Science of the Total Environment 595 (2017) 642–650

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Towards the integration of orbital space use in Life Cycle Impact Assessment

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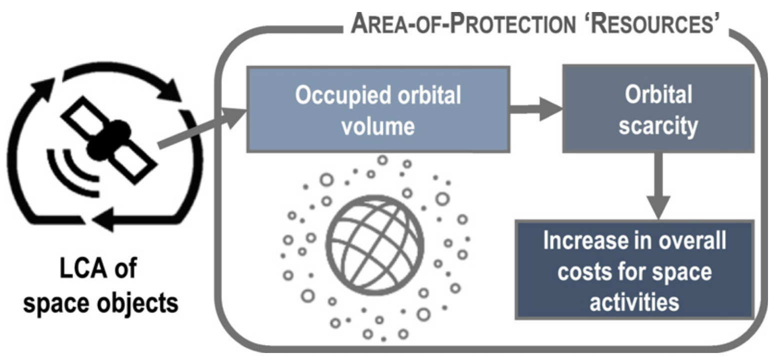
HIGHLIGHTS

- Space debris is an increasing threat to the sustainability of space missions.
- Outer space use by human-related objects is not accounted for in LCA.
- We propose a new framework to consider orbital space as a resource in LCIA.
- An impact pathway linking space mission inventory flows to potential impacts is proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 January 2017
Received in revised form 27 March 2017
Accepted 1 April 2017

Editor: Simon Pollard

Keywords:
Outer space
Space debris
Life Cycle Assessment
Impact pathway
Resource use

ABSTRACT

A rising sustainability concern is occurring in the space sector: 29,000 human-made objects, larger than 10 cm are orbiting the Earth but only 6% are operational spacecrafts. Today, space debris is today a significant and constant danger to all space missions. Consequently, it becomes compelled to design new space missions considering End-of-Life requirements in order to ensure the sustainable use of space orbits.
Furthermore, Life Cycle Assessment (LCA) has been identified by the European Space Agency as an adequate tool to measure the environmental impact of spacecraft missions. Hence, our challenge is to integrate orbital space use into Life Cycle Impact Assessment (LCIA) to broaden the scope of LCA for space systems.
The generation of debris in the near-Earth's orbital regions leads to a decrease in volume availability. The Area-of-Protection (AoP) 'resources' seems to be the most relevant reflection of this depletion. To address orbital space use in a comprehensive way, we propose a first attempt at establishing an impact pathway linking outer space use to resources. This framework will be the basis for defining new indicator(s) related to orbital space use.

1. Introduction

1.1. Current space activity

Satellites orbiting Earth are used in many areas and disciplines, including space science, Earth observation, meteorology, climate research,

Abbreviations: LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; AoP, Area-of-Protection; LEO, Low Earth Orbits; GEO, geostationary orbit.

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http://dx.doi.org/10.1016/j.scitotenv.2017.04.008
0048-9697/

telecommunication, navigation and human space exploration. They provide a unique data collection service, which leads to a wide range of possibilities for research and exploitation, both scientific and commercial. Of the 50 essential variables used to assess Earth's climate, 26 of these are only measurable using satellite technologies (Bonnal, 2016a). Observation satellites play an important role in environmental science (Fukuda et al., 2009; Tyler et al., 2016; Wu et al., 2012).

At the end of 2015, the total number of successful launches since the first artificial Earth-orbiting satellite, Sputnik, in 1957, exceeded 5000 according to the 'Space Launch Report' database. Since 2010, the average number of launches has been approximately 80 per year according to NASA (Liou, 2016). Furthermore, in June 2016, the total number of satellites operating in space orbits reached 1419 units (UCS, 2016).

1.2. Earth's orbits

The majority of operating satellites (54%) 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, between 160 and 2000 km. 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. It is mainly used for Earth observation and remote sensing satellites. The International Space Station and the Hubble Space Telescope are also both located in the LEO.

The second most important area supporting human space activities is the Geostationary Earth Orbit (GEO) region, with 36% 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 exactly 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 $\pm 15°$ in latitude encompasses the unique GEO orbit and forms the GEO region.

