



Earth's Orbits at Risk

THE ECONOMICS OF SPACE SUSTAINABILITY



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Foreword

The OECD Space Forum assists governments, space-related agencies and the private sector to better identify the statistical contours of the growing space sector worldwide, while investigating the economic significance of space infrastructure and its role in innovation for the broader economy.

On the initiative of several of its Steering Group members, the OECD Space Forum launched a project on space sustainability and the economics of space debris in 2019. The use of Earth's orbits, particularly low-earth orbit, is intensifying and is accompanied by a growing accumulation of space debris. The environmental stability of Earth's orbits is therefore a growing concern among policy makers. The main concern is that debris density reaches such high levels that it triggers an irreversible chain reaction of on-orbit collisions, the so-called Kessler Syndrome. This tipping point may ultimately render certain orbits of high socio-economic value unusable.

Several international organisations and bodies, national administrations and space agencies have carried out extensive work on space debris mitigation and the sustainability of space activities, mainly concentrating on the technical aspects of space debris and the congestion of low-earth orbits. The OECD initiative complements these efforts by focusing on economic aspects. This involves the identification and, where possible, valuation of the economic effects generated by the accumulation of space debris as well as their mitigation or potential remediation, distributed over time and for different users.

The first phase of the project outlined the problem and set a research agenda, as summarised in the 2020 OECD policy paper entitled "Space sustainability: The economics of space debris in perspective". In 2021, the second phase engaged new actors and launched novel research in this domain, inviting students and faculty in universities and research organisations to examine the value and sustainability of space infrastructure. This project and its follow-up in 2022-23 will provide new evidence for decision makers when assessing the risks and opportunities of space developments, providing valuable contributions to the international knowledge base. This publication presents the findings of the first phase of this project.

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We also warmly thank the +90 experts who participated in associated workshops, in Montreal in 2019 and in the OECD virtual workshop in November 2021. We also thank the commercial satellite operators who kindly agreed to share their expertise via a short survey that was circulated to more than 20 operators in July-October 2019 to gain a better understanding of industry perspectives on the issues of space debris mitigation, and to inform policy discussions. Survey respondents provided crucial insights on operators' practices and useful pointers for future actions to mitigate space debris.

Finally, very special acknowledgements go to the academic contributors to this project as authors of different chapters, who have provided valuable new evidence on the economics of space sustainability. Without them this publication would not have been possible.

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Abbreviations and acronyms

ADR	Active debris removal
ASAT	Anti-satellite (weapon or test)
ASI	Italian Space Agency (Italy) <i>Agenzia Spaziale Italiana</i>
CAM	Collision avoidance manoeuvres
CNES	National Centre for Space Studies (France) <i>Centre National d'Études Spatiales</i>
CNR	National Research Council (Italy) <i>Consiglio Nazionale delle Ricerche</i>
CRS	Constant returns to scale
CSA	Canadian Space Agency
CTNA	National Aerospace Technology Cluster (Italy) <i>Cluster Tecnologico dell'Aerospazio</i>
DARPA	Defense Advanced Research Projects Agency (United States)
DEA	Data envelopment analysis
DLR	German Aerospace Center <i>Deutsches Zentrum für Luft- und Raumfahrt</i>
DMU	Decision-making unit
EARSC	European Association for Remote Sensing Companies
EO	Earth observation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUR	Euro (currency)
GBP	British pound sterling (currency)
GDP	Gross domestic product
GEO	Geostationary orbit
GNSS	Global navigation satellite system
GPS	Global Positioning System
GVA	Gross value added

HHI	Herfindahl-Hirschman Index
IADC	Inter-Agency Space Debris Coordination Committee
ISO	International Organisation for Standardisation
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
km	Kilometre
KRW	Korean won (currency)
LEO	Low-earth orbit
NACE	Statistical Classification of Economic Activities in the European Community
NASA	National Aeronautics and Space Administration (United States)
OECD	Organisation for Economic Co-operation and Development
OOS	On-orbit servicing
PMD	Post-mission disposal
R&D	Research and development
SAR	Synthetic aperture radar
SE	Scale efficiency
SSA	Space situational awareness
SST	Space surveillance and tracking
ST	Satellite telecommunications
TE	Technical efficiency
UCS	Union of Concerned Scientists
UKSA	UK Space Agency
UN COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
USD	US dollar (currency)
VRS	Variable returns to scale
VRT	Variable rate technology
VSL	Value of statistical life
WMO	World Meteorological Organization
WTA	Willingness to accept
WTP	Willingness to pay

Executive summary

Accumulating space debris puts the sustainability of space activities at risk

Satellite data and signals provide crucial inputs to many economic activities, but Earth's orbits are getting crowded. In 2021, more satellites were launched into space than in the entire preceding decade and tens of thousands of satellites should be launched in the next five years.

Orbital debris has increased remarkably in the last 15 years and the socio-economic impacts of a major space debris accident could be dramatic due to cascading effects. The overwhelming concern is that orbital debris density reaches such levels that it triggers the so-called Kessler Syndrome – a catastrophic and irreversible chain reaction of on-orbit collisions between debris and operational satellites. Certain high value orbits may become unusable, while debris concentrations could even block access to higher orbits.

Losing high value orbits would have negative impacts on multiple space-derived services that are beneficial to society. The provision of weather forecasting, navigation services and climate monitoring, as well as important commercial activities such as telecommunications and satellite broadband, could all be affected. The societal costs could be massive and faced across society – even more so in regions with less developed terrestrial infrastructure and dependent on satellite services.

There is a need for more economic analysis of space sustainability so policymakers have the information they need to effectively compare options for action. The work undertaken by the OECD with space agencies, administrations, industry and academia introduces new research that assesses the potential costs of space debris incidents, estimates the value of space infrastructure and compares the economic effects of different policy options. The first results of this OECD project on the economics of space sustainability are presented in this report as a compilation of original research articles. A second phase in 2022-23 aims to expand this new field of research and broaden the international knowledge base.

New approaches to quantifying the costs of space debris and the value of space infrastructure

Environmental economics provides a set of tools that may be used to analyse the effects of space debris on the sustainability of space activities. Drawing on parallels between space debris accumulation and other environmental issues, an analytical framework for understanding the economic effects of space debris has been developed. The research introduces methods for estimating categories of costs and benefits that have been excluded from previous cost-benefit assessments of satellite projects.

Estimating the loss associated with excessive debris in Earth's orbit in monetary terms suggests more resources should be devoted to mitigating debris. An experimental model has been developed to assess the economic effects of a collision event through global value chains. It estimates worldwide monetary losses in the case of Kessler Syndrome to USD 191.3 billion. This is a large sum in proportion to the resources currently committed to debris mitigation and remediation globally.

Assessing the value of space infrastructure suggests the benefits of sustaining space activities are large. The results of a survey of Italian firms in the earth observation industry reveals that considerable benefits accrue from using earth observation data (e.g. improved quality of products and services, R&D capabilities, etc.). This, in turn, positively affects turnover and employment via the development of new services and products or entrance to new markets or sectors.

New economic evidence on different policy options in space debris management

Assessing the costs and benefits of different space debris mitigation policies suggests government intervention is crucial. Based on estimated growth in space objects in low-earth orbits, different mitigation scenarios with and without active debris removal are explored. Satellite operators' incentives to adopt debris mitigation measures are assessed by comparing their cost to the potential damages in case of a collision.

Evaluating commercial and public markets for active debris removal suggests scope for “active debris removal” business model development. Debris removal is one possible solution to the space debris problem, but business models are still immature. A review of projects targeting debris removal and on-orbit servicing shows a mixture of purely public and private initiatives as well as multiple forms of partnerships between sectors. Public intervention is needed that favours flexible and diversified forms of public procurement, R&D support to firms and dedicated government projects.

Firms' behaviour in competitive markets underlines the need to internalise negative externalities. Firms do not yet internalise the impact of their decisions on space debris and may continue harmful practices unless the costs of doing so become prohibitive. One way explored is to incentivise firms with a new taxation regime.

Assessing the economics of satellite launches and future debris creation suggests that many launches are cost-inefficient but there is scope for improvement. The cost efficiency (i.e. the difference between costs and revenues across a satellite's life cycle) are investigated using openly available data on operational satellites. Findings indicate cost efficiencies could be significantly improved, thanks to specific regulations on satellite design.

Policy implications and next steps

The first set of OECD findings on the economics of space sustainability provides new considerations for decision-makers, when formulating responses to space debris accumulation in Earth's orbits:

- **The space infrastructure generates value to society and supports a whole range of economic activities.** The loss or disruption of certain orbits could have a considerable economic impact, several orders of magnitude higher than the cost of current remediation efforts. This needs to be accounted for when assessing and comparing different options for action.
- **Existing and well-tested analytical frameworks and methodologies such as those used in environmental economics help to understand the costs and benefits of acting to mitigate space debris.** This can provide a more complete assessment of space activities by, for example, identifying and valuing monetarily important negative externalities that would otherwise be excluded from a quantitative analysis.
- **Government intervention is crucial to address the space debris issue.** Governments are encouraged to pursue different measures in parallel. Actions include the development and broad adoption of regulatory measures. They also include the development and commercialisation of technologies and practices for remediation and mitigation.

1 Space sustainability and the OECD

This chapter introduces the concept of “space sustainability” and provides the rationale for OECD activities in this area. It also presents the first findings of the OECD project on the economics of space sustainability as well as proposed next steps.

What is “space sustainability”?

The long-term sustainability of space-based infrastructure on orbit and beyond is an emerging policy issue that is likely to become increasingly important in the coming decades. In 2021, more objects were launched into space than in the entire preceding decade. In the coming years, public and private actors worldwide are planning to launch tens of thousands of satellites into the Earth’s orbits, paving the way for a steep increase in the use of space resources.

Outer space seems infinite. However, certain orbital regions around the Earth are rapidly becoming congested and this raises important questions about the long-term sustainability of space activities. Are there substantial negative externalities associated with space manufacturing and launch activities? What are the environmental implications of producing and launching objects into space? How does it affect the stability of the orbital environment? What about socially equitable access to the services flowing from space resources between nations and over the coming decades and centuries?

In 2019, the United Nations’ Committee on the Peaceful Uses of Outer Space (UN COPUOS) reached an international agreement on guidelines for the “long-term sustainability of outer space activities”, that would ensure:

“[...] the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.” (UN COPUOS, 2018^[1])

This agreement reflects increased awareness about the negative externalities surrounding activities in space and particularly of the unrestricted use of certain orbits of value for activities on Earth.

The accumulation of space debris in the Earth’s orbits and the threat it poses to orbital environmental stability is one of the most pressing challenges to the long-term sustainability of space operations. However, there are other dimensions to space sustainability, such as the management of space traffic, the allocation and use of the electromagnetic spectrum, the environmental terrestrial impacts of space activities, social and economic sustainability, etc.

This publication focuses on the environmental and economic sustainability of human orbital activities, as the economic development of the space sector is closely interlinked with the growing risks of a debris-filled orbital environment. Indeed, economic and environmental objectives will increasingly need to be balanced in the future if the full potential of the space economy is to be realised. The sustainability of space manufacturing and launch activities and their impact here on Earth and in the atmosphere may be the subject of future research.

Why study space sustainability at the OECD?

Over recent decades, international organisations and bodies (e.g. the United Nations’ Committee on the Peaceful Uses of Outer Space, the Inter-Agency Space Debris Coordination Committee), national administrations and space agencies have carried out extensive work on space debris mitigation and the sustainability of space activities. This work has mainly concentrated on the technical aspects of space debris and specific guidelines for the most congested regions in the low-earth orbits and the geostationary orbit.

Less attention has been given to the economic aspects of space sustainability, however. For example, the socio-economic costs that space debris inflict on the direct users of space-based resources and on society as an end-beneficiary of space products and services or the value of space-based infrastructure and the threats to which it is exposed have yet to be analysed in detail. This is despite a growing reliance on space.

Space-based infrastructure provides some of the best, and in some cases only, sources of data and signals for multiple human activities, ranging from weather forecasting and sea navigation to telecommunications. Notably, space is a key component of increasingly digitalised economies. Space activities are playing a role in furthering social well-being and sustainable growth in the post-COVID pandemic recovery; contributing to bridging the digital divide; monitoring the changing climate, extreme weather and the use of natural resources; as well as creating new economic opportunities (OECD, 2020^[2]; 2021^[3]). Collecting evidence on the value of space-based infrastructure and the costs of its potential disruption should be a priority for all space-faring member countries of the OECD and beyond.

The OECD Space Forum, within the OECD Directorate for Science, Technology and Innovation, is at the intersection between the space sector, science and technology policy, and economic and industrial policy and is uniquely placed to address this multidimensional issue. On the initiative of several of its Steering Group members, the OECD Space Forum launched a project on space sustainability and the economics of space debris in 2019. This publication is one of the outputs of this ongoing activity.

The OECD project on the economics of space sustainability

Managing the growth of both the number of operational satellites and debris in space has created new challenges for government agencies and decision makers. Some of these challenges are of a technological or administrative nature. Improving capabilities to detect and track space objects, for example. Others are more strategic in nature and concern policy making for economic development. Currently, on some aspects, policy makers do not have sufficient evidence to take informed decisions about debris mitigation and remediation. Answers to the following questions are particularly crucial:

- What value does space-based infrastructure bring to society?
- What are the potential costs of space debris on space activities and the broader society?
- What are the benefits and costs of different policy options, including “doing nothing”?

The OECD project sets out to answer these questions in co-operation with the international community.

The economics of space debris: Setting a research agenda

The initial phase of this project focused on the economics of space debris and was a considerable team effort. Several Space Forum members – notably the Canadian Space Agency (CSA), the US National Aeronautics and Space Administration (NASA) and the UK Space Agency (UKSA) – guided the work and co-organised the OECD Workshop on the Economics of Space Debris, hosted by the CSA in Montreal in June 2019. Space debris experts from the French National Centre for Space Studies (CNES) and the German Aerospace Centre (DLR) provided further inputs. Commercial satellite operators were consulted through a survey that was circulated to some 20 operators between July and October 2019 to gain a better understanding of industry perspectives on the issues of space debris mitigation to inform policy discussions.

The work presented in Undseth, Jolly and Olivari (2020^[4]) provided a first-time comprehensive economic analysis of space debris. It identified the most relevant socio-economic impacts and explored a range of policy responses. These findings are summarised and updated in Chapter 2 of this publication. The study also identified several areas of research to better support policy decisions, and notably, the need to better quantify both the costs of space debris and the value of space-based infrastructure.

New contributions to understanding the value and sustainability of space-based infrastructure

Building on these initial efforts to understand the value and sustainability of space-based infrastructure, the OECD launched an initiative in early 2021 to bring in the perspective of external actors. The OECD Space Forum invited young researchers, Master's and PhD students, and faculty members in universities and other research organisations from across the OECD to author research papers and provide initial answers to two fundamental questions: 1) what is the value of space-based infrastructure; and 2) what are the potential costs of space debris?

More than 30 academic institutions, many of which are relatively new to the space domain, attended various events organised throughout the year, including the project launch, several bilateral briefings, a “pitching” event, and a “meet-the-experts” questions and answers session. The initiative ended with a workshop in November 2021 that presented the different selected academic contributions and discussed the remaining challenges. The following online events took place in 2021:

- project launch (16 February 2021)
- “Meet the Experts” meeting, with experts from space agencies presenting the latest trends in space policies and space debris evolutions (13 April 2021)
- “Researchers in Action” workshop, with researchers presenting their respective approaches (7 June 2021)
- OECD Workshop on the Value and Sustainability of Space-based Infrastructure, presenting the main results of the initiative, most of which are summarised in this publication (4 November 2021).

The project's preliminary results

The initiative has produced papers that were reviewed by the OECD and its partnering space agencies and ministries from ten countries as well as the European Space Agency.

Several original approaches to addressing the research questions were introduced, building on: environmental economics; organisational theory; data envelopment analysis methods; brand new industry surveys; and cause-and-effect and propagation modelling exercises. This led to innovative studies on the:

- valuation of selected downstream space activities
- modelling of the potential economic costs of space debris
- modelling of possible cost efficiencies
- modelling of policy responses for space debris mitigation
- exploration of an active debris removal market.

Seven papers were selected for publication in this report from authors in five countries and with wide-ranging backgrounds in economics, engineering, environmental science, physics and management studies. Shortened versions of the papers are featured as individual chapters in this publication and are detailed in the outline at the end of this chapter. Other interesting papers that were not selected for publication are referenced in Chapter 2.

Beyond the tangible outputs, the project has also nurtured a community of practitioners in space-related economic research. Many of the participants did not have previous knowledge of or experience in the space sector and this exercise helped encourage the development of expertise throughout key OECD research institutions. In addition, new links have been created between government agencies and academic actors, which may lead to more collaboration in the future.

Next steps of the project

Society is at the beginning of a challenging research effort to accumulate the knowledge and evidence needed to ensure the sustainable use of the Earth's orbits.

As part of this effort, the OECD exercise on the economics of space sustainability will be repeated in 2022-23, with the aim to expand the international knowledge base and ultimately support future policy making.

The following key aspects require further research:

- More evidence is needed on emerging practices and policy options, such as the costs and benefits of space debris remediation. Organisations that licence space activities also need more evidence on the economic impacts of new types of missions (e.g. deploying and announced mega-constellations of several thousand satellites in the low-earth orbit).
- More evidence is also needed on the appropriate policy instruments to internalise the costs of space debris and/or to incentivise space actors to follow debris mitigation guidelines (e.g. standards, market-based instruments such as taxes or insurance). Examples of instruments abound in other domains (e.g. marine and air pollution, hazardous waste), but little is known about their application in the space sector in terms of economic impacts, public acceptance or overall effectiveness.
- More concrete evidence tailored to users' needs is also needed. Evidence risks being ignored if it is too general or abstract.
- Finally, the cost of non-action needs to be determined. There is a strong need to establish a robust counterfactual to compare with the costs of all other actionable policy options.

Developing this new evidence will require advances on multiple fronts, notably:

- Learning more about risks (frequency of incidents and their impacts): Many incidents go unreported by operators either knowingly or because of a lack of observational capacity. Data-sharing between operators needs to be improved.
- Modelling the future limits of human activity in different orbits: Whereas government agencies have made progress in modelling the physical environment, knowledge is still insufficient about the nature and timelines for space debris tipping points of human activity in space. Furthermore, more work is needed on the use of valuable orbits and the electromagnetic spectrum from a resource utilisation perspective.

Charting an effective way ahead will require concerted action from public and private actors, at both the national and international levels. National measures will be key to reaching objectives in the short and medium term, but their impact will be maximised through collaboration with other countries and private actors. Governments may consider:

- supporting further efforts from academia and beyond in developing evidence on the possible impacts of space debris on society, including the possible costs of inaction
- reinforcing efforts to stimulate research and development in support of regulatory action and other policy options (costs and benefits of different policy options, costs of non-action).

Earth's Orbits at Risk: The Economics of Space Sustainability

This publication aims to put the issue of space sustainability higher on the policy agenda and presents the main findings of the first phase of the OECD Project on the Economics of Space Sustainability. It provides a compilation of original research articles.

The contents are organised as follows:

- Chapter 2 sets the scene for the rest of the publication and summarises recent OECD findings. It provides an overview of the major challenges to space-based infrastructure, short- and longer term costs of space debris and mitigation efforts.

The following chapters result from the original work produced in 2021 by academic participants. They provide novel approaches and evidence in two principal areas:

Identifying the potential costs of space debris related to the socio-economic value derived from selected segments of the space-based infrastructure:

- Chapter 3 introduces an analytical framework and econometric model for estimating the cost of space debris from a global and national perspective, based on approaches developed in the field of environmental economics.
- Chapter 4 estimates the potential economic damage resulting from space debris accumulation (and an early onset of the Kessler Syndrome), by quantifying the economic value of space-enabled activities at risk from the deterioration of certain orbital regimes and calculating the average probability of orbital deterioration.
- Chapter 5: Earth observation is one of a number of key activities that is potentially vulnerable to being disrupted by space debris. Serving as a case study representative for many OECD countries, the chapter presents the findings of a survey carried out among earth observation firms in Italy, identifying current and potential socio-benefits of space-based earth observation, as well as barriers that could hamper growth in the sector.

Providing options for debris mitigation and remediation and ways to support potential future markets to address the problem:

- Chapter 6 estimates the growth in space objects in low-earth orbit in the coming decades. It then employs a qualitative approach to assess satellite operators' economic incentives to adopt debris mitigation measures by comparing mitigation costs and potential collision damage costs.
- Chapter 7: Debris removal may at some point become necessary to stabilise the orbital environment, but technological and commercial maturity levels are still quite low. The chapter studies the development of a market for active debris removal, building on a database of active debris and on-orbit servicing projects. It identifies the specificities of the sector and explores the conditions under which such a market could emerge.
- Chapter 8: Inspired by the network structure of co-operation between countries, the chapter models strategic interaction between different firms (that compete but do not fully account for the negative externalities of their actions) to study the outcomes in terms of space debris generation under different market structures. It suggests that welfare loss will increase significantly without global regulatory intervention to address space debris.
- Chapter 9 applies efficiency analysis to a sample of satellites to empirically investigate the efficiency of satellite launches. Findings show an overall low level of efficiency, indicating room for improvement in mission efficiency and ultimately, for limiting future debris creation.

These chapters provide novel contributions to the evolving body of evidence on the economics of space sustainability. The OECD Secretariat would like to thank all the authors and their institutions for their involvement in this initial stage of the project. As a next step to this first original compilation of research, new academic contributions will be spurred by the OECD and partnering space agencies to further deepen some of the issues presented in this publication.

References

- OECD (2021), “Space economy for people, planet and prosperity”, background paper for the G20 Space Economy Leaders’ Meeting, 20-21 September, Rome, Italy, <https://www.oecd.org/sti/inno/space-forum/space-economy-for-people-planet-and-prosperity.pdf>. [3]
- OECD (2020), “The impacts of COVID-19 on the space industry”, *OECD Policy Responses to Coronavirus (COVID-19)*, OECD, Paris, <https://www.oecd.org/coronavirus/policy-responses/the-impacts-of-covid-19-on-the-space-industry-e727e36f>. [2]
- UN COPUOS (2018), *Guidelines for the Long-term Sustainability of Outer Space*, Committee on the Peaceful Uses of Outer Space, https://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0.html/AC105_2018_CRP20E.pdf. [1]
- Undseth, M., C. Jolly and M. Olivari (2020), “Space sustainability: The economics of space debris in perspective”, *OECD Science, Technology and Industry Policy Papers*, No. 87, OECD Publishing, Paris, <https://doi.org/10.1787/a339de43-en>. [4]

2

Space sustainability as the next major societal challenge

This chapter provides a state of play of the key issues associated with the sustainability of the orbital environment. It reviews the growing socio-economic dependence on space assets of our modern societies, and the general threats to space-based infrastructure. It then focuses on the increasing risk of collisions in space and why it matters.

Growing socio-economic dependence on space assets

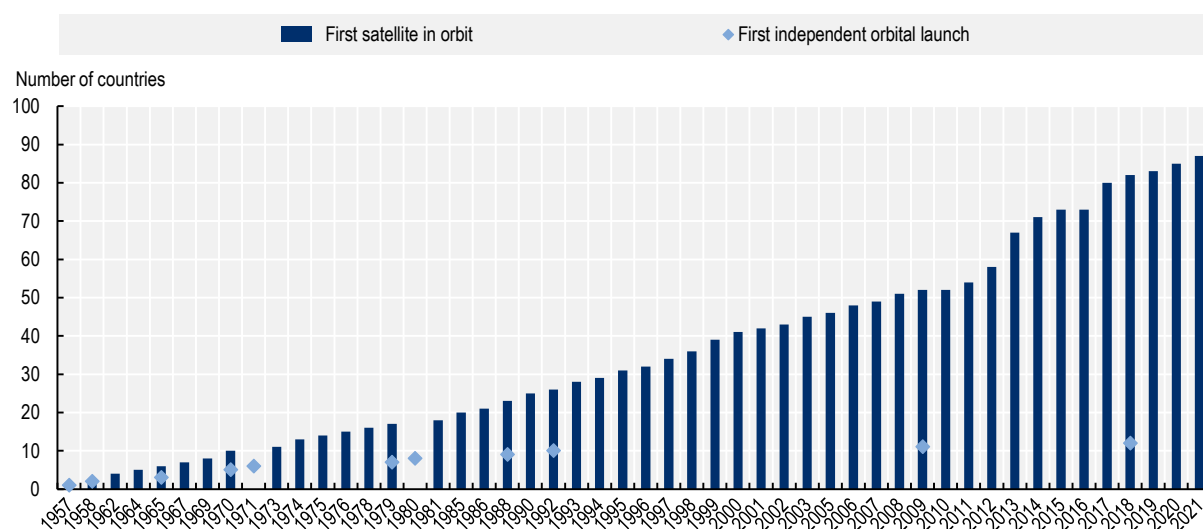
Use of the Earth's orbits, in particular low-earth orbits (LEOs), has significantly increased in recent years. This follows rapid growth in institutional applications and in the commercialisation of space activities, driven by lower launch costs and high expected returns in the data-intensive downstream segments. At the same time, space debris are accumulating and may reach uncontrollable levels unless effective action is taken. Considering the growing importance of space-based infrastructure for society, the sustainable use of the Earth's orbits and the protection of space-based assets will be crucial in the coming decades.

Satellite signals and data have a growing number of commercial and government users and play an increasingly vital role in the functioning of societies and their economic development. This trend is accompanied by a dramatic increase in the use of the orbital environment, which is creating challenges for continued and sustainable access to this resource.

Over the past two decades, the socio-economic importance of the space sector has increased, as space products and services are becoming more affordable and versatile. By 2022, almost 90 countries had operated a satellite in orbit at some point in time (Figure 2.1). Many actors took this step after 2000, and especially after 2010, which coincides with the emergence of miniaturised technology and increased use of standardised and off-the-shelf products that have marginally reduced production and launch costs (OECD, 2014^[1]).

Figure 2.1. Almost 90 countries with a satellite in orbit

Number of countries having had a satellite in orbit (launched between 1957 and October 2021)



Source: Adapted from OECD (2019^[2]), *The Space Economy in Figures: How Space Contributes to the Global Economy*, <https://doi.org/10.1787/c5996201-en>.

At the same time, society's reliance on space-based infrastructure is growing, with space technologies supporting important societal functions such as communications, transportation, food production and a range of government services, including defence and weather forecasting. Many OECD countries have designated space activities, such as space manufacturing and satellite telecommunications, as national critical infrastructure sectors. During the COVID-19 crisis, space sector actors contributed to the response efforts (e.g. studying impacts) and provided high-speed Internet connectivity to remote locations and produced earth observation imagery for industry intelligence and monitoring of remotely located

infrastructure (OECD, 2020^[3]). Participants in the OECD project on the value and sustainability of space-based infrastructure have documented the benefits that space-based infrastructure brings to specific segments of industry and government services, such as civil protection (Box 2.1) and earth observation (see Chapter 5).

Box 2.1. Space-based services for civil protection

Space applications, such as earth observation and communications, contribute to the various phases of the natural disaster management cycle, in disaster preparedness, mitigation, response and recovery. For example, after the underwater volcanic eruption and ensuing tsunami in the southern Pacific in January 2022, which caused severe flooding in several areas in Tonga and severed underwater Internet cables, satellite data and signals detected and monitored the impact and extent of the event and helped restore communications to the island.

Most space-based infrastructure used for civil protection purposes is government-owned (see the examples in Table 2.1), but some commercial companies also provide these services. At the international level, space-based assets and capacities are co-ordinated in the International Charter for Space and Major Disasters, which pools the data resources of 17 government agencies as well as those of several private firms (e.g. ICEYE, Maxar Technologies). In the event of an emergency, the “Universal Access” programme allows recognised government disaster management organisations to request data from the Charter (ICS DM, 2022^[4]). Other important programmes include the Copernicus Emergency Management Service, the National Aeronautics and Space Administration’s Disasters Programme, and the commercial operator DigitalGlobe’s Open Data programme. All provide free data and services for civil protection.

Table 2.1. Selected satellite missions providing civil protection services

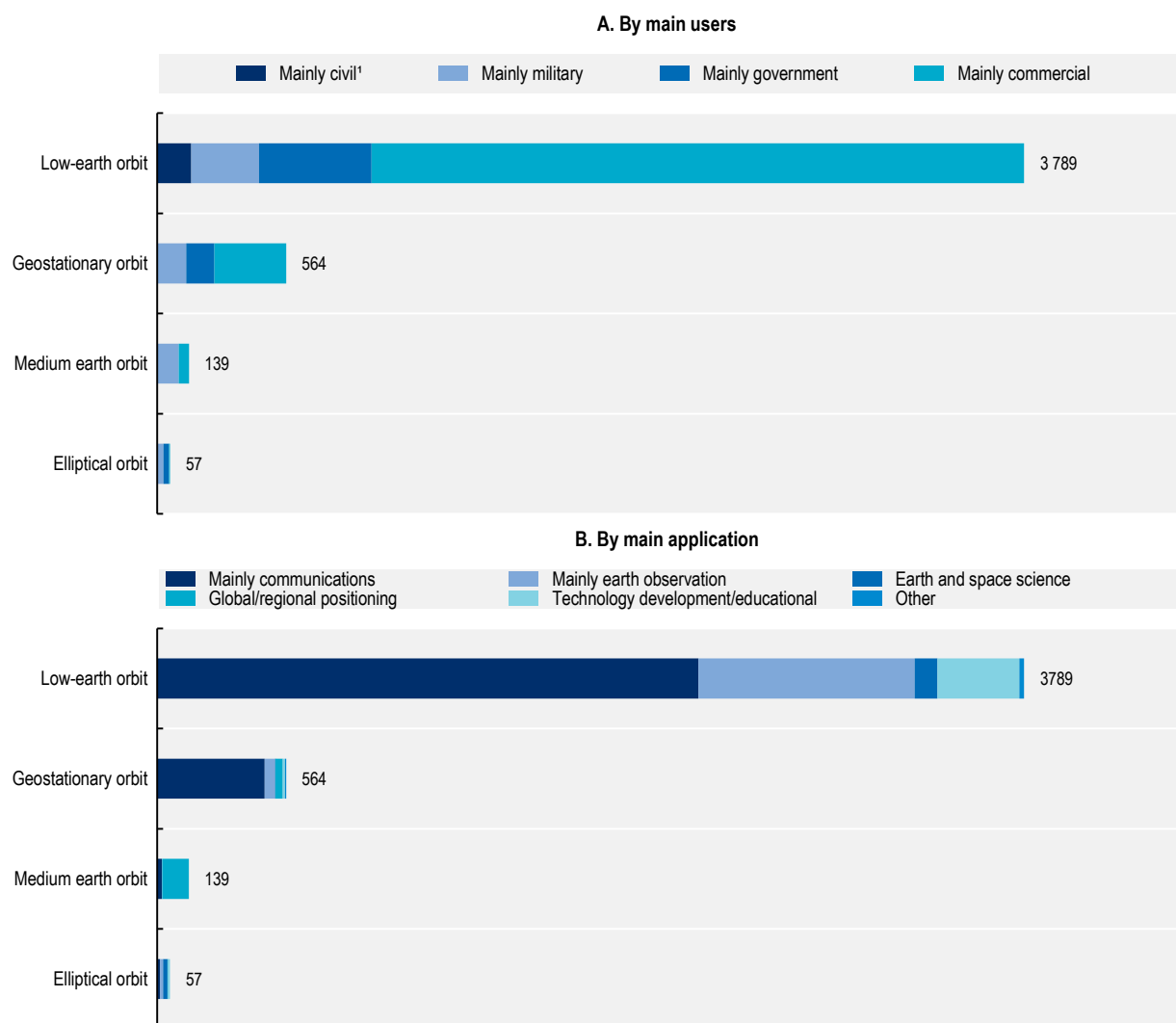
Satellite mission	Organisation (country)	Mission description	Orbit altitude	Civil protection applications
Sentinel-2	European Union	Comprises two polar-orbiting satellites placed in the same orbit, phased at 180° to each other. It provides high-resolution optical data that monitor land surface changes	786 km (sun-synchronous – revisit period five days at the Equator)	Hazards monitoring, risk assessments, impact assessments, damage assessments
TerraSAR-X	DLR/Airbus (Germany)	Provides high-resolution SAR (synthetic-aperture radar) imagery, used in hydrology, geology, climatology, oceanography, cartography and environmental monitoring	514 km (sun-synchronous – revisit period 11 days)	
Aeolus	European Space Agency	Carries the atmospheric laser doppler instrument (ALADIN), which collects data on wind profiles at the lowermost 30 km of the atmosphere, to improve weather forecasts and climate models	320 km (sun-synchronous – revisit period seven days)	Early warning systems

Source: Based on Marsellach Pujolràs (2020^[5]), *The Valuation of Impacts of Space Debris on Space-Based Civil Protection Services*.

Figure 2.2 shows that there were some 4 500 operational satellites in orbit in September 2021 (Union of Concerned Scientists, 2021^[6]). Most can be found in LEO and have mainly commercial operators. In terms of applications, communication satellites dominate followed by earth observation and navigation satellites.

Figure 2.2. Users and applications of space-based infrastructure

Number of operational satellites



1. Refers to academic and other “amateur” operators (e.g. of amateur radio satellites).

Notes: Satellites operational on 1 September 2021. All categories include a small number of dual-use missions (e.g. government-military).

Source: Union of Concerned Scientists (2021^[6]), “UCS Satellite Database: September 2021 update”, <https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database>.

Global commercial revenues reached an estimated USD 271 billion in 2020 and the space sector is increasingly seen as a driver of innovation and growth in the wider economy (OECD, 2019^[2]; Bryce Tech, 2021^[7]). The same year, the US space economy accounted for some 0.5% of national gross domestic product (Highfill, Jouard and Franks, 2020^[8]). The communications industry has historically dominated the space sector in terms of commercial revenues, and expectations of continued high returns in this industry segment are driving private investments and activities. More than ten broadband satellite constellations are in various stages of development, with two companies (SpaceX and OneWeb) having already launched multiple satellites (see Table 2.2). The Starlink constellation had reached more than 1 700 operational satellites by the end of 2021 and offered beta services to a score of countries in Europe, North and South America as well as Australia. Other operators, in North America and the People’s Republic of China (hereafter “China”) in particular, also have projects in the pipeline. In 2021, the Chinese government

announced that it would develop a 13 000-satellite Guo Wang (“national network”) broadband constellation. The same year, the Korean defence company Hanwha Systems published plans to develop a 2 000-satellite constellation, to be finalised by 2030. In addition to these planned communications constellations, numerous other projects are underway, often involving much smaller satellites in other applications, such as the Internet of Things or earth observation.

Table 2.2. Selected planned communications constellations

Constellation name	Company (country)	Expected number of satellites	Status
Astra Constellation	Astra Space (United States)	13 620	Project announced in 2021
Boeing	Boeing (United States)	132 + 15 (HEO)	Received Federal Communications Commission approval in 2021
Guo Wang	China Satellite Network Group (China, People's Republic of)	12 992	Project announced in 2021
Hanwha	Hanwha Systems (Korea)	2 000	Project announced in 2021, trial services planned to begin in 2023
Lightspeed	Telesat (Canada)	298	First demonstration launch in 2018
Mangata Networks	Mangata Networks (United States)	791 (HEO)	Prototype development
OneWeb	OneWeb (United Kingdom)	648 (6 372)	358 satellites launched in November 2021
Project Kuiper	Amazon (United States)	3 236	First satellites scheduled for launch in 2023
Sfera	Roscosmos and private contributions (Russia)	640	Project announced in 2021, building on previous Efir project
Starlink	SpaceX (United States)	11 943	1 700+ satellites launched. In 2021 started providing beta services in certain regions
Yinhe	Galaxy Space (China, People's Republic of)	144	First demonstration launch in 2020

Note: HEO refers to high earth orbit (entirely above the geostationary orbit at about 36 000 km), all other projects are in the low-earth orbit.

Source: Adapted from OECD (2019^[2]), *The Space Economy in Figures: How Space Contributes to the Global Economy*, <https://doi.org/10.1787/c5996201-en>.

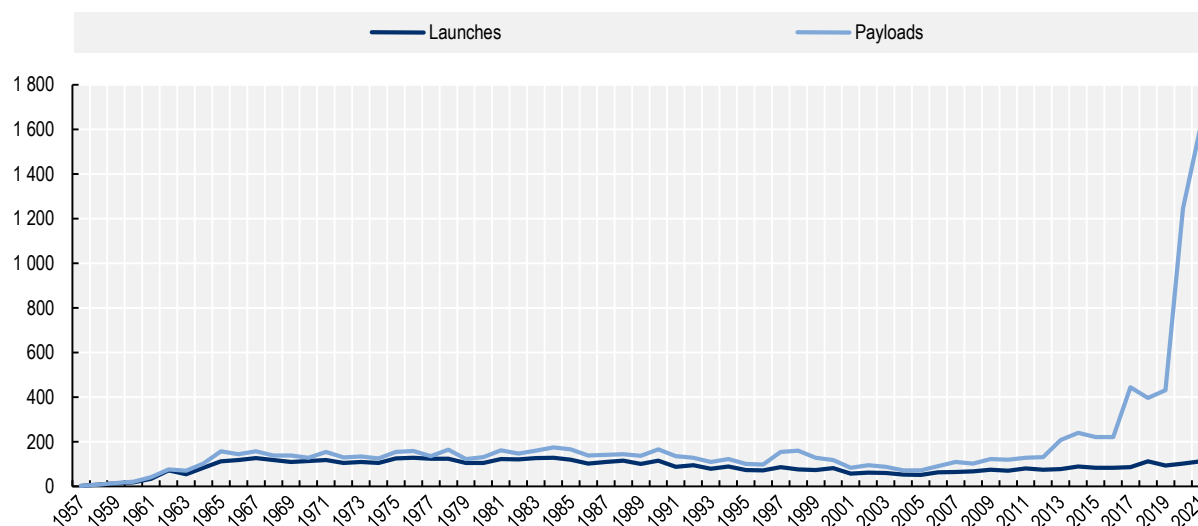
Figure 2.3 shows the number of launches and payloads (e.g. satellites, space probes) inserted into orbit since the launch of the first satellite Sputnik in 1957.

Despite a slump in the number of satellites launched after the burst of the dotcom bubble in the late 1990s, the launch rate remained stable over the decades leading to 2019. Since 2019, however, the number of satellites launched has dramatically increased. This is mainly due to SpaceX's deployment of the Starlink constellation, which in 2021 alone launched 1 000 communications satellites. The number of satellites (or payloads) per launch has increased over time due to smaller satellite size, standardisation of satellite design and improved deployment systems. As an illustration, Starlink and OneWeb satellites are launched in batches of several dozens of satellites – SpaceX can stack more than 50 of its 260 kg Starlink satellites in one launch. But launch frequency would still need to rise quite significantly if multiple mega constellations of several thousand satellites are to be launched and maintained.

The sheer size of these planned mega constellations, leading to an accelerated launch frequency and substantial growth in the number of satellites in orbit, raises new concerns about the environmental sustainability of space activities (Boley and Byers, 2021^[9]). This includes concerns about pollution associated with manufacturing and launch; light pollution from on-orbit satellites disrupting astronomic observations; and, most prominently, space debris' impact on the stability of the orbital environment. Furthermore, as society's reliance on space assets grows, so does the vulnerability to space-based hazards, both natural and man-made.

Figure 2.3. Orbital launch history

Activity as of 23 November 2021



Note: Payloads refer to space objects (e.g. satellites, space probes) designed to perform a specific function in space, excluding launch functionality.

Source: US Space Force (2021^[10]), *Space-Track.Org* website, <https://www.space-track.org>.

Growing risks to space-based infrastructure

Space-based infrastructure is exposed to several threats, both natural and man-made. Considering the limited possibility to service and repair satellites once on orbit, even minor events can have severe consequences.

