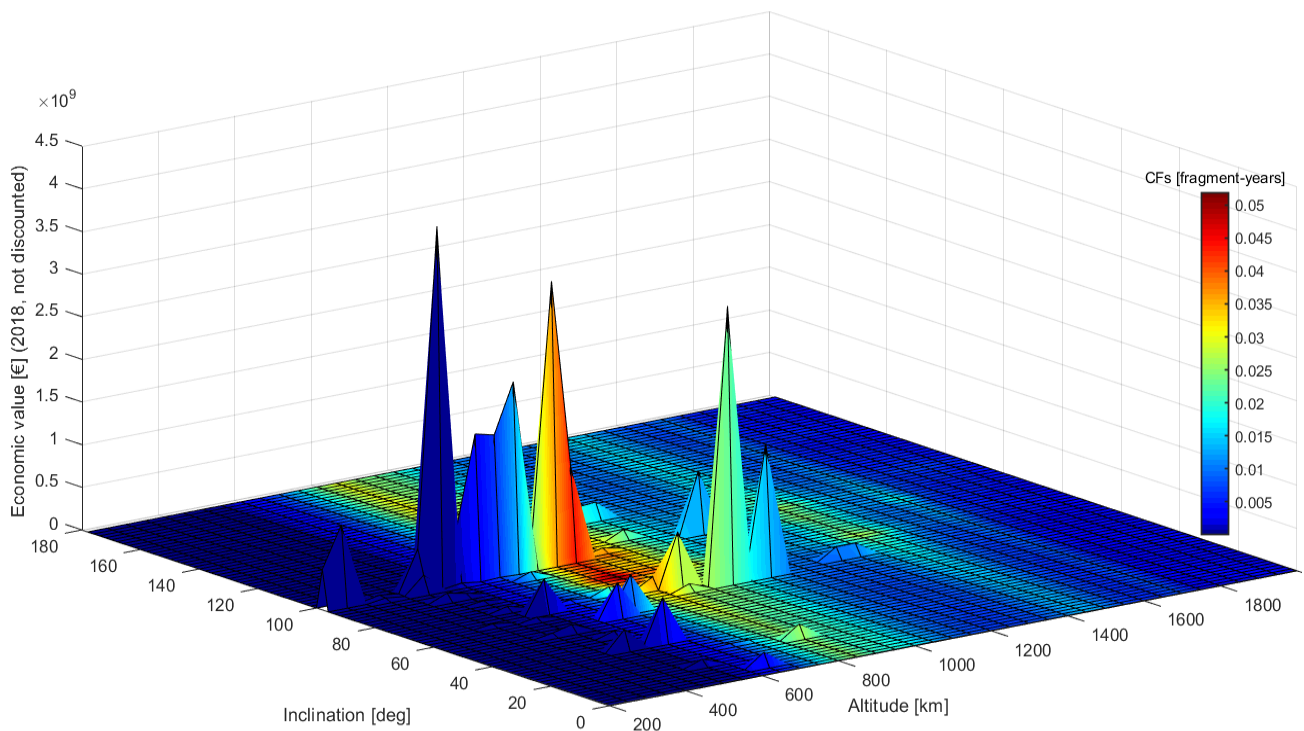


Figure 6.8 – Earth Observation: Estimated benefits for end-users against potential *degradative use* impact. Most critical regions are the ones combining high potential impact and high economic efficiency

## 4. Discussions

### 4.1. Discussion on the results: economic valuation against degradative use impact

The superposition of the estimated economic value and the CFs value for each orbital cell is a first attempt to evaluate the complete criticality state of each orbital cell. Because space is wide, we can see that only a small number of orbital cells generate economic value, among which some are exposed to a high potential impact.

The benefits for end-users provided by EO services are more important than the one focusing on the downstream segment for communication in LEO. Besides, the orbital cells targeted by the EO services face a potentially high impact, particularly in the SSO region. The most critical cell for communication satellites is the one of Iridium 1<sup>st</sup> generation. However, as this constellation is currently reaching its end-of-life, the economic importance of this orbital cell will decrease over time.

Going further, we identified orbital cells of primary economic importance that do not experience high impact scores for the CFs. It is the case for [500 km; 98°] and [600; 86°]. This result reinforces the idea of the particular nature of naturally-compliant orbits targeted in priority by the operators of mega-constellations. It refers to the *consumptive use* defined in Chapitre 3. In the next decades, the orbital cells at low altitude could be favoured because they allow maximising the profit. Because they allow a natural decay within the 25-year interval, no management of the post-mission disposal by operators or particular effort to ensure a high level of reliability is expected. This could lead to a competition between operators for access to this particular orbital resource.

### 4.2. Limitations of the economic valuation

#### 4.2.1. Validity of the assumptions

**Communication satellites.** We acknowledge that the assumptions to estimate the current economic value of communication satellites are debatable. First, we do not take into account the age of the satellite: we could expect that Iridium Next generates more revenue per kg than the previous system which is reaching its disposal. Moreover, we based our analysis on the Iridium company revenue, the current leader in the market. Commercial companies own the majority of the communication satellites. We applied the same growth rate (based on Iridium Corporation) for all these companies but also to non-commercial systems to estimate the revenue in 2018. However, the economic performance of each firm differs largely as highlighted by Figure 6.9.

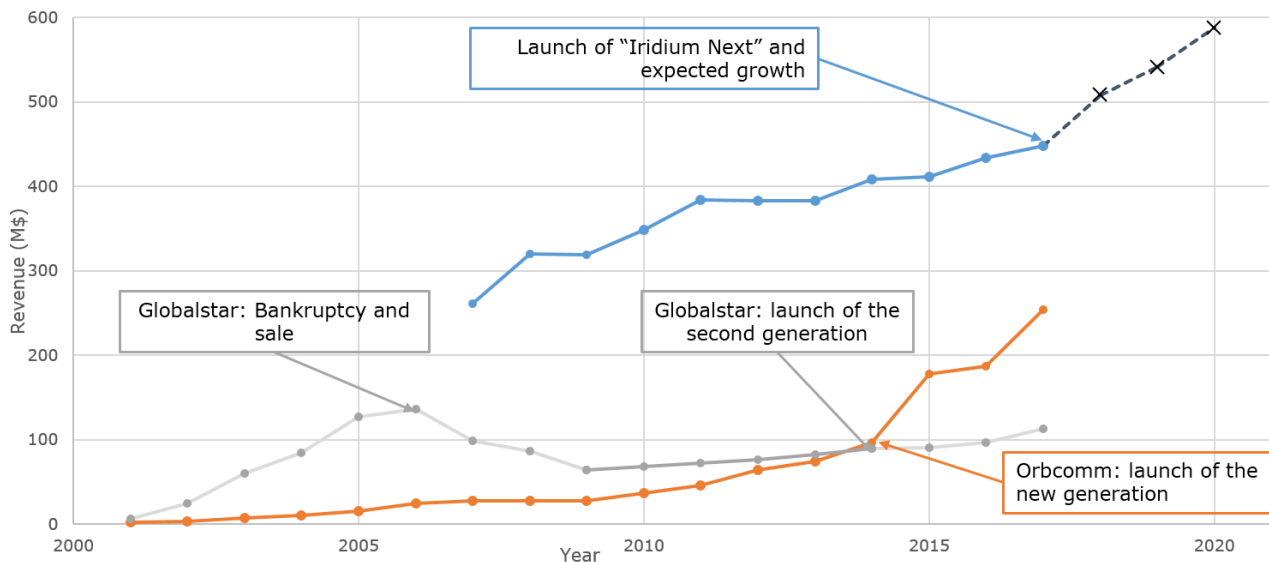


Figure 6.9 – Revenues growth of the three leading commercial communication companies (Midstream segment) in LEO. Data retrieved from YCharts database

We adopt mass criteria to extend the revenues to the whole population. It could be considered as a proxy to represent the performance of the satellite. Nonetheless, the approach is simplistic as it does not catch the miniaturisation process occurring in the space sector (Sweeting, 2018). Finally, to extend the benefits from midstream to downstream segment we assume that 80% of the revenue is generated by the downstream segment (PwC, 2018). Those two elements used as a proxy for this valuation could be refined in further research.

**EO satellites.** We based our study on the ex-ante benefits provided by the Copernicus system (PwC, 2017). The report acknowledges a certain level of uncertainty on the outcomes, providing an order of magnitude of impacts rather than an accurate quantification. There is currently scarce information on the benefits of Copernicus for end-users (i.e. case studies; demonstration of benefits; etc.).

While the “quality score” used for EO seems more relevant than the mass criteria used for communication, data are available for a limited number of EO satellites. The statistical study used to predict the quality score of satellites with a limited number of parameters should be considered as a first attempt that could be greatly improved. Indeed, the correlation coefficient “R-squared” reaches 0.45, meaning that high uncertainties are associated with the model. The model assumes that the correlation with the parameters is linear and that there is no dependence between one another. However, dependencies between those parameters, e.g. the age and the mass, the mass and the altitude, the goal of the mission and the altitude, could have been accounted for by including interaction terms between these variables (non-linear correlation).

The economic value computed for the year 2018 is maximised because it is based on the Copernicus system which is one of the most advanced observation systems available stem from the latest EO satellite generation. Also, the open access policy of this system represents direct positive spillovers for the end-users, which is not the case for all EO systems. Nevertheless, the Copernicus system is still in the early-phase of development, and the benefits for society will be better comprehend – and therefore quantified – in the next years.

#### 4.2.2. Completeness of the valuation

In this study, we only characterise orbital cells of the LEO region whereas other regions of the orbital environment generate substantial economic value. It is the case of the GEO ring where massive

communication satellites operate. The MEO region could also be considered since all the geo-positioning and navigation systems orbit there. Within the LEO regions, we focus our analysis on EO and communication while disregarding scientific demonstrators and technological development satellites that represent around 20% of the overall population.

The perimeter for economic valuation is not the same for EO and communication services. The end-users benefit is adequate in the frame of the quantification of economic externalities: it highlights the benefits for the whole society that goes beyond the economic sphere. This value makes sense for particular applications, i.e. climate change monitoring, where the benefits for the society are directly tangible. In such case, the availability of the data can be found or estimated as shown in the case of the Copernicus system. Dealing with commercial data provided by satellite services, economic valuation dealing with the end-users' benefit were not found as illustrated in the case of communication satellites.

This preliminary study gives an overview of the space situation for the year 2018 based on data retrieved for the year 2017 for Iridium revenue and Copernicus benefits estimation. This study does not capture the potential evolution of the situation in space in the coming decades. As previously mentioned, the space sector experiences a significant growth which should continue in the next decades. Following the approach proposed above it means that the value generated in each orbital cell is expected to increase. To estimate the future value generated a growth rate could be applied depending on the space mission.

In the case of EO satellites, the study could take into account the benefits enabled by Copernicus data & information considering the evolution of the Copernicus program until 2035 (PwC, 2017). A 'baseline scenario' is described in this study: the Copernicus program continues after 2030, including an incremental improvement of the data and service foreseen and a renewal of the EO satellite fleet. Table 6. 1 presents the growth rate computed from the data retrieved from this report.

Table 6. 1 - Copernicus estimated benefits considering a maturity phase after the initial growth. The growth rate is averaged for the periods 2017-2025 and 2025-2035.