Between the LEO and GEO, the Medium Earth Orbit (MEO) region extends from 2000 to 35,586 km and accounts for more than 95% of the volume as reported by Johnson (2010). MEO supports the global navigation satellite networks, but includes only approximately 10% of the global orbiting satellites' population. The MEO region also holds the Geostationary Transfer Orbits (GTOs) which allow for the placement of payloads into the GEO orbit. Fig. 1 shows the main Earth's orbits and regions. The volume encompassed by these three regions (i.e. LEO, MEO and GEO) is defined as the 'useful orbital volume' for space activities.

1.3. Space debris

However, with the increasing space activities, a new and unexpected hazard has started to emerge since the 80's: *space debris*. According to the Inter-Agency Space Debris Coordination Committee (IADC), space debris are all man-made objects including fragments and elements thereof, in Earth's orbit or re-entering the atmosphere. The operating satellites presented above are only a few part of the total catalogued orbit population. Barely 6% of the overall population includes spacecraft (ESA, 2013), whereas more than 50% of all catalogued-objects in the US Space surveillance Network are fragmentation debris; approximatively one quarter of others come from Mission-related Debris and rocket bodies such as the upper stage of launchers (NASA, 2016).

The LEO is the most highly congested region in space. With only 0.3% of the useful orbital volume, it concentrates 77% of all catalogued objects (40% of the on-orbit mass) as determined by Krag et al. (2016). Consequently, some particular orbits within the LEO region called sun-synchronous orbits have the largest debris collision hazard of anywhere in the Earth's Orbit. In this kind of orbits, the annual probability of collision of a 1-cm-sized piece of debris with a 10 m^2 satellite exceeds 0,8% (Chrystal et al., 2011; Liou, 2011). The collisions occur at an average relative velocity of 14 km/s (Pardini and Anselmo, 2017). Therefore, the energy-to-mass ratio for a targeted spacecraft often exceeds 40 J/g which is considered to a 'catastrophic collision' (Liou, 2014). The outcome of a catastrophic collision is the total fragmentation of the target and therefore the failure of the dedicated space mission.

1.4. Post-mission disposal

Consequently, space debris is a significant, constant and indiscriminate threat to all spacecraft today. In this context, the general 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 'Passivation' which means the elimination of all stored energy to reduce the chance of break-up and when it is applicable an orbit retrieval.

Furthermore, the LEO and GEO areas are recognized as "protected regions" due to their unique nature (see Fig. 1, Regions A and B). This means that orbit retrieval is mandatory for any spacecraft or part of

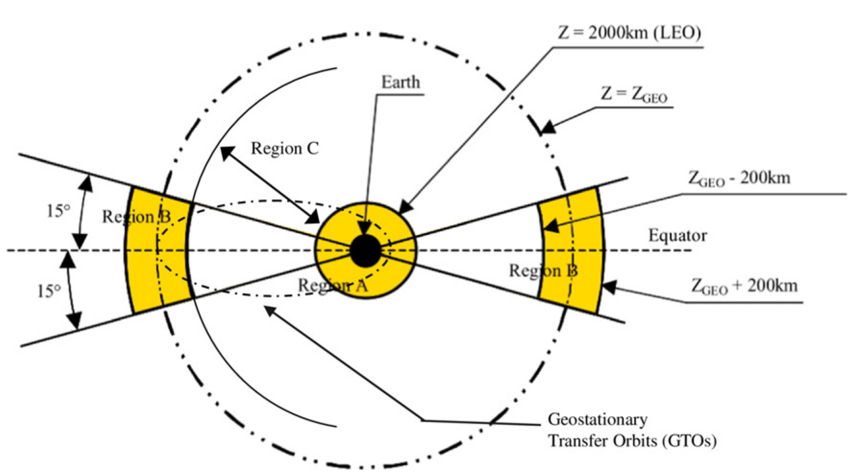

Fig. 1. Main orbital regions representing the useful orbital volume. Abbreviations: Region A: LEO; Region B: GEO; and Region C: MEO. (Freely adapted from IADC, 2007).