Space weather events

Space weather is closely associated with developments on the Sun and refers to changes in the levels and types of radiation and charged particles and plasma that may affect space-based and terrestrial infrastructure. In its 2015 Space Weather Strategy, the US federal government identified space weather as one of the grand challenges for disaster risk reduction (US National Science and Technology Council, 2015^[11]).

While the Sun constantly emits radiation in the optical and near-infrared range, solar weather events see an increase in the radiation of extreme ultraviolet, X-ray and radio wavelengths (solar flares), as well as the emission of ionised energy particles and plasma (e.g. coronal mass ejections) (Royal Academy of Engineering, 2013^[12]). These events can cause radiation or geomagnetic storms, both of which can seriously affect space-based (and ground-based) activities and infrastructure, producing electrical failure, blocking radio communications, modifying Global Navigation Satellite System (GNSS) signals, etc.

One of the largest geomagnetic storms on record occurred in 1859, disabling telegraph systems in North America and Europe and producing auroras visible in Hawaii and Queensland, Australia. A coronal mass ejection of similar magnitude, potentially with catastrophic consequences, missed the Earth by a week in 2012 (NASA, 2014^[13]). The most recent severe space weather incident took place in Quebec in 1989, when Hydro Québec's electrical grid was disabled, leaving 6 million people without electricity for nine hours (Canadian Space Agency, 2017^[14]). While minor events are quite common, very little is known about the statistical occurrence of "superstorms," such as the 1859 Carrington event, named after British astronomer Richard Carrington, who observed it. Various studies indicate a return period of 1 in 100 to

200 years, but these estimates remain highly uncertain because of the lack of historic data (Royal Academy of Engineering, 2013^[12]).

A selection of recent events is listed in Table 2.3.

Table 2.3. Selected space weather events since the beginning of the Space Age

Year	Event	Description	Selected reported damages to satellites
1972	Solar storm of August 1972, solar particle event	Coronal mass ejection with the fastest transit time to Earth recorded (14.6 hours) that created severe technological disruptions and caused the accidental detonation of numerous naval mines.	
1989	March 1989 geomagnetic storm	Caused a nine-hour power outage in the province of Quebec and led to the loss of positional knowledge of space objects for nearly a week.	Multiple satellite anomalies, loss of altitude, signal disruptions
1991	Geomagnetic storm, November 1991	An intense solar storm with about half the energy output of the March 1989 storm. Auroras were visible in the United States as far south as Texas.	
	Bastille Day solar storm, 14 July	Involved a solar flare, solar particle event and a coronal mass ejection, creating a severe geomagnetic storm. Caused minor damage to power transformers and satellites. Strong enough to be observed by Voyager 1 and 2 spacecraft.	Astro-D (ASCA), Japan/United States, scientific satellite in low-earth orbit, loss of altitude
2001	Geomagnetic storm of November 2001	A fast-moving coronal mass ejection with auroras visible as far south as Texas, California and Florida.	
2003	Halloween solar storms, mid-October to early November	Series of solar flares and coronal mass ejections. Auroras visible as far south as Texas and the Mediterranean region. Caused rerouted aircraft and power outages in southern Sweden.	Reportedly some 10% of the total satellite fleet suffered anomalies, including MIDORI 2 (ADEOS), Japan/United States, France scientific satellite in low-earth orbit, anomaly
2006	Solar flare, 5 December 2006	Disrupted satellite-to-ground communications and GPS signals for about ten minutes.	Damaged solar X-ray imager on the GOES-13 weather satellite
2010	Coronal mass ejection, 3 April 2010		Caused a critical failure on the Galaxy-15 communications satellite
2022	Coronal mass ejection, 4 February 2022	First recorded mass satellite failure caused by an increase in atmospheric density.	40 out of 49 recently launched Starlink satellites (SpaceX, United States) destroyed on premature re-entry into the atmosphere

Radiation and geomagnetic disturbances from space weather events can affect space-based infrastructure in several ways. They may cause various satellite malfunctions; degraded or interrupted signals to or from the satellite; loss of altitude (for LEO satellites) due to increased atmospheric drag as it warms and expands; and accelerated aging of components (Abt Associates, 2017^[15]). In recent decades, several events have damaged satellites and disrupted terrestrial electrical and communication networks. In 2006, a solar storm caused a ten-minute disruption to GPS navigation signals (OECD, 2019^[21]). In February 2022, SpaceX reported that a geomagnetic storm caused the loss of up to 40 recently launched Starlink satellites, which lost altitude during orbit-raising and re-entered the atmosphere prematurely (SpaceX, 2022^[16]). However, information on the full impact of space weather on space-based infrastructure is not available, as it may be difficult to distinguish between failures related to space weather events and other malfunctions. Furthermore, operators may sometimes choose not to disclose incidents. According to some academic studies that have compared operator anomaly reports with solar activity, up to 60% of reported anomalies were strongly related to lower energy electron fluxes and to associated magnetic perturbations (Ahmad et al., 2018^[17]).

The World Meteorological Organization co-ordinates the observation of space weather, which currently counts six space-based missions – four US missions and two joint missions between NASA and the European Space Agency – in addition to terrestrial observations (WMO, 2019^[18]). Yet, space weather research and forecasting are still in their infancy and precise forecast horizons (if available) remain short.

Coronal mass ejections transit relatively slowly through space and arrival times can be forecast with six to eight hours of accuracy (Royal Academy of Engineering, 2013^[12]). However, definitive forecasts, determining the orientation of the coronal mass ejection magnetic field, are in the 15-30-minute range. In contrast, solar flares and solar energetic particle ejections travel with the speed of light and cannot be forecasted at all. This gives little time to operators of terrestrial and space-based infrastructure to prepare. Satellite operators may mitigate against damage through different types of shielding and satellite design, integrate multiple redundancies and foresee spare satellites (Abt Associates, 2017^[15]). They may also use a higher orbit, but all these measures raise the costs of the mission. It has been argued that the increasingly widespread use of off-the-shelf components (which are cheaper and more easily accessible but not radiation-hardened) can make satellites more exposed to damage (Horne et al., 2013^[19]).

As the Sun progresses in its 25th solar cycle, more intense solar activity is expected in the 2023-26 time frame (NOAA Space Weather Prediction Center, 2022^[20]).

Mounting pressure on the radio frequency spectrum and increased risk of interference

Issues related to the allocation and use of electromagnetic spectrum frequencies is another growing concern for the long-term sustainability of space activities, due to the intensification of space operations and terrestrial competition (OECD, 2019^[2]).

Radio frequencies, used by spacecraft to communicate with other spacecraft and terrestrial ground stations, are often defined as a limited (albeit reusable) natural resource (ITU, 2015^[21]). The International Telecommunications Union ensures equitable access to this resource by allocating frequency bands to individual countries, and mitigates interference issues by reserving specific bands for specific uses (e.g. fixed satellite service uplinks and downlinks).

There are growing concerns of interference from both terrestrial and space networks (e.g. deployment of 5G, the growth of mobile communications worldwide). Concerning the space networks, the sheer size of many planned constellations in LEO raises concerns about orbital interference. Some satellite operators in the geostationary and medium-earth orbits worry that the increasing crowding of the LEO could eventually jam the link between higher flying satellites and terrestrial satellite dishes (OECD, 2019^[2]). Efforts to improve international co-ordination were most recently discussed at the World Radiocommunication Conference in 2019.

Catastrophic accidents on orbit

Satellites and other types of infrastructure are subject to the risk of collisions with other operational spacecraft, with space debris, and with near-earth objects, such as meteoroids. Of these hazards, collisions with space debris are by far the most pressing and will be further elaborated on in the following sections.

The increasing risk of collisions in space and why it matters

As indicated in the previous sections, the use of Earth's orbits, and in particular the LEOs, has significantly increased in recent years, as shown in Figure 2.3. This growing number of operational satellites and other spacecraft is accompanied by a growth in orbital debris population (Box 2.2). As a result, not only are the risks of collision between satellites and debris growing, but so are the potential socio-economic impacts of such collisions. There has been a notable increase in the orbital debris population in the last 15 years, associated with three specific events, as shown in Figure 2.4. The figure shows the evolution of space objects catalogued by the US Space Force, including operational and defunct spacecraft, fragmentation debris from collisions and on-orbit explosions (e.g. rocket fuel tanks), mission-related debris such as objects intentionally released during deployment and operations, and various stages of rocket bodies.

Box 2.2. What is space debris?

The current tracked debris object population is mainly composed of fragmentations from satellites and rockets, followed by defunct spacecraft, rocket bodies and mission-related debris such as lens caps and solid rocket firings. Rocket bodies account for only around 10% of tracked objects, but almost 40% of mass (ESA, 2019^[22]).

Debris belts are located in the low-earth orbit, mainly between 800 and 1 000 km but also at an altitude of almost 1 400 km. There are additional concentrations of space debris close to the orbits of the existing navigation satellite constellations (19 000-23 000 km), and the geostationary orbit, the home of many large telecommunications and weather satellites, at 36 000 km.

Lower altitude orbital debris objects are eventually pulled closer to Earth by atmospheric drag and other natural processes and are in most cases destroyed when entering the atmosphere. Decay timelines can be counted in days (orbits closest to Earth), in years (in orbits less than 600 km), or in centuries (more than 1 000 km). There is no atmospheric drag in higher altitude orbits such as the geostationary orbit and debris remain in orbit unless moved to dedicated “graveyard” orbits.

In November 2021, the US Space Force tracked 19 100 identifiable debris objects mainly with a 10 cm diameter or bigger (US Space Force, 2021^[10]). The total untracked number of debris probably counts in the hundreds of millions (ESA, 2021^[23]).

Source: Based on Undseth, Jolly and Olivari (2020^[24]), “Space sustainability: The economics of space debris in perspective”, <https://doi.org/10.1787/a339de43-en>.

The first noticeable jump in the debris population followed the intentional destruction of the Chinese weather satellite FengYun-1C in an anti-satellite weapons test in 2007. The second occurred after the first documented collision between two satellites, Iridium-33 and Kosmos-2251 in 2009, and the third jump in 2021 is associated with a Russian anti-satellite weapons test and ensuing break-up of the 2.2 metric tonnes satellite Kosmos-1408. Each of these events created debris clouds of more than 1 000 pieces. Other countries have also conducted anti-satellite tests (e.g. the United States in 1985 and 2008, India in 2019), albeit in lower orbits where debris normally decay within days or weeks.

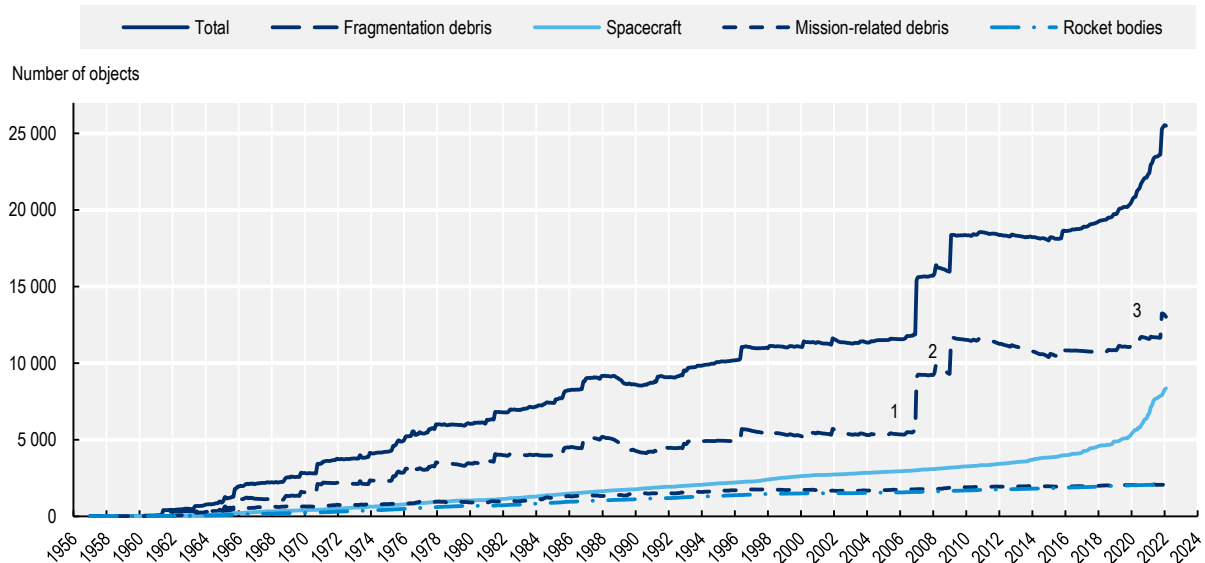
Concerns about space debris accumulation have been rising over the last four decades. Debris objects and fragments constitute a considerable collision hazard for other spacecraft that are on orbit or travelling through debris belts during orbit-raising. Even tiny debris fragments can cause damage because of their high velocity. Furthermore, debris objects constitute an even higher collision risk for each other because they are not manoeuvrable, generate more debris if they collide and thereby compound the number of collisions (Swiss Re Corporate Solutions, 2018^[25]). Modelling exercises suggest that the likelihood of a collision between an operational geostationary orbit (GEO) satellite and a 1 cm debris object is once every 4 years and once every 50 years for a collision with a 20 cm debris object (Oltrogge et al., 2018^[26]).

Several studies show a significant projected increase in collision risk in the coming decades. A study conducted by Swiss Re in 2018 estimated an eightfold increase (from 11% to 90%) of the risk of collision over the next 20 years between a 200 kg broadband satellite and a 1 cm to 10 cm object in a 1 000-satellite constellation at an altitude of 1 200 kilometres (Swiss Re Corporate Solutions, 2018^[25]). Modelling conducted by the Inter-Agency Space Debris Coordination Committee (IADC) in the 2009-12 time frame predicted an average 30% increase in the amount of LEO debris in the next 200 years, with catastrophic collisions occurring every five to nine years, factoring in a 95% compliance rate to mitigation rules (IADC, 2013^[27]). A 2017 study at the University of Southampton found that adding one mega-constellation of

several thousand satellites to low-earth orbit would increase the number of catastrophic collisions by 50% over the next 200 years (University of Southampton, 2017^[28]).

Figure 2.4. Monthly number of objects in Earth's orbits by object type

Historical increase of the catalogued objects based on data available on 1 March 2022



Notes: The three upward jumps in fragmentation debris correspond to: 1) the anti-satellite test conducted by the People's Republic of China in 2007; 2) the accidental collision between Iridium 33 and Cosmos 2251 in 2009; and 3) the anti-satellite test conducted by the Russian Federation in November 2021. More Cosmos 1408 fragments are expected to be added to the catalogue in the coming weeks and months of 2022.

Source: NASA (2022^[29]), "Orbital Debris Quarterly News 26:1", <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNV26i1.pdf>.

While collisions with debris could harm individual satellites, the overwhelming concern is that debris density reaches such levels that it triggers an irreversible chain reaction of on-orbit collisions, the so-called Kessler Syndrome (Kessler and Cour-Palais, 1978^[30]). This tipping point may ultimately render certain orbits of high socio-economic value unusable. If or when this could happen remains unknown, but there is a theoretical possibility that it could occur within the next few decades (National Research Council, 2011^[31]).

The costs of space debris

The impacts of accumulating space debris are distributed across different types of users and are likely to change over time. Current and short-term impacts are relatively limited and affect mainly operators, whereas longer term effects could be much higher in magnitude and will affect broader society.

Identifying current costs for different types of users

Currently, public and private operators of satellites and other spacecraft bear the negative consequences of space debris, carrying the costs of avoiding debris and mitigating further debris creation. There are limited data on some of the specific figures relating to these costs, but they vary according to the orbit and type of spacecraft. Table 2.4 provides an overview of the types of costs, typically including damage-related costs, operations and satellite shielding.

Spacecraft replacement costs and related delays and data loss are the most direct consequence of a fatal collision with space debris. However, many other costs can negatively affect a spacecraft's mass and fuel consumption and hence launch costs and the length of the operational mission life. Actions to address such costs include impact avoidance or reduction measures (e.g. shielding, debris avoidance

manoeuvres), as well as debris mitigation measures (e.g. orbit clearance, venting of residual fuel) and other considerations that alter the spacecraft's design (National Research Council, 2011^[31]).

Table 2.4. Overview of current impacts and related costs of space debris

Type of cost/impact	Description
Debris-related damage	Loss of functionality or loss of entire satellites. Many incidents go unreported.
Satellite and constellation design	Costs associated with satellite shielding, collision avoidance capabilities, safehold modes and redundancies (i.e. launch extra satellites as spares). Satellite constellations increasingly include spares for system resilience, but this solution often becomes part of the problem.
Operations costs	Costs of space situational awareness activities, services and software. Data blackouts when conducting avoidance manoeuvres.
Orbit clearance costs	In the geostationary orbit: Relatively low, equivalent to about three months of station-keeping. In the low-earth orbit at an altitude above 650 km: Very high and requiring specific satellite subsystems (on-board computer).
Insurance costs	Overall, limited use of in-orbit insurance by operators for space debris. Space debris collisions have historically been considered low probability and not affecting insurance premiums.

Source: Based on Undseth, Jolly and Olivari (2020^[24]), "Space sustainability: The economics of space debris in perspective", <https://doi.org/10.1787/a339de43-en>.

There are also all the costs associated with debris surveillance, tracking and reporting. Based on research by Oltrogge et al. (2021^[32]), monthly one-kilometre conjunctions (i.e. close encounters with other space vehicles or debris) in LEO may have increased fourfold between 2017 and 2021, from 1 400-2 400 (depending on the data source) average monthly conjunctions to more than 6 000. This puts severe additional stress on individual operators as well as government agencies managing debris and space traffic.

While data are limited, some estimates indicate that costs associated with protective shielding and avoidance manoeuvres may amount to some 5-10% of total mission costs (National Research Council, 2011^[31]). Orbit clearance costs, which depend on the orbit of the satellite, are not included in this estimate. It is presumed that the relative costs of debris mitigation measures are an important determinant of an operator's compliance with government regulations and guidelines.

As for costs associated with debris-related damage, also here little is known, as only a limited number of operators share information about such events (Table 2.5). This may contribute to creating a false sense of security among operators.

Table 2.5. Selected possible debris impact events in LEO

Satellite/event	Country of operator	Altitude	Anomaly date	Details
SUNSAT	South Africa	400-838 km	19/01/2001	Irreversible multi-point physical failure
JASON-1	United States/ France	1 336 km	03/2002	Impulse of 0.365 mm/s from GPS residuals; hit left solar array from behind; lost 10% of array struck; orbit change of 30 cm
Cosmos 539	Russia	1 340-1 380 km	21/04/2002	Decrease in period of 1 sec. with a 20 cm x 50 cm object created
JASON-1	United States/ France	1 336 km	09/2005	Impulse of 0.182 mm/s from GPS residuals; orbit change of 10 cm
EOS-Terra	United States	705 km	13/10/2009	One battery cell in hexbay unit and heater failed simultaneously with attitude disturbance; 3 mm impactor suggested
Aura	United States	685 km	12/03/2010	Solar panel #11 lost 50% of power

Satellite/event	Country of operator	Altitude	Anomaly date	Details
Pegaso	Ecuador	650-654 km	22/05/2013	Close pass to rocket body but no hit
Iridium-47	United States	785-795 km	07/06/2014	Ten high velocity (80 m/s) debris produced hinting at impact
Iridium-91	United States	785-795 km	30/11/2014	Four low-velocity debris produced insinuating an on-board anomalous event
WorldView-2	United States	770 km	19/07/2016	Nine pieces detected, but WorldView says satellite is still working
Sentinel-1A	Europe	693 km	23/08/2016	Six to eight pieces produced (6 catalogued) and visual verification of solar array damage; impactor of 1 cm and 0.2 gr at 11 km/s
YunHai 1-02	China (People's Republic of)	780 km	18/03/2021	Collision with debris from a Russian Zenit-2 rocket; 37 debris objects detected; satellite remains operational

Source: Based on Swiss Re Corporate Solutions (2018^[25]), "New space, new dimensions, new challenges: How satellite constellations impact space risk", cited in Undseth, Jolly and Olivari (2020^[24]), "Space sustainability: The economics of space debris in perspective", <https://doi.org/10.1787/a339de43-en>.

Longer term costs

The longer term costs of space debris could be of a quite different order of magnitude than current costs. In a worst-case scenario, the Kessler Syndrome, as described above, could render certain orbits unusable. This would have considerable negative impacts on the provision of several important government services and would most probably also curb economic growth and further development in the space sector. The societal costs would be unequally distributed, with some rural regions harder hit, given their growing dependence on satellite communications in particular. Regions that have limited surface observations for, e.g. weather forecasting, would also be disadvantaged. These tend to be lower income countries.

Table 2.6 presents a non-exhaustive selection of possible future costs and other impacts of space debris that are discussed in this section.

Table 2.6. Selected potential longer term costs of space debris

Type of cost/impact	Description
Loss of unique applications and functionalities	Space observations from some of the orbits most vulnerable to space debris are often the best or the only source of data and signals in their domain. This applies in particular to polar-orbiting weather and earth observation satellites. The loss of polar-orbiting weather satellite observations would heavily affect the southern hemisphere, where there are fewer terrestrial observations.
Growing risks to lives	The International Space Station and the Chinese Space Station are inhabited and located at an altitude of about 400 km. More space stations are under consideration. Although debris at that altitude decays naturally, it still poses a real collision threat.
Interrupted time series for earth science and climate research	Uninterrupted time series are crucial for the accuracy and reliability of weather prediction and climate models.
Curbed economic growth and slowdown in investments in the sector	Satellite broadband is widely considered to be a key driver of space activities and revenues in the coming decades. More than ten broadband satellite constellations are in various stages of development. Practically all low-earth orbit communication services would be affected, on orbit and/or during orbit-raising, as most constellations are located near or above the thickest low-earth orbit debris belts. Reduced access to venture finance, with investors preferring more affordable and less risky terrestrial alternatives.
Distributional effects	The loss or perturbation of certain low-earth orbits could be felt more heavily in rural low-density residential areas and low-income countries.

Source: Undseth, Jolly and Olivari (2020^[24]), "Space sustainability: The economics of space debris in perspective", <https://doi.org/10.1787/a339de43-en>.

Disruption to or loss of certain LEOs would in some cases have severe impacts on terrestrial applications, especially those for which space observations from these orbits are either the best or the only source of data and signals. This applies in particular to polar-orbiting weather and earth observation satellites, which make unique contributions to weather forecasting and climate change observations and research. The orbits most likely to be disrupted by the Kessler Syndrome are found at 650-1 000 km and at an altitude of almost 1 400 km in the low-earth orbit, where the thickest debris belts are also located (Table 2.7).

Table 2.7. Affected orbits and space applications

Application	Altitude	Examples of current missions
Human spaceflight	400 km	International Space Station
Weather forecasting	800-830 km	All polar-orbiting satellites in the World Meteorological Organization's Global Observing System, belonging to the People's Republic of China, Europe, Russia, the United States (e.g. Metop, JPSS)
Earth observation	780-900 km	Several earth observation missions, e.g. Sentinel-2/3/5P (Europe), Megha-Tropiques and Saral (France/India), Resourcesat-2 (India). The majority of earth observation missions are in lower orbits (600-700 km).
Communications (telephony, broadband [future])	700-800 km and 1 200-1 400 km	Current low-earth orbit satcom providers include Iridium and Globalstar (United States). Multiple 100+ constellations are planned in the coming years.

Source: Undseth, Jolly and Olivari (2020^[24]), "Space sustainability: The economics of space debris in perspective", <https://doi.org/10.1787/a339de43-en>.

Several services and applications would be considerably affected:

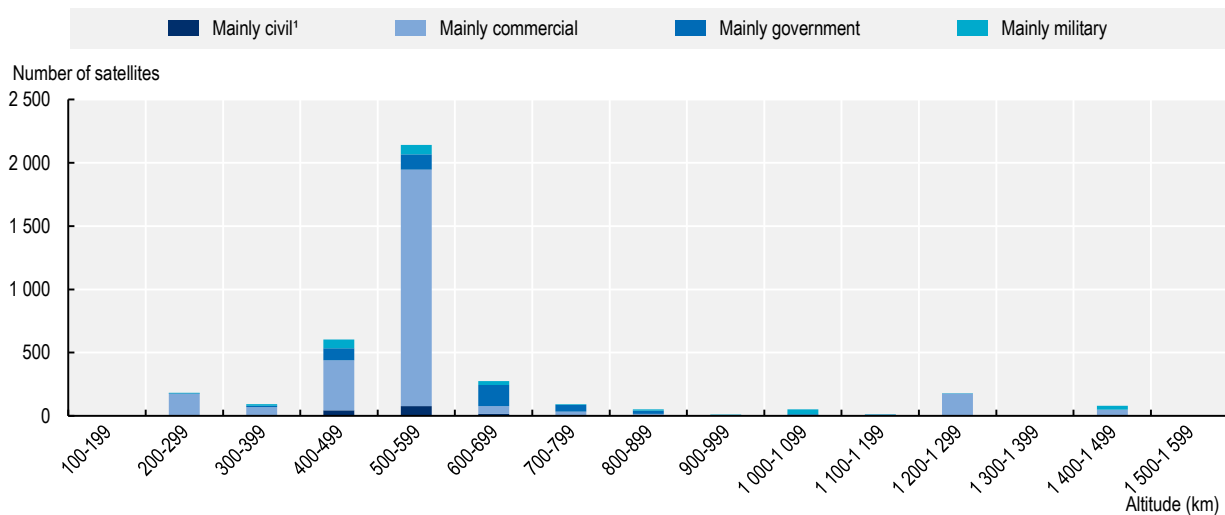
- **Current human spaceflight activities:** The International Space Station and the Chinese Space Station are both located at an altitude of about 400 km. Although debris at that altitude decays naturally, on re-entry into the atmosphere, it still poses a real collision threat. The International Space Station has seen a substantial increase in debris avoidance manoeuvres, with 17 manoeuvres taking place between 2009 and 2017, compared to 8 in the period 1999-2008 (Peters et al., 2013^[33]; Liou, 2018^[34]). In 2020 alone, three manoeuvres were conducted (NASA, 2021^[35]). After the destruction of the Russian satellite Kosmos-1408, the seven-member International Space Station crew had to take shelter in the docked return capsules, to allow for a potential emergency evacuation of the station.
- **Earth and weather observations:** Placing satellites in sun-synchronous orbits (an altitude of about 600-800 km) makes it possible to pass over any given point on Earth at the same time every day, or to place the satellite's solar panels in constant sunlight. Sun-synchronous orbits are particularly useful for the Earth, weather and climate observation, and military intelligence.
In terms of value and societal benefits, UK estimates of benefits from satellite-based meteorological observations to the UK economy range between GBP 670-1 000 million annually (Innovate UK, 2018^[36]). Polar-orbiting weather satellites provide essential inputs to numerical weather prediction models, reducing errors and improving forecast accuracy (EUMETSAT, 2014^[37]). The loss of polar-orbiting weather satellite observations could particularly affect the southern hemisphere, where there are fewer terrestrial observations. Several weather and earth observation satellites in potentially affected orbits also make unique measurements for climate observations, such as variations in sea surface height, the speed and direction of ocean currents, and heat stored in the ocean. There is also a growing number of commercial earth observation satellites in these orbits (Figure 2.5).
- **LEO constellations for satellite communications:** Practically all current and future LEO communication services could be affected by space debris, on orbit and/or during orbit-raising, as most constellations are located near or above the thickest LEO debris belts. There are currently two commercial communications constellations in the low-earth orbit offering satellite telephony

services: Globalstar (at 1 400 km) and Iridium (780 km). So far, the value of commercial operations in LEO is significantly lower than that of telecommunications activities in geostationary orbit. However, as previously noted in this chapter, satellite broadband is widely considered to be a key driver of space activities and revenues in the coming decades, although the profitability and viability of business models remain unproven.

- **Unequal distribution of effects:** The loss or perturbation of certain LEO could be felt more heavily by some groups and geographic regions than others. In some low-income countries, satellite systems may compensate for or complement surface observations or socio-economic survey data. They may furthermore provide connectivity. Indeed, one of the big advantages of space broadband is its ability to connect remotely located areas, including rural regions in both developed and developing countries.

Figure 2.5. Operational satellites by type of operator and orbit altitude in low-earth orbits

As of September 2021



1. Refers to academic and other "amateur" operators (e.g. of amateur radio satellites).

Note: All categories include a small number of dual-use missions (e.g. government-military).

Source: Union of Concerned Scientists (2021^[6]), "UCS Satellite Database: September 2021 update", <https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database>.

Furthermore, the potential onset of the Kessler Syndrome would most likely curb space sector growth. Investment would probably be diverted to other sectors, with investors preferring more affordable and less risky terrestrial alternatives. Also, demand for existing services and segments, such as manufacturing and launch, would slow down. Chapters 3 and 4 provide theoretical frameworks for identifying and quantifying the different costs of space debris.

Addressing the problem

In the last 20 years, numerous measures have been taken at both the international level and in individual countries to improve the capacity to track debris and manage space traffic as well as incentivise operators to create less debris in the first place. A fairly recent addition to this policy portfolio is debris remediation, such as active debris removal or attempts to "nudge" debris out of orbital pathways.

*Efforts to mitigate and remediate space debris***Avoiding collisions**

To protect operating satellites and avoid collisions that generate further debris, governments and private actors keep track of their assets and those of other actors, to their best ability. Space situational awareness can be defined as the “knowledge and characterisation of space objects and their operational environment to support safe, stable, and sustainable space activities” (The White House, 2018^[38]). Effective space situational awareness and space traffic management rely on the co-ordinated efforts of military, civilian and commercial operators and space object trackers, all of which hold essential, but incomplete, data and information about the position of their own and others’ space assets. Considering the size of the space environment, this is a daunting task.

The US Space Force has the largest government surveillance and tracking system in place, relying on terrestrial and space-based observatories, and providing conjunction warnings to more than 100 private and government operators worldwide through data-sharing agreements. Other countries (e.g. China, France and the Russian Federation) also have space tracking radars and telescopes. The Indian Space Research Organisation inaugurated a new dedicated control centre for space situational awareness in 2020, underlining the need to enhance national capabilities.

Several regional organisations have countries working together to pool national resources. The International Scientific Optical Network, co-ordinated by the Keldysh Institute of Applied Mathematics in the Russian Federation, is a global network of telescopes for monitoring space debris and other objects, with sensors in more than a dozen countries. In Europe, the European Union supports a Consortium for European Space Surveillance and Tracking (EUSST), with Consortium members providing surveillance and tracking services to all EU countries, institutions, and public and private operators. The China-led Asia Pacific Space Cooperation Organisation, including Bangladesh, Iran, Mongolia, Pakistan, Peru, Thailand and the Republic of Türkiye, is sharing data and developing a network of sensors, the Asia Pacific Optical Space Observation System.

In both GEO and LEO, private capabilities in space situational awareness have also considerably improved over the last decade, with growing deployment of both terrestrial and space sensors and improved software solutions. Other initiatives, such as the Space Data Association, allow commercial satellite operators to share flight dynamics information, which is combined with other space object information and used to provide conjunction assessment and warning services.

Still, current space tracking capabilities have several shortcomings.

- Government conjunction assessment services, which are free of charge and commonly used by operators, remain inaccurate and do not provide essential data, such as, for example, debris and satellite object dimensions and mass or spacecraft altitude (Oltrogge and Alfano, 2019^[39]). As a result, operators still need to make their own assessment of the collision risk, and, due to a high and growing frequency of conjunction warnings and notable costs associated with moving the satellite, may choose to ignore some of them. Operators’ interpretation of collision risk is highly subjective.
- The United States Air Force currently catalogues and tracks more than 20 000 of the biggest debris objects (10 cm and above). This is deemed to represent less than 0.02% of the total estimated debris population. New sensors, like the recently deployed “Space Fence” observatory, make it possible to detect objects as small as 5 cm in LEO, doubling the space object catalogue (Hejduk, 2019^[40]), but the large majority of potentially harmful debris will remain undetected.
- Space tracking organisations rely entirely on the co-operation of space operators to identify space objects. The trend to deploy multiple spacecraft per launch makes this more difficult, as does the increasing number and diversity of operators.

A further complication is the shortcomings in space traffic management. Space traffic management can be defined as “the planning, coordination, and on-orbit synchronisation of activities [...]” (The White House, 2018^[38]), managing for instance close encounters between two operational satellites or between an operational satellite and debris. Unlike comparable sectors such as air or maritime traffic, there is a lack of international standardised approaches for space traffic (ESPI, 2020^[41]), as there are:

- no protocols handling close conjunctions
- arbitrary best practices for collision alerts
- ad hoc co-ordination procedures between operators.

National practices vary, but government agencies in Europe and the United States report that current collision avoidance processes are often manual and ad hoc (ESA, 2019^[42]), and that practices for “right of way” are negotiated on a bilateral basis (Foust, 2021^[43]).

Two recent episodes, both incidentally involving SpaceX’ Starlink satellites, illustrate this disquieting situation, where operators rely on e-mails and telephone calls for communication and assess collision risk very differently. In 2019, ESA had to conduct an avoidance manoeuvre for its Aeolus satellite in low-earth orbit, as a Starlink satellite was temporarily lowered to the region already occupied by the Aeolus satellite and came within a distance that surpassed the collision risk probability threshold of 1 in 1 000 (ESA, 2019^[42]). Operators for both satellites were in contact before and after the manoeuvre, but SpaceX later communicated that a communications bug prevented the Starlink operator from seeing the correspondence announcing the increased collision risk probability. In 2021, the UK communications operator OneWeb moved one of its satellites after receiving a close conjunction warning from the US Space Force, and later claimed that SpaceX was either unable or unwilling to move its satellite. SpaceX later reported that the incident was below its probability threshold for executing an avoidance manoeuvre (Foust, 2021^[43]).

Governments across the world are taking steps to address the current situation, but progress is slow, with high stakes involved. Space traffic management has a strong military dimension, which creates its own set of challenges, and, more practically, systems need to be created for data sharing and fusion between agencies and different types of public and private actors. Beyond the aspects of safer space operations, there are also considerable first-mover advantages involved in the regulation of space traffic, favouring national standards and industry practices, as well as ensuring national or regional sovereignty of systems. Consequently, industry associations are mobilising to call for government action (see, for instance, Eurospace (2021^[44])).

The United States has been working on the reorganisation of space traffic management for several years. It aims to move commercial traffic management from the Department of Defense to the Department of Commerce, as set out in the US Space Policy Directives 2 and 3. The initiative also foresees the creation of an open-architecture data-sharing platform, combining different data from both government and private data sources. The Office for Space Commerce is also tasked with co-ordinating activities across US agencies to create and update standards, practices and guidelines related to debris mitigation and space traffic management, which will be integrated into respective licensing processes. The process was still ongoing in December 2021. In Europe, the European Commission is supporting the SPACEWAYS project that will inform and shape future space traffic management activities in the region.

Remediating debris

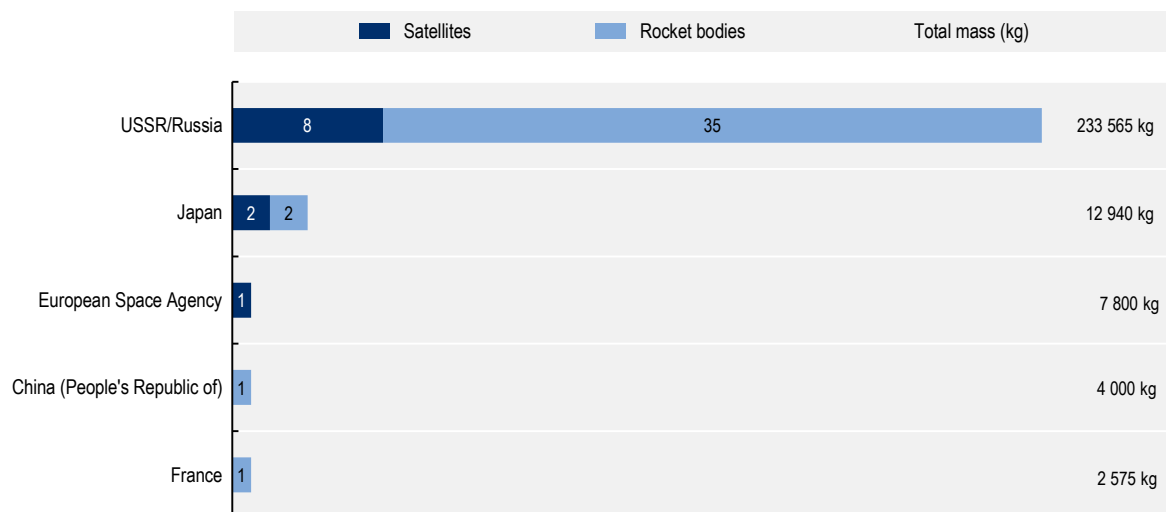
The strict application of space debris mitigation measures is inevitably needed to preserve the Earth’s orbital environment. But some studies have shown that this in and of itself would not be enough to stabilise the debris population and that debris would need to be actively removed from orbit (Liou and Johnson, 2006^[45]; Liou, Johnson and Hill, 2010^[46]).

Active debris removal faces several technological, geopolitical and economic challenges. It is technologically challenging, as it involves far- and close-proximity operations with (non co-operating) space platforms moving at speeds of several kilometres per second. Success is not guaranteed, and there is a notable risk of further debris creation. It is also very costly, involving the manufacturing and launch of dedicated, disposable, debris removal vehicles. Furthermore, the retrieval of debris could involve sharing potentially sensitive data about the debris object's design that could involve national security, foreign policy, intellectual property, etc. (National Research Council, 2011^[31]). Therefore, countries would realistically be limited to removing their own satellites or those of close military allies.

A global consortium has put together a “top 50” list of candidates for active debris removal in low-earth orbit, combining several risk factors of high mass, orbit, inclination, etc. (McKnight et al., 2021^[47]). This mainly includes rocket bodies (39 out of the 50, as illustrated in Figure 2.6), several of which weigh several metric tonnes. Launch activity from the former USSR/Russian Federation accounts for 43 out of the 50 objects and 90% of the total mass. The vast majority of objects were launched before 2000.

Figure 2.6. Top 50 most “concerning” orbital debris objects

Number of satellites and rocket bodies by launch country/institution, with associated total mass



Source: Based on McKnight et al. (2021^[47]), “Identifying the 50 statistically-most-concerning derelict objects in LEO”, <https://doi.org/10.1016/j.actaastro.2021.01.021>.

Despite these underlying challenges, both public and private initiatives are underway, after years of technology development. Several technology demonstration missions are scheduled for the early 2020s, e.g. the ESA’s ClearSpace-1 and the Japanese Commercial Removal of Debris Demonstration (CRD2) mission. Chapter 7 provides a detailed account of the emergence of an active debris removal market.

Alternative solutions that are being explored include “just-in-time” collision avoidance approaches, which could be employed in the case of an imminent collision between derelict objects. The use of space- or ground-based lasers could potentially “nudge” one of the objects out of harm’s way (but it would remain in orbit). Alternative solutions envisage the insertion of an artificial atmosphere in front of one of the colliding debris objects to induce a drag and modify its orbital parameters (Bonnal et al., 2019^[48]). All legal, technological and economic hurdles aside, these approaches depend on a much more accurate capability of space situational awareness and space tracking than exists today.

Creating incentives for operators

Considering the current levels of launch activity, operators' actions to mitigate debris creation are key to stabilising the orbital environment. Voluntary guidelines and recommendations are the main tools for incentivising operators to minimise debris. The first international guidelines were drafted by the IADC in 2001 (Box 2.3). The IADC regroups 13 of the most active space agencies in the world and co-ordinates space debris research and mitigation activities.