<b>Year</b>	<b>M€</b>	<b>Growth rate</b>
2017	1 875,6 €	16,6%
2025	6 400,0 €	7,0%
2035	12 618,6 €	

It should be noted that the average growth rate for the initial period (2017-2025) is closed to the one selected above for the EO sector (15%). To apply these growth rates for the overall orbital cells, the maturity of each EO technology should be assessed similarly to what has been done with the "quality score". A "maturity score" determining the growth rate of the value in the following years could be applied.

The same procedure could be applied for communication satellites to estimate the potential growth of revenues. Broadening the scope of the study, the orbital cells where future services will be developed should be considered within the Figure 6.7. Indeed, the communication sector in LEO should evolve quickly with the arrival of mega-constellations. The internet services, which will be provided continuously to all areas of the earth, could generate a consequent additional revenue for the midstream segment, especially if it supports the Internet-of-Things (IoT) revolution. For instance, the OneWeb constellation (which is being deployed) consists in more than 600 satellites of around 200 kg in mass which should orbit within the [1 200 km; 88°] orbital cell.

Finally, limitations in predicting future growth and economic revenue lie in anticipation of internal or external events potentially affecting the space industry and its related market. The changing structure of the economy

that constantly influences the values over time represents an important challenge to maintain the reliability of the data. Regular updates with the best available data (e.g. coming from annually updated databases) should be considered. Indeed, the growth of the sector can be drastically modified by disruptive innovation, or on the contrary, financial bankruptcy linked to sectorial crisis, e.g. similar to the past bursting of the Dot-com bubble and even environmental or geopolitical constraints.

### 4.3. Integration of the economic evaluation for LCIA endpoint characterisation

Several challenges should be tackled aiming to integrate economic valuation at endpoint level in the LCIA framework. In this chapter, we evaluate the *use value*, i.e. the value of the spacecraft supported by the orbital resource. Based on this, the quantification of economic value generated by each orbital cell during a given period must be performed. In other words, cumulative revenues should be taken into account according to a relevant growth rate for each kind of mission. From there, two valuation methods could be considered:

- Adopting a mechanistic approach, the potential *loss of value* caused by a cascading collision can be addressed. This option could be based on the work of Letizia et al. (2017, 2016). The latter proposed to measure the effect of a potential break-up (i.e. the severity) by the resulting collision probability for a set of target spacecraft with the breakup fragments over time. For this, it is necessary to characterise the temporal and the geographical fate of the fragment cloud, while we only address the temporal dimension in our severity factors (SFs). It can be done estimating the evolution of the spatial density of the cloud over time. This approach allows a direct valuation of the economic damages (i.e. the economic consequences in the criticality framework).
- Another identified approach would be based on the valuation of the negative externalities similarly to what is done in LCIA with the marginal cost increase (MCI) of fossil or mineral resource extraction (Goedkoop et al., 2013b). In this way, the potential cloud of debris generated could force operators to choose a less profitable orbit. The economic loss generated by lower profitability and/or higher exploitation costs could represent potential damages at the endpoint level.

The first option can be performed by adapting current work dealing with the density-based modelling of the cloud. Even if the second option looks more uncertain, it is more in line with the current LCIA framework (Berger et al., 2019; Dewulf et al., 2015) because it considers extensive socio-economic impacts.

In addition, a deprivation aspect of the economic value performed could be applied in the frame of the *consumptive use*. A theoretical ‘congestion rate’ could be computed for each orbital cell in LEO and weighted by the associated potential revenue. The contribution of a given space mission to this ‘congestion rate’ could be calculated using a distance-to-target approach. If the orbital cell is effectively congested, the mismanagement of the mission of the post-mission disposal once the spacecraft reaches its end-of-life would correspond to deprivation in term of revenue generation for other users.

## 5. Conclusion

The work presented in this chapter is a preliminary step towards a characterisation model at the endpoint level which assesses the potential damage of orbital space use from a space object. The economic value of each orbital cell in LEO is estimated focusing on Communication and EO applications. The uncertainties dealing with the economic valuation are important and comes from the assumptions taken into account and then discussed. However, based on these results, we show that only a few orbital regions in LEO generate the majority of the economic value. The latter is mainly concentrated in the SSO regions where the potential impact related to the degradative is high within the orbital band [750; 1 000 km]. These critical orbits are the ones where the Copernicus system operates. Also, the orbital cell corresponding to Iridium 1<sup>st</sup> generation



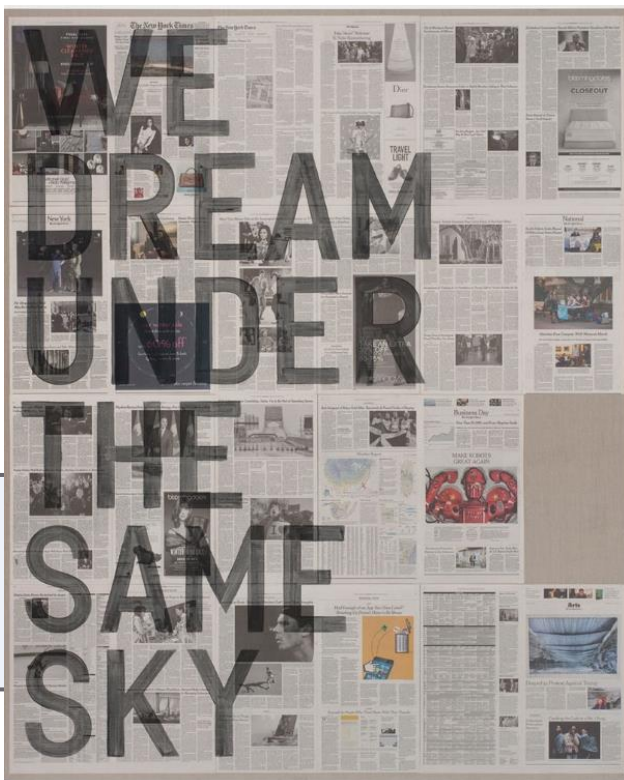
[800 km; 86°] is critical because we consider the year 2018. Nonetheless, this constellation is currently reaching its EoL that will shortly modify the revenue generated in this cell.

The future growth of the sector and the cumulative revenue in a given period should be taken into account because space debris represents persistent *stress* over time for the orbital resource. The latter is degraded by debris in the more or less long term depending on its renewability (mainly driven by the importance of the atmospheric drag effect). In parallel, the economic data must be updated regularly to ensure a fair valuation of the potential damages.

In this chapter, we demonstrate that the most important economic value for each activity (EO and communication), is generated within orbital cells below 650km, i.e. in naturally compliant orbits, where the potential impact linked to the degradative use is reduced. It highlights the need to consider the potential loss of value coming from the *consumptive use* (i.e. resource competition) in the near future.

# 7

## CONCLUSIONS AND PERSPECTIVES



Rirkrit Tiravanija, Untitled 2017

*“Ce qui est important, ce n’est, ni d’être optimiste, ni pessimiste mais d’être déterminé. »*

– Jean Monnet

## 1. General conclusions

In this chapter, it is first summarised to what extent the work of this thesis provides a consistent answer to the overall objective and the sub-objectives initially introduced. Missing aspects are further developed in the perspectives section. Also, the hypotheses formulated in Chapter 1 are tested in light of the findings of the thesis. The conclusions and perspectives chapter broadens the scope of the study in line with the following two axes: (i) the perspectives dealing with the characterisation of the orbital space use and (ii) the challenges and opportunities of applying LCA in the space industry.

### 1.1. Responses to the sub-objectives

The work done in this thesis was carried out to answer the following research question:

*How to consider orbital space use and, in particular, the impact and damage due to space debris population, in the life cycle assessment framework aiming at designing more sustainable space missions?*

This global question has been approached through our main objective, which was: to define an impact category indicator with its associated methodology regarding the integration of the orbital space use in the LCA framework and assessing the space debris related impact in particular. Six sub-objectives were established to deal with this global sustainability challenge.

The first sub-objective was to provide a detailed state-of-the-art regarding the application of LCA within the space sector. The literature review presented in Chapter 2 revealed that LCA is increasingly used to assess the environmental impact of space activities, particularly in Europe due to activities promoted by the European Space Agency. However, several methodological challenges were identified such as the need to extend the scope of space missions to cover the environmental impacts related to in-orbit phases. A special focus has been given on the space debris concern as it is a significant threat to the long-term sustainability of space activities.

The second sub-objective consisted in defining methodology for assessing the *orbital space use* of space objects during a space mission. This was developed in Chapter 3 in defining the orbital environment as a natural resource with functional value, i.e. supporting the space activities. Two distinct impact pathways were defined: a first one describing the *consumptive use* and the other one the *degradative use*. The latter covers the space debris related impacts proposing both *inside-out* and *outside-in* perspectives which are gathered in an adapted criticality assessment approach.

The third sub-objective aims at characterising the orbital environment in term of debris. In chapter 3 we focused on the LEO region because it is today the most critical area concentrating 75% of the orbital population in only 0.3% of the near-Earth orbital volume. The ESA MASTER-2009 model was used to describe the evolution of the density of debris in LEO. The most probable and the weighted average velocity of collision in orbit were also computed based on the outcomes of the model. Finally, the calculation of the flux of debris for the year 2018 is provided.

The fourth and fifth sub-objective are addressed in chapter 5 and deal with the creation and implementation of a characterisation model assessing the potential *degradative use* of the orbital resource. This work can be considered as the core part of the PhD thesis. A set of characterisation factors is developed considering the exposure of a space mission to space debris (outside-in perspective) and the temporal fate of the potential fragment cloud released in case of a catastrophic collision (inside-out). Then, a midpoint indicator was designed that covers the post-launch life cycle phases in orbits. It allows assessing space missions' potential

impact related to space debris on the orbital environment. A case study is proposed comparing the impact of three post-mission disposal scenarios. Going further, the results were discussed against the propellant consumption needed in each case with the purpose of addressing potential ‘burden shifting’ occurring between the Earth environment and the orbital one.

Finally, the feasibility of a characterisation of the damage caused by space debris at the endpoint level was investigated. A methodology to evaluate the economic value of each orbital cell in LEO was applied for the communication and Earth observation spacecraft which represent around 80% of the active population orbiting in LEO. This preliminary work paved the way for further research focusing on the quantification of economic consequences caused by potential debris generated after a collision. The integration of these negative externalities in the characterisation model would ensure complete coverage of the impact pathway defined into the Area-of-Protection ‘Natural Resources’.

## 1.2. Hypotheses testing

In the introduction of the thesis, we formulated three hypotheses representing a starting point of our research. These hypotheses are now discussed considering the results obtained.

- **Hypothesis 1:** *LCA is an appropriate methodology to measure the environmental impact of space mission extending the conventional scope to cover in-orbit operations during the use phase and end-of-life.*

From the literature review, we identified 27 different publications showing a successful application of the LCA in the space sector. It demonstrates that LCA is a worthy methodology in the environmental evaluation of space activities recognised by both space agencies and industrial stakeholders. In Europe, a consistent methodological framework has been established by the European Space Agency. However, LCA development in the space sector is not straightforward, mainly regarding the completion of the LCI phase where the collection of foreground data is a key element and a current challenge. Also, methodological gaps related to the complete environmental impact assessment of space mission were identified: (i) characterisation of the atmospheric impacts during the launch phase and the atmospheric reentry, (ii) marine ecotoxicity linked to the end of life of the launchers’ stages, (iii) impacts occurring in the orbital environment during post-launch phases.