One of the most important recommendations is post-mission orbit clearance, i.e. moving post-mission GEO satellites to a graveyard orbit and deorbiting post-mission LEO satellites (or manoeuvring them to an orbit from which natural decay occurs within a maximum of 25 years) (IADC, 2007^[49]). The IADC stipulates that some 90% of future launches would need to comply with orbit clearance guidelines over the next 100 years to stabilise the LEO environment (IADC, 2013^[27]). These efforts have been followed by other international guidelines, recommendations and standards, such as recommendation ITU-R S.1003-2 (2010) for the GEO orbit, or the engineering standards ISO 24113:2019 from the International Organisation for Standardisation.

Box 2.3. Debris mitigation guidelines and regulations

The Inter-Agency Debris Coordination Committee issued Space Debris Mitigation Guidelines in 2001 and updated them in 2007 (IADC, 2007^[49]). These and similar space agency guidelines aim to:

- Limit space debris released during normal operations: Payloads and rocket bodies should be designed to not release debris during normal operations. Where this is not feasible, any release of debris should be minimised in number, area and orbital lifetime. If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.
- Minimise the potential for in-orbit break-ups: In all operational regimes, the potential for break-ups during operational phases should be minimised, e.g. increase (sub)system reliability, minimise the potential for post-mission break-ups resulting from stored energy (stored in tanks, batteries, etc.).
- Avoid intentional destruction and other harmful activities.
- Post-mission disposal in low-earth orbit (LEO) and geostationary orbit (GEO): Permanent or (quasi-) periodic non-functional man-made objects should be cleared from orbit. For payloads in LEO, this involves active or passive deorbiting within 25 years of mission completion. GEO payloads should be moved to a graveyard orbit.
- Prevention of in-orbit collisions: Mission projects should estimate and limit the probability of accidental collisions with known objects during the payload or rocket body's orbital lifetime.
- In 2018, the 92 members of the United Nations' Committee on the Peaceful Uses of Outer Space approved a much wider set of 21 long-term sustainability guidelines (UN COPUOS, 2018^[50]). The guidelines address a range of issues related to space sustainability (e.g. debris, radio frequency spectrum use, space weather) and call for improved registration and supervision of space objects and activities. They also underline the importance of data collection, sharing and modelling for both space debris and space weather incidents.

The first national provisions appeared in the 1990s, and a growing number of countries have integrated the international framework or parts thereof into laws, technical standards, guidelines, etc. (at least 19 countries by the end of 2019 (Undseth, Jolly and Olivari, 2020^[24])) or are adding new provisions. For instance, in 2019, the United States updated its Orbital Debris Mitigation Standard Practices for the first time since 2001, introducing, among other things, new quantitative limits on debris-producing events and

addressing more recent issues such as the operation of cubesats (miniaturised satellites consisting of one or several stacked 10 cm cubes), large constellations and satellite servicing. New Zealand has launched the pilot “Space Regulatory and Sustainability Platform” to track space objects launched from the country and monitor compliance with permit conditions (MBIE, 2019^[51]). France and the United Kingdom require satellite operators to have in-orbit third-party liability insurance. The UK provision includes a risk-based sliding scale (UK Space Agency, 2018^[52]). France, furthermore, introduced legally binding debris mitigation requirements in 2011.

The private sector and society are also taking steps unilaterally. The Space Safety Coalition was formed in 2019 to promote space safety through the voluntary adoption of international standards, guidelines and practices. The coalition, which includes more than 20 space operators, space industry associations and space industry stakeholders, has published a set of “Best Practices for the Sustainability of Space Operations”, building on international guidelines (SSC, 2019^[53]). At the 2021 edition of the Paris Peace Forum, the global governance equivalent to the World Economic Forum in Davos, the Net Zero Space initiative was launched, in which public and private actors pledged to take concrete actions to reduce orbital debris by 2030 (Paris Peace Forum, 2021^[54]). A third initiative is the Sustainable Space Rating, jointly developed by the World Economic Forum, the European Space Agency and the Massachusetts Institute of Technology, together with the BryceTech consultancy group and the University of Texas at Austin and now led by the Swiss Federal Institute of Technology Lausanne in Switzerland. It has specifically been developed to “help reduce space debris and help ensure [...] space missions are managed safely and sustainably” (eSpace, 2021^[55]). The rating aims to score space missions based on, for example, “evidence-based debris mitigation and alignment with international guidelines.”

Due to the sometimes considerable time lag between a satellite’s launch and its orbit clearance, it will take time to assess the overall effects of these efforts. Some 20% of French-licensed satellites in LEO with an end-of-life in the 2000-15 range and with a de/re-orbit capacity have so far performed a deorbit manoeuvre, after France made it compulsory in 2011 (Cazaux, 2017^[56]). In Italy, researchers have observed an increased compliance with debris remediation measures after Italy adopted international guidelines in the early 2000s (Anselmo and Pardini, 2015^[57]). Indeed, a positive trend in compliance with orbit clearance guidelines can be observed after 2000, but compliance remains highly dependent on the orbits considered and is generally too low to stop further debris accumulation:

- In GEO, satellite clearance surpasses 80% of satellites with an end-of-life in 2019, especially for more recent satellites with an end-of-life after 2000.
- In LEO, almost 75% of payloads with an end-of-life in 2019 cleared their orbits. However, for payloads that are not naturally compliant, the share decreased to less than 20% (ESA, 2021^[58]), as shown in Figure 2.7. It has also been argued that the positive signs observed in recent years may be skewed by SpaceX’s good performance in orbit clearance (Boley and Byers, 2021^[10]).

Overall, many commercial LEO operators lack economic incentives to adhere to voluntary guidelines:

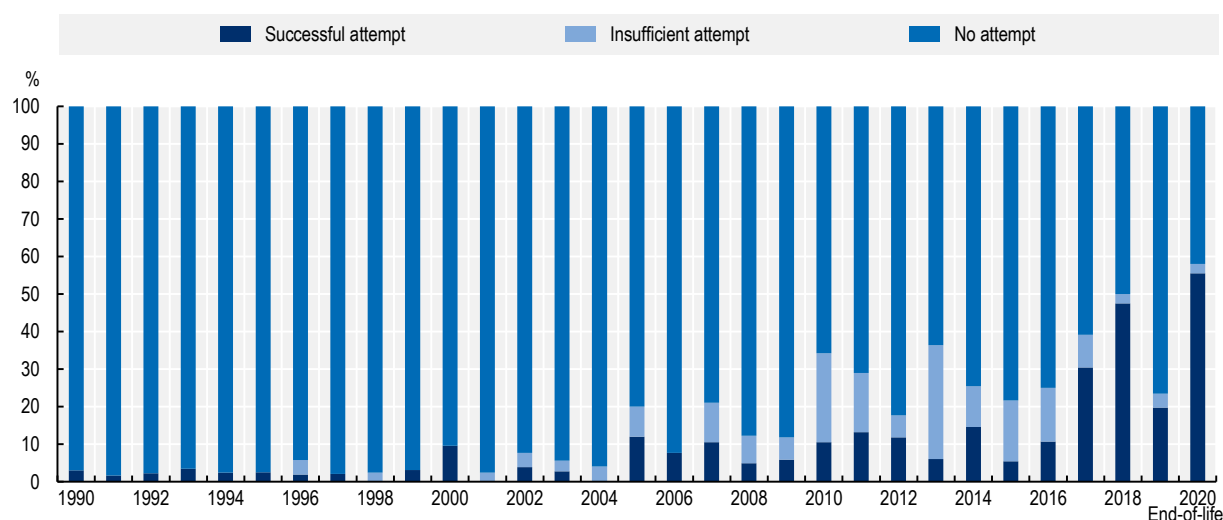
- As already noted above, actively deorbiting a spacecraft in LEO can be expensive for operators. As a ratio of total mission costs, more fuel is needed for deorbiting or moving a spacecraft in LEO to a lower orbit than to move a spacecraft in GEO to a graveyard orbit. It also requires specific equipment, such as an on-board computer and fuel systems.
- Satellites in LEO are becoming increasingly “expendable.” Satellites are becoming relatively affordable to manufacture and launch, often have short mission lives, and are launched in constellations that are more resilient to in-orbit failures and other incidents.
- Compliance with guidelines is difficult to control by regulators, who rely on data from satellite operators to identify and name space objects. In addition, non-compliance often bears few or no consequences, especially considering the long time lags between the launch and orbit clearance.

- Operators do not have sufficient knowledge to fully calculate and address technical and commercial risks involved in orbital space activities. Although observations and modelling are improving in different parts of the world, the number and nature of objects recorded in existing debris catalogues do not accurately reflect reality.

This stands in contrast to GEO operators, which have a common interest in keeping the orbit as debris-free as possible to avoid collisions, and for which the mitigation measures remain relatively affordable.

Figure 2.7. A minority of satellites are cleared from low-earth orbits above 650 km within the recommended 25 years after mission completion

Payload clearance attempts in low-earth orbits above 650 km altitude



Notes: Payloads refer to space objects designed to perform a specific function in space, excluding launch functionality (e.g. satellites, space probes). Payload clearance in the low-earth orbit compliant with debris mitigation guidelines involves deorbiting within 25 years of mission completion. Objects may be naturally compliant (cleared from orbit by atmospheric drag), but clearance above 650 km altitude requires a disposal action for it to occur within the recommended time frame. See also Box 2.2 and Box 2.3.

Source: ESA (2022^[59]), *ESA's Annual Space Environment Report 2022*, https://www.esa.int/Safety_Security/Space_Debris/ESA_s_Space_Environment_Report_2022.

It is important to note that space remains a technologically challenging and failure-prone environment. The share of “insufficient” orbit clearance attempts in LEO varies significantly between years, but can be important. In the last five years, insufficient clearance attempts as a share of total end-of-life payloads fluctuated between some 20% in 2015 and less than 5% in 2020 (ESA, 2022^[59]).

Governments are currently exploring several ways to improve compliance rates, for example through regulations or more market-based approaches, but they lack the evidence to evaluate the effects of different policy options, for instance in terms of socio-economic impacts or levels of popular acceptance. The following chapters address some of these knowledge gaps. Chapters 3 and 4 provide theoretical frameworks for identifying and quantifying the different costs of space debris. Chapter 5 looks at the benefits that space-based earth observation infrastructure brings to specific industry segments in Italy. Chapters 6 and 8 model the effects of different mitigation strategies. Chapter 7 reviews the conditions for creating a market for active space debris removal. Finally, Chapter 9 takes a different approach altogether, looking at how space debris may be reduced through more efficient use of space-based infrastructure.

It follows from the above that for OECD countries and the world as a whole, it is becoming increasingly urgent to better account for and protect space-based infrastructure, as well as the orbital environment.

References

- Abt Associates (2017), *Social and Economic Impacts of Space Weather in the United States*, study commissioned by the National Oceanic and Atmospheric Administration, Washington, DC, <https://www.weather.gov/media/news/SpaceWeatherEconomicImpactsReportOct-2017.pdf> (accessed on 24 January 2022). [15]
- Ahmad, N. et al. (2018), “Diagnosing low earth orbit satellite anomalies using NOAA-15 electron data associated with geomagnetic perturbations”, *Earth, Planets and Space*, Vol. 70/1, <https://doi.org/10.1186/s40623-018-0852-2>. [17]
- Anselmo, L. and C. Pardini (2015), “Compliance of the Italian satellites in low Earth orbit with the end-of-life disposal guidelines for space debris mitigation and ranking of their long-term criticality for the environment”, *Acta Astronautica*, Vol. 114, pp. 93-100, <https://doi.org/10.1016/j.actaastro.2015.04.024>. [57]
- Boley, A. and M. Byers (2021), “Satellite mega-constellations create risks in low earth orbit, the atmosphere and on Earth”, *Scientific Reports*, Vol. 11/1, <https://doi.org/10.1038/s41598-021-89909-7>. [9]
- Bonnal, C. et al. (2019), “Just-in-time collision avoidance (JCA) using a cloud of particles”, *1st International Orbital Debris Conference*, 9-12 December, Houston, <https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6062.pdf> (accessed on 17 February 2020). [48]
- Bryce Tech (2021), *State of the Satellite Industry Report 2021*, Satellite Industry Association, Washington, DC, https://brycetech.com/reports/report-documents/SIA_SSIR_2021.pdf (accessed on 21 February 2022). [7]
- Canadian Space Agency (2017), “Space weather over Canada”, web page, <http://www.asc-csa.gc.ca/eng/sciences/space-weather.asp> (accessed on 23 November 2018). [14]
- Cazaux, C. (2017), “Overview on 2016 space debris activities in France”, CNES presentation at UN COPUOS Scientific and Technical Subcommittee, Vienna, <http://www.unoosa.org/documents/pdf/copuos/stsc/2017/tech-13E.pdf> (accessed on 11 June 2019). [56]
- ESA (2022), *ESA’s Annual Space Environment Report 2022*, European Space Agency, https://www.esa.int/Safety_Security/Space_Debris/ESA_s_Space_Environment_Report_2022. [59]
- ESA (2021), *Annual Space Environment Report 2021*, European Space Agency, Darmstadt, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf (accessed on 24 June 2021). [58]
- ESA (2021), “Space debris by the numbers”, web page, http://m.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers (accessed on 15 March 2019). [23]
- ESA (2019), *Annual Space Environment Report 2019*, European Space Agency, Darmstadt, <http://www.esa.int> (accessed on 13 March 2019). [22]

- ESA (2019), “ESA spacecraft dodges large constellation”, web page, [42]
https://www.esa.int/Safety_Security/ESA_spacecraft_dodges_large_constellation (accessed on 1 November 2019).
- eSpace (2021), “eSpace to operate the Sustainable Space Rating by 2022”, news release, 17 [55]
 June, https://espace.epfl.ch/2021/06/17/espace-to-operate-the-sustainable-space-rating-by-2022/?doing_wp_cron=1648834987.7433431148529052734375.
- ESPI (2020), *Towards a European Approach to Space Traffic Management: Full Report*, ESPI [41]
 Report 71, European Space Policy Institute, Vienna, <https://espi.or.at/downloads/send/2-public-espi-reports/494-espi-report-71-stm> (accessed on 16 June 2020).
- EUMETSAT (2014), *The Case for EPS/Metop Second Generation: Cost Benefit Analysis – Full [37]
 Report*, European Organisation for the Exploitation of Meteorological Satellites, Darmstadt, https://www-cdn.eumetsat.int/files/2020-04/pdf_report_eps-sg_cost-benefit.pdf (accessed on 5 June 2018).
- Foust, J. (2021), “From space traffic awareness to space traffic management”, *Space News*, 20 [43]
 October, <https://spacenews.com/from-space-traffic-awareness-to-space-traffic-management> (accessed on 29 November 2021).
- Galland, C. (2021), *Space Traffic Management (STM): An Opportunity to Seize for the European [44]
 Space Sector*, Eurospace, <https://eurospace.org/eurospace-position-paper-space-traffic-management-stm-an-opportunity-to-seize-for-the-european-space-sector/> (accessed on 2 December 2021).
- Hejduk, M. (2019), “Conjunction assessment Space Fence update”, National Aeronautics and [40]
 Space Administration, <https://ntrs.nasa.gov/api/citations/20190033388/downloads/20190033388.pdf> (accessed on 29 November 2021).
- Highfill, T., A. Jouard and C. Franks (2020), “Preliminary estimates of the US space economy, [8]
 2012-2018”, *Survey of Current Business* 100, December, US Bureau Economic Analysis, Washington, DC, <https://apps.bea.gov/scb/2020/12-december/1220-space-economy.htm> (accessed on 21 June 2021).
- Horne, R. et al. (2013), “Space weather impacts on satellites and forecasting the Earth’s electron [19]
 radiation belts with SPACECAST”, *Space Weather*, Vol. 11/4, pp. 169-186, <https://doi.org/10.1002/swe.20023>.
- IADC (2013), *Stability of the Future LEO Environment*, Inter-Agency Debris Coordination [27]
 Committee, https://www.iadc-home.org/documents_public/file_down/id/4134 (accessed on 14 March 2019).
- IADC (2007), *IADC Space Debris Mitigation Guidelines*, Inter-Agency Space Debris Coordination [49]
 Committee.
- ICSDEM (2022), *International Disasters Charter website*, [4]
<https://disasterscharter.org/web/guest/about-the-charter> (accessed on 5 April 2022).

- Innovate UK (2018), *Value of Satellite-Derived Earth Observation Capabilities to the UK Government Today and by 2020: Evidence from Nine Domestic Civil Use Cases*, study carried out by London Economics, Innovate UK, London, <https://londoneconomics.co.uk/wp-content/uploads/2018/07/LE-IUK-Value-of-EO-to-UK-Government-FINAL-forWeb.pdf> (accessed on 25 February 2019). [36]
- ITU (2015), *Collection of the basic texts adopted by the Plenipotentiary Conference 2015*, International Telecommunications Union, Geneva, <http://search.itu.int/history/HistoryDigitalCollectionDocLibrary/5.21.61.en.100.pdf> (accessed on 15 March 2019). [21]
- Kessler, D. and B. Cour-Palais (1978), "Collision frequency of artificial satellites: The creation of a debris belt", *Journal of Geophysical Research*, Vol. 83/A6, p. 2637, <https://doi.org/10.1029/JA083iA06p02637>. [30]
- Liou, J. (2018), "US space debris environment, operations, and research update", *55th Session of the Scientific and Technical Subcommittee Committee on the Peaceful Uses of Outer Space*, United Nations, Vienna, <http://www.unoosa.org/documents/pdf/copuos/stsc/2018/tech-14E.pdf> (accessed on 28 October 2019). [34]
- Liou, J. and N. Johnson (2006), "Risks in space from orbiting debris", *Science*, Vol. 311/5759, pp. 340-341, <https://doi.org/10.1126/science.1121337>. [45]
- Liou, J., N. Johnson and N. Hill (2010), "Controlling the growth of future LEO debris populations with active debris removal", *Acta Astronautica*, Vol. 66/5-6, pp. 648-653, <https://doi.org/10.1016/j.actaastro.2009.08.005>. [46]
- Marsellach Pujolràs, J. (2020), *The Valuation of Impacts of Space Debris on Space-Based Civil Protection Services*, Master's dissertation, University of Cranfield, unpublished. [5]
- MBIE (2019), "New pilot enables Space Agency to track satellites launched from NZ", news release 26 June, New Zealand Ministry of Business, Innovation and Employment, Wellington, <https://www.mbie.govt.nz/about/news/new-pilot-enables-space-agency-to-track-satellites-launched-from-nz> (accessed on 26 July 2019). [51]
- McKnight, D. et al. (2021), "Identifying the 50 statistically-most-concerning derelict objects in LEO", *Acta Astronautica*, Vol. 181, pp. 282-291, <https://doi.org/10.1016/j.actaastro.2021.01.021>. [47]
- NASA (2022), "Orbital Debris Quarterly News", Vol. 26/1, <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNV26i1.pdf> (accessed on 17 February 2020). [29]
- NASA (2021), "Space debris and human Spacecraft", web page, https://www.nasa.gov/mission_pages/station/news/orbital_debris.html (accessed on 2 December 2021). [35]
- NASA (2014), "Carrington-class CME narrowly misses Earth", web page, https://science.nasa.gov/science-news/science-at-nasa/2014/02may_superstorm/ (accessed on 23 November 2018). [13]

- National Research Council (2011), *Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs*, National Academies Press, Washington, DC, <https://doi.org/10.17226/13244>. [31]
- NOAA Space Weather Prediction Center (2022), "Solar cycle progression", web page, <https://www.swpc.noaa.gov/products/solar-cycle-progression> (accessed on 18 February 2022). [20]
- OECD (2020), "The impacts of COVID-19 on the space industry", *OECD Policy Responses to Coronavirus (COVID-19)*, OECD, Paris, <https://www.oecd.org/coronavirus/policy-responses/the-impacts-of-covid-19-on-the-space-industry-e727e36f/>. [3]
- OECD (2019), *The Space Economy in Figures: How Space Contributes to the Global Economy*, OECD Publishing, Paris, <https://doi.org/10.1787/c5996201-en>. [2]
- OECD (2014), *The Space Economy at a Glance 2014*, OECD Publishing, Paris, <https://doi.org/10.1787/9789264217294-en>. [1]
- Oltrogge, D. and S. Alfano (2019), "The technical challenges of better space situational awareness and space traffic management", *Journal of Space Safety Engineering*, Vol. 6/2, pp. 72-79, <https://doi.org/10.1016/j.jsse.2019.05.004>. [39]
- Oltrogge, D. et al. (2018), "A comprehensive assessment of collision likelihood in Geosynchronous Earth Orbit", *Acta Astronautica*, Vol. 147, pp. 316-345, <https://doi.org/10.1016/j.actaastro.2018.03.017>. [26]
- Oltrogge, D., S. Alfano and P. Wauthier (2021), "Evaluation of LEO conjunction rates using historical flight safety systems and analytical algorithms", *Proceedings of the 72nd International Astronautical Congress 2021*, COMSPOC Corporation and Space Data Association, https://comspoc.com/Resources/Papers/20211029_Eval_of_LEO_Conj_Rates_IAC_Dubai_PREPRINT.pdf (accessed on 29 November 2021). [32]
- Paris Peace Forum (2021), "Net Zero Space", web page, <https://parispeaceforum.org/en/initiatives/net-zero-space> (accessed on 30 November 2021). [54]
- Peters, S. et al. (2013), "Research issues and challenges in autonomous active space debris removal", *Proceedings of the 64th International Astronautical Congress*, https://www.researchgate.net/publication/259899538_Research_Issues_and_Challenges_in_Autonomous_Active_Space_Debris_Removal (accessed on 7 June 2019). [33]
- Royal Academy of Engineering (2013), *Extreme space weather: Impacts on engineered systems and infrastructure: Summary report*, Royal Academy of Engineering, London, <https://www.raeng.org.uk/publications/reports/space-weather-summary-report> (accessed on 24 January 2022). [12]
- SpaceX (2022), "Geomagnetic storm and recently deployed Starlink satellites", press release, 8 February, <https://www.spacex.com/updates> (accessed on 10 February 2022). [16]
- SSC (2019), *Best Practices for the Sustainability of Space Operations*, Space Safety Coalition, https://spacesafety.org/wp-content/uploads/2019/11/Endorsement-of-Best-Practices-for-Sustainability_v28.pdf (accessed on 3 February 2020). [53]

- Swiss Re Corporate Solutions (2018), “New space, new dimensions, new challenges: How satellite constellations impact space risk”, Swiss Re Corporate Solutions, Zurich, <https://www.swissre.com/dam/jcr:8bb6ac1d-a158-4b46-b32e-903ae5f89964/how-satellite-constellations-impact-space-risk.pdf> (accessed on 21 May 2019). [25]
- The White House (2018), “Space Policy Directive-3, National Space Traffic Management Policy”, web page (archive), <https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy> (accessed on 26 June 2018). [38]
- UK Space Agency (2018), “Fact Sheet: The UK Space Agency’s new requirements for in-orbit third-party liability insurance”, web page, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/744408/TPL_Insurance_Fact_Sheetsw2.pdf (accessed on 30 June 2019). [52]
- UN COPUOS (2018), *Guidelines for the Long-term Sustainability of Space Activities*, United Nations Committee on the Peaceful Uses of Outer Space, Vienna, http://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf (accessed on 15 March 2019). [50]
- Undseth, M., C. Jolly and M. Olivari (2020), “Space sustainability: The economics of space debris in perspective”, *OECD Science, Technology and Industry Policy Papers*, No. 87, OECD Publishing, Paris, <https://doi.org/10.1787/a339de43-en>. [24]
- Union of Concerned Scientists (2021), “UCS Satellite Database: September 2021 update”, webpage, data as of 1 September 2021, <https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database> (accessed on 20 March 2019). [6]
- University of Southampton (2017), “Biggest ever space debris study highlights risk posed by satellite ‘mega-constellations’”, news release, 19 April, <https://www.southampton.ac.uk/news/2017/04/space-debris-mega-constellations.page> (accessed on 14 March 2019). [28]
- US National Science and Technology Council (2015), *National Space Weather Strategy*, The White House, Washington, DC, https://www.sworm.gov/publications/2015/nsws_final_20151028.pdf (accessed on 24 January 2022). [11]
- US Space Force (2021), *Space-Track.Org website*, 18th Space Control Squadron, update 23 November 2021, <https://www.space-track.org> (accessed on 23 November 2021). [10]
- WMO (2019), “Satellite status”, *WMO Space programme website*, World Meteorological Organization, <https://community.wmo.int/activity-areas/wmo-space-programme-wsp> (accessed on 4 June 2018). [18]

3

An environmental economics framework for measuring the cost of space debris

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This chapter applies an environmental analytical framework and econometric model for estimating the cost of space debris, providing global and national perspectives. Total cost is broken down into three separate domains and the chapter presents the equation and variables for each domain. The chapter notably closely considers external costs and suggests economic measures to internalise them.

Introduction

Since the launch of the first artificial satellite, the Union of Soviet Socialist Republics' (USSR's) Sputnik 1 in 1957, humanity and its space programmes have come a long way. Attempts have been so numerous in the past 60 years that a primary concern has now ironically become the over-exploration of the formerly unexplored. The scenario in which collisions between space objects, including debris and functional objects, end up causing a cascade where each collision creates debris heightening the risk of further collisions, the “Kessler Syndrome”, is transforming from a distant possibility to a daunting reality for today's space community. Meanwhile, tens of thousands of satellites, individually or in the form of mega-constellations, are allegedly in the pipeline to be launched in the next decade. Despite heightened awareness of the problem and the many technical and normative developments, the global response remains insufficient to turn the tides.

This gap between the level of action required for meaningful change and that actually taken is not new. It has been repetitively raised in relation to various environmental problems, a most recent and salient example of which is climate change. As witnessed, some are still largely unaware of or have denied the problem, while others acknowledge the importance yet remain reluctant to change (or incapable of changing) their own behaviours. The analogy can be taken further: both the problems of space debris and climate change are attributable to different countries to different extents, but the damage is transboundary or global in nature. Contrary to early beliefs, neither the space environment nor the natural environment was found to be sufficiently vast enough to be unbounded and immune to unrestrained human activity. Often classified as public goods, characterised by their non-rivalry and non-excludability, both have been prone to overexploitation by human populations, generally assumed to be self-interested. Presumably under similar lines of reasoning, Gerard Brachet, former Chairman of the United Nations Committee on the Peaceful Uses of Outer Space, has also compared the situation to overfishing and marine pollution, a classic case of the tragedy of the commons (Newman and Williamson, 2018^[1]).

Accordingly, the perspective and approach developed in the field of environmental economics may prove useful in the discussion on space debris and preserving space sustainability. Having extensively grappled with how to understand the cause (e.g. lack of property rights, externalities), measure the associated costs and benefits, and find both non-market and market solutions (e.g. Pigouvian tax or subsidy, cap-and-trade system) related to various environmental problems using economic theory, environmental economics holds a unique strength in capturing the most important aspects of a complex problem and providing practical guidance for decision making. Undoubtedly, the approach also has limits, particularly in regard to the assumptions and resulting inability to fully incorporate the uncertainties of the real world. Such issues and limitations will be clarified when relevant and possible throughout this chapter.

Given this, this preliminary research aims to quantify the cost of space debris in monetary terms and introduce economic tools or approaches to solve the problem. It begins, in the next section, by presenting the framework used here to quantify the cost of space debris and identify the impacts or cost categories that require consideration. Rather than starting from scratch, this study reviews and builds upon the socio-economic impacts outlined in Undseth, Jolly and Olivari (2020^[2]). The following section presents ways to quantify the identified cost categories, bringing in valuation methods developed in the field of environmental economics, especially those concerning the valuation of non-market goods, resources or services. Although numbers or ranges cited in previous literature will be included when appropriate and possible, this chapter does not intend to present a decisive monetary estimate of its own, for significant differences will inevitably exist depending on the precise context and conditions of the space mission under evaluation. The last section presents the conclusion and overall discussion, particularly from the perspective of Korea, a latecomer in terms of exploring outer space.

Modelling the cost of impact events

A model from a global perspective

What is the cost of space debris? How should the costs be defined? Suppose a piece of debris hits satellite *A* and a piece of resulting debris from satellite *A* collides with satellite *B*. In the perspective of the country or company that operates satellite *A*, only the damage to satellite *A* will count; the damage costs associated with satellite *B* will not. However, from a global perspective, the damage inflicted on both satellites will count. The costs will further differ depending on the spatial and temporal scope, such as whether the consideration is confined to outer space or includes the Earth and whether the entire history of space exploration, only selected time periods or implications in the future are covered.

As this study aims to develop a model that is both comprehensive and practical, the cost of space debris centres on the costs incurred as a result of collision events, only after which tangible costs arise, and covers both the space and terrestrial environment. This section will present a model for estimation from the global perspective, while the following section will also suggest a method to apply the model at the national level.

The total cost (C_t): Considering the pace at which the space industry and the number of objects in space have grown, the space environment is also expected to change within short time periods. Therefore, this study presents a model that estimates the total cost on a yearly basis, broken down into the costs pertaining to all operating satellites, space stations and shuttles (e.g. the International Space Station, ISS), and the Earth. Put into an equation, the annual cost of space debris in year t is:

$$C_t = C_{St} + C_{It} + C_{Et} \quad (1)$$

where C_{St} represents the costs associated with satellites, C_{It} , the impact on space stations and shuttles, and C_{Et} , the impact on Earth.

The impact on satellites (C_{St}): The costs related to satellites, specifically attributable to the problem of space debris, can be largely grouped into the additional costs incurred during the stages of development, operation and maintenance on the one hand, and the damage costs resulting from collision events on the other.

The additional development and operational costs arise from the need to avoid collision with space debris or to reduce the level of damage, should a collision inevitably take place. Improving satellite and/or constellation designs and enhancing shielding can increase development costs, while the increased mass may also increase launch costs. Insurance costs may increase due to heightened risks and it may be necessary to secure additional resources to obtain information on approaching objects promptly, as well as to perform evasive manoeuvres.

The most substantive consequence of a collision with space debris would be the loss or impairment of payloads. However, the direct and indirect damage costs may also include the interruption of satellite services (e.g. communication and broadcasting), loss of research data and a decrease in investments in related industries.

In modelling such costs, this study makes several assumptions. First, only those collisions that result in the complete loss of satellite functions are considered. This implies that minor scratches, dents or other types of inconsequential damage to satellites or satellite parts are disregarded, if the satellite remains functioning. This is because “impacts that do not have any value to human beings are not counted” in cost-benefit analysis (Boardman et al., 2018^[3]). The second relates to when costs are assumed to arise and hence accounted for. Development costs will have begun to arise well before the launching stage, yet are accounted for in sum in the first year of the satellite’s lifespan. Operational and maintenance costs that arise each year are assumed to be paid for at the beginning of each year, as this is usually when budgets

are set. Lastly, in comparison to costs, the benefits obtained from satellites are assumed to occur at the end of each year.

Given the above, the annual cost borne by satellites can be modelled as:

$$C_{St} = m_t \bar{D} + n_t \bar{O} + \alpha_t \sum_{k=0}^{\bar{y}} \left\{ \frac{\bar{V}}{\bar{l}} \times \frac{1}{(1+r)^{l-k}} \right\} \quad (2)$$

where $\bar{D}$ stands for average development costs and $\bar{O}$ for average annual operational and maintenance costs; both are confined, however, to those costs additionally incurred due to the space debris phenomenon. m_t refers to the number of newly launched satellites in year t and n_t to the total number of satellites in operation in year t , which includes both newly and formerly launched satellites. α_t is the number of satellites that lost their function as a result of a collision with space debris in year t . $\bar{V}$ stands for the average monetary value of satellites, $\bar{l}$ for the average lifespan of satellites and $\bar{y}$ for the average number of years satellites have been in operation. Finally, r is the social discount rate, which is used in cost-benefit analysis to convert future values into present values. In the context of this equation, it comes into account when estimating the benefits obtained from the continued operation of satellites in the future. It must be further noted that, with the exception of $\bar{D}$, all average values are the average of all operating satellites; in the case of $\bar{D}$, the average will concern only newly launched satellites.

Conceptually, the annual cost borne by satellites is the sum of the additional development, operational and maintenance costs arising from the space debris phenomenon and the expected benefits lost due to collision events.

The impact on space stations and shuttles (C_{It}): Although there have not been any fatal incidents so far, the ISS has been under increasing threat of collision with space debris. In 2020 alone, several narrow incidents were reported, followed in the next year by actual or near collisions creating a hole in the station's robotic arm and forcing astronauts on board to prepare for evacuation (see Kettley (2020^[4]) and Ali and Gorman (2021^[5])). Further implications exist concerning the invaluable research conducted at the ISS. With rising attention to space tourism, the threat may extend to various other types of crewed vehicles in the future.

The costs that arise in such cases can be modelled as:

$$C_{It} = \beta_t (\bar{P}_I + \bar{L}_I) \quad (3)$$

where β_t refers to the number of collision events in year t , $\bar{P}_I$ the average cost of damage to space stations and shuttles (including material and non-material aspects), and $\bar{L}_I$ the average cost related to the loss of lives. All are limited to collisions with space debris.

The impact on Earth (C_{Et}): Existing literature rarely takes into account the impact of space debris on Earth when calculating the related costs, presumably because there have not been many reported cases of serious damage to terrestrial ecosystems and creatures. However, such cases, where resources, property or human lives on Earth were indeed affected, have continuously occurred. In 2002, a six-year-old Chinese boy was reported to have been injured from a falling space object while sitting under a tree (Maley, n.d.^[6]). A more serious and recent case involves a region in Guangxi, People's Republic of China, where debris identified to have broken apart from Long March 3B's rocket booster fell and exploded on the ground, posing severe health risks to local residents. Many more cases exist, involving damages of various types and magnitudes to land and property across the globe (e.g. Lemoine (2016^[7])). Although USD 6 million was the amount filed by the Canadian government against the USSR for the damage caused by radioactive debris traceable to the state's satellite in 1978,¹ the extent of the damage can be expected to be much higher in present values and if the collision involves populated areas. In addition, the threats are expected to loom larger with growth in the number of space debris.

Put into an equation, the annual costs to Earth can be modelled as:

$$C_{Et} = \gamma_t(\bar{P}_E + \bar{L}_E) \quad (4)$$

where γ_t refers to the number of collision events on Earth in year t , $\bar{P}_E$ the average cost of damage to property and resources on Earth, and $\bar{L}_E$ the average cost related to the loss of lives on Earth.

Combining equations (1)~(4), the annual cost of space debris in year t can be expressed as shown below. Table 3.1 presents a summary of the variables.

$$C_t = C_{St} + C_{It} + C_{Et}$$

$$= [m_t\bar{D} + n_t\bar{O} + \alpha_t \sum_{k=0}^{\bar{y}} \left\{ \frac{\bar{V}}{\bar{I}} \times \frac{1}{(1+r)^{\bar{I}-k}} \right\}] + \beta_t(\bar{P}_I + \bar{L}_I) + \gamma_t(\bar{P}_E + \bar{L}_E) \quad (5)$$

Table 3.1. Variables for estimating the cost of space debris at the global level

Variable type	Variable	Description	Unit
Count	m_t	Number of satellites launched in year t	
	n_t	Number of satellites in operation in year t (including satellites launched in year t)	
	α_t	Number of satellites that lost their function due to space debris in year t	
Frequency	β_t	Number of collisions between space stations/shuttles and space debris in year t	
	γ_t	Number of collisions on Earth in year t	
Cost	$\bar{D}$	Average increase in development costs due to space debris	per satellite
	$\bar{O}$	Average increase in operational and maintenance costs due to space debris	per satellite
	$\bar{P}$	Average cost of non-human damage	per collision
	$\bar{L}$	Average cost of human damage	per collision
Value	$\bar{V}$	Average monetary value of satellites	per satellite
Duration	$\bar{I}$	Average lifespan of satellites (years)	per satellite
	$\bar{y}$	Average number of years satellites have been in operation (years)	per satellite
Rate	r	Social discount rate (%)	

Applying the model to the national level

The problem of space debris is inevitably a global issue: the action of one country or company carries repercussions for all others around the globe that cannot but share the space environment and Earth's orbits. However, in the perspective of each country, a major concern would be the cost of space debris that each country specifically faces. Alternatively, in the process of finding global solutions or evaluating impacts, comparisons between countries may surface as a matter of interest. The equation below is the result of converting the variables in equation (5) into national units and reflects the cost of space debris for country j in year t .

$$C_{jt} = C_{Sjt} + C_{Ejt}$$

$$= [m_{jt}\bar{D}_j + n_{jt}\bar{O}_j + \alpha_{jt} \sum_{k=0}^{\bar{y}_j} \left\{ \frac{\bar{V}_j}{\bar{I}_j} \times \frac{1}{(1+r)^{\bar{I}_j-k}} \right\}] + \gamma_{jt}(\bar{P}_{Ej} + \bar{L}_{Ej}) \quad (6)$$

As apparently noticeable, a large difference is the exclusion of the impact on space stations and shuttles. One reason is attributable to the fact that the ISS is a joint venture of only 15 countries and plans for it after 2024 (or, at most, 2028) are unclear. If astronauts or tourists from a particular country face injuries or death, such costs can be added to the equation on an individual basis (Table 3.2).

Table 3.2. Variables for estimating the cost of space debris at the national level

Variable type	Variable	Description	Unit
Count	m_{jt}	Number of satellites launched by country j in year t	
	n_{jt}	Number of satellites operated by country j in year t (including satellites launched in year t)	
	α_{jt}	Number of satellites operated by country j that lost their function due to space debris in year t	
Frequency	γ_{jt}	Number of collisions on country j 's territory in year t	
Cost	$\bar{D}_j$	Average increase in development costs due to space debris for country j	per satellite
	$\bar{O}_j$	Average increase in operational and maintenance costs due to space debris for country j	per satellite
	$\bar{P}_{Ej}$	Average cost of non-human damage due to space debris in country j	per collision
	$\bar{L}_{Ej}$	Average cost of human damage due to space debris in country j	per collision
Value	$\bar{V}_j$	Average monetary value of satellites operated by country j	per satellite
Duration	$\bar{l}_j$	Average lifespan of satellites operated by country j (years)	per satellite
	$\bar{y}_j$	Average number of years satellites operated by country j have been in operation (years)	per satellite
Rate	r	Social discount rate (%)	

Discussion on the OECD's impact categories

As noted in the introduction, the cost categories or variables considered in this study build upon the impact categories outlined in the OECD policy paper. Some categories were merged into a single variable to simplify the model, while some others were removed because they were beyond scope or irrelevant. Table 3.3 presents how the original categories can be reclassified according to the model of this study.

Table 3.3. The OECD's impact categories reclassified

Time frame	Type of impact	Description	Reclassified
Current impacts	Debris-related damage	Loss of functionality or loss of entire satellites. Many incidents go unreported.	$\bar{V}$
	Satellite and constellation design	Costs associated with satellite shielding, collision avoidance capabilities, safe hold modes and redundancies (i.e. launch extra satellites as spares). Satellite constellations increasingly include spares for system resilience, but this solution often becomes part of the problem.	$\bar{D}$
	Operational costs	Costs of space situational awareness activities, services and software. Data blackouts when conducting avoidance manoeuvres.	$\bar{O}$
	Orbit clearance costs	In the geostationary orbit: Relatively low, equivalent to about three months of station-keeping. In the low-earth orbit (LEO) above 650 km altitude: Very high and requiring specific satellite subsystems (on-board computer).	Removed
	Insurance costs	Overall, limited use of in-orbit insurance by operators for space debris. Space debris collisions have historically been considered low-probability and not affecting insurance premiums.	$\bar{O}$
Potential future impacts	Loss of unique applications and functionalities	Space observations from some of the orbits most vulnerable to space debris are often the best or only source of data and signals in their domain. This applies in particular to polar-orbiting weather and earth observation satellites. The loss of polar-orbiting weather satellite observations would heavily affect the southern hemisphere, where there are fewer terrestrial observations.	$\bar{V}$
	Loss of lives	The International Space Station is located at an altitude of about 400 km. Although debris at that altitude decays naturally, it still poses a real collision threat.	$\bar{L}$

Time frame	Type of impact	Description	Reclassified
	Interrupted time series for earth science and climate research	Uninterrupted time series are crucial for the accuracy and reliability of weather prediction and climate models.	$\bar{V}$
	Curbed economic growth and slowdown in investments in the sector	Satellite broadband is widely considered to become a key driver of space activities and revenues in the coming decades. More than ten broadband satellite constellations are in different stages of development. Practically all LEO communication services would be affected, on orbit and/or during orbit-raising, as most constellations are located near or above the thickest LEO debris belts. Reduced access to venture finance, with investors preferring more affordable and less risky terrestrial alternatives.	$\bar{V}$
	Distributional effects	The loss or perturbation of certain LEOs could be felt more heavily in rural low-density residential areas and low-income countries.	Removed

The variable $\bar{D}$ includes the cost increase due to the addition of shielding or spare parts noted in the OECD report and may further include other costs that arise during the stages of development and launch. Likewise, the variable $\bar{O}$ captures the operational and insurance costs identified in the OECD policy paper and may further include other maintenance costs previously overlooked (e.g. following the increase in staffing to monitor and respond to collision risks more closely).