Besides, LCA offers a holistic evaluation that can be combined with a risk assessment (RA) approach. On the one hand, LCA and RA can be carried out separately and then their results can be used in a complementary way using multi-criteria decision analysis to convert and weigh both sets of results. On the other hand, both methodologies can be blended at different levels of integration. Combining both methodologies, as presented in Chapter 3, allows a harmonisation of the results which depend on the functional unit of the system under study. Given this context, the combination of RA and LCA seems particularly relevant in the space sector for a wide range of applications: (i) obsolescence or supply risk assessment due to environmental regulations, directives or geopolitical circumstances (e.g. REACH, CRMs), (ii) toxicity-related impacts of manufacturing processes (e.g. using engineered nanomaterials), (iii) criticality of the orbital environment, (iv) casualty risk during the atmospheric reentry.

- **Hypothesis 2:** *Impact(s) occurring in the orbital environment can be integrated into the LCA framework to identify potential burden shifting between the Earth and the orbital environment.*

In this thesis, we demonstrated that the orbital environment could be considered as a resource. The impact category ‘orbital space use’ was defined through impact pathways in line with the recommended approach regarding impacts in the AoP ‘natural resources’. A characterisation model was developed and tested.

Potential impacts calculated with this model are scaled on the functional unit and associated inventory parameter of the product system under study (see Chapter 3). Consequently, the potential burden shiftings along the overall life cycle of space mission covering the Earth and orbital environments can be identified and measured among conventional impact categories, such as toxicity, terrestrial acidification and climate change), and now also space debris related impacts. The applicative case study in Chapter 5 illustrates this statement.

- **Hypothesis 3:** *The characterisation of new environmental impact(s) in LCA brings ways of improvements to ensure more sustainable space missions.*

The need of consistent metrics in sustainability assessment can be described as follows (Meadows, 1998): “*indicators arise from values (we measure what we care about), and they create values (we care about what we measure)*”.

In this context, the LCA methodology can be considered as a starting point guiding eco-design efforts in a broader sustainability perspective. The thesis proved the adaptability and versatility of this methodology for the space sector.

Designing new impact indicators in compliance with the LCIA framework reinforces the evaluation of the environmental performance of the system under study. In the frame of this thesis, space debris was identified as the main stressor of the orbital environment threatening the long term sustainability of space activities. The potential contribution of a space mission was quantified through simple metrics, allowing its assessment from the preliminary design phases. In this way, the design of the space systems can be modified at an early stage ensuring more efficient systems. Thus, the integration of the *orbital space use* in the LCIA framework enables to measure (and then reduce) the resource intensity factor (T) mentioned in Chapter 1, considering the orbital resource in addition to the conventional ones, such as land, water and abiotic resources.

## 2. Perspectives

### 2.1. Towards a complete characterisation of the impacts related to orbital space use

Limits of the developed characterisation model to assess degradative use in LCA are related to the completeness of the scope and the scientific robustness of the model. They require the following further developments:

- The severity factors (SFs) developed in Chapter 5 should be refined. The model considers systematic catastrophic collisions. Non-catastrophic and catastrophic collisions should be characterised following the relationships given by Krisko (2011). In this way, the flux of debris encountered by the satellites (exposure factors) 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 often reaches an sufficient energy-to-mass ratio to provoke 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 manoeuvres that should be taken into account.
- The CFs focus only on the temporal fate of the cloud. A density model of the cloud should be considered to evaluate potential cascading collision (Frey et al., 2019; Letizia et al., 2017).
- Only the LEO region is covered by the characterisation model developed. Since GTO are non-circular orbits, the characterisation model must integrate the eccentricity as an additional orbital parameter to characterise this orbital regime. In case of break-up, the prediction of the fate of the fragments appears challenging (Frey et al., 2018). Furthermore, the sustainability of the GEO ring needs further investigations due to recent break-ups (NASA, 2018). The MEO region which hosts the geo-positioning and navigation systems should also be studied because no particular space debris mitigation (SDM) requirements target this orbital regime.

However, several opportunities of development were listed in the thesis chapters:

- The estimation of a carrying capacity based on a political consensus about SDM requirements would allow normalising each contribution. This emerging concept is proposed by Krag et al. (2018, 2017). Other thresholds could be envisaged based on physical or social optimum.
- The *consumptive use* of the orbital resource and associate resource competition would deserve further research in the light of the current debates on space traffic management scenarios (Jah et al., 2017) and revisions of the orbital debris guidelines provided by the Federal Communications Commission (FCC, 2018). A “consumption-to-availability” ratio could be developed for the orbital regimes of interest (e.g. the GEO region), similar to what has been done in the frame of water use assessment (Loubet et al., 2013; Pfister et al., 2009).
- The feasibility of assessing the potential economic damages caused by space debris was demonstrated although further development is needed. Anticipating the future economic growth of the sector seems a crucial point to ensure a consistent valuation of the orbital resource. The additional cost in access to the resource similar to a marginal cost increase (Goedkoop et al., 2013a), or an assessment of the potential loss of value considering negative externalities seems to be relevant options to extend the characterisation model of *degradative* and *consumptive use* at the endpoint level.

### 2.2. LCA for space applications: challenges & opportunities

The challenges and opportunities related to the LCA application in the space sector were widely described in chapter 2. Several key elements are detailed hereafter following the structure of the LCA framework.

- **Goal and Scope:** LCA can be applied to emerging space systems. The case of the mega-constellation is seen as a *game changer* in space activities. The industrialisation of the space systems with the increase of

the production rate could allow a broader deployment of the LCA practices in the sector. Assessing the potential impacts on the orbital environment of this kind of space systems appears to be of prime necessity (Bastida Virgili et al., 2016; Liou et al., 2018). Also, the hybrid systems activities could be a relevant case study merging in the same perimeter LCA of both space and terrestrial activities. For instance, the environmental performance of drone or airborne imagery integrated into high-resolution satellite remote sensing can be performed as suggested by Durrieu and Nelson (2013). Hybrid telecommunication systems could be envisaged (Faulkner et al., 2015).

- **Functional unit:** The functional unit of a space mission suggested by ESA (ESA LCA Working Group, 2016) is “*one space mission in fulfilment of its requirements*”. The definition may integrate the evolution of future space debris mitigation requirements. More particularly, the post-mission disposal success rate (related to the reliability of the system) is a highly debated requirement dealing with the impact on the orbital environment (Bastida Virgili et al., 2016; Letizia et al., 2018b; Liou et al., 2018; Radtke et al., 2017). The functional unit should consider a given value (e.g. 85% reliability at the end of the mission) as it could greatly influence the use phase and the EoL durations. (ESA, 2018).
- **Inventory phase:** The elementary flows dealing with the atmospheric reentry should be characterised to fully cover the EoL phase. Going further, potential future solutions could be envisaged to tackle the topic of *resource dissipation* (Zampori and Sala, 2017). The so-called ‘Design for Demise’ is currently implemented by several stakeholders of the space industry to mitigate the casualty risk on ground and so maximising the combustion of materials in the atmosphere (Trisolini et al., 2016). Consequently, limiting the dissipation in the outer space (i.e. creating debris) will lead to increase it during the atmospheric re-entry. Future design approach should allow containment of the materials during the re-entry aiming at closing the loop of materials. Regarding the launcher systems, the reusability of the upper-stage after a space mission seems a promising option to mitigate the *resource dissipation* on both orbital environment and ecosphere.
- **Life cycle impact assessment:** With an expected increase of the flight rate of space transportation in the next decades, the burdens on ozone depletion, global warming or toxicity could become critical and change the perception of ‘marginality’ associated with the contribution of space sector compared to other industries (Larson et al., 2017; Ross and Vedda, 2018). Hence, there is a need to compute the effects of space industry specific emissions, focusing on those occurring within the ozone layer or the stratosphere where the chemical reactions leading to environmental impacts are poorly characterised.

## On sustainability aspects of the space activities

The global environmental impact of the space sector is expected to increase because of the experienced growth driven by the emergence of innovative systems (e.g. mega-constellation or space tugs) that foster new space applications such as broadband internet services, or complete monitoring of the Earth environment. We may be on the edge of a new Space Age, launching more objects in the next five or ten years than during the first 60 years of space exploitation.

The definition of a consistent framework and appropriate metrics shared between operators, agencies and international institutions are required to adequately assess and thus enhance the whole environmental performance of space systems. Because the orbital environment is a global Common, its sustainability represents a major challenge in order to enable and develop a peaceful use of this resource for the benefit of the whole humankind. Sustainability is a cross-cutting concern which cannot be solved by a single corporation of engineers, scientists, lawyers or politicians. None of the social, economic, legislative and environmental dimensions should be left out to tackle this issue.

*Is eco-design/ sustainability for space a utopia?* This question was the topic of the introductory round table organised during the Clean Space Industrial Days in 2018. After more than three years involved in the topic, a personal answer could be that it is more than a utopia... Actually, it is an ideal for which it is worthwhile to commit, merely because it merges the two universal and infinite dimensions stated by Immanuel Kant: the starry sky above and the moral law within.





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**A**

**SPACE DEBRIS MITIGATION AND DISPOSAL  
REQUIREMENTS**

## Contents

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## 1. Overview of the space debris mitigation guidelines

Space debris is a significant, constant and indiscriminate threat to all spacecraft today. In this context, the consensus in the space industry and at national space agencies is emerging in order to ensure the feasibility of future space missions (Bonnal, 2016b). The national delegations of the Inter-Agency Space Debris Coordination Committee, founded in 1993, published the first “IADC Space Debris Mitigation Guidelines” in October 2002, which were revised in 2007 (IADC, 2007). According to these guidelines, operators of space missions must complete ‘Post-Mission Disposal’ (PMD) to ensure that the entire spacecraft or parts of a launch vehicle do not become debris. PMD includes a *passivation* process. The latter is defined as *the elimination of all stored energy on a spacecraft or orbital stages to reduce the chance of break-up* (IADC, 2007). Typical passivation measures include venting or burning excess propellant, discharging batteries and relieving pressure vessels.

Furthermore, the LEO and GEO areas are recognised as “protected regions” due to their unique nature. This means that orbit retrieval is mandatory for any spacecraft or part of launcher crossing or residing in LEO or GEO regions. In the case where objects are located in the GEO region, they have to be re-orbited far enough away from the original orbit to a graveyard orbit. In the LEO, the 25-year rule must be applied, i.e., space objects must complete a post mission disposal within 25 years after the end of the mission. A de-orbiting manoeuvre is recommended with the aim of ensuring direct atmospheric re-entry (Bonnal, 2014). In 2010, members of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) approved Guidelines for Space Debris Mitigation based on IADC Guidelines and recommendations (UN COPUOS, 2010). Also, an international standard, the *ISO 24113* (2011) dealing with space debris mitigation (SDM) requirement for space systems was published in 2011. In Europe, recommendations and guidelines for limiting orbital population are managed by the European Space Agency (ESA). The ESA’s current policy is based on the latter standard. Moreover, ESA mentions that the *casualty risk*, i.e. the probability that a person is killed or seriously injured due to the re-entry, shall not exceed 1 in 10,000 for any re-entry event, controlled or uncontrolled (ESA, 2014).

In 2008, the French National Centre of Space Research (CNES) announced the first law dealing with space debris mitigation. The French Space Operation Act (Loi n° 2008-518, Legifrance) has provided a national legislative framework for French space operators. The French Space act is directly derived from ISO 24113 and compliant with IADC and UN-COPUOS Mitigation Guidelines. Compliance with the technical regulations shall be implemented for all space operations lead by French space operators or for all operations conducted on French territory, particularly the Kourou Launch site. A 10-year transition period is foreseen (2010 – 2020), within some of the requirements may be not fulfilled (Moury, 2015). The operator shall demonstrate that best efforts have been accomplished taking into account the existing designs. After the transition period, all the requirements will be mandatory.

Figure A.1 gives an overview of the existing International, European and National guidelines published during the last decade. It presents the requirements from the most general and broad perimeter also the less restrictive (i.e. United Nations), to the most legislatively binding (i.e. The French Space Operation Act or LOS).

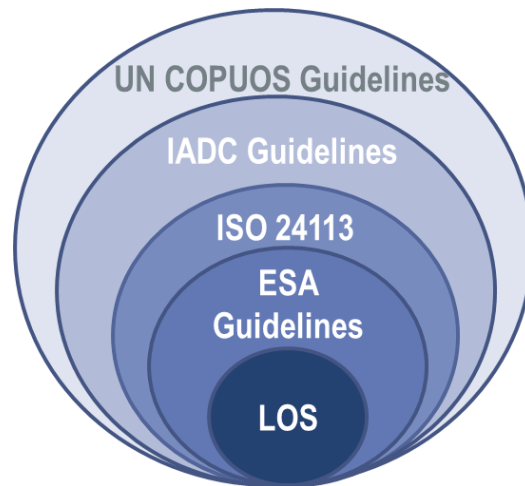


Figure A.1 – Overview of various guidelines concerning Space Debris Mitigation

## 2. Scope of application for space systems

A space system is composed of various elements included in three main categories (IADC, 2007):

- **Spacecraft (S/C):** an orbiting object, like for example satellites, designed to perform a specific function or mission (e.g. communications, navigation or Earth observation). A spacecraft that can no longer fulfil its intended mission is considered non-functional. Spacecraft in reserve or standby modes awaiting possible reactivation are considered functional.
- **Launch vehicle, or launcher (LV):** any vehicle constructed for ascent to outer space, and for placing one or more objects in outer space, and any sub-orbital rocket.
- **Launch vehicle orbital stages:** any stage of a launch vehicle left in Earth orbit.

As described in the IADC guidelines (IADC, 2014) the operational phases of a space system are the following:

- **Launch phase:** begins when the launch vehicle is no longer in physical contact with equipment and ground installations that made its preparation and ignition possible (or when the launch vehicle is dropped from the carrier-aircraft, if any), and continues up to the end of the mission assigned to the launch vehicle
- **Mission phase:** begins at the end of the launch phase and ends at the beginning of the disposal phase. The spacecraft or orbital stage fulfils its mission during this phase.
- **Disposal phase:** begins at the end of the mission phase for a spacecraft or orbital stage and ends when the space system has performed the actions to reduce the hazards it poses to other spacecraft and orbital stages

Figure A.2 refers to the ISO 24113 (2011) about space debris mitigation requirements for space systems. It shows the post life-cycle phases of an Earth-orbiting launch vehicle and spacecraft. The end of the disposal phase is the point in time,  $T_{\text{disposal}}$ , at which all disposal actions are completed. Nominally, it occurs at the end of life after the passivation process.

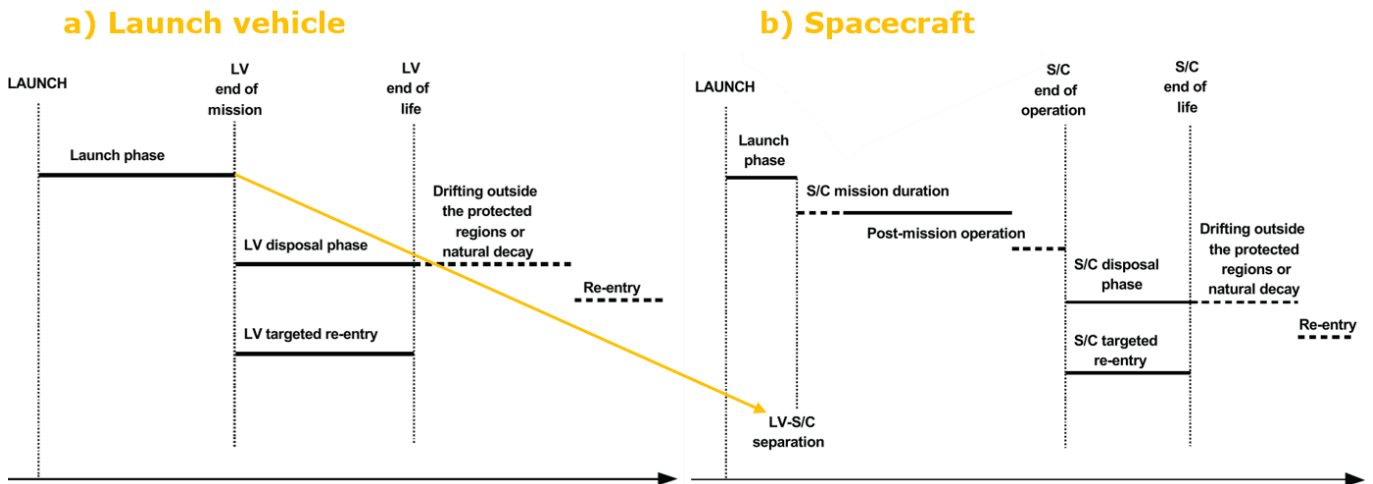


Figure A.2 – Post-launch life cycle phases of an Earth-orbiting a) launch vehicle and b) spacecraft according to the ISO 24113 (2011). The separation between the launch vehicle and the spacecraft marks the end of the mission for the launcher and the beginning of the mission for the spacecraft

### 3. Comparison of Space Debris Mitigation guidelines

Table A.1 allows comparing the various degrees of exigence concerning the Space Debris Mitigation (SDM) guidelines. According to Figure A.1, there are today a certain number of documents which enforce on different scales (International, European and National). Parts of them are only recommendations based on “the best effort” with only qualitative measures (‘should’). It is the case for the UN COPUOS and, to a lesser extent, the IADC Guidelines. By contrast, Space French Act is the first legislative text on the issue with strong quantitative requirements and a legal obligation from 2020 (‘shall’ and ‘must’). The ESA guidelines also deal with mandatory requirements within a standardised framework (ISO 24113).



Table A.1- Comparison matrix for disposal and SDM requirements (freely adapted from Antonetti, 2015)

	Prevention of break-ups (Passivation)	Disposal at LEO	Disposal at GEO	Re-entry risk assessment
UN COPUOS	<p>&gt; All on-board sources of stored energy <b>should be depleted or made safe</b> when they are no longer required for mission operations or post-mission disposal.</p>	<p>&gt; Spacecraft and orbital stages <b>should be removed from orbit in a controlled fashion.</b></p> <p>&gt; If this is not possible, they should be disposed of in orbits that avoid their long term presence in the LEO region.</p>	<p>&gt; Spacecraft and orbital stages <b>should be left in orbits that avoid their long-term interference with the GEO region.</b></p>	<p>&gt; Debris that survives to reach the surface of the Earth <b>should not pose an undue risk</b> to people or property, including through <b>environmental pollution</b> caused by hazardous substances.</p>
IADC GUIDELINES	<p>&gt; After the completion of mission operations, all on-board sources of stored energy of a spacecraft or orbital stage <b>should be depleted or safe</b> when they are no longer required for mission operations or post-mission disposal.</p>	<p>&gt; Spacecraft or orbital stages pass through the LEO region <b>should be de-orbited</b> (direct re-entry is preferred)</p> <p>&gt; The presence in LEO Region after the end of the mission <b>should be limited to 25years.</b></p>	<p>&gt; Spacecraft that have terminated their mission should be manoeuvred <b>far enough away from GEO</b> so as not to cause interference with spacecraft or orbital stage still in geostationary orbit.</p>	<p>&gt; Debris that survives to reach the surface of the Earth <b>should not pose an undue risk</b> to people or property.</p> <p>&gt; <b>Ground environmental pollution</b> should be prevented or minimised in order to be accepted as permissible.</p>
ESA guidelines - based on ISO 24113 and ESA, 2014 (IPOL)	<p>&gt; The probability of an <b>accidental break-up</b> of a spacecraft or launch vehicle orbital stage <b>shall be no greater than <math>10^{-3}</math></b> until its end of life.</p> <p>&gt; During the disposal phase, a spacecraft or launch vehicle orbital stage shall permanently deplete or make safe all remaining on-board sources of stored energy in a controlled sequence.</p>	<p>&gt; A spacecraft or orbital stage shall limit its <b>post-mission presence</b> in the LEO protected region to a maximum of <b>25 years from the end of the mission.</b></p> <p>&gt; If casualty risk <math>&gt; 10^{-4}</math>, <b>controlled re-entry compulsory is needed.</b></p> <p>&gt; The probability of successfully completing the disposal manoeuvres <b>must be at least 0,9.</b></p>	<p>&gt; A spacecraft operating within the GEO protected region <b>shall</b>, after completion of its GEO disposal manoeuvres, <b>be re-orbited sufficiently above</b> the geostationary altitude for at least 100years.</p> <p>&gt; The probability of successfully completing the disposal manoeuvres <b>must be at least 0,9.</b></p>	<p>&gt; <b>The casualty risk shall not exceed 1 in 10,000 for any re-entry event</b> (controlled or uncontrolled). If the predicted casualty risk for an uncontrolled re-entry exceeds this value, a targeted controlled re-entry shall be performed in order not to exceed a risk level of 1 in 10,000.</p> <p>&gt; <b>Declared Re-entry Area</b> (99%) and the <b>Safety Re-entry Area</b> (99,999%) should be computed</p>

<p><b>French Space Operation Act</b></p>	<ul style="list-style-type: none"> <li>&gt; The probability of occurrence of accidental break-up <b>must be less than <math>10^{-3}</math></b> until the end-of-life of the object</li> <li>&gt; All the on-board energy reserves are <b>permanently depleted</b> or placed in a state such that depletion of the on-board energy reserves is inevitable, or in such a condition that they entail no risk of generating debris;</li> <li>&gt; All the means for producing energy production means are <b>permanently deactivated</b>.</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Post-mission presence in the LEO protected region is limited to a maximum of 25 years from the end of the mission</li> <li>&gt; For a controlled reentry, a probability lower than or equal to <math>2 \cdot 10^{-5}</math> of there being at least one victim is required.</li> <li>&gt; If a controlled re-entry is not possible (appropriate justification is required), best efforts to comply with an objective of <math>10^{-4}</math> are required.</li> <li>&gt; The probability of successfully completing the disposal manoeuvres <b>must be at least 0,9</b>.</li> </ul>	<ul style="list-style-type: none"> <li>&gt; A spacecraft operating within the GEO protected region shall, after completion of its GEO disposal manoeuvres, <b>be re-orbited sufficiently above</b> the geostationary altitude for at least 100years.</li> <li>&gt; The probability of successfully completing the disposal manoeuvres must be <b>at least 0,9</b>.</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Controlled reentry: <math>&lt; 2 \cdot 10^{-5}</math></li> <li>&gt; Uncontrolled reentry : <math>&lt; 10^{-4}</math></li> <li>&gt; Determination of the <b>impact zones</b> of the stages, the space vehicle and the surviving debris, with a confidence level of 99% and 99.999% is needed</li> </ul>
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## 4. End-of-life scenarios

Focusing on the end-of-life of space objects, several scenarios directly linked to the kind of space mission can be established. Figure A.3 provides a global overview of all the end-of-life possibilities for a satellite or an upper stage. Both protected areas crossed by space objects, i.e. GEO and LEO, are included. Inside each area, the fact that satellite could be manoeuvrable or not is taken into account and has a strong influence on end-of-life possibilities. Reliability is also an important parameter: some of manoeuvrable objects will not be able to perform compliant disposal due to technical failures or a lack of available fuel.