The convergence of various categories into the variable $\bar{V}$, however, may raise questions: how can the interruption experienced by the research community, the impact on the economy and investments, or other intangible benefits be reflected? Although the answer would ultimately depend on the specific valuation method applied (more details can be found in the next section), it is indeed possible to measure the entire value of satellites that encompasses such intangible, indirect or non-use values. For instance, when surveying the public's willingness to pay for a particular satellite (service), researchers only need to clearly explain such aspects, which will then be reflected in the responses. At the same time, many of the categories are, in effect, the value of data transmitted from different types of satellites and do not need to be treated as distinct categories.

Two categories have been removed in the context of this study. Orbit clearance costs were removed because collision events with space debris do not necessarily entail the act of clearing orbits. While related activities can be viewed as efforts to reduce the risks and, hence, costs of space debris, including such costs can also give rise to double counting. This is because the cost of damage caused by a certain problem and the cost of alleviating it are essentially two different sides of the same coin.

Distributional effects, the other removed category, largely refers to the problem in which the degree of loss or damage varies depending on the economic level of a country. This matter is undoubtedly important and requires attention; however, such inequalities should be reflected in the process of estimating the costs, rather than treated as a separate cost category. When applying the model of this study, for instance, the cost of space debris at the national level will vary widely depending on the context of each country, such as one's income level and the extent to which one's space industry has developed.

Estimating the costs

Economic valuation is understood as attaching a monetary value to things based on the preference and welfare of individuals. This is most often measured by how much individuals would be willing to pay to receive a certain service or benefit (willingness to pay, WTP) or, at times, by how much individuals would be happy to accept as compensation for a decrease in benefit or welfare (willingness to accept, WTA). Such individual preferences can be measured based on either a revealed or stated preference. Revealed preference refers to preferences that have been observed and thus revealed to the world, such as prices in the market; stated preference, on the other hand, refers to preferences that have been self-reported by, for instance, survey respondents. Generally, economists tend to trust and prefer revealed preferences, which are believed to reflect "the world as it is" or the "real" behaviour of economic actors.

Notwithstanding the limitations, stated preference methods are, however, often the only option possible for valuation purposes. This is the case when no observable price exists, which is true of many environmental goods and services, as well as health interventions, cultural heritage sites and other public goods. In such cases, applying the contingent valuation or choice experiment method is gaining popularity and increasing support in terms of validity.

Among the variables included in this study's model to estimate the cost of space debris, development, operational and maintenance costs ($\bar{D}$ and $\bar{O}$) are assumed to be easily observable and, thus, rather straightforward. The main challenges, therefore, are expected to surround the value of goods and services for which prices are not easily observable, such as the value of satellites ($\bar{V}$) or the environment (included in $\bar{P}$), and values that are intangible or immeasurable, such as the value of human lives ($\bar{L}$). The remainder of this chapter will explore such contentious subjects, based on the developments thus far in the field of environmental economics.

The value of satellites ($\bar{V}$)

The largest and most serious impact of space debris and incidents thereof is the destruction of or damages to operational satellites, leading to the loss of functionalities either entirely or partially. Following the observations of Murtaza et al. (2020^[8]), even millimetre-sized debris can cause substantial damage due to the hypervelocity (typically 8~10 km/s) and uncontrolled nature that characterise space objects. The precise extent of the loss and how it can best be measured, however, would vary depending on the characteristics of the satellite (e.g. function, altitude, service area, etc.).

The value of satellites that provide communication or broadcasting services, for example, would mostly concern direct use value. Therefore, the welfare enjoyed by individuals in monetary value can be estimated using market transactions data, such as the bills paid for telephone and Internet services. How about satellites performing earth observation missions? Weather forecasting services are generally provided without charge, while the scope and application of obtained data and information are extremely vast (see Häggquist and Söderholm (2015^[9]) for a non-exhaustive list of areas for which geological information is used). Although likely an underestimation of actual benefits, a simple approach based on revealed preferences would be to use the total revenue enjoyed by satellite operators from data and information sales.

An alternative method, based on stated preference, is to run a survey using the contingent valuation. Eom and Hong's work (2011^[10]) is an example, where the value of a geostationary satellite expected to provide improved information on atmospheric pollution was measured through a survey with a sample size of 1 000. Respondents were given an easily understandable scenario explaining the situation (with vs. without the improved information) and the potential effects the improved information could have on individuals, then asked to respond to a series of questions following the dichotomous choice method. As a result, the average WTP per household was estimated to be approximately USD 3.6 (KRW 4 200).² Once such a WTP has been drawn, the value of a satellite can be estimated by the product of the WTP and the beneficiary population.

Nonetheless, the amount would differ for different types of satellites. Accordingly, to estimate the global average value, $\bar{V}$, the average value for and the proportion of each type must be considered as shown in the following equation:

$$\bar{V}_t = \sum_{f=1}^{n_f} w_{ft} \bar{v}_{ft} \quad (7)$$

where $\bar{V}_t$ refers to the global average value of satellites in year t , n_f the number of different types of satellites, w_{ft} the proportion of satellite type (or function) f , and, $\bar{v}_{ft}$ the average value of satellite type f .

The value of property and resources ($\bar{P}$)

An impact event that causes damage to public/private property and/or resources, including the natural environment, has much in common with natural disasters in the sense that neither can be fully prevented, while the consequences can be truly devastating. Methods commonly used to estimate the cost of damage due to natural disasters have been based on either insurance claims, clean-up costs or recovery costs.

The catastrophic flooding in Western and Central Europe in July 2021, for instance, has been estimated to have cost at least USD 20 billion in Germany alone and based solely on insurance claims (Aon, 2021^[11]). This approach is most accessible in that the data are readily available and can reflect the damages to property; however, in many cases, the numbers are likely to be gross underestimations of actual damage costs as other types of damages (e.g. to unowned land or resources) are not accounted for.

In the aforementioned example, in which the Canadian government filed a case against the USSR under the Liability Convention, the requested USD 6 million amounted to roughly half of the costs borne to clean up the radioactive debris generated. Such an approach has an advantage over the method based on insurance claims in terms of measuring the impact on the environment.

Recovery costs can include all types of costs incurred to undo the damages and return property, the natural environment, etc. to their original state. Therefore, this method has the potential to be the most comprehensive, but, for the same reason, can show the largest variance. For instance, the amount would differ depending on how far ahead in time recovery efforts are recognised or whether non-material damages, such as the psychological damages to families and communities, are also considered (see Bonanno et al. (2010^[12]) for a discussion on this topic).

Once the appropriate method is chosen and the damage costs estimated, the global average, $\bar{P}$, can be calculated by the following:

$$\bar{P}_t = \frac{\sum_{i=1}^{n_{ct}} p_i}{n_{ct}} \quad (8)$$

where $\bar{P}_t$ stands for the global average cost of damage to property and resources in year t , n_{ct} the number of collision events in year t , and, p_i the damage costs incurred for collision event i .

The value of statistical life ($\bar{L}$)

The mere idea of putting a price tag on human lives can be extremely controversial. Earlier methods of estimation based on wages as a proxy for one's lifetime lost ("forgone earnings") only aggravated the problem, since, following such a logic, the value of one's life would differ according to one's paycheck. The value of statistical life (VSL), on the other hand, does not measure the value of one's time or life *per se*, but rather reflects the WTP of individuals for a reduction in the risk of death or the WTA for bearing an increase; hence, the term "statistical". In theory, the VSL can be conveniently calculated by the function below, where a is the WTP or WTA and w is the change in risk (Boardman et al., 2018^[3]).

$$VSL = \frac{a}{w} \quad (9)$$

For the purpose of illustration, let us assume that an individual can choose to buy a private alarm system that notifies its users of any approaching (space) object well enough in advance to safely evacuate. If the system increases the probability of survival by 1/100 000 and costs USD 300 to install (or lifetime service), the VSL in this specific case – reducing the risk of death due to a space debris collision – would be USD 30 million.

Despite the seeming simplicity, however, this method would be altogether impractical when either a or w or both cannot be identified. Under the status quo, much uncertainty remains over w , underscoring the need to obtain precise estimates of the probability of fatal space debris collisions as a prerequisite. In the meantime, the VSL can be estimated through a benefit transfer, which refers to the practice of plugging in estimates

from earlier findings. Through a meta-analysis that was adjusted for publication selection bias, Viscusi and Masterman (2017^[13]) suggest a US VSL of USD 9.6 million; using this as a base value and taking into account the respective income elasticities of each country, the authors further suggest the VSL for “lower income, lower middle-income, upper middle-income, and upper income countries to be USD 107 000, USD 420 000, USD 1.2 million, and USD 6.4 million, respectively” (Viscusi and Masterman, 2017, p. 226^[13]).

Discussion and conclusions

To quantify the cost of space debris, this chapter presented an analytical framework and econometric model for estimation, which is the first such attempt to the best of the researchers’ knowledge. Valuation methods developed in the field of environmental economics were further elaborated on so that the developed model can be of practical use.

Emphasis was put on making a model that is easily understandable and readily applicable. Therefore, the framework first broke up the cost of space debris into three domains: the impact on satellites, that on space stations and shuttles, and that on the Earth. Based on extant research and records, the specific variables under each domain focused on the most relevant and substantial impacts. In the process, a number of cost categories previously discussed were merged into a single variable or removed. Finally, the model estimates costs on a yearly basis, so that situational changes can be reflected promptly.

Another contribution of this study is the inclusion of previously excluded cost categories. In developing the analytical framework, the researchers found satellites to be both the largest victim and perpetrator of the problem: not only are satellites the most heavily affected by space debris, they are also the predominant cause. Accordingly, launching an additional satellite into space inevitably increases the density of orbits and thus heightens the collision risk for all other operating payloads. However, the researchers observed that most cost-benefit analyses of satellite projects do not consider this fact and instead exclusively centre on those costs directly borne by operators (i.e. development and operational costs). While this may relate to an underestimation of the costs, previous calculations may also be guilty of overestimating the benefits. For the same reason – the collision risk with space debris – the expected benefits can be much smaller if a satellite is damaged before its life expectancy is reached. Such uncertainties and the resulting costs, both internal and external, are incorporated into the study’s model.

Taking it a step further, this study extends the consideration of externalities to the possible impact of space debris on the Earth’s environment. For instance, in the process of developing and launching satellites, various materials and resources, including potentially hazardous substances and fossil fuels, are needed in large volumes. When re-entering Earth’s atmosphere and ultimately landing either on the ground or in water, hitherto uninvestigated air, marine and soil pollution may occur and accumulate over time. The environmental consequences, however, are not limited to the pollution directly resulting from falling space debris, as the ecological footprint begins from resource extraction. In terms of carbon, emissions due to rocket launches have been reportedly increasing by 5.6% each year (see Gammon (2021^[14])). With climate change worsening, this study calls for heightened attention to these matters. Table 3.4 shows the suggested categories for a more comprehensive cost-benefit analysis of satellite projects.

The internalisation of external costs can, therefore, be an effective approach to restrain launch behaviour and alleviate the problem of space debris. For instance, as suggested by Rao, Burgess and Kaffine (2020^[15]), an orbital fee equal to the gap between the collision rate under open access and the optimal collision rate could be introduced. According to the authors, such a measure will not only correct incentives for launching satellites, but also quadruple the value of the space industry. Alternatively, as with the case of carbon, an emissions trading system could be introduced. Whatever the response, however, the contribution of each country in generating space debris must be considered. The more a country has launched rockets and satellites, the more it has conducted anti-satellite missile testing, the more responsibility it necessarily holds.

Table 3.4. An improved framework for cost-benefit analyses of satellite projects

Benefit	Cost
Protection of property and infrastructure	Development costs (including R&D)
Safety of life	Satellite body
Protection of property	Payload
Added value to the economy	Ground station
Private use by citizens	Launch cost
	Operational costs
	Insurance
	Space situational awareness
	Other maintenance costs
	Collision risks
	Damage/loss of my satellite
	Damage/loss of other satellites
	Other possible damages (e.g. human lives, property, etc.)
	Environmental impacts on Earth
	Carbon emissions
	Other pollution (e.g. air, marine, soil)

While the model in this study can be useful in the discussion of economic incentives or as a tool to solve the problem, limits and avenues for improvement also exist. First, the key variables of the current model (i.e. α_t , β_t , γ_t) are based on counting or frequency, implying that the model is less suitable for predictions. Attempts to replace the values with functions would be promising. Second, for simplicity, most variables are defined as gross averages, while several assumptions were also made, according to which damages that do not seriously affect a satellite's function were excluded. Therefore, much room exists for sophistication. For such reasons, the researchers were wary of presenting an explicit estimate in this study. Related prospects would be more encouraging with further accumulation of data and modelling improvements.

References

- Aganaba, T. (2021), "If a satellite falls on your house, space law protects you – but there are no legal penalties for leaving junk in orbit", *The Conversation*, 19 May, <https://theconversation.com/if-a-satellite-falls-on-your-house-space-law-protects-you-but-there-are-no-legal-penalties-for-leaving-junk-in-orbit-160757>. [16]
- Ali, I. and S. Gorman (2021), "Russian anti-satellite missile test endangers space station crew – NASA", *Reuters*, 17 November, <https://www.reuters.com/world/us-military-reports-debris-generating-event-outer-space-2021-11-15>. [5]
- Aon (2021), *Global Catastrophe Recap: July 2021*, Aon, http://thoughtleadership.aon.com/Documents/20211008_analytics-if-july-global-recap.pdf. [11]
- Boardman, A. et al. (2018), "Introduction to cost–benefit analysis", in *Cost-Benefit Analysis*, Cambridge University Press, <https://doi.org/10.1017/9781108235594.003>. [3]
- Bonanno, G. et al. (2010), "Weighing the costs of disaster", *Psychological Science in the Public Interest*, Vol. 11/1, pp. 1-49, <https://doi.org/10.1177/1529100610387086>. [12]
- Gammon, K. (2021), "How the billionaire space race could be one giant leap for pollution", *The Guardian*, 19 July, <https://www.theguardian.com/science/2021/jul/19/billionaires-space-tourism-environment-emissions>. [14]

- Häggquist, E. and P. Söderholm (2015), “The economic value of geological information: Synthesis and directions for future research”, *Resources Policy*, Vol. 43, pp. 91-100, <https://doi.org/10.1016/j.resourpol.2014.11.001>. [9]
- Hong, J. and Y. Eom (2011), “Estimating demand for public goods using survey methods: Issues and application to the valuation of environmental satellite project”, *Journal of Korean Economic Analysis*, Vol. 17/1, pp. 1-64. [10]
- Kettley, S. (2020), “Space debris threatens satellites and we’re not paying attention, UK astronomers warn”, *Express*, 24 September, <https://www.express.co.uk/news/science/1339612/Space-debris-threat-satellites-astronomy-space-news>. [4]
- Lemoine, B. (2016), “What is that?!” Unidentified, unexplained large object damages man’s van on Milwaukee’s north side”, *FOX6*, 23 December, <https://www.fox6now.com/news/what-is-that-unidentified-unexplained-large-object-damages-mans-van-on-milwaukees-north-side>. [7]
- Maley, P. (n.d.), “Space debris: 1960-1980”, *Direct Travel website*, <https://eclipsetours.com/paul-maley/space-debris/space-debris-1960-1980>. [6]
- Murtaza, A. et al. (2020), “Orbital debris threat for space sustainability and way forward (review article)”, *IEEE Access*, Vol. 8, pp. 61000-61019, <https://doi.org/10.1109/access.2020.2979505>. [8]
- Newman, C. and M. Williamson (2018), “Space sustainability: Reframing the debate”, *Space Policy*, Vol. 46, pp. 30-37, <https://doi.org/10.1016/j.spacepol.2018.03.001>. [1]
- Rao, A., M. Burgess and D. Kaffine (2020), “Orbital-use fees could more than quadruple the value of the space industry”, *Proceedings of the National Academy of Sciences*, Vol. 117/23, pp. 12756-12762, <https://doi.org/10.1073/pnas.1921260117>. [15]
- Undseth, M., C. Jolly and M. Olivari (2020), “Space sustainability: The economics of space debris in perspective”, *OECD Science, Technology and Industry Policy Papers*, No. 87, OECD Publishing, Paris, <https://doi.org/10.1787/a339de43-en>. [2]
- Viscusi, W. and C. Masterman (2017), “Income elasticities and global values of a statistical life”, *Journal of Benefit-Cost Analysis*, Vol. 8/2, pp. 226-250, <https://doi.org/10.1017/bca.2017.12>. [13]

Notes

¹ The case was filed under the Convention on the International Liability for Damage Caused by Space Objects. For more information, see Aganaba (2021_[16]).

² Throughout this report, an exchange rate of USD 1 $\equiv$ KRW 1 166 was used. In the original study, the value converted to USD was USD 3.7. See also Hong and Eom (2011_[10]) for a more comprehensive discussion on this topic (in Korean).

4

Identifying the costs caused by an irreversible deterioration of the orbital regimes

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This chapter explores the consequences of a partial stop in space activities due to the excessive presence of orbital debris. It first models causes and effects to illustrate a vicious cycle of negative domino effects that permeate society at large. It then calculates the expected economic repercussions by combining the monetary worth of the orbital regimes with their average probability of deterioration, which could be used to create the basis for an orbital toll.

Introduction

Since the launch of Sputnik 1 in 1957, the number of man-made objects orbiting Earth has dramatically increased (Klinkrad, 2006^[1]). Unfortunately, this growth was not always controlled and intentional, leading to the creation of abundant space debris. Defined as “all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional” (IADC, 2007^[2]), space debris today crowd many orbital regions and have become a threat to the long-term sustainability of space activities.

A number of events have marked the history of space debris, from the first spontaneous on-orbit break-up in low-earth orbit (LEO) in 1961 (Transit-4A) and the first satellite explosion in geostationary orbit (GEO) in 1978 (Syncom-3) to the first collision of two spacecraft in 2009 (Iridium-33, Kosmos-2251). Moreover, along with these fortuitous episodes, deliberate anti-satellite tests such as the Chinese FengYun-1C of 2007 and the recent Russian Cosmos-1408 have significantly exacerbated the situation.

Besides polluting the space environment, orbiting debris pose a high risk to other spacecraft. In fact, even a small fragment could cause a catastrophic event due to its high speed and resulting destructive energy. As of November 2021, nearly 30 000 objects are tracked, of which about 60% are in LEO (ESA, 2021^[3]). In addition to those items, however, there are millions of debris smaller than 10 cm in diameter that cannot be identified and followed from Earth due to the limitations of ground radars and telescopes (Klinkrad, 2006^[1]).

The problem of space debris is not new. Already in 1978, Donald J. Kessler hypothesised the concerning possibility of a self-sustained growth in the number of objects in space due to a cascading scenario whereby each collision would increase the likelihood of further impacts (Kessler and Cour-Palais, 1978^[4]). Recent studies highlight that what was once a remote possibility could soon become reality. In fact, in certain LEO orbits, the population of objects may already be intrinsically unstable and prone to perpetual growth even in the absence of new launches (Pardini and Anselmo, 2021^[5]).

While there are abundant guidelines designed to mitigate the uncontrolled exploitation of the orbital environment (Undseth, Jolly and Olivari, 2020^[6]), compliance is still under par. It is not even clear whether the widespread adoption of these standards from this point forward would alone be sufficient for long-term sustainability, or whether we are already at a point of no return. Moreover, the supranational nature of space makes rules and obligations virtually unenforceable, incentivising market participants to prioritise economic interests over societal concerns.

To address these issues, this chapter makes two main contributions. First, we model the complex cause-and-effect relationship kickstarted by space debris and collision events, highlighting how the downfalls generated by excessive debris reverberate throughout the global value chain. We then add on the qualitative results with quantitative considerations, assessing the global economic value at risk of being lost due to excessive amounts of space debris. This is done by interpolating the monetary value of the orbital regions in the lower Earth orbits with their average deterioration probability – a condition here defined as the point in time in which the orbital region becomes subject to a self-reinforcing cycle of debris creation, making the risks of mission failure too great to justify the deployment of new satellites in that area.

This chapter is organised as follows. Section 2 defines the direct and indirect consequences of space debris, graphically illustrating the vicious cycle of self-reinforcing costs. Section 3 estimates the total value of space-enabled economic activity through a dependency model, which encompasses all sectors of the global economy. Section 4 quantifies the economic value at risk of selected LEO orbits by calculating the probability of irreversible deterioration. Finally, Section 5 provides a summary and a discussion of the results.

Direct and indirect costs

Space debris is an issue that has been long disregarded. The costs of implementing strong mitigation measures have been perceived as higher than the potential benefits, resulting in a tendency to delay the development and implementation of concrete solutions. Such behaviour is part of human nature, as our inability to understand complex relationships (Sterman, 2000^[7]) leads to a consistent proclivity for short-term benefits over long-term concerns. As with other grave dilemmas of today's world, we might simply be waiting for the straw that breaks the camel's back – in this case, one or more large collisions between objects in space that significantly increase the debris population and probability of further collisions. Thus, to encourage a change of attitude, it is necessary to first gain a solid understanding of the real consequences of such negligence, which is still very limited.

Cost dynamics

To address this lack of knowledge, we attempt to model the complex cause-and-effect reactions stemming from a persevering and uncontrolled exploitation of the orbital regimes. Our objective is to highlight how, beyond the immediate and obvious consequences, a series of cascading outcomes will inevitably arise. This cycle is visually represented in Figure 4.1 and summarised in Table 4.1. We have distinguished the costs into two broad groups: 1) those that arise directly because of space debris or actual collision events ("direct costs"); and 2) those that take place as a downstream consequence of the former two ("indirect costs").

Table 4.1. Space debris cost overview

Cost	Direct/indirect	Affected party	Source
Need for space situational awareness (SSA) services	Direct	Private companies	Space debris, uncontrolled re-entry of debris
Modified design for single satellite and constellation	Direct	Private companies	Space debris
Increased manoeuvres, including collision avoidance measures (CAM) and orbit clearance	Direct	Private companies	Space debris
Higher operational risks in a polluted space environment	Direct	Private companies	Space debris, deterioration of the orbital regimes
Uncontrolled re-entry of debris	Direct	Private companies	Collision event, scattering of spacecraft pieces
Loss of functionality of satellite	Direct	Private companies	Collision event
Scattering of spacecraft pieces	Direct	Private companies	Collision event
Reduction in satellite operational lifetime	Indirect	Private companies	Increased manoeuvres, including CAM and orbit clearance
Replacement of dead satellite	Indirect	Private companies	Reduction in satellite operational lifetime
Increased in-orbit insurance costs	Indirect	Private companies	Higher operational risks in a polluted space environment
Higher satellite mission costs	Indirect	Private companies	Higher operational risks in a polluted space environment, increased manoeuvres (including CAM and orbit clearance), need for SSA services, modified design for single satellite and constellation, replacement of dead satellite, increased in-orbit insurance costs
Higher cost of data to primary users	Indirect	Private companies and public entities	Higher satellite mission costs
Reduced demand for space-based activities	Indirect	Private companies	Higher cost of data to primary users, interrupted and inconsistent data
Lower attractiveness of space-based businesses	Indirect	Private companies	Higher satellite mission costs, reduced demand for space-based activities

Cost	Direct/indirect	Affected party	Source
Slowdown in sector investments due to higher risks, lower demand, weaker financial prospects	Indirect	Private companies	Lower attractiveness of space-based businesses
Higher cost of data to secondary users	Indirect	Private companies and public entities	Higher satellite mission costs, higher cost of data to primary users, slowdown in sector investments (due to higher risks, lower demand, weaker financial prospects), degradation of the orbital regimes
Potential injury to people or damage to property and environment on Earth	Indirect	Public entities	Uncontrolled re-entry of debris
On ground insurance costs	Indirect	Public entities	Potential injury to people or damage to property and environment on Earth
Lives lost in manned spaceflight	Indirect	Public entities	Uncontrolled re-entry of debris
Reduced human-based research in microgravity	Indirect	Public entities	Reduced human-based research in microgravity
Replacement of lost satellite	Indirect	Private companies	Loss of functionality of satellite
Interrupted and inconsistent data	Indirect	Private companies and public entities	Loss of functionality of satellite
Degradation in quality and quantity of service offered to the users	Indirect	Private companies and public entities	Interrupted and inconsistent data, deterioration of the orbital regimes
Increase in number of orbiting objects	Indirect	Private companies and public entities	Scattering of spacecraft pieces, replacement of dead satellite, replacement of lost satellites
Deterioration of the orbital regimes	Indirect	Private companies and public entities	Increase in the number of orbiting objects, higher operational risks in a polluted space environment

Notes: CAM: collision avoidance manoeuvres; SSA: space situational awareness.

Specifically, the left side of Figure 4.1 represents the repercussions associated with the presence of space debris. The right side instead portrays the fallouts from in-orbit collisions. As evidenced by the red circular arrows in the centre, there is a positive feedback loop between the two: space debris increases the probability of collisions, and collisions increase the quantity of space debris. These factors give rise to direct costs, connected through black dotted arrows, which in turn are the source of indirect costs. All the elements identified result in, and compound upon, the deterioration of the orbital regimes. Figure 4.1 also provides a classification of the users most impacted by the identified costs, broadly separated between private and public actors.

Starting from space debris, the direct costs encompass: 1) need for space situational awareness (SSA) activities; 2) modified design for single satellites and constellations (Schaub et al., 2015^[8]), for instance to improve passive shielding capabilities or to ensure redundancy; 3) increased flight dynamics operations, including collision avoidance manoeuvres (CAM), evasive actions and orbit clearance; and 4) higher operational risks from the polluted space environment (such as collision risk). Combined, these elements lead to higher mission costs. Downstream consequences then comprise: 1) higher cost of data to primary users, and thus reduced demand for space-based activities; and 2) lower attractiveness of space-based businesses. Lower demand, higher risks, and weaker financial prospects have the potential to slow down investments in the space sector.

Moving on to collision events, the direct costs include: 1) uncontrolled re-entry of debris; 2) loss of satellite functionality; and 3) scattering of spacecraft pieces, therefore the creation of even more debris. The uncontrolled re-entry could be fatal to manned spaceflight missions, for instance on the International Space Station (ISS), and could also damage property or equipment on Earth (Undseth, Jolly and Olivari, 2020^[6]). The loss of satellite functionality can instead be the source of interrupted and inconsistent data, causing a degradation in the service delivered by spacecraft operators thus decreasing demand for space-based activities. Moreover, it will then be necessary to replace the failed satellite, leading to an additional number of objects in space and thus in the likelihood of collisions. In the end, the vicious cycle culminates in the deterioration of the orbital regime.

Temporal evolution

Space infrastructure is best known for its role in everyday digital applications, from supporting smartphone map driving routes and assisting financial transactions to delivering television programmes, among others. However, satellites also provide services that are indispensable for rural communities, from tracking crop conditions on farms and monitoring illegal deforestation to assessing poverty in hard-to-reach areas (Shekhtman, 2016^[9]). In fact, space-based technologies are now pillars of the global effort to eradicate poverty (United Nations, 2016^[10]). Therefore, while the deterioration of the Earth's orbits has the potential to negatively affect all people on Earth, the temporal progression of its fallout will differ starkly depending on the socio-economic status of the subjects under consideration.

To assess these differences, we can broadly subdivide society into wealthy nations and the rest of the world, as shown in Figure 4.2. The initial consequences of the hypothesised orbital deterioration – which we assume to happen very rapidly, not permitting prevention measures but only subsequent mitigation – will be globally profound, resulting in an immediate loss of services enabled by the infrastructure in the affected area of space. Starting from wealthy nations, we can confidently foresee a swift response characterised by the deployment of additional satellites in different orbits to re-establish essential services, such as those for military purposes. While such a measure will increase congestion in certain regions of space, it will also enable a partial recovery of functionality, although with an inconvenient but tolerable lower quality of service. Concurrently, investments will be made to develop technologies with comparable or superior performance to the previously available satellite configuration, which will – in the long-term – lead to a return to operational normality.

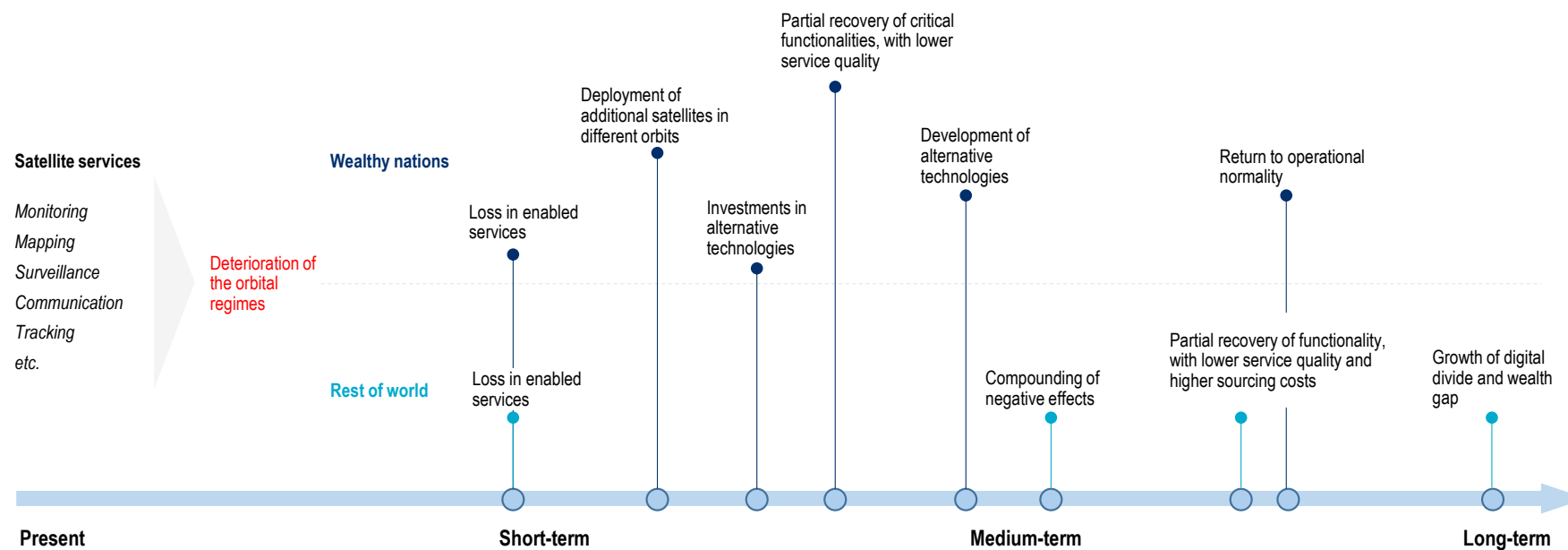
The response of the rest of the world will likely be quite different, mostly impeded by the widespread unavailability of resources. Lower-income countries do not have the capabilities to effectively respond to an irreversible deterioration of the Earth's orbits. Eventually, they could leverage the alternative or substitute technologies developed by the wealthier countries, but these will likely come at a higher price and with lower performance. Moreover, the negative effects of the loss would be only compounded with time, ultimately leaving these communities even further behind in their development.

Value of space-enabled economic activity

The socio-economic relationships reported in the space debris costs dynamics and their evolution over time come with a degree of abstraction, a caveat that can cause further trivialisation of the problem. Given the importance of financial considerations for decision making, we attempt to quantify the costs identified and to measure the aggregate economic value that could be lost if the uncontrolled exploitation of the Earth's orbits is not promptly addressed.

Our methodology is based on two pillars: 1) the monetary worth of the various orbital regimes; and 2) their average probability of deterioration. The first component is estimated by calculating the economic activity dependent on space assets and allocating those assets throughout the orbital areas. The second is instead simulated through modelling tools of the European Space Agency (ESA). Further details are outlined below.

Figure 4.2. Temporal evolution of the fallouts from an irreversible orbital deterioration



Space-enabled economic activity

The OECD defines the space economy as “the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilising space” (Undseth, Jolly and Olivari, 2020^[6]). Valued at an estimated USD 385 billion in 2020 (Euroconsult, 2021^[11]), the space economy is dominated by commercial downstream services (USD 306 billion), followed by government space budgets (USD 70 billion) and finally commercial upstream revenues (USD 9 billion). Similar space economy valuation reports, which can vary marginally based on methodology, are, however, not comprehensive of all the terrestrial downstream activities that indirectly rely on space infrastructure (IDA, 2020^[12]).

Since our reference scenario we quantify the economic value at risk from the deterioration of certain orbital regimes, the aforementioned definition of the space economy is insufficient. We overcome this limitation by including in our analysis the propagated impacts of space assets throughout downstream industries. Specifically, we identify:

- dependent activities:
 - direct dependence: space economy activities as defined above
 - indirect dependence: economic activities that use space-based products and services as key inputs (primary users) and those dependent on the output of primary users to provide inputs for their economic processes (secondary users)
- non-dependent activities: all other sectors of the economy whose dependence on space-based assets is minimal or absent.

In other words, our classification accounts for the complex cascade effects whereby a loss of the enabling infrastructure has repercussions throughout the downstream value chain.

Dependency model

A precise analysis of how each economic sector is permeated by space-enabled services would require significant time and resources that are beyond the scope of this project. For simplicity, we build upon the model proposed by PwC (2017^[13]) in a study tailored for the European Union (EU). Following PwC (2017^[13]), within dependent activities, we consider Global Navigation Satellite Systems (GNSS) (hereafter satellite navigation), satellite telecommunications (ST), and earth observation (EO) assets, along with their relative products, which include positioning, navigation and timing signals, orbital signal relay, and space imagery, among others. These three groups of assets account for the majority of space-enabled services, while the impact of other mission types (i.e. space observation, in-orbit servicing, etc.) is deemed negligible for simplification purposes.

GNSS, ST and EO are themselves space-based infrastructures, therefore their dependency rate on space assets is quantified at 100%. The classification of indirect activities is instead based on the Statistical Classification of Economic Activities in the European Community (“NACE”). Starting from the overall dependency rate proposed by PwC (2017^[13]), we calculate the reliance on GNSS, ST and EO for each economic sector (Table 4.2).

Table 4.2. Dependent versus non-dependent economic sectors

NACE code	Economic sector	Dependency rate
Dependent (indirect dependence)		
A.01	Agriculture	25.5%
A.02	Forestry and logging	70.0%
A.03	Fishing and aquaculture	41.3%

NACE code	Economic sector	Dependency rate
B	Mining and quarrying <i>Including H.49.5 "Transport via pipeline"</i>	80.0%
D	Electricity, gas, steam and air conditioning supply <i>Renamed: "Energy production and distribution"</i>	8.2%
F	Construction	27.1%
H.49	Land transport <i>Including H.52.21 "Service activities incidental to land transport"</i>	54.0%
H.50	Water transport <i>Including H.52.22 "Service activities incidental to water transport"</i>	75.0%
H.51	Air transport <i>Including H.52.23 "Service activities incidental to air transport"</i>	71.5%
J	Information and communication	13.3%
K	Financial and insurance activities	24.5%
x	Meteorology and climate change	50.0%
x	Disaster management	20.0%
Non-dependent		
C	Manufacturing	x
E	Water supply; sewerage, waste management and remediation activities	x
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	x
I	Accommodation and food service activities	x
L	Real estate activities	x
M	Professional, scientific and technical activities	x
N	Administrative and support service activities	x
O	Public administration and defence; compulsory social security <i>Renamed: "Public services and defence"</i>	x
P	Education	x
Q	Human health and social work activities	x
R	Arts, entertainment and recreation	x
S	Other service activities	x
T	Activities of households as employers; undifferentiated goods and services producing activities of households for own use	x
U	Activities of extraterritorial organisations and bodies	x

Notes. Primary dependence (space economy) has been considered as separate, with a dependence of 100%; x = Not applicable.

Specifically, we identify the space-based services used by the various sectors, and approximate their reliance on the related enabling asset. For example, agriculture is estimated by PwC (2017_[13]) to be 25.5% dependent on space infrastructure. Starting from this assumption, we then subdivide this 25.5% between GNSS (80%), EO (15%) and ST (5%) by accounting for the key satellite services leveraged, such as precision farming. Results are presented in Table 4.3.

Table 4.3. Breakdown of dependency rate by economic sector

Economic sector	Space applications	% breakdown
Agriculture	GNSS: precision farming, mapping services, machine monitoring and guidance, controlled traffic farming, variable rate technology (VRT), soil monitoring, yield and biomass monitoring	80%
	EO: precision farming, VRT, soil monitoring, yield and biomass monitoring	15%
	ST: machine-to-machine connectivity	5%
Forestry and logging	GNSS: machine guidance, asset monitoring, forest mapping, forest surveying, VRT	80%
	EO: forest mapping, forest surveying, VRT	20%
	ST: x	0%
Fishing and aquaculture	GNSS: water navigation, fleet management, maritime surveillance, search and rescue (SAR), marine mapping	70%

Economic sector	Space applications	% breakdown
Mining and quarrying	EO: maritime surveillance, marine mapping	5%
	ST: communication at sea, fleet management, maritime surveillance, SAR	25%
	GNSS: resource reserve exploration, mine site surveying, precise drilling, machine monitoring and guidance, surveillance	65%
	EO: resource reserve exploration, mine site surveying, precise drilling	20%
Electricity, gas, steam and air conditioning supply	ST: communication in remote sites, surveillance	15%
	GNSS: smart grid, infrastructure monitoring	80%
	EO: smart grid, infrastructure monitoring	15%
Construction	ST: integrated communication network	5%
	GNSS: surveying and planning, machine guidance and automation	85%
	EO: surveying and planning	5%
Land transport	ST: integrated communication network	10%
	GNSS: road navigation, fleet management, electronic tolling, rail management system, passenger information system, road maps, traffic monitoring, goods tracking	95%
	EO: road maps, traffic monitoring	3%
Water transport	ST: goods tracking	2%
	GNSS: water navigation, fleet management, maritime surveillance, SAR, ship security alert system, goods tracking	75%
	EO: fleet management, maritime surveillance, SAR, ship security alert system, goods tracking	20%
Air transport	ST: communication at sea	5%
	GNSS: performance-based navigation, broadcast, aviation charts and flight maps, emergency locator transmitters	70%
	EO: security tracking	2%
Information and communication	ST: emergency locator transmitters, air traffic management communications, voice communications and in-flight connectivity	28%
	GNSS: telecom network timing and synchronisation	15%
	EO: x.	0%
Financial and insurance activities	ST: programme transfer and handover, satellite newsgathering, telecom network backhaul, telecom network backup	85%
	GNSS: financial operations management (timing and synchronisation), motor insurance telematics	30%
	EO: risk modelling, index products	60%
Meteorology and climate change	ST: trading systems	10%
	GNSS: weather forecasts, emissions monitoring, optimisation effects connected to other sectors (transport, agriculture, forestry)	60%
	EO: weather forecasts, emissions monitoring, climate change effects	40%
Disaster management	ST: x	0%
	GNSS: study disasters and anticipate and/or detect them	70%
	EO: study disasters and anticipate and/or detect them	25%
	ST: intervention co-ordination	5%

Notes: x = Not applicable; EO: earth observation; GNSS: Global Navigation Satellite Systems; ST: satellite telecommunications.