Each option has to be confronted with the Space Debris Mitigation guidelines (see §3). These requirements directly influence the EoL scenarios. Four possibilities can be addressed for the end of life of a space object:

- In the case of controlled re-entry (deorbit scenario): we assist on a partial demisability of the materials into the Earth's atmosphere. A safety re-entry has to be determined for the fall into the ocean.
- In the case of uncontrolled re-entry (deorbit): we assist on a total demisability of the materials after a passivation step.
- In case of reorbitation scenario, the object is moved after a passivation step, into a graveyard orbit out of the protected area during at least 100 years.
- In case of presence into a protected area during more than 25 years, the object becomes a debris. If the hazard is very high for other space objects, an Active Debris Removal (ADR) manoeuvre could be envisaged. The latter option is out of the scope of the thesis due to its non-mature state.

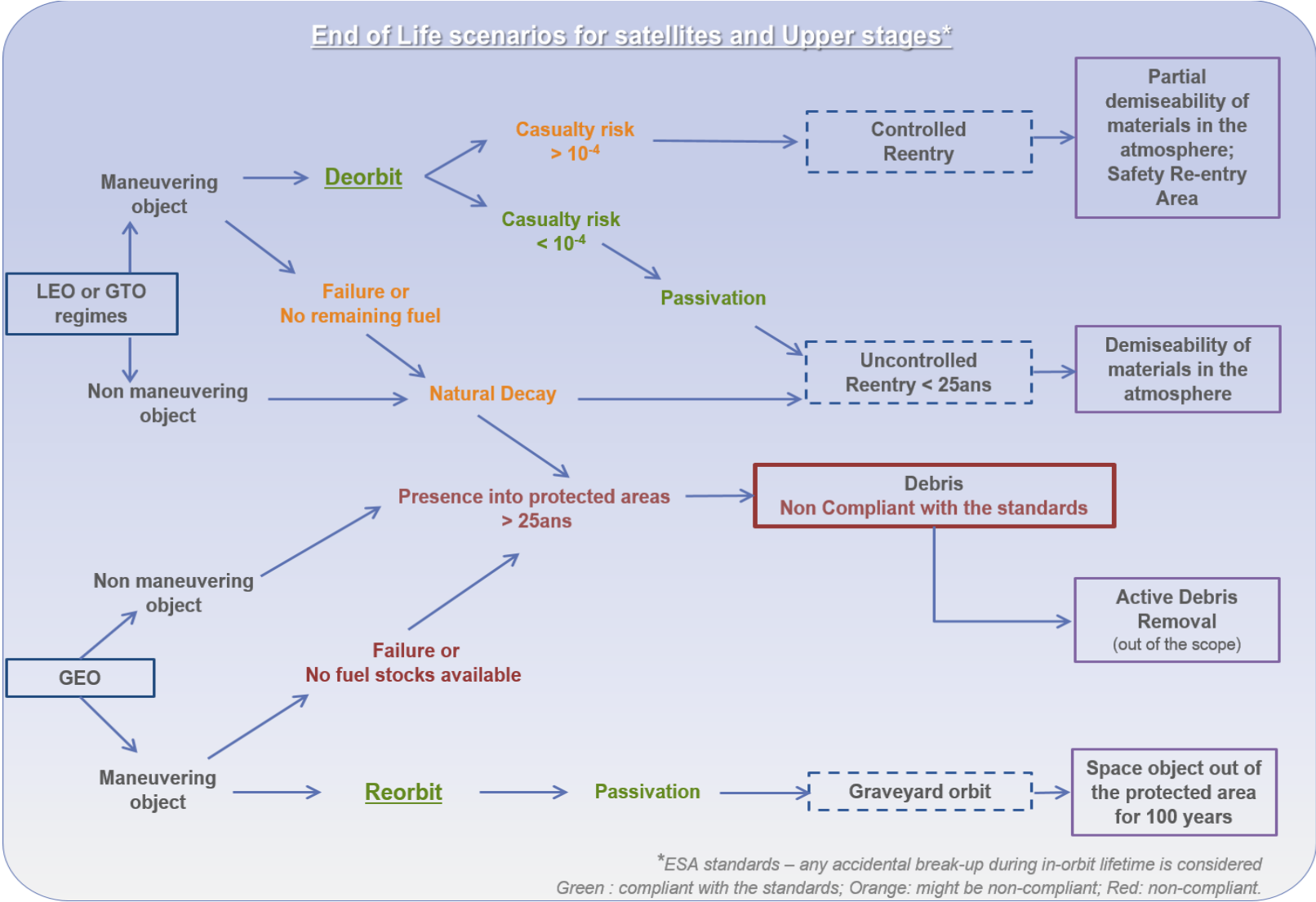


Figure A.3 – End of Life scenarios for satellites and Upper stage



**B**

**KEPLERIAN ELEMENTS & TRAJECTORY  
MODELLING**

## Contents

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## 1. Keplerian orbits

### 1.1. Definition of Keplerian elements

According to Kepler, an object which orbits the Earth travels on an ellipse (or on a circle as a special case), with the Earth's centre of mass in one of the two foci. In a classical two-body system, six Keplerian elements are used to identify a specific orbit uniquely. These parameters are presented in Figure B.1 – Representation of Keplerian elements (according to Wikipedia). In our case, the orbital plane intersects the Earth's equatorial plane (i.e. the reference plane). The intersection is called the line of nodes, as it connects the centre of mass with the ascending and descending nodes. The reference plane, together with the vernal point ( $\Upsilon$ ), establishes a reference frame Figure B.1 and described hereafter.

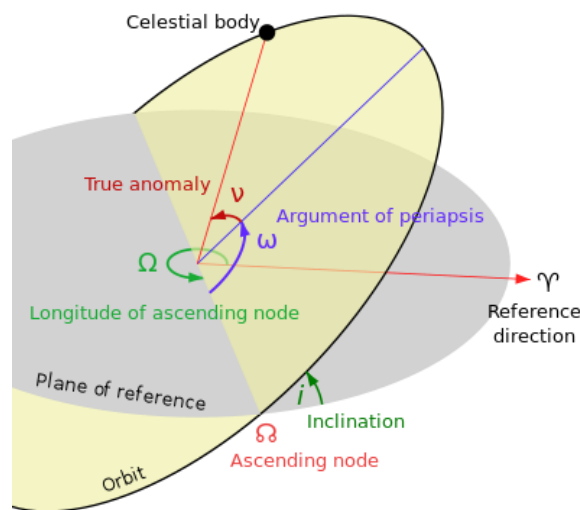


Figure B.1 – Representation of Keplerian elements (according to Wikipedia). In our case, the orbital plane intersects the Earth's equatorial plane (i.e. the reference plane). The intersection is called the line of nodes, as it connects the centre of mass with the ascending and descending nodes. The reference plane, together with the vernal point ( $\Upsilon$ ), establishes a reference frame

A planar, unperturbed 2-body Kepler motion can be described by the following Keplerian elements:

- **Eccentricity ( $e$ ):** the shape of the ellipse, describing how much it is elongated compared to a circle (not marked in Figure B.1). The eccentricity of an ellipse which is not a circle is greater than zero but less than 1.
- **Semi-major axis ( $a$ ):** the sum of the perigee and apogee distances divided by two (not marked in Figure B.1).
- **True anomaly ( $\nu$ ):** angle defining the position of the orbiting body along the ellipse at a specific time
- **Inclination ( $i$ ):** angle between the orbital and the reference plane, i.e. the equatorial plane plane
- **Right ascension of the ascending node ( $\Omega$ ):** angle defining the horizontal orientation of the ascending node (where the orbit passes upward through the equatorial plane) with respect to the reference frame's vernal point.



- **Argument of perigee ( $\omega$ ):** angle defining the orientation of the ellipse in the orbital plane, measured from the ascending node to the perigee.

## 1.2. Case of circular orbits

As seen above, the initial position of an object orbiting around Earth can be defined with the following parameter:  $\{e_0, a_0, i_0, \Omega_0, \omega_0, \nu_0\}$ .

Into the LEO region, the vast majority of objects adopts a casi-circular orbital regime (Alessi et al., 2018). It means that the eccentricity parameter is close to 0. In such case, the relative velocity of the object is constant, only dependent on the standard gravitational parameter  $\mu$  (constant) and the radius  $r$  of the orbit with  $r=a$ . There is no perigee nor apogee: the semi-major axis parameter is equal to the radius. Thus, the argument of perigee  $\omega$  is not a relevant parameter and the altitude ( $h$ ) is given by  $h = r - R_E$  where  $R_E$  is the average equatorial radius of the Earth.

Consequently, the position of latter object becomes:  $\{e_0 \approx 0, h_0, i_0, \Omega_0, \nu_0\}$ .

## 1.3. Orbit determination in MASTER-2009 model

The goal of our work is to characterise casi-circular orbital regimes into the LEO region. As we focus on the shape of the orbit and not on precise positioning of the orbital object at a specific time, the true anomaly  $\nu$  is not taken into account. Also, we assume an eccentricity  $e$  equals to  $10^{-3}$ , and an argument of perigee  $\omega$  equals  $0^\circ$  (which in this case does not influence due to circularity).

Dealing with the Right Ascension of the Ascending Node  $\Omega$  (RAAN), its variation influences the characterisation of the orbital shape even in the case of a case-circular regime. However, the MASTER-2009 model averages the value of the flux with regard to the RAAN variation for a given Semi-Major Axis (SMA), inclination and eccentricity as shown in Figure B.2. Therefore, the RAAN can be fixed according to an arbitrary value without affecting the value of the flux. In our case, the RAAN was chosen at  $180^\circ$ .