Financial model

With the initial dependency assumptions complete, we then proceeded to build the financial model. The first step of the exercise consisted of calculating gross value added (GVA) for each economic sector, a metric that measures the overall value generated in a period of time. As no worldwide aggregate measurement appeared to be available for the subsectors of the NACE classification, we took as a reference the relative sectorial breakdown of European countries and applied it to the world GVA as reported by the World Bank (2021^[14]), estimating the GVA of each sector in the global economy (Table 4.4).

Table 4.4. Gross value added by economic sector

Economic sector	World GVA (USD billion)	Adoption rate (% of GVA)	Dependent GVA (USD billion)
Direct dependence			
Satellite navigation downstream	54.3	100.0%	54.3
Satellite telecommunications downstream	61.0	100.0%	61.0
Earth observation downstream	2.8	100.0%	2.8
Indirect dependence			
Agriculture	922.0	25.5%	235.1
Forestry and logging	146.7	70.0%	102.7
Fishing	35.3	41.3%	14.6
Mining and quarrying	487.0	80.0%	389.6
Energy	1 299.9	8.2%	106.6
Construction	3 583.3	27.1%	971.1
Land transport	1 788.0	54.0%	965.5
Air transport	248.0	75.0%	186.0
Water transport	202.6	71.5%	144.9
Information and communication	2 851.6	13.3%	379.3
Finance and insurance	3 829.6	24.5%	938.2
Meteorology and climate change	156.7	50.0%	78.4
Disaster management	3.9	20.0%	0.8
Total dependent sectors	15 672.7	29.5%	4 630.8
Non-dependent sectors	58 129.0	0.0%	x
Total economy	73 801.7	6.3%	4 630.8

Note: x=Not applicable.

Moreover, since our scenario of reference assumed that selected orbits would be subject to deterioration, it was necessary to compute the value of the potential loss not only at present, but to perpetuity. We thus proceeded with the projection in the future of both the sectorial GVA and its dependency rate. The present value was approximated by taking as a reference the world GDP growth forecasts (OECD, 2018^[15]) (Table 4.5).

Table 4.5. World GDP growth

Year	Global GDP (USD billion)	Global GDP growth	GVA (USD billion)
2018	95 823	3.90%	73 802
2019	99 585	3.93%	76 699
2020	103 037	3.47%	79 358
2021	106 369	3.23%	81 924
2022	109 668	3.10%	84 465
2023	112 970	3.01%	87 008
2024	116 310	2.96%	89 580
2025	119 708	2.92%	92 197
2026	123 159	2.88%	94 855
2027	126 661	2.84%	97 552
2028	130 212	2.80%	100 287
2029	133 809	2.76%	103 058
2030	137 451	2.72%	105 863
2031	141 135	2.68%	108 700
2032	144 855	2.64%	111 565
2033	148 610	2.59%	114 457

Year	Global GDP (USD billion)	Global GDP growth	GVA (USD billion)
2034	152 397	2.55%	117 374
2035	156 212	2.50%	120 312
2036	160 055	2.46%	123 272
2037	163 928	2.42%	126 255
2038	167 832	2.38%	129 262
2039	171 769	2.35%	132 294
2040	175 741	2.31%	135 353
Terminal value (average 2040-60)		2.13%	

Sources: Global GDP: OECD (2018_[15]), "GDP long-term forecast (indicator)". <http://doi.org/10.1787/d927bc18-en>. GVA: World Bank (2021_[14]), "Gross value added at basic prices (GVA) (current USD) (indicator)", <https://data.worldbank.org/indicator/NY.GDP.FCST.CD>.

The perpetual value was instead quantified at a 2% yearly increase until 2040, and assumed to stop thereafter. This value is based on three main arguments: 1) constant development of new space-based applications; 2) increasing synergy with terrestrial frontier technologies; and quantification of the related monetary value 3) integration of space applications into the regulatory framework applied to various sectors. Finally, the resulting outputs were discounted to present through the net present value methodology, using a 5.4% rate based on the total market average as of August 2021 (NYU Stern, 2021_[16]). The latest data available were taken as the starting point for each entry, namely 2018 for global GVA (World Bank, 2021_[14]), 2020 for GDP (OECD, 2018_[15]) and 2017 for the dependency rate (PwC, 2017_[13]).

Total GVA to perpetuity dependent on space assets resulted in a value of USD 226 trillion. To ensure the accuracy of the computed figure, we performed a validity analysis by comparing our output with an alternative methodology. This consisted in taking as reference the value of space-enabled activities in relation to global GVA (PwC, 2017_[13]). Global GVA was then projected in the future as a fraction of GDP, accounting for the same increase in dependency rate as in the first methodology. The resulting USD 242 trillion sum was approximately 7% higher than the prior estimation, confirming the general soundness of our approach. These data points were then used as low and high estimates for the final output, which is an average of the two; in other words, the final worldwide dependent GVA has been established at USD 234 trillion. The products of this analysis are reported in Table 4.6.

Table 4.6. Total GVA added to perpetuity by application

Application	Total GVA (USD billion) low estimate	Total GVA (USD billion) high estimate	Average (USD billion)
Satellite navigation	148 893	159 029	153 961
Earth observation	42 166	45 037	43 601
Satellite telecommunications	35 258	37 658	36 458
Total	226 317	241 723	234 020

Economic value at risk

After computing the estimated value of the global economic output that could be lost by an irreversible deterioration of the Earth's orbits, we subdivided the overall figure among the different regions of space. The building blocks for this procedure included: 1) allocation of GNSS, EO and ST spacecraft throughout the orbital regimes; 2) quantification of the related monetary value (and therefore valuation of each orbital region, divided by 100 km); and 3) assessment of collision probability.

For our economic model, we focused on LEO (with maximum altitudes of 2 000 km), since this area of space is already at a relatively high risk of deterioration, with over 3 000 operational satellites active as of

August 2021 (UCS, 2021^[17]). Using the *UCS Satellites Database* (UCS, 2021^[17]) (updated as of May 2021), which keeps track of the operational satellites currently in orbit, we divided the satellites into orbital regions of 100 km each by taking the average of perigee and apogee. It is important to note that we excluded elliptical orbits from the exercise for simplification purposes, as their peculiar characteristics would have entailed a separate computation. A detailed overview of our categorisation approach, along with the allocation results, is portrayed in Table 4.7.

Table 4.7. Satellite class subdivisions

Excludes elliptical orbits. From 300 km to 2 000 km

UCS database entry	Macro area	Number of satellites
Navigation/global positioning	Satellite navigation	136
Navigation/regional positioning		12
Earth observation	Earth observation	921
Earth observation/technology development		7
Earth observation/communications		2
Earth/space observation		2
Earth observation/earth science		1
Earth observation/space science		1
Earth science		17
Surveillance		6
Earth observation/communications/space science		1
Earth science/earth observation		1
Communications	Satellite telecommunications	2 467
Communications/navigation		1
Communications/maritime tracking		5
Communications/technology development		5
Educational	Not included	1
Mission extension technology		2
Space observation		8
Space science		96
Space science/technology demonstration		1
Space science/technology development		1
Technology demonstration		29
Technology development		322
Technology development/educational		2
Unknown		5

Successively, we multiplied the fractional composition of satellites in each orbit by the overall value of each asset group, obtaining the approximate monetary value for that orbit. Our results, presented in Table 4.8 estimate the average net present value of the global space-dependent GVA to perpetuity in LEO at USD 71 trillion (30% of the overall USD 234 trillion).

Table 4.8. Breakdown of low-earth orbits

Altitude (km)	Satellite navigation		Earth observation		Satellite telecommunications		Low-earth orbit total
	% breakdown	Value (USD billion)	% breakdown	Value (USD billion)	% breakdown	Value (USD billion)	Value (USD billion)
300	x	x	1%	272	3%	927	1 199
400	x	x	19%	8 376	1%	280	8 656
500	x	x	46%	20 103	60%	22 054	42 157

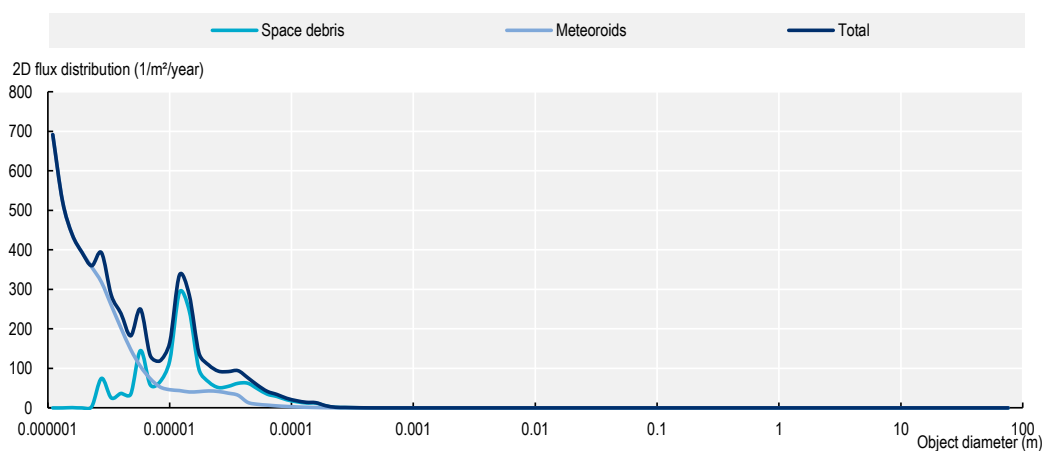
Altitude (km)	Satellite navigation		Earth observation		Satellite telecommunications		Low-earth orbit total
	% breakdown	Value (USD billion)	% breakdown	Value (USD billion)	% breakdown	Value (USD billion)	Value (USD billion)
600	x	x	12%	5 297	5%	1 648	6 945
700	x	x	6%	2 671	1%	397	3 069
800	x	x	4%	1 902	0%	44	1 946
900	x	x	1%	453	–	–	453
1 000	x	x	4%	1 630	0%	15	1 645
1 100	x	x	1%	589	0%	88	677
1 200	x	x	0%	181	7%	2 604	2 785
1 300	x	x	0%	91	0%	29	120
1 400	x	x	x	x	3%	1 015	1 015
1 500	x	x	x	x	0%	177	177
1 600	x	x	x	x	x	x	x
1 700	x	x	x	x	x	x	x
1 800	x	x	x	x	x	x	x
1 900	x	x	x	x	x	x	x
2 000	x	x	x	x	x	15	15
Total	x	x	95%	41 654	80%	29 293	70 857

Notes: Reported altitude defines the lower bound, i.e. 300 = 300-399 km; x = Not applicable.

Collision probability calculations

To estimate the collision probability in LEO, we used as a reference data provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (2021^[18]; 2016^[19]). Among the satellites operated by EUMETSAT, the three-spacecraft constellation Metop was selected as a case study.

Figure 4.3. Simulated 2D flux distribution of space debris and meteoroids



Notes. 900 km mean altitude circular polar orbit (98° inclination); reference epoch: 2016.

Source: Simulations carried out using the European Space Agency MASTER simulation tool.

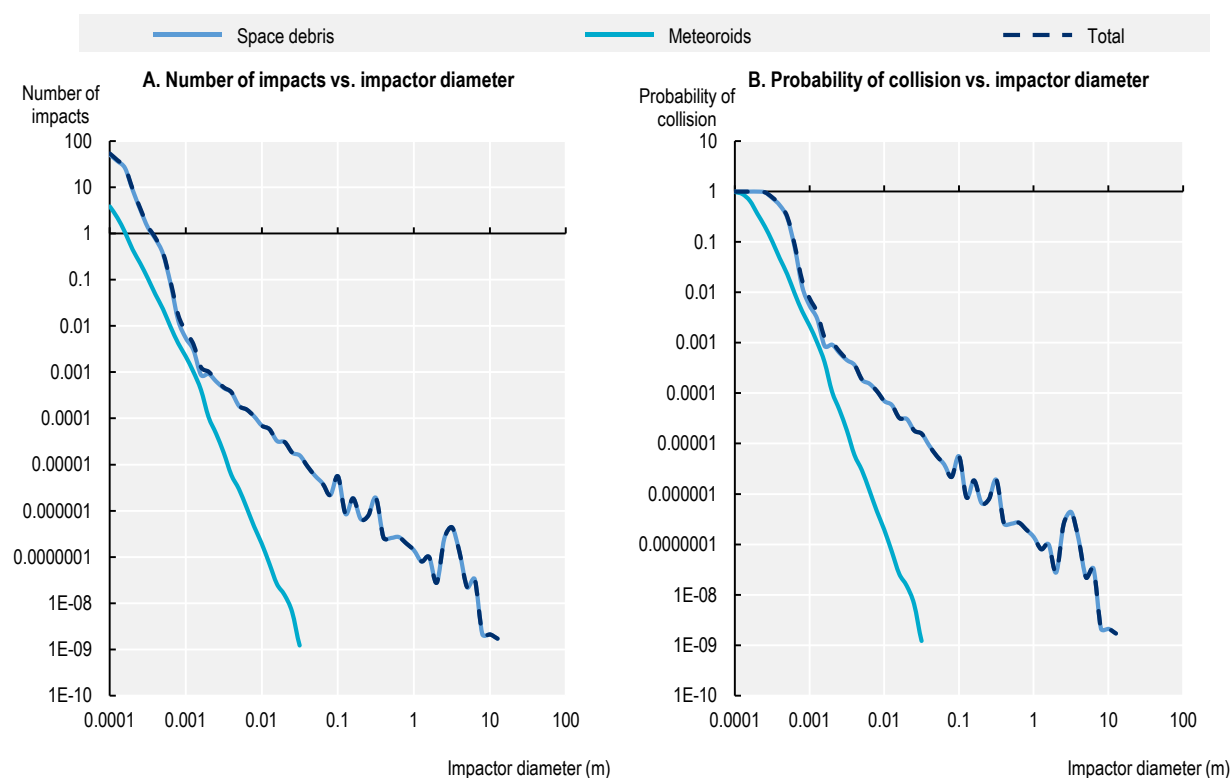
According to EUMETSAT guidelines, their primary criteria for intervention is an estimated probability of collision for the satellite above $1.0\text{E-}4$ (i.e. 10^{-4} or 0.0001). Upon meeting this condition, and considering additional factors such as overall miss distance, collision energy, data consistency, etc., a collision avoidance manoeuvre (CAM) is performed. The objective of the CAM is to reduce the collision risk below

1.0E-9 whilst minimising the impact on the mission (e.g. on fuel consumption). EUMETSAT data reveal that yearly risk warnings for the Metop mission have been consistently above 15 in the past five years. As an example, 29 warnings were raised in 2020. Of these, six prompted escalation meetings and four resulted in the execution of a CAM (EUMETSAT, 2021^[18]).

For our analysis, we considered a hypothetical spacecraft with characteristics similar to those in the Metop constellation, but either not functional or with limited manoeuvring capabilities. From the simulations on the ESA's public tool MASTER, we found that an orbiting target on a 900 km mean altitude circular polar orbit (98° inclination) would face a 2D flux distribution as shown in Figure 4.3.

The total flux in this spectrum would be 0.8E4/m² (i.e. 8 000/m²) per year, resulting from 17.1E6 (17.1 million) simulated cell passage events – a non-negligible amount of particles. The simulation accounts for man-made space debris population and meteoroid background. The selected tool uses a projection of future constellation traffic for condensed population and Gruen (constant velocity) meteoroid model for background meteoroids (ESA, 2020^[20]). Additional simulations were performed with the ESA's DRAMA-MIDAS tool (Figure 4.4).

Figure 4.4. Simulations of the number of impacts and probability of collision for the same orbital area



Notes: 900 km mean altitude circular polar orbit (98° inclination); reference epoch: 2016.

Source: Simulations carried out using the European Space Agency DRAMA-MIDAS simulation tool.

These findings were then complemented with adjustments to reflect the most recent debris developments, resulting in an estimated 2.7E-3 average probability of orbital deterioration in LEO. This appears realistic when considering the latest statistics for the EUMETSAT Metop constellation mentioned above: the manoeuvring capabilities and prompt intervention were essential to mitigate the risk below an acceptable threshold. In 2020, four CAM were executed, which provided a mitigation of the total risk by ~1.3E-2. The

total neglected risk cumulated during the year was $\sim 8.0\text{E-}5$, so more than 99% of the total observed risk was mitigated.

This assumption has resulted in a total expected value at risk for LEO of USD 191.3 billion. Full results, subdivided by 100 km regions, are reported in Table 4.9.

Table 4.9. Expected value at risk for each low-earth orbit region

Altitude (km)	Total value (USD billion)	Expected value at risk (USD billion)
300	1 198.6	3.2
400	8 655.7	23.4
500	42 157.0	113.8
600	6 945.2	18.8
700	3 068.6	8.3
800	1 945.8	5.3
900	452.8	1.2
1 000	1 644.7	4.4
1 100	676.9	1.8
1 200	2 785.2	7.5
1 300	120.0	0.3
1 400	1 015.2	2.7
1 500	1764.7	0.5
1 600	x	x
1 700	x	x
1 800	x	x
1 900	x	x
2 000	14.7	0.0
Total	70 856.7	191.3

Note: x = Not applicable.

Interpretation of results

The calculated value at risk quantifies the expected financial loss due to the presence of excessive debris in LEO. The figures reported here are static, but they have been modelled in the source file to evolve with time, as the exploitation of space continues. Among the possible ways of explaining the results, we have identified two main interpretations. First, the USD 191.3 billion output represents the value that, as a society, we must be willing to allocate towards solutions for space debris. In fact, it is the expected loss to be endured even if no further satellite launches take place moving forward. The sum is overwhelmingly superior to the resources invested thus far, which likely amount to a few billion dollars globally. Thus, our findings are very useful in providing visibility on the order of magnitude in commitment that is warranted.

Second, and perhaps more importantly, the expected value at risk for each region of space could be used as the base for the calculation of an “orbitoll”, i.e. orbital regime toll. Each time a new spacecraft is sent to space, the relative probability of collision within its orbiting region increases. The sum to be paid could thus be calculated as the difference between the new value at risk and the base value. For instance, using our estimates as a foundation, if a new satellite operating around the 500 km altitude were to increase the $2.7\text{E-}3$ probability of cascading collisions by 1.5%, then the spacecraft operator would have to pay USD 2.2 million in fees to operate in that area. A similar logic could even be applied to in-orbit servicing, devising a pricing model based on the relative decrease in collision risk.

The orbitoll scenario relies on strong technical and logistical simplifications. If this scheme were to be implemented, all the parameters and calculations would have to be significantly more accurate and reliable.

Also, there would be a need for a supranational entity with the authority of levying the binding tax on all operators from every country. The resources collected could then be spent toward the development of solutions for space debris. While the former consideration can be resolved with manpower and expertise, the latter is quite unlikely, as it falls within the complex scope of foreign policy and international relations. Nevertheless, we are confident that this work can inspire policy makers to devise and execute further measures to solve the issue at hand.

Discussion and conclusions

The rapid growth in the number of orbiting objects is threatening the sustainability of space-based infrastructure. The in-orbit accidents and intentional destructive events witnessed to date have produced large quantities of orbital debris that will remain a threat for decades or centuries to come. Moreover, as an increasing number of satellites is sent to space to satisfy the demand for space services, the likelihood of collisions is rising rapidly.

Space debris is a global problem that can only be solved through international co-operation. Efforts to date have been broadly ineffective and adherence to international mitigation guidelines (IADC, 2020^[21]) under par, likely because of the seemingly distant nature of the problem. Moreover, it is important to highlight that, in the present era of mega-constellations, these rules have become obsolete and insufficient.

This chapter contributes to the literature on space debris by presenting a novel way to conceptualise the issue. We first provided a qualitative representation of the downstream consequences that could arise if the problem of space debris is not promptly tackled. Through a dynamic dependency model, we traced the fallouts from a vicious, self-reinforcing cycle of collisions. This analysis is accompanied by the temporal evolution of the consequences stemming from an irreversible deterioration of certain orbital regimes. In the end, we find that – as is often the case in similar issues with global relevance – low-income countries are those that stand the most to lose. This deduction is tied to the role of space infrastructure in the global effort to eradicate poverty and the scarcity of resources that will prevent those communities from effectively responding to the looming catastrophe.

The qualitative considerations are complemented by quantitative analyses. Specifically, we estimated the monetary value that could be lost if the risk of collision in certain orbital regions becomes too high to permit nominal spacecraft operations. The first part of the exercise estimated that, from present to perpetuity, space-based infrastructure will contribute USD 234 trillion to the global economy. Allocated throughout LEO, this sum amounts to a cumulative USD 71 trillion for the orbits between 300 km and 2 000 km. Next, using publicly available simulation tools, we estimated the possibility of cascading collisions for the LEO region. With an average probability of $2.7\text{E-}3$, we computed an expected monetary loss over the long term of USD 191.3 billion. This result can be used to both highlight the concerning scale of the issue as well as to devise financial solutions to mitigate the uncontrolled congestion of the orbits.

Space debris is a concerning problem that, if unsolved, will cause severe economic damage on a global scale and leave a permanent mark on already impoverished nations that lack the resources to adequately respond. A parallel can be drawn with climate change, a reality that has arguably also arisen from the deliberate and uncontrolled exploitation of widely available resources. In the climate change era, those already burdened by poverty and oppression suffer the harshest consequences, mostly due to their inability to cope (Harrold et al., 2003^[22]). Similarly, in our reference scenario, where certain subsets of the Earth's orbits become unusable, wealthy nations will certainly be able to find alternative solutions to the related space-based services, for instance by developing substitute technologies. History proves, however, that before these potential systems will become accessible to the broader population, years will pass, and the wealth gap will inevitably increase.

Limitations and future developments

The present document has evident limitations that provide, nevertheless, an opportunity for further research. Starting from the qualitative section, we must note that the dynamic mapping of space debris-related costs and the temporal evolution of related fallouts are subject to simplifications and would be significantly more complex in the real world. An interesting and useful contribution to augment the present chapter could derive from the application of a system dynamics methodology to the problem, potentially quantifying the various costs in relation to changes in the number of orbiting objects.

With respect to the economic exercise, we must first emphasise that the PwC (2017^[13]) report on which our paper builds was tailored for the EU, introducing a margin of error due to the difference in fractional composition of the EU GVA compared with the world GVA. Second, the primary enabling assets considered were only GNSS, EO and ST. While these applications represent the majority of space-based activities, there is still a portion that was unaccounted for. Third, simplifications were made in the allocation of the satellites considered throughout LEO, for instance by excluding elliptical orbits. Fourth, we assumed that, following potential collisions, the created debris remains within the orbital region of origin and does not contaminate other areas of space; and does so until infinity, meaning we assume there is no orbital decay. This is a strong assumption, particularly for orbits below 600 km (ARES, 2021^[23]). For all these limitations, a more in-depth and technically sound exploration could improve the results.

Regarding the statistical considerations, several shortcomings were intrinsic to the tools used. For instance, both MASTER and DRAMA have a population only validated until November 2016, thus overlooking the mega-constellations trend already underway, as well as the recent in-orbit destruction events. While we performed adjustments to address this issue, our calculations might be inaccurate. Moreover, the computed probability was based on a single real-life scenario (Metop), which could be considered to have limited statistical relevance. Therefore, a deeper analysis – potentially tailored for each orbital region, and simulating different types of spacecraft and collision types – could significantly improve the soundness of results. Finally, a further enhancement of the study could be focused on modelling how the background debris population changes when superimposing a simulated breakup of another satellite.

Despite these limitations, which can be addressed in future projects, we are confident that this work can contribute to highlighting the urgency and scale of the problem, incentivising private and public players to join forces for the benefit of all.

References

- ARES (2021), “NASA Orbital Debris Program Office – Frequently asked questions”, web page, <https://orbitaldebris.jsc.nasa.gov/faq> (accessed on 4 July 2021). [23]
- ESA (2021), *Space Environment Statistics (database)*, <https://sdup.esoc.esa.int/discosweb/statistics> (accessed on 1 December 2021). [3]
- ESA (2020), *Software User Manual – MASTER, Issue 1.2*, European Space Agency. [20]
- EUMETSAT (2021), *Collision Avoidance Statistics for 2020, EUMETSAT CA operational logs*, European Organisation for the Exploitation of Meteorological Satellites, Darmstadt. [18]
- EUMETSAT (2016), *EUMETSAT CAM Decision Process*, SSA Operators’ Workshop, Denver. [19]
- Euroconsult (2021), *The Space Economy Report: An Outlook of the Key Trends in the Global Space Market, 8th edition*, Euroconsult, <https://digital-platform.euroconsult-ec.com/product/space-economy-report>. [11]

- Harrold, M. et al. (2003), *Poverty and Climate Change: Reducing the Vulnerability of the Poor through Adaptation*. [22]
- IADC (2020), *IADC Space Debris Mitigation Guidelines*, IADC Steering Group and Working Group 4, Inter-Agency Space Debris Coordination Committee, <https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf> (accessed on 13 July 2021). [21]
- IADC (2007), *IADC Space Debris Mitigation Guidelines*, Inter-Agency Space Debris Coordination Committee. [2]
- IDA (2020), *Measuring the Space Economy: Estimating the Value of Economic Activities in and for Space*, Institute for Defense Analyses, Science & Technology Policy Institute, <https://www.ida.org/-/media/feature/publications/m/me/measuring-the-space-economy>. [12]
- Kessler, J. and B. Cour-Palais (1978), "Collision frequency of artificial satellites: The creation of a debris belt", *Journal of Geophysical Research*, Vol. 83/6, pp. 2637-2646, <https://doi.org/10.1029/JA083iA06p02637>. [4]
- Klinkrad, H. (2006), *Space Debris: Models and Risk Analysis*, Springer Praxis, Berlin-Heidelberg, <https://doi.org/10.1007/3-540-37674-7>. [1]
- NYU Stern (2021), *Cost of Capital (database)*, http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/wacc.htm (accessed on 17 July 2021). [16]
- OECD (2022), *Real GDP long-term forecast* (indicator), <https://doi.org/10.1787/d927bc18-en> (accessed on 9 August 2022). [15]
- Pardini, C. and L. Anselmo (2021), "Evaluating the Impact of Space Activities in Low Earth Orbit", *Acta Astronautica*, Vol. 184, pp. 11-22, <https://doi.org/10.1016/j.actaastro.2021.03.030>. [5]
- PwC (2017), *Dependence of the European Economy on Space Infrastructures: Potential Impacts of Space Asset Loss*, Publications Office of the European Union, Brussels, <https://doi.org/10.2873/81127>. [13]
- Schaub, H. et al. (2015), "Cost and risk assessment for spacecraft operation decisions caused by the space debris environment", *Acta Astronautica*, Vol. 113, pp. 66-79, <https://doi.org/10.1016/j.actaastro.2015.03.028>. [8]
- Shekhtman, L. (2016), "How to fight global poverty from space", *The Christian Science Monitor*, <https://www.csmonitor.com/Business/new-economy/2016/0818/How-to-fight-global-poverty-from-space> (accessed on 28 May 2021). [9]
- Sterman, J. (2000), *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin/McGraw-Hill, Boston. [7]
- UCS (2021), *UCS Satellite Database: In-depth Details on the 4 084 Satellites Currently Orbiting Earth, Including their Country of Origin, Purpose, and other Operational Details*, <https://www.ucsusa.org/resources/satellite-database> (accessed on 23 July 2021). [17]
- Undseth, M., C. Jolly and M. Olivari (2020), "Space sustainability: The economics of space debris in perspective", *OECD Science, Technology And Industry Policy Papers*, No. 78, OECD Publishing, Paris, <https://doi.org/10.1787/23074957>. [6]

United Nations (2016), “Benefits of exploration crucial for eradicating poverty, say speakers, as Fourth Committee takes up international cooperation in outer space”, press release, [10]
<https://www.un.org/press/en/2016/gaspd614.doc.htm>.

World Bank (2021), “Gross value added at basic prices (GVA) (current US\$)”, World Bank data, [14]
<https://data.worldbank.org/indicator/NY.GDP.FCST.CD> (accessed on 3 June 2021).

5

Socio-economic benefits of earth observation: Insights from firms in Italy

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The increasing availability of earth observation (EO) data results in a growing number of firms penetrating the “downstream” space sector, providing a diverse range of innovative services and applications. This makes space-based infrastructure ever more valuable to society at large. This chapter presents the results of a survey carried out within a sample of Italian firms in the EO downstream sector, providing an overview of their main characteristics, their points of view on EO’s current and potential socio-economic benefits, and on still existing barriers for adoption in Italy.

Introduction

Earth observation (EO) is a strategic domain of the space industry. It consists of the collection of a wide variety of chemical, biological and physical information about the Earth via remote sensing technologies (GEO, 2020^[1]).¹ This domain has undergone dramatic changes since the beginning of this century (Craglia and Pogorzelska, 2019^[2]). It has rapidly developed over recent years, enabling a wide array of services, applications for national and local governments, public and private firms, scientists, and citizens (PwC, 2016^[3]; Tassa, 2019^[4]). According to the Union of Concerned Scientists database (UCS, 2021^[5]), 27% of the 3 372 satellites in orbit (or around 900) are EO satellites, while this percentage was only 16% in 2014.

This chapter focuses on firms operating in the EO downstream sector, which is one of the most dynamic and promising segments of the value chain. The sector includes the “intermediate users” of EO data who provide EO services and applications for final users (governments, firms and individuals) in a wide range of fields, including climate change, natural disasters, human health and resource efficiency, to name just a few. We are particularly interested in this category as the downstream sector is expected to contribute the most to the growth and maximisation of the socio-economic value of EO and its socio-economic impact (Pogorzelska, 2018^[6]). Indeed, in the coming decades, the expansion of EO will be achieved by advancing firms’ capabilities in Big Data collection, storage and analysis through algorithms, artificial intelligence and computing power to effectively manage and intersect a growing amount of information from different sources.

This chapter aims to answer the following research questions: 1) what are the main characteristics of the firms operating in the downstream sector?; 2) what benefits may stem from the increasing availability of EO data?; and 3) what types of barriers currently hinder the development of this sector?

Our research focuses on Italy. Among European countries, Italy is at the forefront of the EO sector (Kansakar and Hossain, 2016^[7]). However, although the Italian space manufacturing sector is at the lead of the international space industry (including the construction of cutting-edge satellites), little is known about the return of EO along the value chain, particularly for downstream operators and final users, where the market potential and socio-economic impact is still underexploited.

To answer our research questions, we collected primary data through an online survey of firms operating in the downstream sector to know their characteristics, needs and view on the benefits stemming from EO.

This chapter is divided into five sections. Section 2 introduces a brief review of the literature related to firms in the EO downstream sector, their characteristics, and socio-economic benefits arising from the production and exploitation of EO services. Section 3 discusses the method and the survey design, while Section 4 presents the results. Finally, the last section concludes by presenting possible obstacles to the sector’s development and policy recommendations.

The downstream sector and the socio-economic benefits of earth observation

An overview of the earth observation downstream sector

While satellite technology is advancing quickly, a vast and varied amount of new data is becoming increasingly available to improve decision making and quality of life and to solve pressing societal problems (RFF, 2017^[8]).

The EO downstream sector mainly includes small and medium-sized companies with high technological know-how, developing commercial applications from satellite data² (value added services), geo-information firms, consultancy companies, research institutes with artificial intelligence expertise and hardware/software development companies, among others (PwC, 2016^[3]). In this category, we also include companies and departments within large organisations that deal with data archiving, storage, data pre-processing, and the delivery of middle services to facilitate and enable the creation of final services and applications (Pogorzelska, 2018^[6]; PwC, 2016^[3]) (this segment is sometimes called midstream).

According to Euroconsult (2020^[9]) the global market for value-added EO services was USD 3.0 billion in 2019,³ growing at a five-year compounded average growth rate (CAGR) of 7%, and it is expected to reach about USD 6 billion by 2030. At the European level, EARSC (EARSC, 2020^[10]) estimated EUR 1.38 billion of revenues for the European industry in 2019 and a 17% employment growth over 2018, mainly due to new micro-companies or start-ups entering the sector. Europe counts around 580 companies, mostly located in the United Kingdom, followed by Germany and France, while Italy is in fifth position (EARSC, 2020^[10]).

The growth and dynamism of this sector are mainly driven by automation with artificial intelligence development and large volumes of high-revisit low-cost data that contribute to the proliferation of new services and applications, mainly for the public sector (Euroconsult, 2020^[9]; EARSC, 2020^[10]). Fields of applications are numerous, including agriculture, urban planning, transport, land use, monitoring ocean activities, health and civil protection, among others (NEREUS, European Commission and European Space Agency, 2018^[11]; Daraio et al., 2014^[12]; PwC, 2019^[13]). Additionally, the increasing availability of free and open-source data sets such as those provided by Copernicus of the European Union is further raising the awareness of EO services and products, boosting the creation of value-added products (Robinson and Mazzucato, 2019^[14]).

Although international and European studies are informative, it is not easy to obtain information about the current situation of the downstream sector in Italy; information is scant and dispersed, a gap that we would like to fill with this research by providing a snapshot of the Italian market. Gaining more information about this sector, its characteristics and its way of working is the first step towards promoting its development and, consequently, pushing the whole EO frontier forward.

The socio-economic benefits stemming from earth observation data

Several socio-economic benefits may derive from the increasing availability of satellite imagery and data and accrue to different stakeholders along the value chain (Pogorzelska, 2018^[6]; Craglia and Pogorzelska, 2019^[2]; Hof et al., 2012^[15]; PwC, 2016^[3]). Focusing on the downstream sector, one of the most relevant benefits for firms is the learning by doing effect, which refers to an increase in long-term performance achieved through practice (Arrow, 1971^[16]; Lucas Jr., 1988^[17]). This benefit may stem from the new technological and challenging task firms are called to face, such as creating cutting-edge EO service/applications or archiving, storing and pre-processing large quantities of data with innovative, affordable and smart solutions. Having to face new challenging tasks, firms will likely increase their research and development (R&D) activity, generating new knowledge, which may translate into an innovation or another positive change in their processes (i.e. market, commercial or organisational effects) with an ultimate impact on their productivity and profitability (Edquist et al., 2015^[18]; Uyarra and Flanagan, 2010^[19]; Edler and Georghiou, 2007^[20]). In this learning process, the role played by public sector procurement is crucial, as the global EO downstream market is primarily driven by applications commissioned by governments, representing 50-60% of the revenues (PwC, 2019^[13]). Hence, we expect firms in the downstream sector to register long-term positive effects in their performance driven by a learning process related to data exploitation and mainly pushed by public procurement activities.

In addition, the benefits of new information captured by EO ultimately accrue to final users of services and applications. In the last 20 years, various methodologies have been applied to evaluate the socio-economic benefits derived from the use of EO services and applications (Smart et al., 2018^[21]; PwC, 2016^[3]; WMO, 2015^[22]; Hof et al., 2012^[15]; Craglia and Pogorzelska, 2019^[2]), drawing on various techniques, including the value of information (Macauley, 2006^[23]; Gallo, Bernknopf and Lev, 2018^[24]), cost-benefit analysis (Booz & Company, 2011^[25]; Halsing, Theissen and Bernknopf, 2004^[26]), cost-effectiveness analysis (Dawes et al., 2013^[27]) and value chain approach (Sawyer, Boyle and Khabarov, 2020^[28]; Sawyer et al., 2015^[29]), among others. This chapter explores the perceptions of downstream firms on the benefits accruing to the final users of their services.

First, with EO, final users can deliver usual or innovative services to groups of citizens (e.g. in the case of governments) or customers (e.g. in the case of private companies) by saving money, gaining efficiency, increasing efficacy and quality (see, for example, the European Association of Remote Sensing Companies [EARSC] for a review of case studies of EO applications and related benefits) (EARSC, 2022^[30]). For instance, in Belgium, a group of potato farmers has started using an application based on EO data to get information on their fields for better crop management practices (Sawyer, Oligschläger and Oligschläger, 2019^[31]). This information helps to improve yields by up to 20% and the overall quality of potatoes, hence increasing revenues and income for the farmers and the whole potato industry value chain (agronomists, processors, distributors, supermarkets, etc.) up to the final consumers. In road infrastructure and management, a new mapping service showing ground motion based on EO is supporting public administration in Norway. The EARSC estimates an economic benefit of between EUR 3.8 million and EUR 8.7 million per year, mainly deriving from cost savings in the construction and management of the road infrastructure (Sawyer, Boyle and Khabarov, 2020^[28]).

Besides economic gains, EO may have an impact on social challenges, such as better protecting fragile ecosystems, ensuring resilient infrastructures, managing climate risks, enhancing food security and building more resilient cities, among others. This is why EO contributes to progress toward the 17 Sustainable Development Goals and its 169 associated targets (GEO, 2017^[32]). EO services and applications bring positive externalities and non-market effects for the general public, such as, for instance, improved air quality, reduced traffic accidents or increased safety of citizens (European Commission, 2014^[33]). Such benefits can be enormous, although still unexpressed and mostly unmeasured.

All this considered, we expect EO services and applications delivered by firms in the downstream sector to have a significant socio-economic impact on final users and positively contribute to solving critical societal challenges.

Despite the enormous potential of EO and its applications, several obstacles are currently hindering the development of the final segment of the value chain. Thus, an important issue is identifying and overcoming barriers limiting the widespread use of EO services and applications. Such obstacles will be discussed in the concluding section of this chapter.

Method

To answer our research questions, we mapped Italian firms operating in the downstream industry. We integrated information coming from different sources, including ASI and ICE (2020^[34]), users of the main Italian EO satellite constellations, members of Italian associations active in the space sector⁴ and the national cluster (*Cluster Tecnologico dell'Aerospazio, CTNA*). We validated such sources through interviews with key experts in the industry. Hence, we collected primary data through an online survey based on around 30 semi-structured questions to explore the main characteristics of firms, what benefits they think stem from the availability of EO data and what barriers they identify to the development of this sector in Italy. Most of the questions exploit answers based on a Likert scale.⁵

Six pilot tests were also carried out with companies and other experts in the sector to verify the clarity of the questions. The questionnaire was then administered by e-mail between February and July 2021 through an online survey. Reminders were sent by e-mail and made by telephone.

The final database consists of 85 companies which, as confirmed by the sector experts interviewed, represent the whole population of companies operating in the downstream sector in Italy. Of these, 63 companies participated in the survey, which has a response rate of approximately 74%. A study available at the European level (EARSC, 2020^[10]; 2019^[35]) reports information only for about 40 Italian companies.

Main results

Firms' characteristics, use of earth observation data and services offered in Italy

About half of the 63 interviewed companies (46%) are micro firms with less than ten employees (Table 5.1). This could highlight a lower dynamism of Italian start-ups and newborn firms compared to the European average, where about 70% of companies operating in the sector are micro-sized (EARSC, 2020^[10]). Just under a third (32%) of the sample consists of small firms (10-50 employees), 9.5% have 50-250 employees, while 13% are large firms (Table 5.1). The composition of our sample highlights the critical role of medium and large IT firms, which penetrate the EO market by directly opening new EO units and divisions. The average number of employees involved in EO activities is 21. Some firms declare zero employees devoted to EO, as these companies use external collaborations, stressing the difficulty in finding the needed competencies internally in the companies themselves, which is in line with the overall European trend (EARSC, 2020^[10]).

Table 5.1. Firms' size by number of employees

Firm size	Percentage of firms (%)
Micro (< 10)	46.0%
Small (< 50)	31.7%
Medium (<250)	9.5%
Large	12.7%
Total	100%

In terms of turnover, 17% of the firms interviewed declare earning less than EUR 100 000/year, while about 40% earn more than EUR 1 million (Table 5.2). The share of turnover deriving from EO activities varies between 1% and 25% in 48% of cases and is more than 76% for one-quarter of the firms (Table 5.2). Considering the distribution of firms by dimension and the share of turnover from EO activities, we gain interesting insights. Seventeen per cent of micro firms declare a percentage of EO turnover between 1% and 25% while 14% declare between 76% and 100%. As expected, most large firms show a share between 1% and 25%, confirming that large firms dedicate special units to EO, but usually this is not their core business.

Table 5.2. Earth observation turnover as a percentage of total turnover by firm size

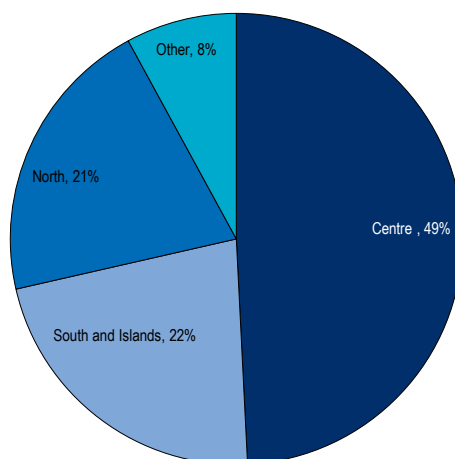
Turnover related to earth observation (%)	Micro	Small	Medium	Large	Total firms (%)
0%	1.6%	1.6%	0.0%	0.0%	3.2%
1-25%	17.5%	14.3%	6.3%	9.5%	47.6%
26-50%	0.0%	4.8%	0.0%	1.6%	6.3%
51-75%	6.3%	1.6%	0.0%	0.0%	7.9%
76-100%	14.3%	6.3%	3.2%	1.6%	25.4%
Don't know	6.3%	3.2%	0.0%	0.0%	9.5%
Total	46.0%	31.7%	9.5%	12.7%	100.0%

The average age of firms in our sample is 20 years,⁶ although the average time since they started some EO activities is 13 years. Twenty-two percent of firms define themselves as a “startup”, while 49% are registered at “registro delle start up e piccole e medie imprese innovative”. Innovative small and medium enterprises (SMEs) represent a step forward compared to startups since they have consolidated their business activity and achieved a stable growth rate. Therefore, this category of firms is crucial for the country's innovative development (MISE, 2021^[36]).

In terms of geographical distribution (by headquarter, which mostly matches with the branch carrying out the EO activities), 49% of companies interviewed are located in the Centre region, 21% in the North and

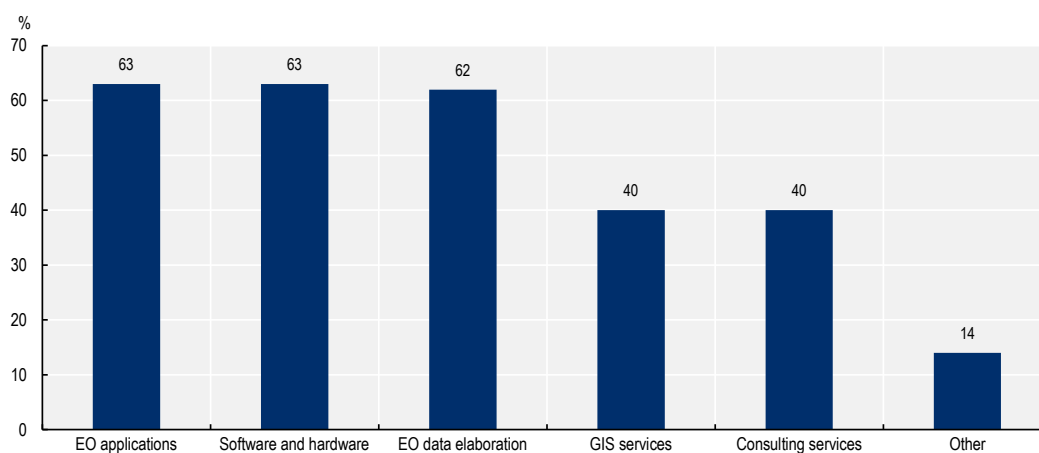
22% in the South and Islands (Figure 5.1). In particular, almost 41% of firms are located in the province of Rome, 8% in Naples and then, with lower percentages, in Genova, Potenza, Matera, Bari, Milan and so on. The higher concentration of firms in the centre of Italy is due to the presence of clusters of companies working in other segments of the space industry, the presence of the Italian Space Agency (ASI) and the ESA Centre for Earth Observation (ESRIN) which all together act as catalysts.

Figure 5.1. Geographic location of EO firms in Italy by headquarter



Firms use EO data to offer several products and services (Figure 5.2). 63% of the sample develops hardware and software in the IT sector (not necessarily related to EO), while 62% of firms elaborate EO data to deliver various types of information. In particular, 62% of firms develop innovative EO applications in several fields (e.g. agriculture, environmental monitoring, infrastructures, and natural disasters, among others), 40% of firms offer consulting services, 40% offer GIS services⁷, and 14% use EO data for other purposes, such as cyber security and research.

Figure 5.2. Main earth observation services offered



Notes: Multiple answers allowed; EO: earth observation; GIS: geospatial information systems.

Copernicus Sentinels of the European Union are the satellites that support the companies' EO activities the most, utilised by 75% of the respondents. Copernicus data have the advantage of being open and free to public, private organisations and citizens. In the following positions, the most used data are those from

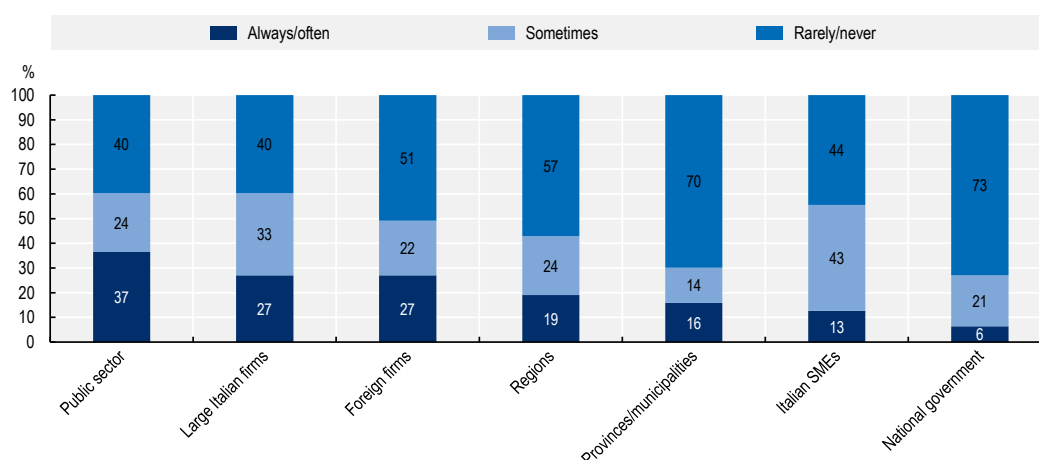
the constellation CosmoSkymed of ASI (46% of the firms), Landsat of NASA (38%), and Prisma of ASI (29%). While Landsat data can also be obtained free of charge by applying online on the United States Geological Survey (USGS) website, there are two alternatives to access CosmoSkymed data. For commercial purposes, the company e-geos sells both the raw satellite data and the information extracted from the latter. For national civil purposes, data are made available directly by ASI by granting a license following an onerous bureaucratic procedure (Clò et al., 2019^[37]). Lastly, around 30% of companies use EO data from other satellites such as Eumetsat, ESA Heritage Missions, ESA Earth Explorers, Airbus, Maxar, MDA, Planet, SpaceView, Cubesat, Worldview 2-3-4, TerraSAR-X/Paz, CNES, Pleiades Satellogic, and Capella, among others. In percentages, the data that supports most of EO business activities are those from Copernicus Sentinels as 24% of companies declares to use them for about 76% -100% in support to their EO activities (Table 5.3).

Table 5.3. Main satellites supporting downstream firms and their percentage of use

	Copernicus Sentinels (ESA)	Cosmo Skymed (ASI)	Landsat (NASA)	Prisma (ASI)	Modis (NASA)
Total use	75%	46%	38%	29%	19%
% of use					
76% - 100%	24%	5%	6%	0%	3%
51% - 75%	21%	11%	5%	2%	2%
26% - 50%	19%	13%	10%	6%	3%
1% - 25%	11%	17%	17%	21%	11%
0%	25%	54%	62%	71%	81%

Note: Multiple answers allowed.

Figure 5.3. Main clients and final users of EO services and applications



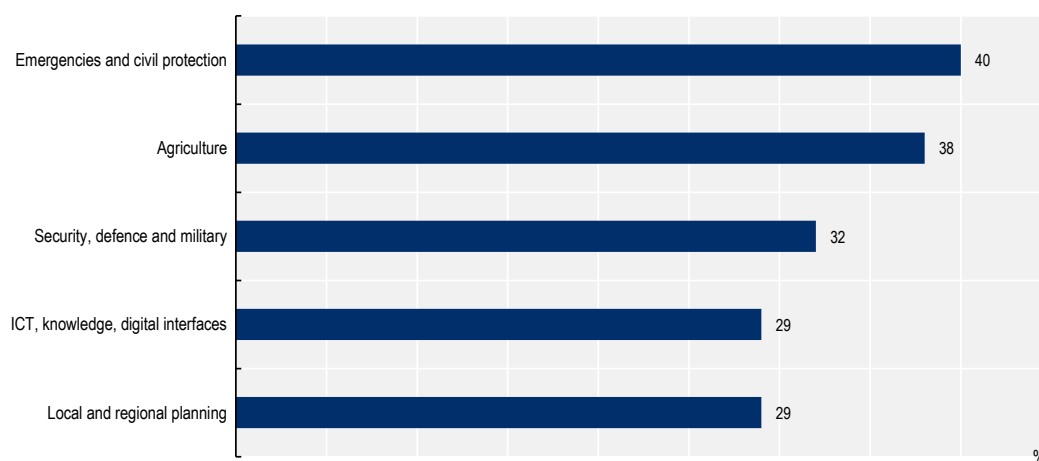
In most cases, 67% of respondents access free data in open mode, 38% of firms pay to use data, 27% use free licensed data, while in 19% of cases, they access data in another way e.g. via collaborations with service providers, acquisition from their own satellites, through partners, or by developing solutions that integrate services created by others (Figure 5.3). Furthermore, in 60% of cases, EO data are (always or often) combined with other data and information sources. In contrast, 19% of the companies declare not to integrate them with additional sources of information or do so rarely.

Concerning the final users to whom EO services and applications are addressed, mostly in line with our expectations, these are (often and very often) Italian bodies operating in the public sector (for 37% of the firms interviewed), large Italian companies for 27%, foreign firms for 27%, regions for 19%, provinces and

municipalities for 16%, Italian SMEs for 13%, while only 6% usually work with the national government (Figure 5.4). Other clients and users include the European Commission, international agencies, multilateral development banks, and foreign governments. Hence it is evident that services are most popular among public bodies, including entities such as civil protection forces (Protezione Civile) or regional agencies for environment protection (ARPA), among others.

Indeed the main areas of application of EO services are emergency and civil protection (40% of firms offer EO services to support this sector), agriculture (38%), security and defence (32%), the ICT sector, knowledge and digital interfaces (29%), local and regional planning (29%) as shown in Figure 5.4. Other areas include ecosystems, ocean and climate monitoring, buildings, insurances, oil and gas, fishing, health, with lower percentages.

Figure 5.4. Main areas of application of earth observation services



Note: Percentage of firms (%); multiple answers allowed.

In this respect, most firms (73%) recruit customers mainly in public tenders, stressing the crucial role of public procurement in the demand for EO services (Table 5.4).

Table 5.4. Methods for recruiting customers

Methods	Percentage of firms (%)
Participation in tender	73%
Marketing/Advertisement	54%
Personal acquaintances	52%
Word of mouth	30%
Italian Space Agency (ASI) support	25%
Other	19%

Note: Multiple answers allowed.

The socio-economic benefits of EO from the point of view of firms

As explained in previous section, we have explored the point of view of downstream firms by distinguishing their opinion about the benefits accruing to themselves and those to final users. Concerning the first category, results from our survey highlight the critical contribution of EO to improving the operational processes of firms in the downstream sector. Indeed, the vast majority of companies (83%) agree (totally or partially)

that the availability of EO data has contributed to improving the quality of their products and services. 83% of respondents declare that their R&D capabilities have improved thanks to satellite data, while 63% have created new R&D teams/units. Seventy-five percent have also enhanced their technical know-how, meaning that thanks to satellite data, they have increased the knowledge and technical skills necessary to carry out certain activities within their industrial sector of activity, even outside EO. Fifty-six percent have also improved the production processes while 44% their management and organisation skills. Forty-one percent have opened new business units. Residual percentages have instead declared that they disagree (totally or partially) with the statements above (Figure 5.5).

Figure 5.5. Earth observation contribution to firms' process innovation

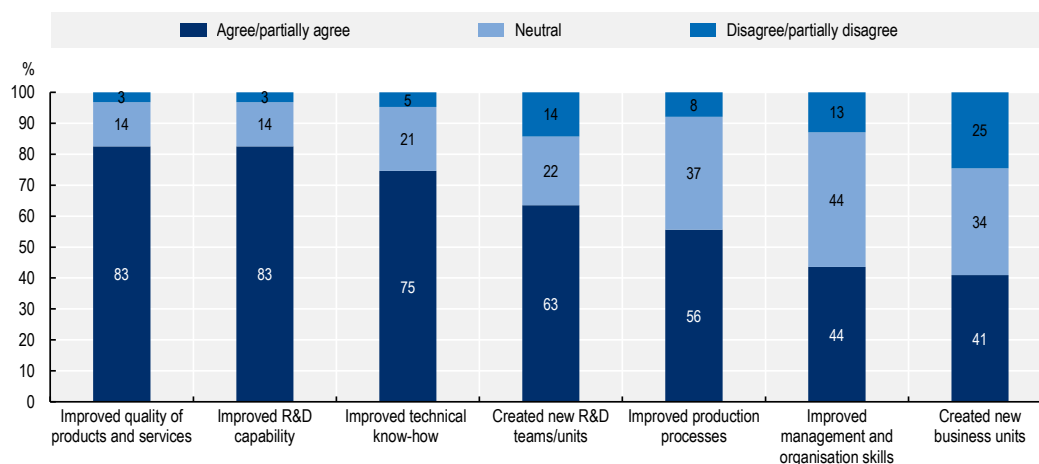
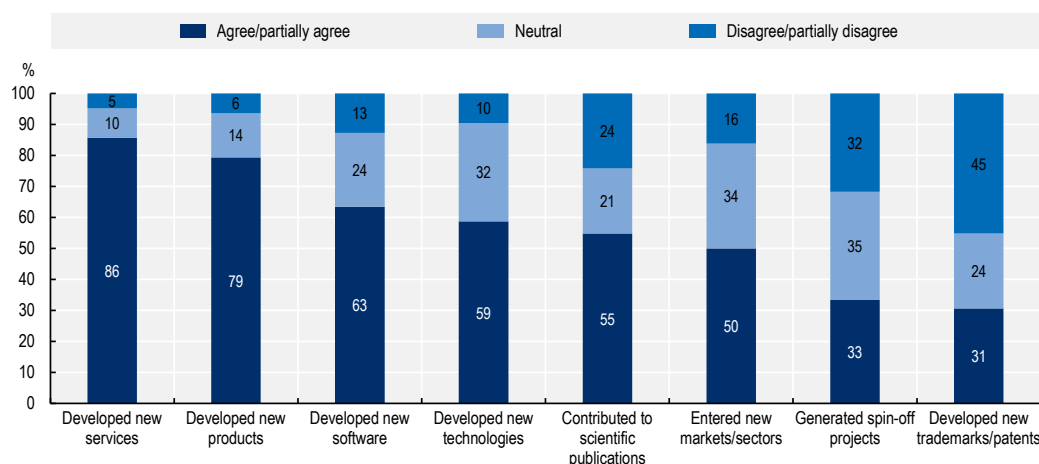


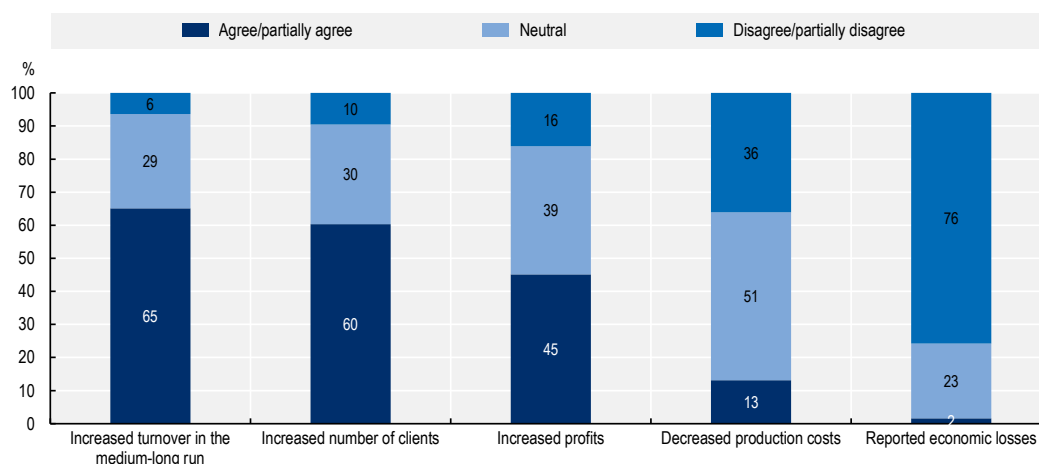
Figure 5.6. Earth observation contribution to firms output and process innovation



EO has also significantly contributed to improving corporate output and product innovation. Indeed, 86% of firms declare to have developed new services and 79% new products thanks to EO. 63% have created new software, Fifty-nine percent have developed new technologies, while 55% have contributed to scientific publications. As a consequence, 50% of respondents have entered new markets or sectors, and 33% have registered new spin-off projects. In addition, 31% have developed new trademarks and patents. However, Forty-five percent disagree (totally or partially) with the latter statement highlighting that many of these innovations have not been patented for reasons which would require further investigation (Figure 5.6).

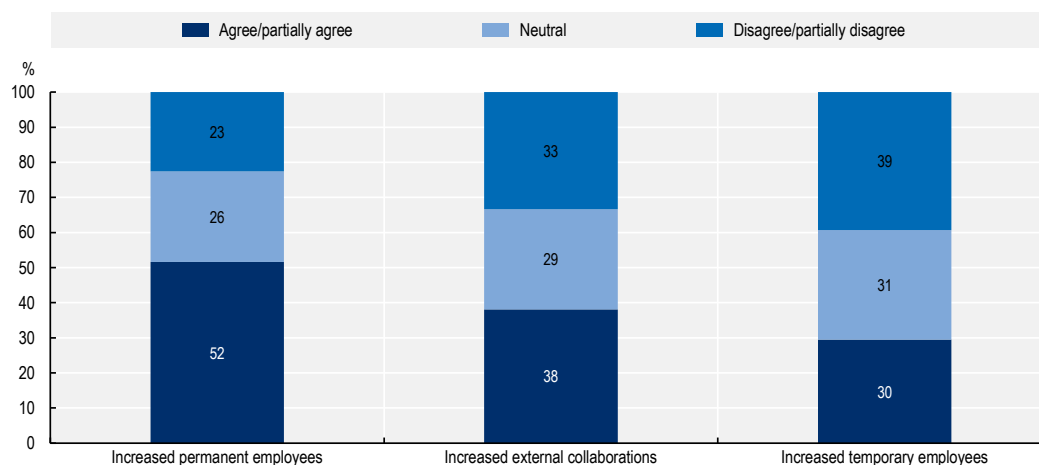
Concerning the ultimate impact of EO in economic terms, 65% of firms declare to have increased their long-term turnover, 60% the number of customers, 45% have raised profits, 13% have decreased production costs. In comparison, only 2% have reported losses (Figure 5.7).

Figure 5.7. Earth observation contribution to firms' economic performance



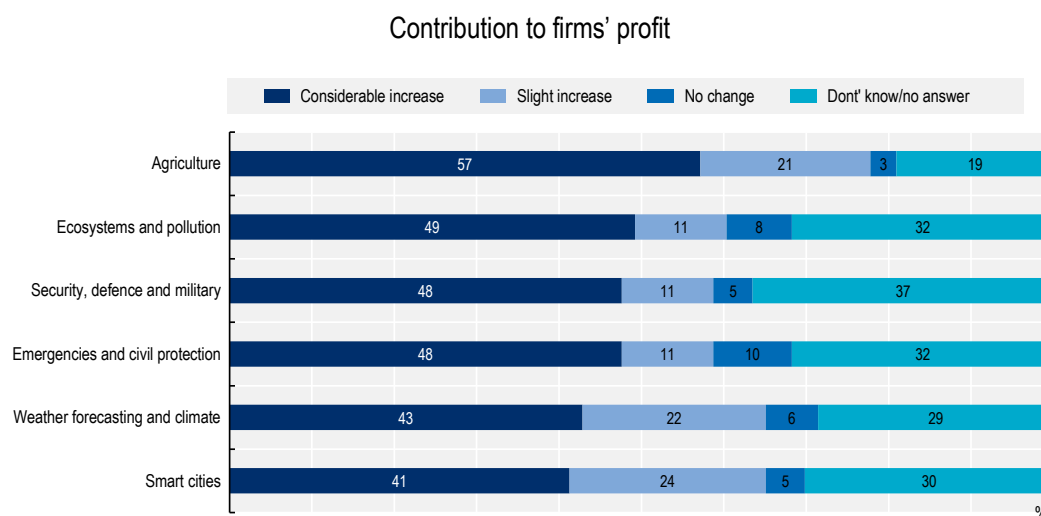
Additionally, in terms of effects on employment, 30% of companies agree (totally or partially) with the statement that, due to the EO, they have increased the number of temporary employees, 52% permanent employees, while 38% have expanded the number of collaborations with self-employed workers (Figure 5.8).

Figure 5.8. Earth observation contribution to employment



Concerning the impact of EO for final users, firms were asked to give an opinion about the expected economic gain for users of their EO services. A considerable increase in profits is expected in agriculture (57% of respondents), ecosystems and pollution (49%), emergencies and civil protection (48%), security, defence and military (48%), weather forecasting and climate (43%) and smart cities (41%) as shown in Figure 5.9.

Firms were also asked to choose three ATECO⁸ sectors that, in their opinion, will mainly benefit from the EO services offered in the next five years. About 26% of the answers went to agriculture, silviculture, and fishing, 12% to public administration and the defence sector, 7% to scientific and professional activities.

Figure 5.9. Earth observation contribution to the economic performance of final users by sector

Note: Percentage of firms (%).

Lastly, regarding the social impact, companies have been called upon to express which Sustainable Development Goals (SDGs) their EO services primarily contribute to (Table 5.5). The first target appears to be number 13 (Adopting urgent measures to combat climate change and its consequences), with 12% of the answers and in line with the European survey (EARSC, 2020_[10]). In the second position, target 9 (Building a resilient infrastructure, promoting inclusive and sustainable industrialisation and supporting innovation) with 11% of preferences, and in the third position (10%) both target 11 (Make cities and human settlements inclusive, safe, resilient and sustainable) and target 15 (Protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse soil degradation and stop the loss of biodiversity). Regarding the contribution to targets 9 and 11 these are more peculiar for firms working in the Italian market as their European counterparts have given a lower credit to the contribution of their EO services to such goals (EARSC, 2020_[10]).

Table 5.5. Earth observation main contribution to Sustainable Development Goals

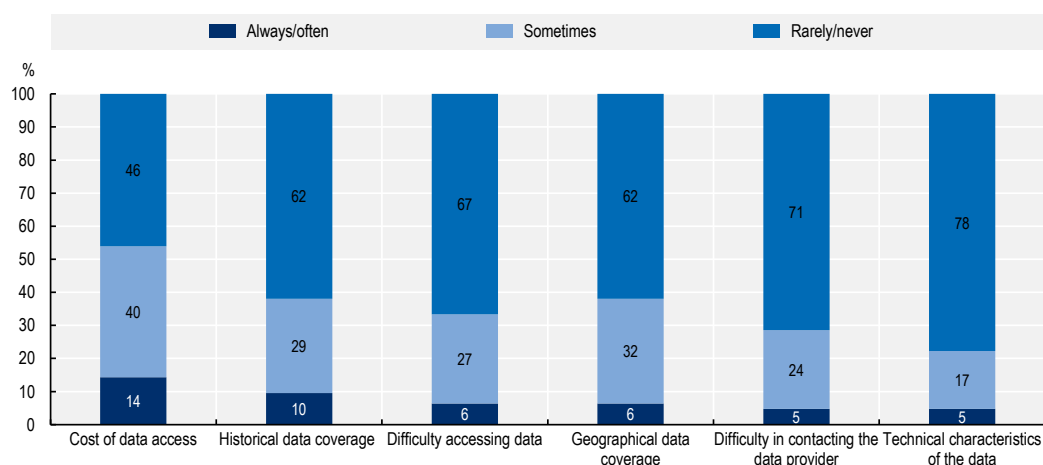
SDGs	Percentage of firms (%)
13: Take urgent action to combat climate change and its impacts	12%
9: Building resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation	11%
11: Make cities and human settlements inclusive, safe, resilient and sustainable	10%
15: Protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse soil degradation and stop the loss of biodiversity	10%

To sum up, according to the view of firms working in the Italian downstream market, EO significantly contributes to their performance in terms of several indicators of innovation, employment and long-term turnover. EO also positively contributes to the economic performance of final users and in tackling critical societal challenges.

The main obstacles to the diffusion of earth observation products and services according to firms

The factors hindering the development of EO vary. For this survey, it was essential to investigate the difficulties that firms in the downstream sector encounter in developing EO services and applications and disseminating the services and applications to final users, as shown in Figure 5.10.

Figure 5.10. Main criticalities in using earth observation data



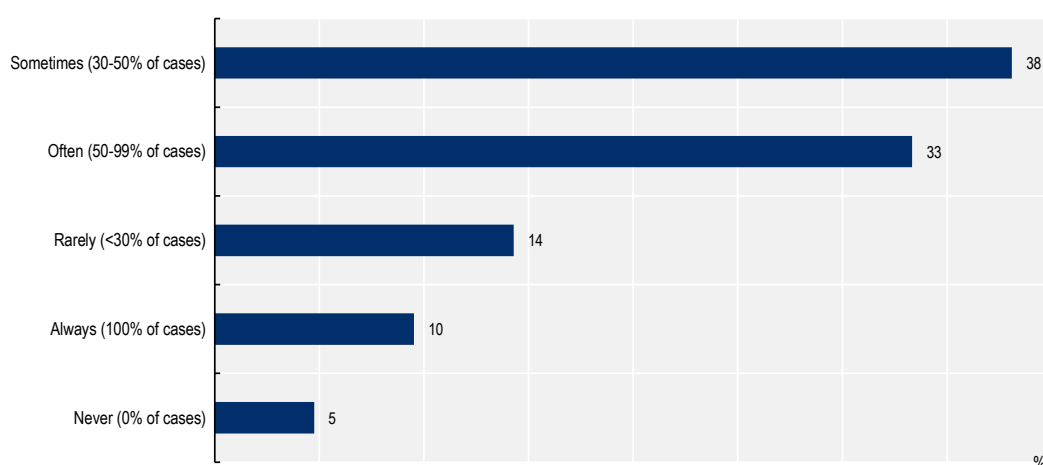
Note: Answers refer to the main data used

According to our survey, companies in the downstream sector do not seem to encounter any particular difficulties in accessing data. Only 14% of companies declare having (often or very often) problems with the cost of data, while 40% responded “sometimes.” Furthermore, only 10% of firms declared that there are no time series suitable to develop their services effectively, 6% have problems accessing data or geographical coverage issues, while 5% encounter difficulties in the data’s technical characteristics and interacting with the data provider.

As for the relationship with the data provider, 38% of intermediate users said they often or very often had a stable relationship. A similar percentage is found when asking if the firms received support from the data provider. At least in 35% of cases, firms have reached solutions with data providers in the event of an unexpected situation.

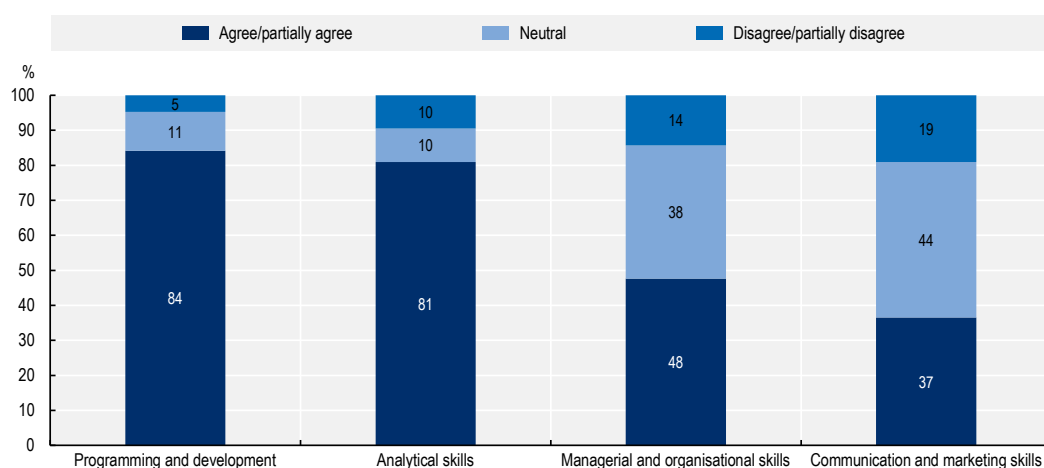
In contrast, a significant obstacle for firms in the Italian downstream sector concerns recruiting qualified personnel. Forty-three percent of companies have (always or often) challenges in recruiting, while 19% declared not having such a problem or only rarely (Figure 5.11).

Figure 5.11. Difficulty in finding qualified personnel



Firms are mainly looking for professionals who deal with programming and development (84%), analytical skills (81%), managerial and organisational skills (48%), and communication and marketing skills (37%), as shown in Figure 5.12. Similar results are found at the European level. EARSC (2019^[35]) reports that 80% of the respondents to its survey have difficulties finding and hiring candidates, particularly people with suitable programming and development skills.

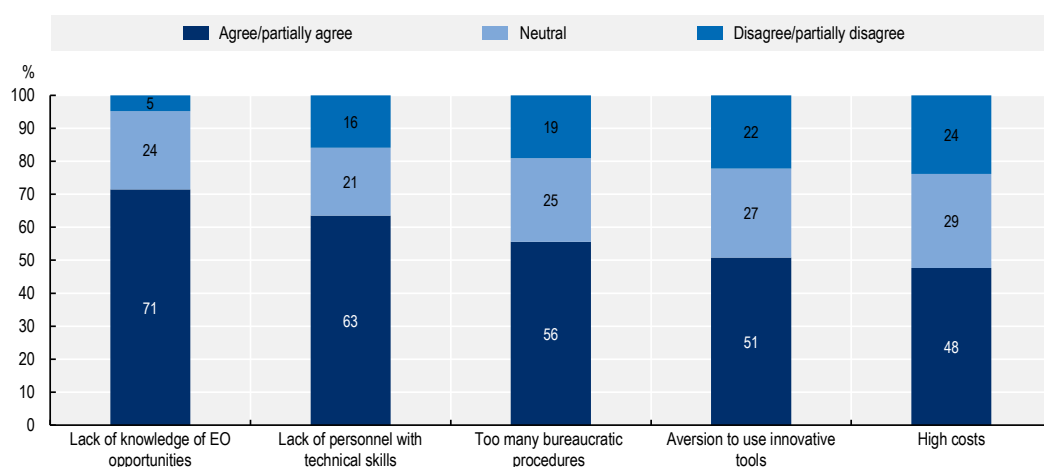
Figure 5.12. Required skills and technical qualifications



Regarding the second type of barrier to the sector development, firms were asked to express their opinions about factors hindering the diffusion of their EO services and applications to final users, displayed in Figure 5.13. These include the lack of knowledge of the opportunities deriving from EO (71%), the lack of personnel with technical skills capable of receiving information (63%), too many bureaucratic procedures (56%), aversion to the use of innovative tools (51%) and high costs⁹ (48%).

Such results are consistent with the taxonomy of the main obstacles defined by NEREUS (2016^[38]), ranging from political barriers (e.g. low awareness at the political level concerning the social value of EO data), to economic obstacles (e.g. concerning the efficient allocation of financial and human resources), social barriers (e.g. reluctance to accept new tools of work) and technological ones (e.g. lack of infrastructure to analyse the information to take decisions).

Figure 5.13. Main barriers to earth observation diffusion among final users



Note: EO: earth observation.

Conclusions and policy recommendations

This work contributes to understanding the importance of maximising the socio-economic value of EO from the perspective of firms in the Italian downstream sector. Results from our survey confirm that the development and widespread use of EO applications, products and services is one of the most promising channels to maximise the effect of space investment on several performance indicators, such as new job creation, economic growth, innovation and a better quality of life.

The EO Italian downstream sector counts less than 100 firms primarily concentrated in the central regions of Italy, and our sample represents a good approximation of the industry. Most interviewed firms operate in the IT sector and elaborate EO data to deliver various information and services. About half of these companies have less than ten employees, while medium and large firms have also invested in EO technologies. Half of the sample is represented by innovative consolidated small and medium-sized enterprises and less than a quarter by start-ups.

Firms in the Italian downstream sector primarily work with data provided by Copernicus Sentinels, followed by CosmoSkymed, Landsat, Prisma and other minor satellites. Their customers are primarily Italian public bodies followed by large national companies. Most firms recruit their clients by participating in public tenders and the main application areas are emergency and civil protection, agriculture, security and defence.

Our survey confirms that EO data availability improves the quality of firms' products and services, R&D capabilities, technical know-how, production processes, and management and organisation skills. Thanks to EO, most firms have developed new services and products; opened new business units; developed technologies; entered new markets or sectors; and developed trademarks, patents and scientific publications. In such a way, EO contributes to increasing firms' long-term turnover, number of customers, profit and number of employees.

EO also benefits final users of services and applications by increasing their profits, particularly those working in agriculture, ecosystems, pollution, emergencies and civil protection, security, defence and the military. In addition, EO supports work towards the achievement of critical societal challenges, including the Sustainable Development Goals. The main contribution of Italian firms relates to climate change, industry innovation and infrastructures, sustainable cities and communities, and life on land.

Regarding the main factors hindering the full development of the sector, the first category of obstacles concerns the downstream operators themselves. While firms in our sample do not encounter any particular difficulties handling data or in the relationship with their service providers, simplifying data accessibility, as in the case of Copernicus, would widen the data use, boosting the number of services. In terms of accessibility, after past privatisation and commercialisation trends with low success for the entire market (Borowitz, 2017^[39]), space agencies are now increasingly moving toward an open data model to maximise the return of public investment in EO (Harris and Baumann, 2015^[40]). In terms of firms' capabilities, machine and deep learning techniques have made remarkable advances in recent years in a large and ever-growing number of disparate application areas. However, an obstacle faced by Italian downstream firms refers to the shortage of skills, particularly programming and development and analytical skills. Promoting multidisciplinary groups from industry and academia could be an effective way to overcome these difficulties (see, for example, eo4geo (2018^[41])).

Another category of barriers relates to the lack of competencies and knowledge about the cost-benefits of EO technology among final users. Hence, there is a need to raise awareness of EO technology applications and related benefits. As suggested by the European Commission (Probst et al., 2016^[42]), larger and established players can increase awareness of applications based on EO data. This could be achieved by building international networks and clusters to favour connections between downstream players, bringing together the customers and the products available on the market. Other important obstacles for final users refer to a shortage of personnel with the technical skills capable of receiving information, bureaucratic procedures, aversion to using innovative tools, and related high costs. The diversity of the user communities in the public and private sectors and their dispersion at different geographic levels also cause user uptake initiatives to be complex to manage (European Commission, 2016^[43]). Additionally, the increased capacity of individual

administrations is insufficient for an efficient use of these information assets in the absence of standards and tools that allow full interoperability and sharing of information between public entities (PNRR, 2021^[44]).

These issues are a long-lasting concern within the space community, and efforts for user uptake and capacity building have already been put in place (e.g. on earth observation) (European Commission, 2016^[43]). User uptake initiatives have been undertaken or are currently under development by the European Commission to promote the use of Copernicus data, including business incubators, master prices, networks and relays, training sessions, data-handling tools and, recently, tailored cloud computing services (European Commission, 2016^[43]; Tassa, 2019^[4]). The Copernicus Services are now operational, and their products are increasingly leveraged for policy making. However, experience has proven that there is a clear need for a more systemic and integrated framework to ensure the continuity and sustainability of these initiatives (European Commission, 2016^[43]), something that should be increasingly pursued at the Italian level as well. Understanding data governance and policies aimed at overcoming the barriers that currently inhibit the use of these data is a key element to overcoming the current obstacles to the full exploitation of EO and maximisation of its socio-economic impact.