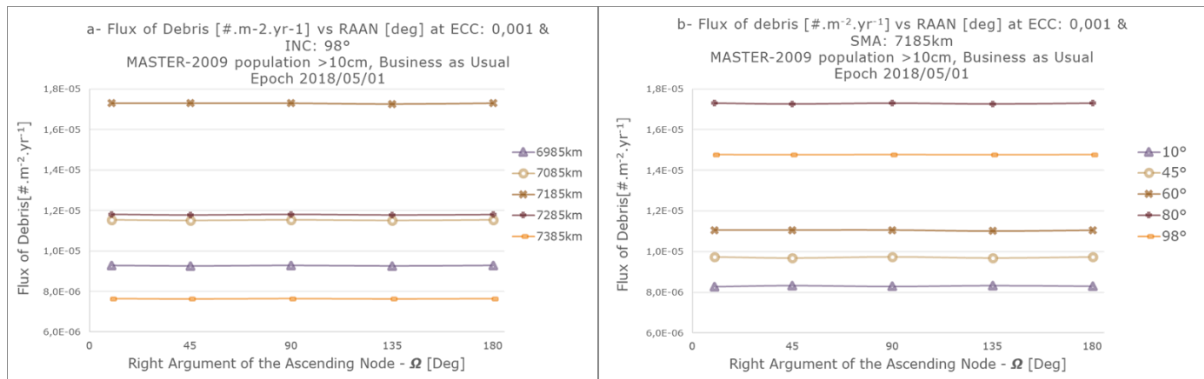


Figure B.2– Flux of debris calculated with MASTER-2009 model wrt RAAN variation for (a-) several semi-major axes and (b-) several inclination grades. No variation is observed for the value of the flux because the latter is averaged according to the RAAN.

To differentiate the orbits in the LEO region, only altitude and inclination are taking into account, the other Keplerian elements are fixed-parameters. Giving these assumptions, the shape of a given orbit  $i$  is characterised as follows:

$$orbit_i = \{h_i, i_i, e = 0.001, \Omega = 180^\circ, \omega = 0^\circ\}$$

## 2. Trajectory modelling

### 2.1. Orbital propagation

The path of an orbiting object evolves during its whole life cycle. During its mission phase, a satellite (if manoeuvrable) can modify its trajectory thanks to a propulsion system. It allows maintaining the same orbital position during the whole time of its mission. The propulsion system can also be used to realise collision avoidance manoeuvre with debris. Generally, this kind of manoeuvre is envisaged each time that the accepted collision probability level becomes higher than  $10^{-4}$  between the targeted spacecraft and a debris element.

Once the typical orbit of the mission is known, mathematical propagation techniques can be used to predict the future positions of the object. For instance, Figure B.3 provides a simplified illustration of the variation of the dwelling time into an orbital region versus the altitude of the spacecraft.

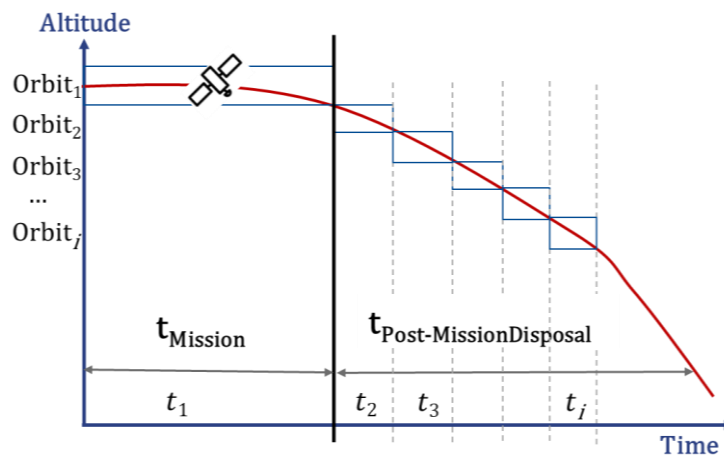


Figure B.3 – Dwelling time into orbits crossed by the spacecraft trajectory

### 2.2. Major perturbations on Earth orbits

A satellite or debris object on an Earth orbit does not strictly follow a planar, circular or elliptic Kepler orbit of constant energy and orbit momentum. Perturbing forces cause orbits to become perturbed from a perfect Keplerian orbit. Therefore, these perturbations must be characterised to ensure a realistic orbit simulation. Major perturbations on Earth orbits are listed hereafter (Klinkrad, 2006):

- **Geopotential perturbations** which are due to asymmetries in the Earth's gravitational field. To account for variations in gravitational potential around the surface of the Earth, the gravitational field of the Earth is modelled with spherical harmonics. The most important geopotential perturbation is by far the Earth oblateness (also called J<sub>2</sub> perturbation).
- **Perturbations related to the magnetic field** can also play a role. Similarly to the gravitational field, it can be expressed through spherical harmonics.
- **Third body perturbations** are due to the Sun and the Moon gravity forces (luni-solar perturbations).
- **Aerodynamic perturbations** due to atmospheric drag are considered as the main non-gravitational force acting on space objects in LEO. Drag will act in opposition to the direction of velocity in a non-conservative and energy-dissipating way. This force depends on the area-to-mass ratio of the spacecraft as well as ballistic coefficients. Also, the density of air can vary significantly in the thermosphere where most low Earth-orbiting satellites reside. The variation is primarily due to solar activity, and thus solar activity can greatly influence the force of drag on a spacecraft.

- **Solar radiation pressure perturbations** is an important source of perturbations to orbits. This force is generated by the interaction of emitted photons from the Sun, or of reflected photons from the Earth atmosphere or surface, with the satellite. Due to its dependence on the area-to-mass ratio of the satellite, the solar radiation pressure (as the atmospheric drag) is denoted as “skin force”. Depending on the solar activity level it exceeds the aerodynamic perturbation level above altitudes of 500 km to 600 km.

In addition to those environmental perturbations, the propulsive forces allow accelerating the spacecraft thanks to a propulsion system. Satellites can be transferred from an orbit to another performing a net velocity change called delta-v ( $\Delta v$ ). It is a scalar that has the units of speed. More details about delta-v calculation are given for a particular case in **Annex E**.

### 2.3. Orbital propagation tools

In chapter 5, the trajectories of the case study during the nominal mission lifetime and the post-mission disposal are propagated thanks to the Planetary Orbital Dynamics (PlanODyn) suite (Colombo, 2016). This dynamical semi-analytical orbit model allows determining the time variation of the main Keplerian orbital elements along the mission lifetime. In our case, only the altitude parameter is propagated over time. 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.

C

**VELOCITY OF COLLISION AND FLUX  
DISTRIBUTION IN LEO**

## 1. Comparison of the most probable velocity and the weighted average velocity

Figure C.1 shows the maps of the velocity of collision in orbit dealing with both approaches, most probable velocity and weighted average velocity. We observe that the 'most probable' approach overestimates the collision velocity compared to the weighted averaged velocity approach.

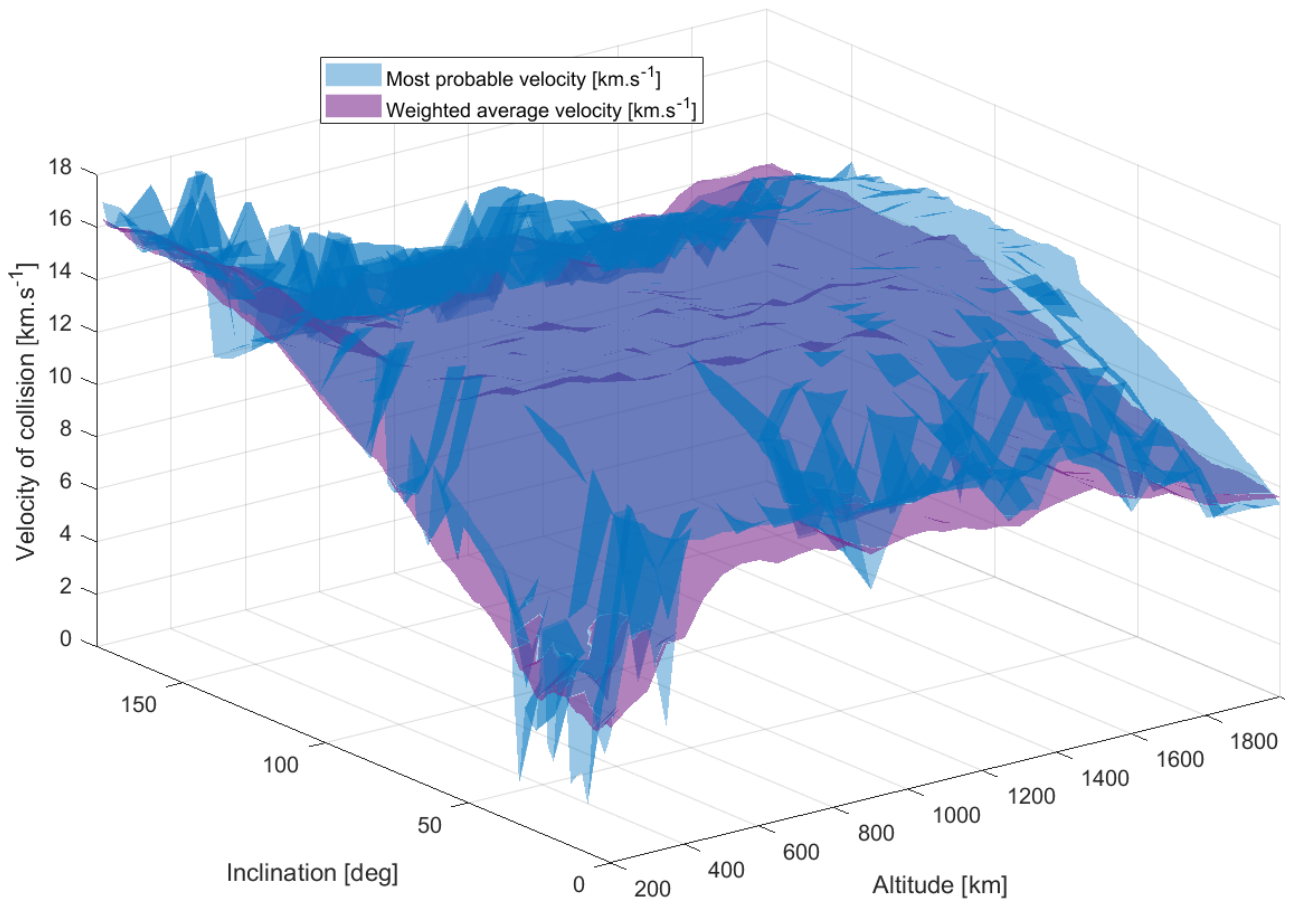


Figure C.1– Comparison of the most probable velocity and the weighted average velocity [km·s<sup>-1</sup>] of collision vs Altitude [km] and Inclination [deg] – 2018 epoch – size (m) [0.01-100] – MASTER-2009 Model, Business as Usual perspective