References

- Arrow, K. (1971), "The economic implications of learning by doing", in *Readings in the Theory of Growth*, pp. 131-149, Palgrave Macmillan, London. [16]
- ASI and ICE (2020), *Italian SPace Industry Catalogue 2020: Products – Services – Applications – Technologies*, Italian Space Agency, Rome, <https://www.asi.it/wp-content/uploads/2020/10/Catalogo-2020-aggiornato.pdf>. [34]
- Booz & Company (2011), *Cost-benefit Analysis for GMES*, European Commission, Brussels, https://www.copernicus.eu/sites/default/files/2018-10/ec_gmes_cba_final_en.pdf. [25]
- Borowitz, M. (2017), *Open Space: The Global Effort for Open Access to Environmental Satellite Data*, MIT Press. [39]
- Clò, S. et al. (2019), "Earth Observation in a cost-benefit analysis perspective: Cosmo SkyMed satellites of the Italian Space Agency", Università degli Studi di Milano, Department of Economics, Management and Quantitative Methods. [37]
- Craglia, M. and K. Pogorzelska (2019), "The Economic Value of digital Earth", in Guo, H., M. Goodchild and A. Annoni (eds.), *Manual of Digital Earth*, pp. 623-643, Springer, Singapore, https://doi.org/10.1007/978-981-32-9915-3_19. [2]
- Daraio, M. et al. (2014), "Cosmo-SkyMed data utilization and applications", *Proceedings of the International Astronautical Congress*, pp. 2621–2631. [12]
- Dawes, S. et al. (2013), *Socioeconomic Benefits of Adding NASA Satellite Data to AirNow*, US Environmental Protection Agency, Research Triangle Park, NC, https://www.ctg.albany.edu/media/pubs/pdfs/sti_finalreport.pdf. [27]
- EARSC (2022), *Sentinel Benefit Studies Project website*, <https://earsc.org/sebs/all-cases> (accessed on 8 August 2022). [30]
- EARSC (2020), *Industry Survey 2020*, European Association of Remote Sensing Companies. [10]
- EARSC (2019), *A Survey into the State & Health of the European EO Services Industry*, European Association of Remote Sensing Companies, Brussels, https://earsc.org/wp-content/uploads/2020/11/Industry-survey-2019-final-version-07_11_2019.pdf. [35]

- Edler, J. and L. Georghiou (2007), “Public procurement and innovation – Resurrecting the demand side”, *Research Policy*, Vol. 36/7, pp. 949-963, <https://doi.org/10.1016/j.respol.2007.03.003>. [20]
- Edquist, C. et al. (eds.) (2015), *Public Procurement for Innovation*, Edward Elgar Publishing. [18]
- EO4GEO (2018), *EO4GEO Project website*, <http://www.eo4geo.eu/about-eo4geo> (accessed on 8 August 2022). [41]
- Euroconsult (2020), *Satellite-Based Earth Observation Market Prospects to 2028*, Euroconsult. [9]
- European Commission (2016), *Copernicus User Uptake: Engaging with Public Authorities, the Private Sector and Civil Society – Final Version*, European Commission, Brussels, https://www.copernicus.eu/sites/default/files/2018-10/Copernicus_User_Uptake_Engaging_with_Users_0.pdf. [43]
- European Commission (2014), *Guide to Cost-benefit Analysis of Investment Projects: Economic Appraisal Tool for Cohesion Policy 2014-2020*, European Commission, Brussels, https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf. [33]
- Gallo, J., R. Bernknopf and S. Lev (2018), “Measuring the socioeconomic value of data and information products derived from earth observations and other geospatial data”, in Kruse, J., J. Cromptvoets and F. Pearlman (eds.), *GEOValue: The Socioeconomic Value of Geospatial Information*, CRC Press. [24]
- GEO (2020), *FAQ: What is earth observation?*, web page, Group on Earth Observations, https://www.earthobservations.org/g_faq.html. [1]
- GEO (2017), *Earth Observations in Support of the 2030 Agenda for Sustainable Development*, Group on Earth Observation, https://www.earthobservations.org/documents/publications/201703_geo_eo_for_2030_agenda.pdf. [32]
- Halsing, D., K. Theissen and R. Bernknopf (2004), *A Cost-benefit Analysis of The National Map*, US Geological Survey Circular 1271, US Department of the Interior, <https://pubs.usgs.gov/circ/2004/1271>. [26]
- Harris, R. and I. Baumann (2015), “Open data policies and satellite Earth observation”, *Space Policy*, Vol. 32, pp. 44-53, <https://doi.org/10.1016/j.spacepol.2015.01.001>. [40]
- Hof, B. et al. (2012), *Design of a Methodology to Evaluate the Direct and Indirect Economic and Social Benefits of Public Investments in Space*, SEO Economic Research, Amsterdam, https://25cjk227xfsu3mkyfg1m9xb7-wpengine.netdna-ssl.com/wp-content/uploads/2020/04/2012-42_Public_Investment_in_Space.pdf. [15]
- Kansakar, P. and F. Hossain (2016), “A review of applications of satellite earth observation data for global societal benefit and stewardship of planet earth”, *Space Policy*, Vol. 36, pp. 46-54, <https://doi.org/10.1016/j.spacepol.2016.05.005>. [7]
- Lucas Jr., R. (1988), “On the mechanism of economic development”, *Journal of Monetary Economics*, Vol. 22/1, pp. 3-42, [https://doi.org/10.1016/0304-3932\(88\)90168-7](https://doi.org/10.1016/0304-3932(88)90168-7). [17]

- Macauley, M. (2006), "The value of information: Measuring the contribution of space-derived earth science data to resource management", *Space Policy*, Vol. 22/4, pp. 274-282, <https://doi.org/10.1016/j.spacepol.2006.08.003>. [23]
- MISE (2021), *PMI innovative*, <https://www.mise.gov.it/index.php/it/impresa/piccole-e-medie-imprese/pmi-innovative> (accessed on 2 June 2022). [36]
- NEREUS (2016), *Improving Copernicus Take Up among Local and Regional Authorities (LRAs) via Dedicated Thematic Workshops*, <http://www.nereus-regions.eu/wp-content/uploads/2017/11/Analysis.pdf>. [38]
- NEREUS, European Commission and European Space Agency (2018), *The Ever Growing use of Copernicus across Europe's Regions: A Selection of 99 User Stories by Local and Regional Authorities*, NEREUS, European Commission and European Space Agency, <https://www.copernicus.eu/sites/default/files/2018-10/copernicus4regions.pdf>. [11]
- PNRR (2021), *Mission 1: Digitalisation, Innovation, Competitiveness and Culture*, Funding Aid Strategies Investments, <https://fasi.eu/images/PNRRSchede.pdf>. [44]
- Pogorzelska, K. (2018), *EOValue: Review of EO Market Studies*, European Commission, <https://ec.europa.eu/jrc/communities/en/community/eovalue/document/review-eo-market-studies>. [6]
- Probst, L. et al. (2016), *Business Innovation Observatory: Space Tech and Services: Applications Related to Earth Observation*, Case Study 63, European Union, <https://ec.europa.eu/docsroom/documents/16591/attachments/1/translations/en/renditions/native>. [42]
- PwC (2019), *Copernicus Market Report: February 2019, Issue 2*, European Union, <https://doi.org/10.2873/011961>. [13]
- PwC (2016), *Study to Examine the Socio-economic Impact of Copernicus in the EU: Report on the Copernicus Downstream Sector and User Benefits*, European Commission, Brussels, https://www.copernicus.eu/sites/default/files/2018-10/Copernicus_Report_Downstream_Sector_October_2016_0.pdf. [3]
- RFF (2017), "Understanding the benefits of observing Earth from space", web page, <https://www.rff.org/events/all-events/understanding-the-benefits-of-observing-earth-from-space>. [8]
- Robinson, D. and M. Mazzucato (2019), "The evolution of mission-oriented policies: Exploring changing market creating policies in the US and European space sector", *Research Policy*, Vol. 48/4, pp. 936-948, <https://doi.org/10.1016/j.respol.2018.10.005>. [14]
- Sawyer, G., D. Boyle and N. Khabarov (2020), *A Case Study: Ground Motion Monitoring in Norway*, Sentinels Benefits Study (SeBS), European Association of Remote Sensing Companies, <https://earsc.org/sebs/wp-content/uploads/2020/07/Ground-Movement-Monitoring-in-Norway-final.pdf>. [28]
- Sawyer, G. et al. (2015), *Copernicus Sentinels' Products Economic Value: A Case Study of Winter Navigation in the Baltic*, European Association of Remote Sensing Companies, https://esamultimedia.esa.int/docs/EarthObservation/case_report_winter_navigation_in_the_baltic_final.pdf. [29]

- Sawyer, G., C. Oligschläger and N. Oligschläger (2019), *A Case Study: Growing Potatoes in Belgium*, Sentinels Benefits Study (SeBS), European Association of Remote Sensing Companies, https://earsc.org/sebs/wp-content/uploads/2019/08/1_full-report-Growing-Potatoes-in-Belgium.pdf. [31]
- Smart, A. et al. (2018), “A review of socioeconomic valuation methods and techniques”, in Kruse, J. (ed.), *GEOValue: The Socioeconomic Value of Geospatial Information*, Chapter 10. [21]
- Tassa, A. (2019), “The socio-economic value of satellite earth observations: Huge, yet to be measured”, *Journal of Economic Policy Reform*, Vol. 23/1, pp. 34-48, <https://doi.org/10.1080/17487870.2019.1601565>. [4]
- UCS (2021), *UCS Satellite Database*, <https://www.ucsusa.org/resources/satellite-database>. [5]
- Uyarra, E. and K. Flanagan (2010), “Understanding the innovation impacts of public procurement”, *European Planning Studies*, Vol. 18/1, pp. 123-143, <https://doi.org/10.1080/09654310903343567>. [19]
- WMO (2015), *Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services*, WMO-No. 1153, World Meteorological Organization, Geneva, https://library.wmo.int/doc_num.php?explnum_id=3314. [22]

Notes

¹ Remote sensing is the process of detecting and monitoring an object at a distance.

² EO may include other means of data collection, such as aircraft, drones, etc. In this study, we focus exclusively on satellites.

³ Figure refers to companies offering commercial solutions for data and services.

⁴ Associazione delle Imprese per le Attività Spaziali (AIPAS), Federazione Aziende Italiane per l'Aerospazio, la Difesa e la Sicurezza (AIAD) and Associazione per i Servizi, le Applicazioni e le Tecnologie ICT per lo Spazio (ASAS).

⁵ This is a multidimensional scale that allows “measuring” opinions and attitudes of the interviewees. It is made up of a series of statements semantically linked to the phenomena we want to investigate (e.g. I totally agree, I partially agree, I neither agree nor disagree (neutral), I partially disagree, I totally disagree).

⁶ Min = 0; Max = 160; standard deviation = 27.

⁷ Geo information systems allow the acquisition and analysis of spatial and geographical data.

⁸ IStat classification of economic activity.

⁹ For acquiring the service and incorporating it into their decisional process.

6

Economic theory applied to space debris scenarios

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The stability of the space environment is a growing source of discussion among policy makers. This chapter first estimates the growth in the number of objects in low-earth orbit in the next decades under various mitigation scenarios, and then qualitatively assesses satellite operators' economic incentives to adopt mitigation measures. The chapter concludes with a discussion of whether effective solutions to space debris challenges can emerge from a free-market setting or if public institutions need to intervene.

Introduction

The space debris issue

The increasing number of space objects in Earth's low orbit poses a threat to the space environment's long-term sustainability, increasing the risk of collision between active satellites and space debris. This problem is now on the agenda on international tables, especially since the latest episode regarding the Russian anti-satellite (ASAT) test in November 2021, when a Russian anti-satellite device destroyed a Russian satellite and created thousands of fragments, which are now travelling at high speed in Earth's orbits and may cause future accidents (adding to the multitude of existing space debris). The Russian Federation and other countries such as the People's Republic of China (hereafter "China"), India and the United States have conducted ASAT tests before, turning space objects into debris. Other potential sources of debris may be accidental collisions between active satellites (as proven by the first-ever unintentional impact, in 2009, which involved Iridium-33 and Cosmos-2251 and caused the dispersion of approximately 2 300 fragments), explosions or collisions, anomalous break-ups, and break-ups with unknown causes. To date, according to the European Space Agency's estimates, in the Earth's orbits there are around 36 500 debris greater than 10 cm, 1 million between 1 cm and 10 cm, and 330 million from 1 mm to 1 cm.

Table 6.1. Space debris in numbers

Number of launches since the start of the space age in 1957	About 5 253
Number of satellites placed in Earth's orbit	About 7 500
Number of satellites in Earth's orbit	About 4 300
Number of operational satellites	About 1 200
Number of debris objects regularly tracked by the US Space Surveillance Network and maintained in its catalogue	About 23 000
Estimated number of break-ups, explosions and collision events resulting in fragmentation	More than 290
Total mass of all space objects in Earth's orbit	About 7 500 tonnes
Number of debris objects estimated by statistical models to be in orbit	29 000 objects >10 cm 750 000 objects from 1 cm to 10 cm 166 million objects from 1 mm to 1 cm

Source: Data from the European Space Agency, cited in OECD (2019^[1]), *The Space Economy in Figures: How Space Contributes to the Global Economy*, <https://doi.org/10.1787/c5996201-en>.

Moreover, over the last two years, the launch of mega-constellations in low-earth orbit (LEO) by private companies has significantly increased the space traffic in the LEO, potentially exacerbating future debris scenarios. Indeed, the number of active and defunct satellites in the LEO has grown by over 50%, to about 5 000. Communication satellite deployments in 2020 grew by 477% with respect to 2019's record-high deployment of 175 communications satellites. Such an increase comes primarily from the deployment of 955 Starlink satellites from SpaceX and the deployment of 358 satellites from OneWeb. As regards earth observation, following a January 2021 launch of 48 SuperDoves, Planet now operates a global constellation of more than 437 active satellites.

Despite these threats, there is still no global binding regulation about satellites' end-of-life to reduce the issue of space debris, as public institutions have provided mostly only voluntary guidelines about deorbiting activities. The United States, with the National Aeronautics and Space Administration's Orbital Debris Mitigation Guidelines, originally introduced such voluntary norms in 1995 and with the US government's Orbital Debris Mitigation Standard Practices in 2001 (updated in 2019). Similar mitigation guidelines were developed by the United Nations Office for Outer Space Affairs' Committee on the Peaceful uses of Outer Space (UN COPUOS), with inputs from the Inter-Agency Space Debris Coordination Committee, and were

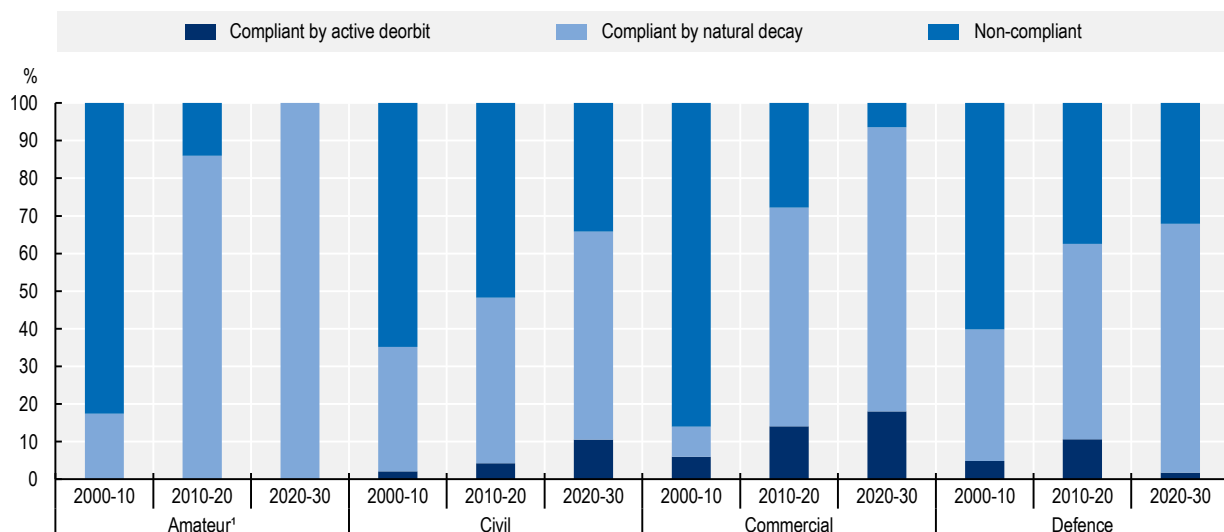
adopted in 2007. Together with the 21 guidelines for the long-term sustainability of outer space activities, they form a set of measures that COPUOS member states and international organisations can voluntarily follow.

Despite the progress made by the international community in space debris mitigation over the last ten years (at the national and international levels) and despite the rapid increase in space debris, it is also becoming of primary importance for private companies (threatening future orbit operations and the terrestrial activities that rely on them, as well as space-related scientific research) to solve the technical and policy challenges hindering the potential solutions. The most important ones concern (Undseth, Jolly and Olivari, 2020^[2]):

- **Compliance with the international guidelines and national provisions:** Current compliance by public and commercial actors is insufficient, especially in the LEO. As reported in Figure 6.1, there has been a slight increase in compliance with such voluntary guidelines in recent years, both by active deorbit and natural decay, but the share of non-compliance is still high for all types of missions: defence, commercial and civil.

Figure 6.1. Share of compliance with international guidelines and national provision in terms of clearing the low-earth orbit protected region by mission type

Achievement (end-of-life after 2000) by mission type, excluding rocket stages and human spaceflight



1. Includes payloads associated with academic institutions where none of the other entities (commercial, defence, civil) are the driving contributor.

Source: ESA (2022^[3]), *ESA's Annual Space Environment Report 2022*,
https://www.esa.int/Safety_Security/Space_Debris/ESA_s_Space_Environment_Report_2022.

- **Third-party liability:** While the development of active debris removal (ADR), meaning the removal of obsolete spacecraft or fragments through an external disposal method, is still under development, the unresolved legal questions of satellites' ownership and liability pose several uncertainties as to whether a third party can remove the satellite owned by another country or company. Indeed, many countries consider interference with their space assets or capabilities as serious national threats and many of the technologies and techniques that are candidates for ADR operations could also be used to damage or destroy a spacecraft.

In recent times, there has also been a long international debate on mitigation measures regarding the feasibility of the so-called 25-year rule, which invites satellite operators to dispose of any satellite in the LEO to an orbit with at most 25 years of residual lifetime after the end of life. The discussion has arisen mainly with the increase of the mega-constellations in the LEO composed of short-lived satellites. Many actors in the space community criticised that the 25-year deadline is too long to allow dead satellites, which are ultimately dangerous space debris, to linger in orbit. They called for reducing the period in which satellites should be deorbited to as little as five to ten years, although there is little consensus about what that revised time frame should be. The major complaint with the hypothetical five-year rule is that it would incur additional costs for satellite operators (i.e. increased propellant costs). However, this rule may prove to be economically convenient if it demonstrates that in the long term it can help to avoid collision-related costs. It is worth stressing that the currently deployed mega-constellations (e.g. Starlink and OneWeb) are aiming at a much shorter residual lifetime with respect to the aforementioned 25-year rule, also thanks to their electric propulsion systems on board.

Orbits ecosystems as Earth natural ecosystems: Common-pool resources issues

Earth's natural ecosystems and orbits have several similarities. Most importantly for our analysis, both can be defined as common-pool resources, as anyone can access them, and the current overuse may hinder future generations' possibility to enjoy them. Indeed, they are threatened by the irresponsible behaviour of individual operators who opt for personally beneficial strategies that do not correspond with the social optimum.

Orbits can be labelled as common-pool resources since it is difficult to prevent someone from occupying a place in an orbit, but overuse can reduce the benefits that all derive from it. Usually, those who benefit from common-pool resources have no incentive to preserve them, unless a shared organising principle imposes it. Indeed, as none of the users has a property right on the common-pool resource, and as the resource degradation occurs gradually as a response to its over-consumption, users are not stimulated to internalise the costs of their misconduct. This corresponds to the phenomenon of free-riding, meaning that some individuals do not contribute to the maintenance of the resource, waiting for others to do it and benefiting from their initiative. Currently, only a limited portion of the actors that benefit from orbits are taking care of their preservation, meaning that some players are adopting a free-rider strategy. Moreover, as risk related to satellite collisions, which is the main indicator of orbits' degradation, is not yet perceived to be urgent and there are no laws requiring the management of space debris, orbit users do not have any incentive to take charge of expensive clean-up services.

Nonetheless, the number of space debris endangering orbits is projected to grow exponentially if no mitigation action is undertaken, the same way it is already happening to environmental stressors on Earth (e.g. carbon dioxide concentration, forest loss, ocean acidification) (Maury et al., 2019^[4]). In the case of the Earth, the degradation of ecosystems has been attributed to the so-called “tyranny of small decisions”: “a situation in which a series of small, individually rational decisions, cumulatively results in a larger and significant outcome which is neither optimal nor desired and can negatively change the context of subsequent choices, even to the point where desired alternatives are irreversibly destroyed” (Kahn, 1966^[5]). This dynamic now applies to the space debris issue as well. Even though this threatens future space activities, responses are still too piecemeal.

Given the many similarities, what differentiates terrestrial ecosystems and orbits is that while the cumulative impacts of pollutants that occur on Earth are derived from complex and still partially unknown ecological interactions (think about how little has been understood to date on how marine ecosystems interact with industrial activities pollutants), the probability of satellites colliding is at least partially predictable, as is the related generation of fragments, which result in an increased probability of further collisions. Such predictability leaves no room for interpretation concerning the relevance of the issue and

it could help stakeholders to intervene in time to preserve the orbits' integrity for current and future generations.

Methodology

The question this analysis seeks to address is: can satellite operators within a free market solve the problem of space debris? Namely, is there an economic incentive for them to apply and finance mitigation technologies or binding regulations and is financial support needed from public institutions to overcome space debris challenges? To answer these questions, the Space Economy Evolution (SEE) Lab of SDA Bocconi School of Management, in collaboration with the Italian National Research Council (CNR), has explored the economic perspective of private satellite operators on the adoption of mitigation measures to reduce the risk of collision. Indeed, research-based evidence on private players' economic incentive to act unilaterally may help to better understand mitigation practices and the potential of technology diffusion and, eventually, encourage private-public partnerships to accelerate the process and enhance compliance with international guidelines on space debris.

To answer this question, we divided the study into two parts: 1) the development of scenarios to assess the probability of a collision between active satellites and space debris, and the effectiveness of selected technologies in reducing the collision risk; and 2) an economic analysis based on a level of attractiveness model of the selected technology and a qualitative decision analysis.

In the first part, the CNR uses the SDM 5.0 (Rossi, Petit and McKnight, 2020^[6]; Rossi et al., 2009^[7]) evolutionary model to assess the collision probabilities and the effectiveness of mitigation measures. The first step of the analysis is to estimate the growth of the space objects in the LEO in the coming decades (up to 150 years from now). A more realistic reference scenario takes into consideration, on top of the traditional launch traffic, the presence of three mega-constellations and introduces post-mission disposal (PMD) according to the 25-year rule which fall into the category of relocation activities with a compliance rate similar to the one observed in recent years, collision avoidance for active spacecraft, refuelling and ADR measures, projecting their current level of adoption in the coming decades. The remaining scenarios test different increased adoption levels of mitigation and remediation measures to investigate their efficacy in reducing the number of foreseen collisions.

Then, starting from the results of the SDM 5.0 evolutionary model, we use a qualitative decision analysis model to evaluate the economic incentives of satellite operators to adopt selected mitigation measures (namely, those whose economic incentives are more ambiguous from a private satellite operator's point of view). To develop this model, the first step was evaluating the attractiveness of the technologies of interest, looking at regulatory and technology risks, competition, and customer value to investigate how internal and external factors influence a company's choice to adopt a technology. The selected technologies are the PMD and the ADR, which fall into the category of relocation activities.¹ Table 6.A.7 The criteria adopted for the choice of these two technologies are based on their effectiveness to mitigate the risk of collision (if these technologies are used together) and the objective to understand if there is an economic convenience to adopt these technologies with a first qualitative analysis. PMD and ADR technologies can prevent further debris (deorbiting space objects) or reduce the number of pieces of debris (removing already existing debris) in space. More specifically, PMD solutions are used when satellites that have terminated their mission should be manoeuvred away from the LEO so as not to cause interference with other satellites. In this case, the satellite operator must choose whether to justify the cost of the fuel needed to deorbit its satellite within 25 years after the end of its useful life or to retain the same fuel for other mission objectives and simply accept the higher mission risks. ADR solutions involve the rendezvous and docking with, and ultimately removal of, an item of space debris. If satellite operators did not apply PMD solutions in the short term, there would be a need to develop a substantial number of ADR solutions in the medium and long term that are more expensive than post-mission solutions.

Second, we develop the qualitative decision model, which focuses more specifically on the economic incentive, taking into consideration the:

1. different scenarios characterised by varying collision risks, based on the actions of other companies (which determine the overall adoption level of mitigation measures and, as shown by the SDM, the corresponding number of collisions and space debris)
2. costs incurred by a single satellites operator for each potential choice (i.e. adoption or non-adoption) of mitigation measures.

The qualitative model is the first stage of a future quantitative analysis that will calculate the expected values of the outcomes of alternative choices and outline the optimal decision (i.e. adoption or non-adoption) for satellite operators.

SDM 5.0 Evolutionary Model

Our analysis focused on the LEO (where the number of objects is rapidly increasing and where most collisions are expected), considering space objects bigger than 5 cm and looking ahead to 150 years from now. The CNR used the SDM 5.0 Evolutionary Model to assess collision probabilities and the effectiveness of mitigation measures in reducing them. The SDM estimated the growth of the space objects, as determined by future launches from Earth and by in-orbit collisions (Rossi et al., 2009^[7]; Rossi, Petit and McKnight, 2020^[6]). To explore the future potential collision risk (i.e. probability), the CNR developed different scenarios representing the possible evolutions of the space debris population as determined by different levels of adoption of selected mitigation technologies: collision avoidance, PMD and ADR.

Among these, we decided to focus on PMD and ADR, as the economic incentives for adopting them are ambiguous. In the case of PMD, satellites operators need to devote part of their satellites' fuel to deorbiting manoeuvres, potentially renouncing some mission objective; in the case of ADR, the technology development or purchase still implies high investments. Moreover, in both cases, the adoption of these measures by a single operator does not imply a reduction of the overall collision probability. On the other hand, refuelling and collision avoidance adoption provide an intuitive economic return, as refuelling allows extending satellites' useful life, and collision avoidance helps to avoid a collision when it is going to occur.

For the current work, five different scenarios were considered: a reference scenario (REF), against which to compare all the others, represents a "business-as-usual" projection, while the remaining four mitigated scenarios (C1, C2, C1_ADR, C2_ADR) simulate additional mitigation and remediation measures.

Description of the scenarios

REF encompasses a standard launch traffic derived from past activities (i.e. not including mega-constellations) and currently observable levels of compliance with mitigation measures. On top of this, as SDM allows for the inclusion in the launch traffic of large constellations with their own specific traffic and maintenance procedures, three large constellation launches are simulated. The three constellations are respectively similar to the Starlink, Oneweb and Kuiper constellations, featured with a 150-year lifetime and adding 1 594, 720 and 1 156 satellites to the standard satellites (non-constellation) population.

In REF, the 25-year rule is supposed to be applied only to 50% of the satellites (in the following, we refer to this behaviour as "50% compliance to the 25-year rule"). All the active satellites not belonging to a constellation perform collision avoidance with an efficiency of 60%; while those that are part of a constellation perform it with a 95% efficiency against objects not belonging to the constellation itself (no impacts between operational satellites of a given constellation are allowed). It is important to highlight that only objects larger than 10 cm can be avoided. Indeed, no objects between 5 cm and 10 cm can be avoided because of the assumed limits in space surveillance systems. Refuelling is performed for two standard

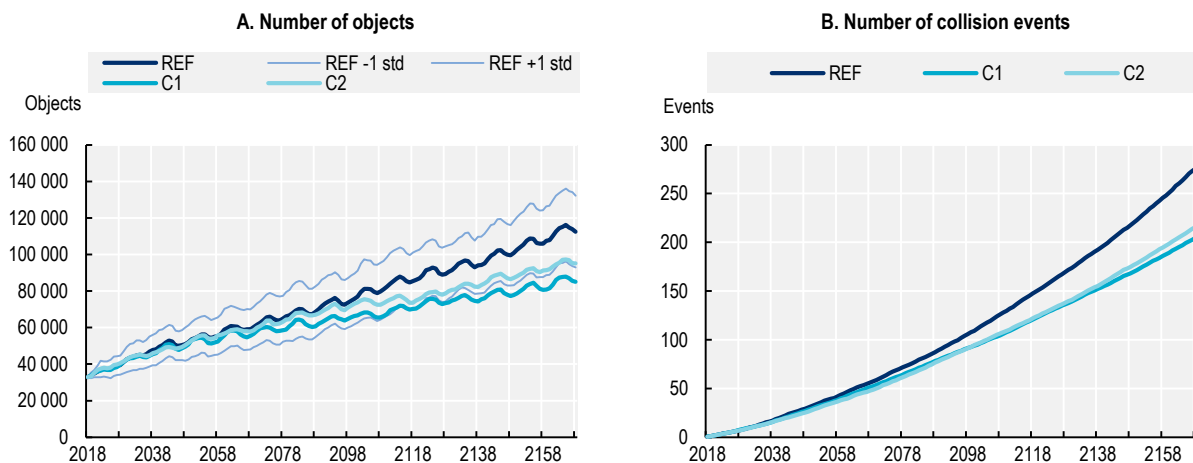
(non-constellation) satellites larger than 500 kg per year (starting from the year 2030), implying that two less satellites are launched.

In C1, all the measures described for REF apply, with the following differences: the 25-year rule is applied with a compliance rate of 80% (compared to 50% in REF) and the efficiency for the collision avoidance of standard satellites is 70% (compared to 60% in REF). In C2, the only differences from REF are that the residual lifetime in the PMD is changed from 25 years to 5 years, and the compliance to this 5-year rule is assumed to be 60%. This allows investigating whether it is better to “impose” fast deorbit, with the risk that many operators will not follow the rule (due to increased costs in propellant) or if it is better to deorbit over a longer timeframe (less propellant required), but with higher compliance. Finally, 70% efficiency for the collision avoidance of standard satellites is simulated (compared to 60% of the REF case). In C1_ADR, the same setting as scenario C1 applies, with the addition of four ADR per year, starting in the year 2028 (i.e. every year the four abandoned objects with the highest product – *mass x collision probability* – are removed from the simulation). In C2_ADR, the same setting as Scenario C2 applies, with the addition of four ADR per year, starting in the year 2028.

Space debris mitigation results

Figure 6.2 shows the number of objects larger than 5 cm (panel A) and the overall number of collisions against objects larger than 5 cm (panel B) in the REF, C1 and C2 scenarios. To start, it is worth saying that active satellites represent about 0.5-0.6% of the total population of objects at the final epochs of the simulations. Abandoned spacecraft and fragments compose the vast majority of the population.

Figure 6.2. Space debris mitigation results for scenarios without active debris removal



Notes: Panel A: The number of objects larger than 5 cm in the Reference (REF), C1 and C2 scenarios. The lighter blue lines show the +/- 1 sigma limits of the Reference result. Panel B: Cumulative number of collisions with objects larger than 5 cm in the Reference (REF), C1 and C2 scenarios.

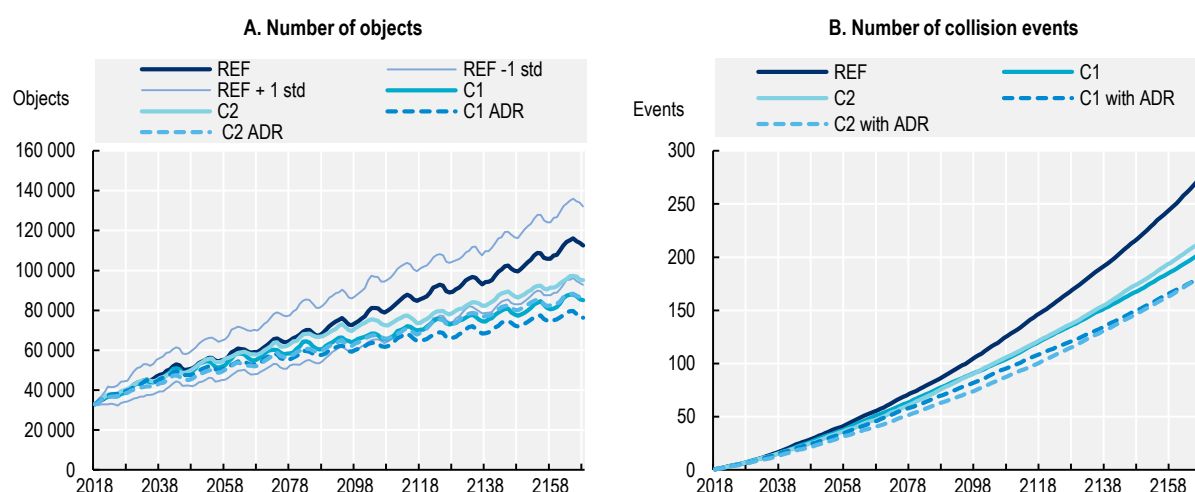
When comparing REF with C1, increasing the compliance with the 25-year rule from 50% to 80% (along with a slightly better collision avoidance) reduces the number of objects larger than 5 cm by 25% and the total number of collisions by about 26%. This, once again, highlights the importance of full compliance with the currently adopted mitigation measures.

Further on, comparing C1 and C2, a stricter mitigation measure (a 5-year rule as opposed to the 25-year rule) but with a lower compliance rate (60% as opposed to 80%) leads to an increase of about 11% in the

number of objects and about 5% in the total number of collisions. Indeed, although initially the C2 scenario appears comparable or even slightly better than the C1 scenario thanks to the reduced residual lifetime, in the longer run, the accumulation of objects abandoned in space (due to reduced compliance) starts to damage the environment and generate additional collisions.

In mitigated scenarios C1_ADR and C2_ADR (Figure 6.3), each year four objects are removed through ADR. As expected, the ADR significantly improves the situation, leading to a ~10% reduction in the final number of objects larger than 5 cm in both the C1_ADR and C2_ADR scenarios and a ~11% reduction in the overall number of collisions for the C1_ADR case and of ~15% for the C2_ADR case. Note that in panel B, the final number of collisions is nearly equal in the C1_ADR and C2_ADR scenarios. Nonetheless, it is worth stressing that the growth pace of the C2_ADR is significantly steeper than for the C1_ADR case due, as already mentioned, to the accumulation of inactive spacecraft (i.e. collisional cross-section) in the case where only 60% of the spacecraft are disposed at the end-of-life (even if with a lower residual lifetime).

Figure 6.3. Space debris mitigation results for scenarios with active debris removal



Notes: The number of objects larger than 5 cm in the Reference (REF), C1 and C2 scenarios. The lighter blue lines show the ± 1 sigma limits of the Reference result. Panel B: Cumulative number of collisions with objects larger than 5 cm in the Reference (REF), C1 and C2 scenarios. Dotted lines in both panels refer to scenarios taking into account active debris removal (ADR).

The attractiveness model analysis

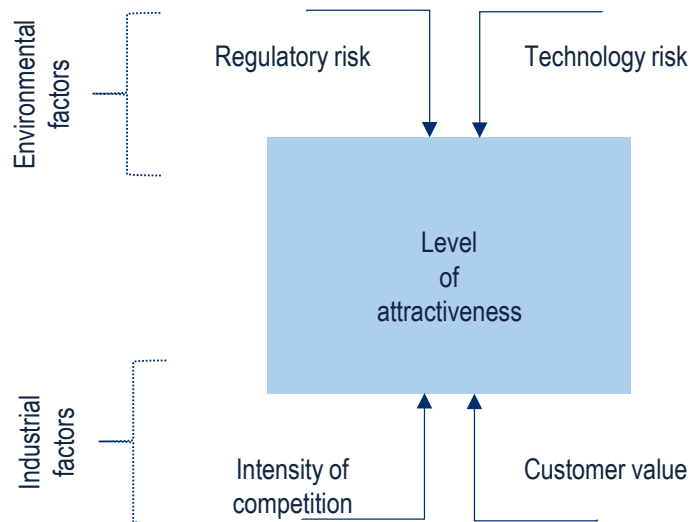
Considering the results of the CNR's analysis and the mitigation effects of the PMD and ADR combinations, the SEE Lab evaluates the level of attractiveness of these technical solutions considering business and international risks.

The attractiveness model analyses the context in which a firm operates to evaluate how external and internal factors (environmental and industrial aspects respectively) influence a company's adoption of a technology. The higher level of attractiveness indicates the most valuable business segment to invest in.

Environmental aspects include two factors: 1) the regulatory risk, which describes the possible occurrence of adverse interpretation of the legislative framework and contracts governing the operations of service companies; and 2) the technology risk that arises in projects based on technologies that have not been fully consolidated in the past. In parallel, the analysis of industrial factors considers how the technology of interest could help respond to customer demand and the intensity of competition, referred to as the supply-

side structure of the market. The result of this analysis provides a comprehensive evaluation of the technology's level of attractiveness (Figure 6.4).

Figure 6.4. Level of attractiveness



What emerged from the analysis (see Annex 6.A) is that PMD has the highest level of attractiveness and the lowest level of risk and barriers to entry in terms of technology feasibility, technology maturity and value proposition. As regards ADR, there are high risks in particular related to the regulatory framework, which limits market development. For example, the liability issues need to be clarified on the following aspects:

- Identification of the proportion of debris for which each country is responsible.
- Development of protocols/agreements between launching country and third-party removal entities.
- Defining who is responsible if a third party is damaged during the removal process.
- Security issues related to military satellites induce some countries like China, the Russian Federation and the United States to be reluctant to allow other governments and private companies to interfere with their satellites, and this could be a limitation for developing this market.
- Many countries view interference with their space assets or capabilities as serious national threats. Many of these threats come in the form of ASAT capabilities, which can be used to deceive, deny, degrade, disrupt or destroy space capabilities. Although ADR operations are not inherently ASAT activities, they may cause instability and mistrust, as many of the technologies and techniques that are candidates for ADR operations could also be used to damage or destroy a spacecraft.

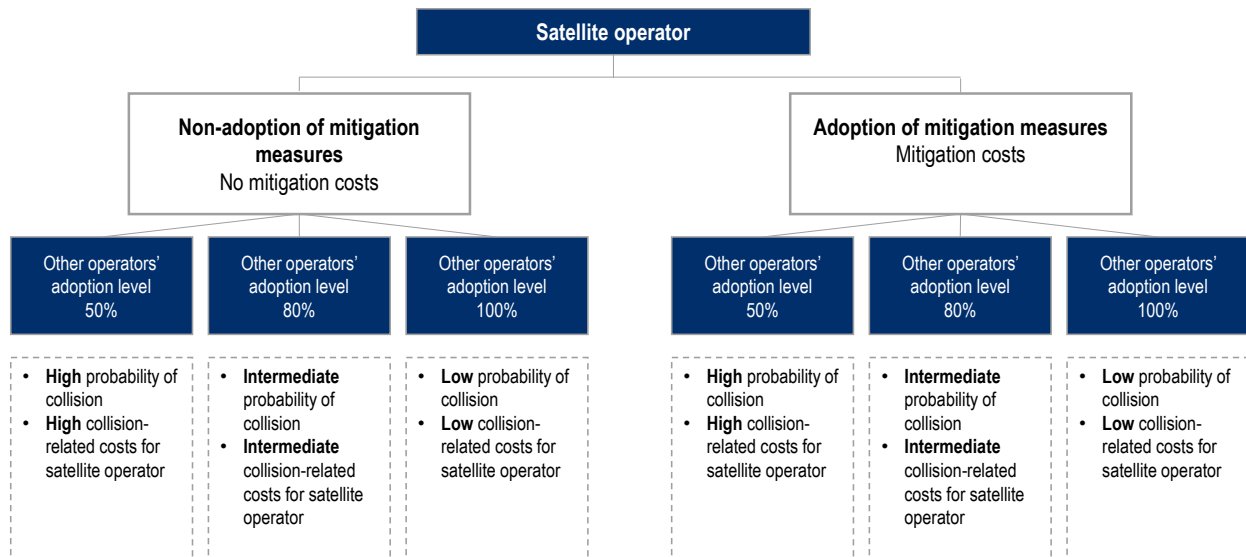
The decision analysis model

Given the key role envisaged for PMD and ADR, it is worth asking whether private space operators have the economic incentive to enact such measures to tackle space debris. Our decision analysis investigated if reducing the collision risk provided by PMD and ADR and the consequent decrease of the collision-related economic losses can drive satellite operators to adopt these practices (Figure 6.5).

The analysis took into consideration three main factors that may influence satellite operators' decision to adopt (or not) mitigation measures:

- collision probability, assuming that a higher probability of collision may be an incentive to deploy mitigation practices
- costs derived from collisions, meaning the cost of substituting hit satellites, if they cannot be repaired, or the cost of repairing services, if collision-related damages can be fixed, as well as the costs derived from the interruption of the hit satellites' functionalities
- costs of adopting mitigation measures, which, with regards to PMD, could be mainly represented by fuel costs for disposal manoeuvres, while in the case of ADR it could correspond either to the cost of internally developing the ADR technology or to that of a third-party provided ADR service.

Figure 6.5. Decision analysis



Our model started by considering these three elements, as they are very basic factors that impact on each space operator's choice to adopt mitigation measures or not.

Nonetheless, another aspect needs to be taken into account. As in the case, for example, of greenhouse gas emissions, when a large number of actors exerts negative pressure on a common-pool resource, individual mitigation initiatives do not necessarily correspond to a timely decrease in the overall environmental risk. Consider a company that opts for limiting its carbon dioxide releases: although this choice could have an impact, air quality would still be affected by other firms' emissions. The same holds true for space debris. This means that other players' decisions could bias a single operator's choice. For this reason, our decision analysis investigated a single player's opportunities (i.e. bearing or not costs related to PDM and/or ADR) in relation to three scenarios:

- low overall adoption of mitigation measures (i.e. only 50% of objects are removed from the orbit), corresponding to a high probability of collision and high collision-related costs
- medium overall adoption of mitigation measures (i.e. 80% of objects are removed from the orbit), corresponding to an intermediate probability of collision and intermediate collision-related costs
- full overall adoption of mitigation measures (i.e. 100% of objects are removed from the orbit), corresponding to a low probability of collision and low collision-related costs.