## 2. Average flux of debris in 2018 against active population coordinates in LEO

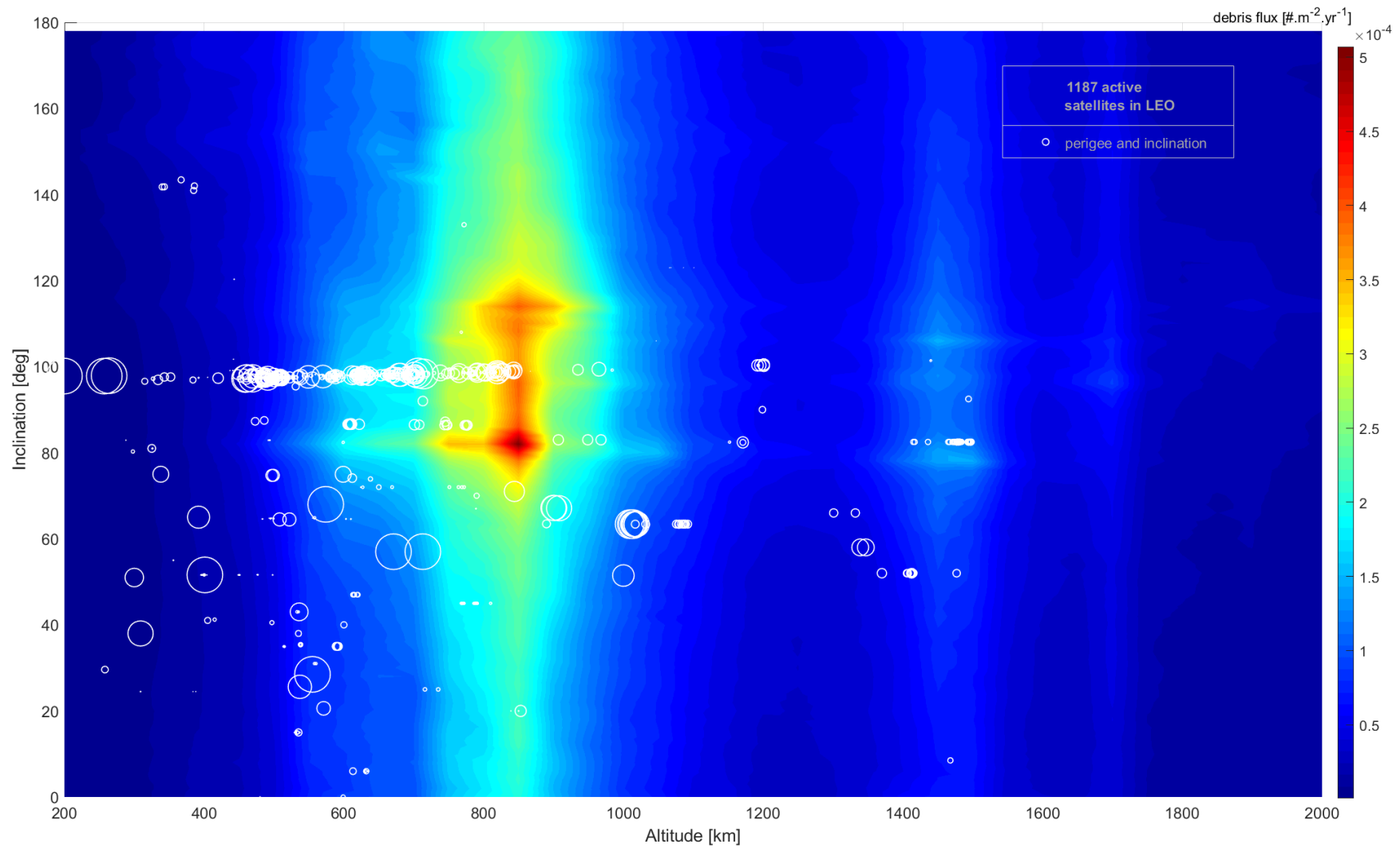


Figure C.2 – Average flux of debris against active satellite population in LEO. White circles represent active satellites with size according to their launch masses. Flux of debris computed with Master-2009 Model, epoch: 2018, size > 1cm, BAU perspective.

### 3. Comparison of the average flux of debris in 2018 and average flux over the period [2018-2053]

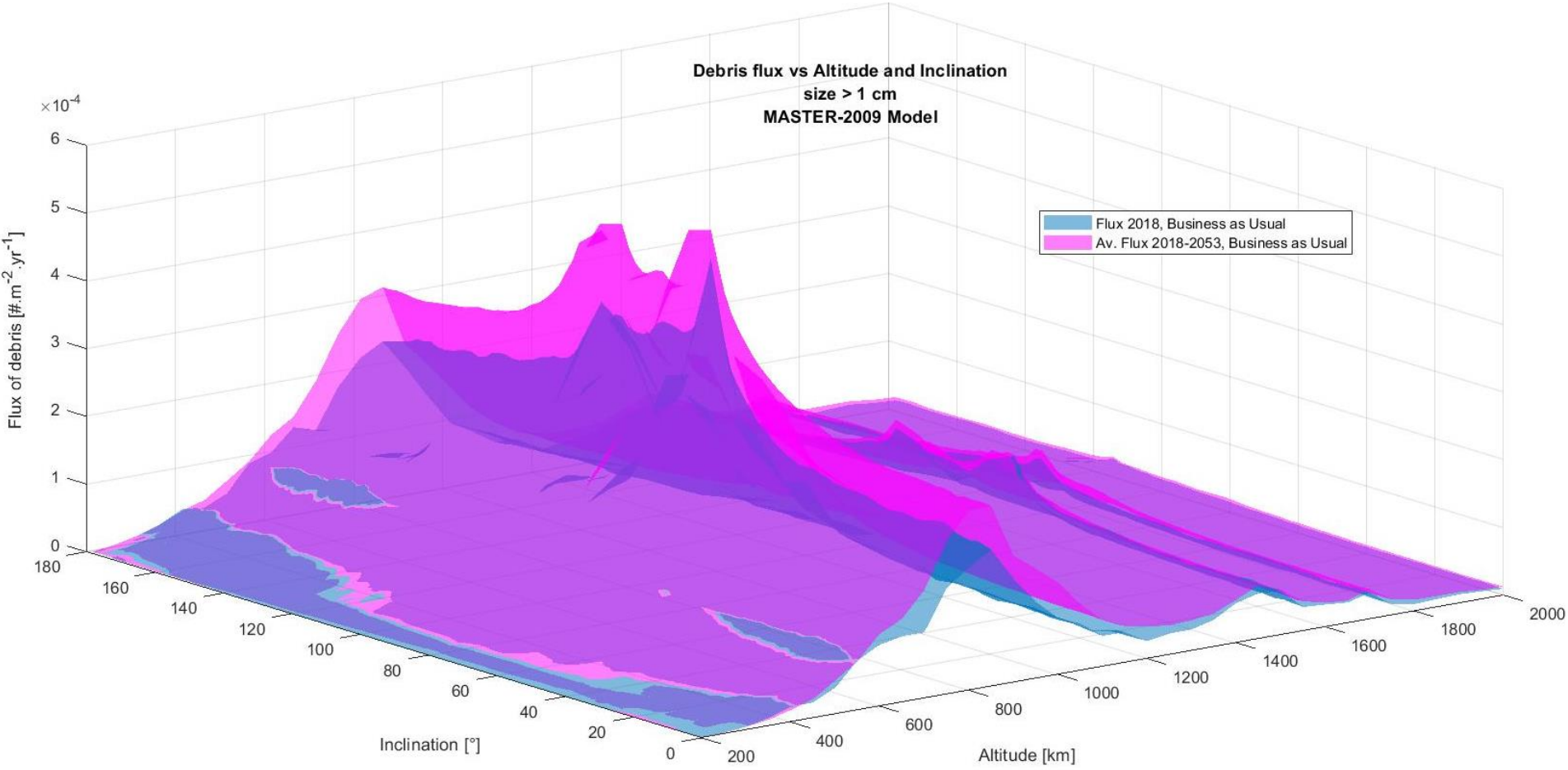


Figure C.3 - Average flux computed over the period [2018-2053] against the flux of debris computed for the year 2018. Both fluxes are obtained following a Business-as-usual perspective (MASTER model, reference year: 2009) – size > 1 cm

# D

## CALCULATION OF THE SEVERITY FACTORS & DATASETS



## CONTENTS

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## 1. Survivability of the cloud of debris over time

According to Krag et al. (2018, 2017), the percentage of the fragments  $> 10\text{cm}$  released from an altitude  $h$  (km) still on orbit after a given time  $t$  (yrs) can be modelled by:

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

The results are given in Figure D.1 and detailed in Table D.1.

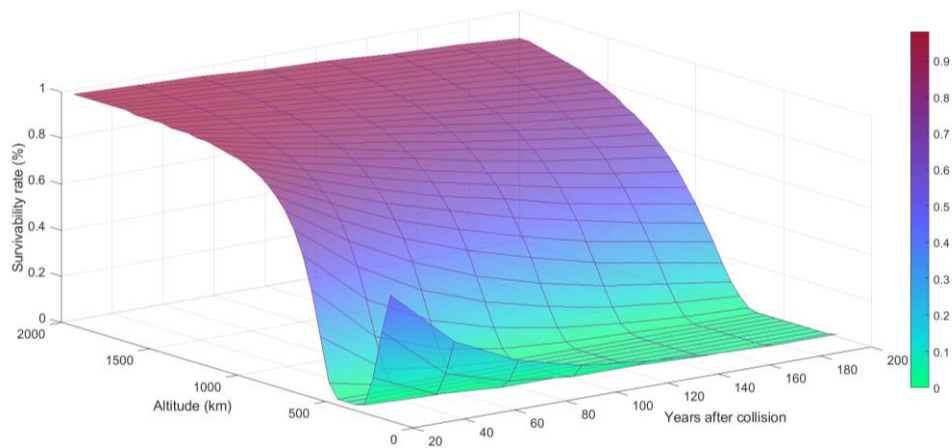


Figure D.1– Fraction of the debris still in orbit according to the initial altitude of the cloud and after a given period

As highlighted by Figure D.1, the model is valid for altitudes from 450 km (minimum survivability rates) to 2.000 km (maximum survivability rates). The values corresponding to 450 km is then applied for altitude above to extend the characterisation domain until 200km.

Table D.1 – Fraction of the debris still in orbit according to the initial altitude of the cloud and after a given period

Alt. (km)	Time after the break-up (yr)							
	200	175	150	125	100	75	50	25
200	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
250	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
300	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
350	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
400	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
450	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
500	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
550	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06
600	0,00	0,00	0,00	0,00	0,00	0,02	0,06	0,25
650	0,00	0,00	0,01	0,02	0,04	0,09	0,19	0,44
700	0,01	0,02	0,04	0,07	0,12	0,20	0,34	0,58
750	0,05	0,07	0,10	0,15	0,22	0,32	0,47	0,68
800	0,10	0,14	0,18	0,24	0,32	0,43	0,57	0,75
850	0,17	0,22	0,27	0,34	0,42	0,52	0,65	0,80
900	0,25	0,30	0,35	0,42	0,50	0,59	0,71	0,84
950	0,32	0,37	0,43	0,49	0,57	0,65	0,75	0,87
1000	0,39	0,44	0,49	0,56	0,62	0,70	0,79	0,89
1050	0,45	0,50	0,55	0,61	0,67	0,74	0,82	0,91
1100	0,51	0,55	0,60	0,65	0,71	0,78	0,84	0,92
1150	0,56	0,60	0,64	0,69	0,75	0,80	0,86	0,93
1200	0,60	0,64	0,68	0,73	0,77	0,83	0,88	0,94
1250	0,64	0,67	0,71	0,75	0,80	0,84	0,89	0,95
1300	0,67	0,70	0,74	0,78	0,82	0,86	0,90	0,95
1350	0,70	0,73	0,76	0,80	0,84	0,87	0,91	0,96
1400	0,72	0,75	0,79	0,82	0,85	0,89	0,92	0,96
1450	0,75	0,78	0,80	0,83	0,86	0,90	0,93	0,96
1500	0,77	0,79	0,82	0,85	0,88	0,91	0,94	0,97
1550	0,79	0,81	0,83	0,86	0,89	0,91	0,94	0,97
1600	0,80	0,82	0,85	0,87	0,90	0,92	0,95	0,97
1650	0,82	0,84	0,86	0,88	0,90	0,93	0,95	0,97
1700	0,83	0,85	0,87	0,89	0,91	0,93	0,95	0,98
1750	0,84	0,86	0,88	0,90	0,92	0,94	0,96	0,98
1800	0,85	0,87	0,89	0,90	0,92	0,94	0,96	0,98
1850	0,86	0,88	0,89	0,91	0,93	0,95	0,96	0,98
1900	0,87	0,89	0,90	0,92	0,93	0,95	0,97	0,98
1950	0,88	0,89	0,91	0,92	0,94	0,95	0,97	0,98
2000	0,88	0,90	0,91	0,93	0,94	0,96	0,97	0,98

## 2. Survivability of the fragment cloud within the orbital environment

The survivability of debris into orbits is given by the integral over  $P(t, h)$  in a given interval of time, here [0:200] yrs. The polynomial part of the equation is expressed as  $\rho$  and can be considered as a constant only dependent of a given altitude in the integral.

$$\rho = 128.5 - 0.585892h + 0.00067h^2$$

$$SF_i = \int_0^{200 \text{ yrs}} e^{-\frac{t}{\rho}} = \left[ -\rho \cdot e^{-\frac{t}{\rho}} \right]_{0 \text{ yrs}}^{200 \text{ yrs}} \quad [\text{years}]$$

The results are presented in Table D. 2 Applying this equation, for a set of the time interval and given altitude.

Table D. 2 – Cumulative survivability of debris in years into orbits according to the altitude of break-up over a given period

Alt. (km)	$SF_{i,200yrs}$							
	200	175	150	125	100	75	50	25
200	0,32	0,32	0,32	0,32	0,32	0,32	0,32	0,32
250	0,32	0,32	0,32	0,32	0,32	0,32	0,32	0,32
300	0,32	0,32	0,32	0,32	0,32	0,32	0,32	0,32
350	0,32	0,32	0,32	0,32	0,32	0,32	0,32	0,32
400	0,32	0,32	0,32	0,32	0,32	0,32	0,32	0,32
450	0,32	0,32	0,32	0,32	0,32	0,32	0,32	0,32
500	2,85	2,85	2,85	2,85	2,85	2,85	2,85	2,85
550	8,73	8,73	8,73	8,73	8,73	8,73	8,71	8,24
600	17,96	17,96	17,96	17,95	17,90	17,69	16,85	13,50
650	30,50	30,45	30,32	30,04	29,39	27,92	24,60	17,07
700	45,85	45,40	44,63	43,32	41,07	37,22	30,63	19,34
750	62,62	61,16	59,04	55,93	51,39	44,74	35,02	20,80
800	79,19	76,18	72,19	66,90	59,87	50,55	38,19	21,78
850	94,47	89,61	83,56	76,03	66,66	55,01	40,50	22,46
900	107,97	101,18	93,10	83,49	72,05	58,43	42,23	22,95
950	119,63	110,98	101,02	89,55	76,33	61,09	43,54	23,31
1000	129,57	119,22	107,58	94,49	79,76	63,19	44,55	23,58
1050	138,01	126,13	113,01	98,53	82,53	64,86	45,35	23,80
1100	145,17	131,94	117,54	101,86	84,79	66,21	45,99	23,97
1150	151,27	136,85	121,33	104,63	86,66	67,32	46,50	24,10
1200	156,47	141,01	124,52	106,95	88,21	68,23	46,93	24,22
1250	160,93	144,56	127,24	108,91	89,51	68,99	47,28	24,31
1300	164,77	147,60	129,55	110,57	90,62	69,64	47,58	24,38
1350	168,10	150,23	131,54	112,00	91,56	70,18	47,83	24,45
1400	171,00	152,51	133,26	113,23	92,37	70,65	48,04	24,50
1450	173,53	154,50	134,76	114,29	93,07	71,05	48,22	24,55
1500	175,76	156,24	136,07	115,22	93,68	71,40	48,38	24,59
1550	177,72	157,78	137,22	116,04	94,21	71,71	48,52	24,63
1600	179,47	159,14	138,24	116,76	94,68	71,98	48,65	24,66
1650	181,01	160,34	139,14	117,40	95,09	72,22	48,75	24,69
1700	182,40	161,42	139,95	117,97	95,46	72,43	48,85	24,71
1750	183,64	162,39	140,67	118,47	95,79	72,62	48,93	24,73
1800	184,76	163,25	141,31	118,93	96,09	72,78	49,01	24,75
1850	185,76	164,03	141,89	119,34	96,35	72,94	49,08	24,77
1900	186,68	164,74	142,42	119,71	96,59	73,07	49,14	24,78
1950	187,51	165,38	142,90	120,04	96,81	73,20	49,19	24,80
2000	188,26	165,97	143,33	120,35	97,01	73,31	49,24	24,81

### 3. Complete set of exposure, severity and characterisation factors (CFs)

The values of the CFs supporting the study are openly available through the datasheets following this link:

[https://www.dropbox.com/s/gwcjf22h3kfu3zu/Thesis\\_Maury\\_Complete%20set%20of%20exposure%2C%20severity%20%26%20characterisation%20factors.xlsx?dl=0](https://www.dropbox.com/s/gwcjf22h3kfu3zu/Thesis_Maury_Complete%20set%20of%20exposure%2C%20severity%20%26%20characterisation%20factors.xlsx?dl=0)



**E**

**PROPELLANT CONSUMPTION**

## 1. Delta-v calculation

A simplified study addressing the potential ‘burden shifting’ between orbital and environmental impacts related to EoL management is proposed in the paper. The goal is to analyse the environmental impact of the additional Hydrazine budget allocated for the disposal manoeuvre (*deorbiting* or *reorbiting*) against the *orbital exposure* to space debris obtained for each mission profile. The delta-V budget ( $\Delta v$ ), which measures the impulse needed to perform an orbital manoeuvre, is used to determine the hydrazine mass required for the disposal through the ‘Tsiolkovsky rocket equation’ (see Eq. E1).

$$\Delta v = I_{sp} \cdot g_0 \cdot \ln \frac{m_i}{m_f} \quad \text{Eq. E1}$$

In this case, the delta-v budget can be calculated with Hohmann transfer, which moves from one circular orbit to another coplanar circular orbit via an elliptical transfer orbit. In addition, the ‘Specific Impulse’ ( $I_{sp}$ , in seconds) which is a measure of the efficiency of the spacecraft propulsion engine must be known. For Sentinel-1A, we determine a specific impulse of 221s according to manufacturer’s documentation (Thales Alenia Space, 2012). The constant  $g_0$  is the standard gravity, which is nominally the gravity at Earth’s surface and equals to  $9,81\text{m}\cdot\text{s}^{-2}$ . Finally, the dry mass ( $m_f$ ) is determined with (Panetti et al., 2014) and equal to 2003kg. Thus, the hydrazine budget needed is obtained with  $m_{\text{hydrazine}} = m_i - m_f$ , where  $m_i$  is the mass of the spacecraft with on-board propellant before completing the disposal manoeuvre.

To calculate the  $\Delta v$  related to the Hohmann transfer maneuvers, the following equation (Eq. S3 and Eq. S4) are used:

$$v^- = \sqrt{\frac{2\mu}{r_{a^-}} - \frac{\mu}{a^-}} \quad \text{and} \quad v^+ = \sqrt{\frac{2\mu}{r_{a^+}} - \frac{\mu}{a^+}} \quad \text{Eq. E2}$$

$$\Delta v = \|v^- - v^+\| \quad \text{Eq. E3}$$

$v^-$  is the velocity of the higher orbit while  $v^+$  is the velocity of the lower orbit.  $\mu$  is the standard gravitational parameter of a celestial body which is the product of the gravitational constant and the mass of the Earth. Giving  $a$  the semi-major axis and  $e$  the eccentricity,  $r_a$  defines the radius of the apogee as  $r_a = a(1 + e)$ . The results of the calculations using Eq. E2 and E3 are given in Table E.1.

Table E.1 - Delta-v budget calculated for a Hohmann transfer manoeuvre for the Delayed re-entry and the direct re-entry scenarios. No manoeuvre is performed in the frame of the no disposal management scenario.

Sentinel-1A coordinates	Delayed re-entry	Direct Re-entry
$a^-$ initial orbit (km)	7081	7081
$r_{a^-}$ (km)	7082	7082
$a^+$ final orbit (km)	7029	6784
$r_{a^+}$ (km)	7078	7069
$\Delta v$ (m/s)	23,7	152,2

## 2. Mass of hydrazine needed to perform the manoeuvre

Based on Equation E1 and the  $\Delta v$  obtained, we are able to calculate the mass of hydrazine needed. The results are presented in Table E.2. While the mass of hydrazine is estimated to 128 kg for the operating phase, the amount needed for a *delayed re-entry* and a *direct re-entry* manoeuvre is respectively 22 kg and 146 kg. The direct re-entry does not seem the most suitable option due to the dedicated mass of hydrazine closed to the total initial capacity of the spacecraft. When no PMD is performed, the consumption equals to zero.

Table E.2 - Theoretical fuel consumption linked to a 10-year mission for Sentinel-1A and its associated post-mission disposal options

Space mission	Mission duration (yr)	Mass hydrazine (kg)	% of initial propellant mass (154kg)	
Use phase	10	128	83%	
End-of-Life scenarios	EoL duration (yr)	required $\Delta v$ for EoL (m/s)	m_hydrazine (kg)	% of initial propellant mass (154kg)
No disposal management	53	0	0	0
Delayed re-entry	25	23,7	22	14%
Direct deorbiting	$\approx 0$	152	146	95%

### 3. Hydrazine inventory data

The product system consists of primary production of 64 % of anhydrous hydrazine in China, a purification step to 99 % anhydrous grade in China, before it is shipped to Europe for quality control and then transported to Kourou where hydrazine storage, handling operations, and decontamination process (purges and flush) with associated waste treatment stages are taken into account.

Most of the LCI data was collected internally at ArianeGroup by the Design for Environment team. Some datasets dealing with the handling operations at the European Space Port (Kourou, French Guiana) come from the ESA LCI database which has not been yet publicly released (Morales Serrano and Austin, 2017). Moreover, the *Ecosolvent* tool (Capello et al., 2006) has been used to perform the inventory analysis of the solvent incineration (isopropyl alcohol) during the ‘decontamination and waste treatment’ stage. The combustion of Hydrazine occurring during the mission and PMD is out of the scope: no emissions of pollutant is considered into the Outer Space. Therefore the system adopts a cradle to launch pad approach until the fuelling operation in Kourou just before the launch event.

The environmental impacts of hydrazine propellant are computed with SimaPro 8.5 (Pré Consultants, 2018). The LCIA method is ILCD 2011 midpoint+ (v1.10) (European commission-JRC, 2011b). In the frame of this simplified study, only the indicator ‘Climate Change’ is taking into account as a proxy of the whole environmental impacts. It is expressed in metric tonnes of carbon dioxide equivalent (t.CO<sub>2</sub> eq.)