Assuming a private operator's perspective, PMD and/or ADR adoption is worthwhile when the cost of their deployment is lower than the potential losses derived from collision events. However, this fundamental dynamic based on a comparison between the cost of the mitigation measures and the cost of collisions depends on satellites' actual exposure to damages, meaning the risk of collision and what influences it. As anticipated above, other players' behaviour assumes here a crucial relevance, as the overall rate of

adoption of mitigation measures determines the number of space objects left in the orbit as debris that may cause an accident. Consequently, as highlighted in our model, if a satellite operator decides to enact mitigation measures in parallel with a low overall rate of adoption, its initiative may result in a very limited impact on the risk of collision. Such a dynamic could discourage unilateral initiatives. Conversely, collective actions would be more effective and encourage single players to proceed. Importantly, in the latter case, guarantees against freeriding should be provided. Indeed, a high rate of deployment of mitigation measures may tempt some operators to benefit from the majority's mobilisation while continuing their misconduct. Even if the presence of an economic incentive to enact mitigation measures leads a large portion of players to make the same choice without co-ordinating, it is probable that a wide adoption would be achieved gradually, leaving space for freeriding. Thus, our model shows how both mitigation measures costs and collision probability and costs, as determined by the overall rate of adoption of mitigation measures, are key factors in a single operator's choice. How could public institutions intervene to support this fragile free-market framework?

At first, public actors' intervention may lower the costs of adopting mitigation measures through the deployment of co-financing measures (e.g. public-private partnerships model). For example, current estimates about ADR costs make it hard to believe that private parties could develop and operate ADR technologies without any external support. In this case, public bodies may help either by contributing to the creation of a market for space debris disposal, in which new companies may provide an ADR service to private and public space operators, or by providing direct financial support to ADR technology development. Second, as broad adoption of mitigation measures is crucial to effectively reduce the amount of space debris, binding guidelines issued by public institutions may boost the overall rate of deployment of mitigation practices as well as prevent the risk of freeriding.

Conclusions

Our analysis showed that the two most effective bundles of mitigation measures include different practices whose deployment requires the collaboration of private parties with public institutions. As in the case of climate action, orbits' stakeholders are beginning to mobilise. During the last Paris Peace Forum, held in November 2021, ten companies and organisations from the space sector gave birth to the Net Zero Space, a multi-stakeholder initiative including different players, from satellite operators to launchers, from space agencies to universities and civil society, all committed to develop and deploy concrete measures to reduce the amount of space debris by 2030. As claimed by some of the signatories, partnerships with governments and public institutions will be key to achieving the long-term sustainability of outer space activities.

The SDA Bocconi SEE Lab is continuing its studies on the space debris issue, furthering its effort to find the best solution for all the stakeholders involved. In particular, the next steps will consist of shifting the discussed model from a qualitative to a quantitative approach and, through a cost-effectiveness perspective, helping companies outline the best route concerning collision risk stewardship.

References

- ESA (2022), *ESA's Annual Space Environment Report 2022*, European Space Agency, [3]
https://www.esa.int/Safety_Security/Space_Debris/ESA_s_Space_Environment_Report_2022
- Kahn, A. (1966), "The tyranny of small decisions: Market failures, imperfections, and the limits of economics", *Kyklos*, Vol. 19/1, pp. 23-47, <https://doi.org/10.1111/j.1467-6435.1966.tb02491.x>. [5]

- Maury, T. et al. (2019), “Assessing the impact of space debris on orbital resource in life cycle assessment: A proposed method and case study”, *Science of the Total Environment*, Vol. 667, pp. 780-791, <https://doi.org/10.1016/j.scitotenv.2019.02.438>. [4]
- OECD (2019), *The Space Economy in Figures: How Space Contributes to the Global Economy*, OECD Publishing, Paris, <https://doi.org/10.1787/c5996201-en>. [1]
- Rossi, A. et al. (2009), “The new space debris mitigation (SDM 4.0) long term evolution code”, in *Proceedings of the 5th European Conference on Space Debris*, <https://conference.sdo.esoc.esa.int/proceedings/sdc5/paper/48> (accessed on 17 January 2022). [7]
- Rossi, A., A. Petit and D. McKnight (2020), “Short-term space safety analysis of LEO constellations and clusters”, *Acta Astronautica*, Vol. 175, pp. 476-483, <https://doi.org/10.1016/j.actaastro.2020.06.016>. [6]
- Undseth, M., C. Jolly and M. Olivari (2020), “Space sustainability: The economics of space debris in perspective”, *OECD Science, Technology and Industry Policy Papers*, No. 87, OECD Publishing, Paris, <https://doi.org/10.1787/a339de43-en>. [2]

Note

¹ Relocation activities regard the modification of a satellite’s orbit with the aim to boost the satellite to higher or lower orbits for end-of-life retirement, to perform a controlled re-entry of LEO satellites, or to rescue satellites stranded from a manoeuvre or due to launch vehicle failure.

Annex 6.A. Risk assessment of post-mission disposal and active debris removal approaches

Post-mission disposal

Annex Table 6.A.1. Post-mission disposal: Technology risk

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Technology maturity	Active deorbit strategies basically need continuous power supply together with attitude and orbit control subsystems (AOCS) to achieve the deorbit. Among the active methods are on-board propulsion, electric propulsion and solid propulsion (e.g. smart propulsive device currently at qualification level). Deorbiting is particularly challenging for micro and nanosatellites, as they are limited in terms of mass and volume. Consequently, there is no mature deorbiting technology targeted toward this class of satellite. Passive technologies: There are only a few high devices with a technology readiness level equal to 7 guaranteed to satisfy the 25-year requirement as most small spacecraft are unable to relocate to a graveyard orbit due to propulsion limitations. NanoSail-D2, CanX-7, TechEdSat-3, TechEdSat-4 and TechEdSat-5 are all CubeSat platforms that have successfully demonstrated the use of drag sails for deorbiting in low-earth orbit within the 25-year post-mission requirement.	√			Medium
Feasibility	Technical feasibility: Active technologies reached a higher level of maturity whereas the development of passive devices has been revitalised over the last decades, mostly driven by the space debris problem. The absence of mature devices and the existence of a long flight history for some of them make it difficult to identify the deorbit technology that will dominate the market in the coming decades. However, a comparison of different studies shows that bare electrodynamic tethers (BETs) may dominate other technology in terms of performance and reliability. The word fair is used here to highlight the importance of recent BET progress.		√		
Threats	Private spacecraft operators may not be motivated to carry out end-of-life disposal, because they have to sacrifice economic interests in proportion to the fuel consumption for deorbiting or re-orbiting. Additionally, small satellites that are making inroads into every area of space applications and will change the orbital environment as we know it substantially, may not have a propulsion system to perform such a manoeuvre.			√	

Annex Table 6.A.2. Post-mission disposal: Customer value

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Market target	Low-earth orbit, commercial satellites (in particular satellite constellations).		√		Medium
Potential opportunity	Potential customers Active technologies: Electric propulsion (EP): given the size limit of small satellites combined with this multimanoeuvre requirement. In particular, cubesats have a strictly limited volume and mass, an obstacle when it comes to propellant storage.		√		
Value proposition	Passive disposal strategies that take advantage of aerodynamic drag as the deorbit force are particularly attractive because they are independent of spacecraft propulsion capabilities.	√			

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
	Active deorbit technologies Satellite operators sacrifice propellant, and therefore the satellite's life and potential revenues, to perform collision-avoidance manoeuvres. Direct costs such as propellant consumption for collision avoidance manoeuvres, downtime during manoeuvres and end-of-life decommissioning have a big impact on the cost of orbital slot occupation and insurance premiums. This strategy can strongly limit operational lifetime, as fuel mass is dedicated to the deorbiting (up to 20% of the spacecraft mass. For this reason, it could be interesting to adopt EP systems, with the aim to cut down on propellant mass.				

Annex Table 6.A.3. Post-mission disposal: Intensity of competition

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Active technologies Trend: electric propulsion for small satellites or cubesat (active technologies)	Satellites companies with electric propulsion: SpaceX, Astro Digital, Kinèis, ExoTerra Resources LLLC Production of electric propulsion: - Suppliers – main actors: Boeing is using L-3 XIPS-25 on its 702SP platform. Lockheed Martin and Airbus are currently offering Aerojets XR-5 on the AEHF missions and Snecma's PPS-5000 on the NeoSat platform. - Suppliers – start-up: Enpulsion, Accion System, Surrey Satellites technologies, Exotrail, Busek, Morpheus Space			√	High
Passive technologies Trend: solar sails, deployables, electromagnetic tethers	Production of passive technologies - MMA Design: product Drag-net (Technology Readiness Level [TRL] status: 9) – electromagnetic tethers - Composite technology development: product RODEO (TRL status: 7) – deployable - Cylde Space: product AEOLDOS (TRL status: 79) – deployable - TethersUnlimited: product TERMINATOR TAPE (TRL status (7) – electromagnetic tethers - UTIAS SFL: product Drag Sail (TRL status 9) – solar sail - ROCCOR: product Rocfall (TRL 6) - NASA: product Exo-Brake (TRL 9) – solar sail			√	

Annex Table 6.A.4. Post-mission disposal: Regulatory risk

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Obligation	The lack of an obligation of countries to deorbit their objects at the end of lifetime.			√	High
Criteria	The difficulty in defining criteria on deciding which objects should be removed or manoeuvred if they pose a risk for other space objects.			√	
Space traffic management	The challenges for establishing a space traffic management system.			√	

Debris mitigation and avoidance regulations are steadily becoming more restrictive. So far, all of the most exploited regions of orbital space are protected by regulations. Best practices formulated by the

Inter-Agency Space Debris Coordination Committee are being implemented at the national level in new licensing, in satellite manufacturing and in insurance contracts. In some cases, national legislation implements additional regulations for debris prevention.

The French Space Operation Act requires all national and international operators active on French territory to decommission all LEO satellites orbiting within 2 000 km at the end of their operational lives. This will involve making the satellite re-enter the atmosphere in a controlled way independently from the casualty risk criteria that is highlighted in several other international standards.

Active debris removal

A specific field falling in the on-orbit servicing domain is active debris removal (ADR), which includes a variety of technical solutions and approaches to deorbit target objectives in space.

Traditionally, space sustainability has been approached as a government-to-government issue, but several emerging private companies, entrepreneurs and commercial space ventures are racing to take part in this market.

Annex Table 6.A.5. Active debris removal: Technology risk

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Technology maturity	Active debris removal (ADR) is not a straightforward operation, especially in cases where the targeted satellites to be removed are to some extent uncooperative.			√	High
Feasibility	Economic feasibility There need to be industries involved in this new market, and interests might be given through the definition of a valuable business model that could provide commercial benefits. In addition, the feasibility of ADR should be based on the following concepts: • International agreement and transparency on which objects are selected for removal, and who should remove debris. • The clarification of the liability regime: ○ identification of the proportion of debris for which each country is responsible ○ development of protocols/agreements between the launching country and third-party removal entities ○ defining who is responsible if a third-party is damaged during the removal process. • International agreement on the implementation of ADR activities, with binding rules and regulations.			√	
Threats	There are unresolved questions as regards liability from ADR operations: if the launching country is removing the space object, and in the process of disturbing the object it fragments, is the launching country liable for any damage those fragments cause to other space objects in the future? No standard of care exists for ADR operations, and thus it may be impossible to currently establish whether or not the removal operations were carried out in a negligent manner. If the ADR is being performed by a third party, this creates additional complexities if the removal spacecraft incurs damages in the process of the removal, or if they damage other spacecraft as a result of the removal operations.			√	

Annex Table 6.A.6. Active debris removal: Customer value

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Market target	Environmental critical debris: rocket upper stages and defunct satellites that are already in orbit.			√	High
Potential opportunity	Potential customers - Public sector: the primary customers for this service will be governments. According to the UN's Online Index of Objects, 79 countries have launched satellites into outer space. Close to 50 countries have government space budgets, 9 over USD 1 billion and nearly 20 under USD 100 million. - Satellite operators: within the next ten years, the number of satellites in low-earth orbit is expected to increase to over 10 000 satellites. - Satellites insurance: there are 20 aviation insurance products worldwide. Existing insurance products include launch and in-orbit insurance that covers the risk of damage or breakdown of a satellite during and after launch and third-party liability insurance that provides protection for third-party property damage (and disability) due to the possession, use and management of satellites.			√	
Value proposition	The revenue model given by the active debris removal (ADR) technologies are not based on a classical business model that delivers profits to customers, but through a probability of saving the current profits. Indeed, the value of ADR is mainly preserving the long-term space activities, not necessarily on giving direct profits to the ADR manufacturers.			√	

The ADR activities do not provide this added value in terms of commercial business, neither for satellite manufacturers nor for the launcher operators. It is therefore difficult to identify the relationship between debris removal and individual commercial interests. There are three types of potential customers for debris removal services: satellite operators, insurers and national agencies. The market for ADR services includes all these potential customers and each of them has different needs for debris removal services, meaning that a tailored value proposition is required. The general business model of a debris removal service is not based on a business model that delivers profits to customers, but through a probability of saving the current profits.

Annex Table 6.A.7. Active debris removal: Intensity of competition

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Opportunities created by public programmes	Business opportunity seekers: companies leveraging opportunities created by public programmes in the field of space debris removal. AIRBUS (CleanSat and eDeorbit), Start Technology and Research (ElectroDynamic Debris Eliminator [Technology Readiness Level, TRL] 5-6) vehicle.		√		Medium
Solutions developed independently from public institutions	Autonomous space debris removal-related businesses: companies whose business model is based on solutions developed independently from public institutions and addressing mainly commercial markets: Astroscale, ClearSpace, Share my Space, Orbit Fab, Georing.		√		
Commercial solutions integrated into public programmes	Support service providers: companies offering commercial solutions that can support other private		√		

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
	endeavours or be integrated into public programmes related to the removal of space debris. Seer Tracking, LeoLabs, D-Orbit, Altius Space Machine, Scout Aerospace, Obruta Space Solutions.				

The ADR business line is focused on removing existing orbital debris, none of which have been prepared with a docking plate and thus are more difficult to capture.

Most of these existing debris are the result of institutional missions and thus will be a market driven by governments and space agencies.

Annex Table 6.A.8. Active debris removal: Regulatory risk

Components	Key features	Level of threat			Threat score
		Low	Medium	High	
Treaties	These treaties did not mention who must remove debris or their fragments and the space law did not mention any obligation to do so. The Liability Convention and the Outer Space Treaty consider the debris and the fragments as individual projects and in the case of an active debris removal (ADR) process, these two treaties do not identify who is responsible if a third party removes a piece of debris by mistake or causes trouble to a piece of debris which can damage another satellite.			√	High
Satellites with military and security purposes	Some satellites have been launched for military and security purposes. For political reasons, some countries like the People's Republic of China, the Russian Federation and the United States are reluctant to allow other governments to interfere with their satellites or fragments, for these reasons the dual-use nature of ADR technologies imply strategic and military implications in the framework of policy considerations.			√	
Owner-operators	ADR spacecraft that conduct repeated or continual manoeuvres to collect multiple pieces of debris may require special traffic management procedures. Their owner-operators will likely be required to continually publish updates of the spacecraft's position.			√	
Dual-use nature of ADR	The dual-use nature of ADR operations can cause instability and mistrust. Thus, many countries view interference with their space assets or capabilities as serious national threats. Many of these threats come in the form of anti-satellite (ASAT) capabilities, which can be used to deceive, deny, degrade, disrupt or destroy space capabilities. Although ADR operations are not inherently ASAT activities, many of the technologies and techniques that are candidates for ADR operations could also be used to damage or destroy a spacecraft.			√	

All the laws and regulations regarding space policy should be reviewed. Space law includes five major treaties; two of them address ADR issues: 1) the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space – the Outer Space Treaty of 1967; and 2) the Convention on International Liability for Damage Caused by Space Objects of 1973 (the Liability Convention), defining the liable party as the “launching state”.

Different space agencies (such as the European Space Agency, the Italian Space Agency, the National Centre for Space Studies in France and the German Aerospace Center) are showing the shared awareness about space debris problem. The issue is these efforts are non-binding guidelines, without addressing any legal or political measures that would oblige the space industries to comply with them.

7

On the emergence of an active debris removal market

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Developing an active debris removal (ADR) market poses a “chicken and egg” problem. Under what conditions can an ADR market emerge? This chapter explores two hypotheses: the ADR market develops as a segment of the on-orbit servicing market; or it is a market in itself following its own dynamics. Building on a database gathering ADR and on-orbit servicing projects, different policy options for further market development are discussed.

Introduction

Economic theory has approached the question of market emergence from the perspective of transaction costs (Williamson, 1975^[1]). Markets appear when transaction costs are low. However, recent research shows that this is not automatically the case. Markets are sophisticated institutions that require the construction of an architecture and categories shared by the actors (Jacobides, 2016^[2]; Fligstein, 2018^[3]; Navis and Glynn, 2010^[4]). Even when a new market seems promising, if the different players only achieve a weak compromise on market architecture due to their diverging interests, the market does not emerge, as illustrated in the case of mobile payments (Ozcan and Santos, 2015^[5]). In fact, the birth of a market is often a “chicken and egg” paradox. For example, historically, the development of the automobile market was linked to the proliferation of gas stations, but these same gas stations could not multiply at a time when there were only a few cars. The electric vehicle market is currently experiencing the same situation (Gnann, Plötz and Wietschel, 2015^[6]; Delacrétaz, Lanz and van Dijk, 2020^[7]; Zink, Valdes and Wuth, 2020^[8]; Viola, 2021^[9]). This paradox is ultimately soluble by the very dynamics of the market when the volume of products or services is very large, as is the case with electric vehicles. However, from this point of view, we cannot compare the prospects for cleaning up space debris with those of the electric vehicle. Cleaning up space debris seems to be more of a niche in the sense of Helfat and Lieberman (2002^[10]). On the one hand, it poses a classic “chicken and egg” problem: industry players wait for the market to be established before engaging in costly developments of new technologies, themselves necessary for the emergence of the market. On the other hand, despite the increasing number of debris, the expected size of the market seems to remain quite limited. Finally, this market involves a large variety of players: the firms themselves, but also parent-company ventures (especially joint ventures) and new entrants (start-ups and entrepreneurial spin-offs).

The following question, therefore, arises: under what conditions can an active debris removal market emerge?¹ Two hypotheses seem possible. First, if this market is not in itself of sufficient size, it could nevertheless develop as a segment of a stronger market, that of on-orbit servicing (OOS), and benefit from of its dynamics. Second, the ADR market could be a market in itself and, then, can only appear if forms of interaction and cost sharing between public and private actors develop. It is these two hypotheses that we propose to explore in this chapter.

To build our analysis, we carried out an inventory of OOS and ADR projects. From this database, we distinguish three categories of initiatives: 1) those that are carried out by private actors; 2) those carried out by public actors; or 3) those carried out by both types of actors at the same time. In this last category, the role of the actors varies. Space agencies position themselves alternately as a sponsor or as financial support. At the same time, firms play the role of implementer in the development of technology or active creators of a new market.

We first present the methodology adopted. Then we come back to the definitions of OOS and ADR. Finally, we discuss these results by considering the ADR market as a segment of OOS, or following its own dynamic.

Methodology

To explore the two hypotheses presented above, we decided to study the projects carried out to fight the proliferation of debris. We adopted a qualitative methodology, based on the analysis of multiple cases (Yin, 2009^[11]; Dumez, 2016^[12]). This approach allows us to envision each case in a unique way, while facilitating the comparison between several projects of the same type.

Several steps were necessary to build a database of existing projects as complete as possible. First, we turned to the literature already reviewing and detailing multiple OOS projects (Davis, Mayberry and Penn, 2019^[13]; Li et al., 2019^[14]; Mark and Kamath, 2019^[15]). A first list of initiatives emerged from mixing the

information found in these articles. Then, we tried to enrich this list with more recent projects that did not appear in the literature, such as the Airbus PERIOD project launched in 2021. We also added less publicised initiatives, such as the Japan Aerospace Exploration Agency (JAXA's) CRD2 project. Most of the research was carried out using data available on line, in space agencies' annual reports, in international conferences' proceedings and specialised journals. We do not claim to have listed every project that exists or has existed. Our data collection cannot be exempt from biases, given that some projects are not covered by the media or even remain systematically confidential in certain countries. However, we consider that our database covers a large part of the existing projects, as it relies on mixed sources of information such as the existing literature and information from space agencies. This data set should be considered as a base that could be completed for example by carrying out additional interviews with stakeholders.

Then, we gathered more precise information on each of the projects identified. We relied on public documents, as well as articles on specialised literature or international conference proceedings describing the development of a mission (e.g. Schervan et al. (2017_[16]) and Graziano et al. (2017_[17])). In some cases, we found open access presentations (e.g. the sales presentation of the Altius Bulldog satellites). Finally, on a more ad hoc basis, press releases have enabled us to specify the funding methods or the progress of the missions (e.g. the press release of the new PERIOD project from Airbus). For each project identified, a list of recurring criteria has been established. They are divided into four categories: 1) the main features of the project; 2) the timeline; 3) the structure of the project; and 4) the technology developed. Table 7.1 details the database structure.

Table 7.1. Database structure

Category	Sub-category	Description
Main features	Organiser	Name of the main actor in the project
	Country of design	Country where the project was first developed
	Type of project	Mission, demonstration, programme or technology
	Type of funding	Public funding, internal funding, external funding (fundraising)
	Source of funding	Name of the organisation that funded most of the project
	Cost	Known cost of the project
Timeline	Start and end dates	Known dates of when the project started and ended
	Current status of the project	Achieved, abandoned, in progress, unknown
Project structure	Nature of the actors involved	Public or private actor
	Type of partnership	Agency project, public project, private project, public-private partnership
Technology	Type of on-orbit servicing activity	Active debris removal, orbit maintenance, refueling, on-orbit assembly, on-orbit manufacture (e.g. Easdown & Felicetti (2020 _[18]))
	Main technology	Description of the technology used or developed within the framework of the project
	Targeted orbit	Low-earth orbit or geostationary orbit

Before presenting the results of our material analysis, it seems necessary to clarify the definitions of on-orbit servicing and active debris removal.

Definition of on-orbit servicing and active debris removal

On-orbit servicing refers to the operations carried out on satellites in orbit, in order to inspect them, control them, repair them and manage their end of life. Several definitions of OOS are collected in Table 7.2.

Table 7.2. Definitions of on-orbit servicing

Definition	References
“On-orbit activities conducted by a space vehicle that performs an up-close inspection of, or results in intentional and beneficial changes to, another resident space object”.	Davis, Mayberry and Penn (2019 _[13])
“The on-orbit alteration of a satellite or its orbit after its initial launch, using another spacecraft to conduct these alterations. Examples include relocating the satellite to a new orbit, refueling, repairing broken parts, replacing parts, deploying systems that failed to deploy after launch, and cleaning components.”	Carioscia, Corbin and Lal (2018 _[19])
“OOS is defined as all types of in-space servicing of space assets through human supported or autonomous means.”	Knudtson and Peeters (2010 _[20])
“On-orbit servicing refers to the performance of operations to repair, maintain, refuel, or upgrade a space asset while it remains in or near its operational orbit.”	Krolkowski and David (2013 _[21])

OOS is not a recent concept. It dates back to the early days of the conquest of outer space, when astronauts on mission started repairing space stations. OOS has remained omnipresent in the daily life of astronauts and refers today to a broader set of activities. In the literature, there are several ways to categorise what OOS covers, based on the types of services, functions, operations performed or capabilities, as shown in Table 7.3.

Table 7.3. On-orbit servicing categories

Category	Description	References
Services	Motion (re-orbiting; de-orbiting; salvage), manipulation (maintenance; repair; retrofit; docked inspection), observation (remote inspection)	Kreisel (2003 _[22]) Knudtson and Peeters (2010 _[20])
Functions	Inspect, relocate, restore, augment, assemble	Long, Richards and Hastings (2007 _[23])
Operations	Active debris removal, orbit maintenance, hardware replacement/refueling, on-orbit assembly and on-orbit manufacture	Easdown and Felicetti (2020 _[18])
Capabilities	Non-contact support; orbit modification and maintenance; refueling and commodities replenishment; upgrade; repair; assembly; debris mitigation	Davis (2019 _[13])

ADR is often considered a subcategory of OOS and defined as “any system that removes or neutralises space debris” (Alver, Garza and May, 2019_[24]). It therefore designates all the technologies used to clean space debris and concerns several types of situations, in which the debris object may or may not be co-operative or in which there is direct or indirect contact (Mark and Kamath, 2019_[15]; Ribeiro et al., 2018_[25]). The technologies considered are therefore numerous, especially as it is sometimes difficult to distinguish between what is solely active debris removal and, more generally, on-orbit servicing. In fact, as most of the technologies are still in the development stage, missions often encompass several objectives.

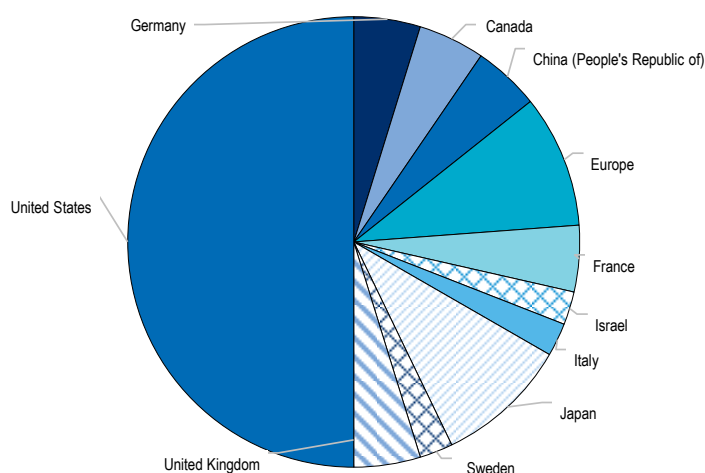
Several studies identify existing projects developed to tackle the problem of space debris. Some relate to OOS in general (Davis, Mayberry and Penn, 2019_[13]; Li et al., 2019_[14]; Pelton, 2015_[26]). Others focus more specifically on ADR (Colmenarejo et al., n.d._[27]; Zhao, Liu and Wu, 2020_[28]). These articles address the issue of space debris from a technical angle by categorising the technologies used (nets, harpoons, contactless or with contact, vehicle, etc.) according to their nature and their effectiveness. For example, Li et al. (2019_[14]) set out to identify all the methods used in general for OOS with a particular focus on “technical developments”. Zhao, Liu and Wu (2020_[28]) seek to evaluate the different methods considered for ADR by proposing a model built around indicators. It seems to us that these projects are also of interest from more than purely a technical angle. Indeed, these initiatives adopt various forms and involve heterogeneous actors. Their financing and their organisation vary greatly. In this chapter, we propose to study these initiatives from an organisational perspective. Pelton (2015_[26]) has already proposed a list of projects around ADR, distinguishing between those that come under the initiative of the private sector and the public sector. We build on these results, and propose to complement them with a set of other more

hybrid initiatives, mixing public and private actors in different ways. With these clarifications made, we present the results of our study.

Results

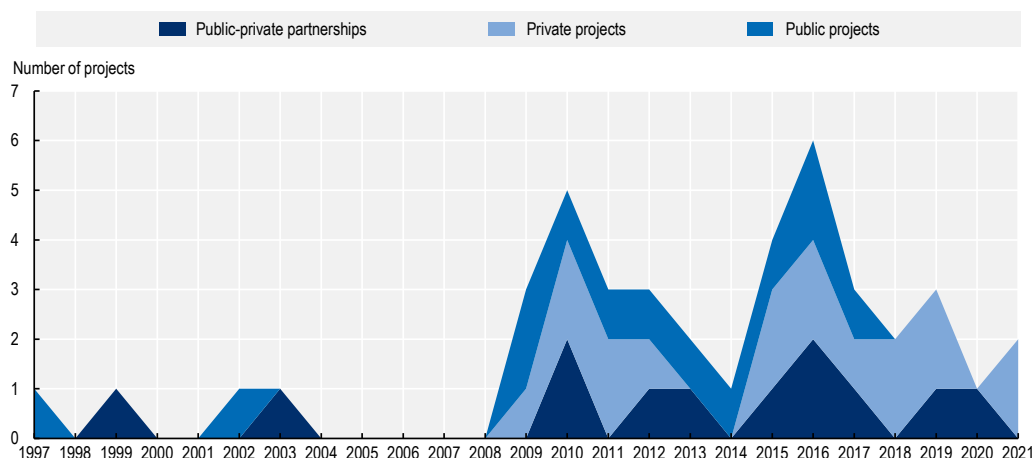
Our database consists of 42 projects. Most of them originate from the United States (21). There is also a significant number of projects in Europe (four at the European level, two in France, two in Germany, one in Italy, one in Sweden and two in the United Kingdom). In the rest of the world, the projects are divided between Japan (4), the People's Republic of China (hereafter "China") (2), Canada (2) and Israel (1) (Figure 7.1).

Figure 7.1. Geographic distribution of on-orbit servicing projects



There has been a clear increase in the number of projects over the years as well as a sharp increase in private initiatives since 2010 (Figure 7.2).

Figure 7.2. Evolution in the number of on-orbit servicing projects



We have distinguished three main categories of projects according to the nature of the actors that initiated them (private actors, public actors and a mix of the two). Different actors are gathered under the term

“public actors”. To simplify, we distinguish space agencies from other public institutions that provide funding, such as the European Commission. Within each of these three main categories, we have distinguished several types of projects, which could vary, for example, according to their structure (single actor or partnership) and their activity (centered on the development of a technology or a service). We have divided the OOS projects and the ADR projects into two columns, highlighting, in bold, the ADR projects that also have one or more other dimensions of OOS.

Projects initiated by public actors

The first initiatives related to OOS were led by space agencies and funded by national programmes (see Table 7.4). For ADR, the first project was the European Space Agency (ESA’s) ROGER robot in 2002, which aimed to test the first prototypes of robotic arms and harpoons. There were also other programmes of the same type in Japan, with SDMR developed in 2009 by JAXA or in the United States with NanoSail, a solar sail technology making it possible to de-orbit debris and tested by the National Aeronautics and Space Administration (NASA) in 2011. Private actors have since been largely involved in the development of this type of mission. Nevertheless, some projects have continued to be developed by public actors in some countries. This is, for example, the case in China with the Aolong-1 programme launched in 2016 that aimed to demonstrate its ability to de-orbit small debris by dropping it into the atmosphere. Public projects for the remainder of OOS are both more numerous and more recent. We note that they have mainly been developed by American institutions such as NASA (Robotics Refueling Mission with the Canadian Space Agency in 2009) or the US Defense Advanced Research Projects Agency (DARPA, the Phoenix programme in 2011).

We also observe that space agencies are not the only public actors interested in ADR or OOS. Some universities are also involved in the deployment of this type of project. The University of Toronto, for example, spearheaded the CanX-7 initiative deployed in 2017, which aims to test the de-orbitation of low-orbital nano-satellites (LEO).

Table 7.4. On-orbit servicing and active debris removal projects initiated by public actors

Categories	On-orbit servicing projects	Active debris removal projects
R&D projects developed internally by space agencies, with their own resources	ETS-VII – NASDA (1997) NASA Robotic Refueling Mission - NASA/CSA (2009) Phoenix – DARPA (2011) RAVEN – NASA (2015) Tianyuan 1 – NUDT (2016)	ROGER – ESA (2002) SDMR – JAXA (2009) NanoSail-D2 – NASA (2010) Aolong-1 – Harbin Institute, CNSA (2016)
Projects developed by universities	Gecko Griper – NASA and Stanford (2012)	CanX-7 – University of Toronto (2017)

Notes: ADR: active debris removal; OOS: on-orbit servicing; ADR projects in bold also have one or more other dimensions of OOS.

Projects initiated by private actors

If space agencies were the first to take an interest in on-orbit or de-orbiting techniques and to develop missions until the 2010s, private initiatives are today at least as numerous as those from public actors (Table 7.5). Some firms relied on the development of new technologies; others sought to offer de-orbitation services, in particular through the construction of a vehicle or space tug.

Recently, some firms have developed new technologies thanks to internal financing and fundraising. Since May 2019, Tethers Unlimited has been offering its customers an ADR solution called the Terminator Tape, a mechanism built to deploy a conductive tape causing de-orbiting of the equipped satellite. MMA Designs, a company based in Colorado, is showcasing this same type of technology with dragNET, a net for de-orbiting debris, since 2016.

Other firms financed the internal development not of a technology, but of a service. In this category, ADR and OOS often overlap. The Space Drone Servicing Vehicle, developed by Effective Space Solutions since 2018, offers an on-orbit maintenance and repair service. On the ADR side, the US company Altius Space Machines, launched the Bulldog family of satellites in 2019. It provides capture, de-orbitation and maintenance services in low-earth orbits. Most of these OOS offers were developed after 2018.

Table 7.5. On-orbit servicing and active debris removal projects initiated by private actors

Categories	On-orbit servicing projects	Active debris removal projects
Technology developed and financed by a firm	Roll-Out DeOrbiting device (RODEO) – Composite technology Development Inc (2013)	SpaDe – Raytheon BNN Technologies (2011) GRASP – Tethers Unlimited (2016) Terminator Tape – Tethers Unlimited (2019) DragNET De-orbit Systems – MMA Design (2016)
Demonstration or mission developed and financed by a firm	Space Drone Servicing Vehicle – Effective Space Solutions (2018) Insure Sat – Chandah Space Technologies (2019)	Space Infrastructure Servicing – MDA and Intelsat (2010 – abandoned) O.CUBED Services – Airbus (2018) Bulldog – Altius Space Machines (2019) ELSA d – Astroscale and SSTL (2020) Vigoride – Momentus (2021)

Notes: ADR: active debris removal; OOS: on-orbit servicing; ADR projects in bold also have one or more other dimensions of OOS.

Projects involving public and private actors

While there are initiatives led respectively by private actors or by public actors, most of the identified projects are developed through partnerships between public and private actors (Table 7.6). We distinguished several configurations based on the roles played by public and private actors. Space agencies can indeed be sponsors or provide financial support. Firms can be performers of a contract with the space agency or position themselves as creators of a new market. Finally, a distinction was made between projects carried out in partnership with universities.

The space agency often plays the role of sponsor: it launches a call for proposals and chooses a firm or a consortium to carry out the project, build a satellite or vehicle, or develop a new technology. This classic form of partnership has been used several times in Europe for ADR, as in the e.Deorbit programme, launched in 2012 and funded by the ESA with a consortium of manufacturers including SSTL, Airbus, Kayser-Threde and Thales Alenia Space. This form of contract between public and private actors also seems common for OOS, particularly in the United States. In 2017, DARPA also invested USD 64.6 million in a project in partnership with Space Logistic to develop RSGS, a vehicle capable of extending the life of satellites in geostationary orbit.

In another configuration, the space agency chooses a firm – more often a start-up – to entrust with the responsibility of carrying out a demonstration mission, to create market dynamics. In 2009, the ESA launched a call for proposal as part of the Clean Space Initiative for an ADR solution, won by the Swiss start-up Clearspace surrounded by a consortium of firms. The resulting Clearspace-1 demonstration project is therefore led by a start-up. It is partly funded by the ESA, which has allocated EUR 70 million for the first three years, supplemented by funds raised by the start-up. Unlike a classic partnership, described above, financing is developed gradually at key performance milestones. The space agency seeks to spur the creation of a new market around space debris removal.

In some cases, the space agency is no longer the sponsor, but plays a financial support role. In the United States, the SOUL project developed by Busek in 2016 and mixing ADR and OOS services was funded by a NASA grant. This model also exists in Europe. The Decommissioning Device D3 technology of the Italian company D-orbit notably was funded by the European Commission, as part of the

Horizon 2020 project. In this configuration, governments support the development of technologies, which continue to belong to the firms that developed them. Unlike CRD2 or Clearspace, space agencies are not involved in the development of these technologies, which is entirely entrusted to the company and the consortium of industrialists it has surrounded itself with.

Finally, a final form of partnership between public and private actors involves actors from the academic world. Indeed, some universities have developed projects in collaboration with firms. This is the case, for example, with the Remove Debris research programme, initiated by the Space Surrey Center, carried out by a consortium of firms and funded by the European Commission from 2013 to 2019.

Table 7.6. On-orbit servicing and active debris removal projects involving private and public actors

Categories	Description	On-orbit servicing projects	Active debris removal projects
The space agency as a sponsor	Agency as operator of the market: an agency launches a call for proposals and signs a contract with one or more manufacturers	Orbital Express - DARPA (1999) Dragonfly NASA (2015) OSAM-1 NASA (2016) RSGS SIS Vehicle - DARPA (2017)	DEOS DLR (2010) e.Deorbit ESA (2014)
	Agency as creator of new markets: an agency designates a firm or a start-up to carry out an entire mission and become a central actor of a new market	iBoss Iboss consortium (2010)	CRD2 JAXA and Astroscale (2019) Clearspace 1 Clearspace and ESA (2013)
The space agency or the government as financial support	An agency or a government financially supports a firm or a start-up for the development of a technology	MEV Northrop Grumman (2011) Archinaut Made in Space (2016)	Electro Dynamic Debris Eliminator Star-Tech Inc. (2012) SOUL Busek co.inc (2016) Decommissioning Device D-Orbit (2020)
	One or more agencies financially support one or more firms for the development of a demonstration or a mission	PERIOD - Airbus Defense and Space (2021)	SMART-OLEV Orbital Satellite Ltd (2003) ANDROID GMV Innovative Solutions (2017)
Research projects involving private actors and universities		AEOLDOS AAC Clyde Space and University of Glasgow (2009)	Remove debris Surrey Space Center (2013)

Notes: ADR: active debris removal; OOS: on-orbit servicing; ADR projects in bold also have one or more other dimensions of OOS.

Table 7.7. Multiple forms of on-orbit servicing and active debris removal projects

Categories	Description
Public	Agency-driven University partnering
Public-private	Agency as operator of a market Agency as creator of new markets
Private-public	Technology oriented Mission oriented
Private	Technology oriented Mission oriented

Discussion

The results of our study allow us to reflect on the possibility of the emergence of an ADR market. We can first hypothesise that it constitutes a segment of OOS, as an extension of it. However, the particularities of this activity prompt us to explore, in a second step, the specific dynamics of ADR projects.

Hypothesis 1: Active debris removal as a segment of on-orbit servicing

The literature presents ADR as a sub-segment of OOS (Carioscia, Corbin and Lal, 2018^[19]). OOS has long been considered an emerging market with a “chicken and egg” problem (Mueller and Kreisel, 2006, p. 2^[29]; Knudtson and Peeters, 2010, pp. 5-8^[20]). Today, this sector seems to have succeeded in going beyond this stage and is considered to be a market in its own right, still young, admittedly, but real: “The servicing industry has reached a tipping point at which a commercially viable OOS capability is becoming a reality. Advancement of technology, demonstration missions that reduce risk, and the prospect of customers throughout industry are driving the development of an OOS commercial market” (Davis, Mayberry and Penn, 2019, p. 4^[13]). It could therefore be considered that the ADR market could rely on the more advanced OOS market.

Several arguments support this thesis. First, the technologies required for OOS and ADR are in part similar. Whether it is to de-orbit or repair debris, it is essential to approach the object in orbit and secure it properly (what is called rendezvous and proximity operations). Our results also show that many projects aim to simultaneously develop several segments of OOS, in particular space tugs, these space vehicles, mainly developed by private players, have multiplied in recent years. They are designed like Swiss Army knives and allow several activities to be carried out at the same time. For example, the US firm Momentus Space is currently developing the Vigoride, a vehicle capable of operating in low orbit on all segments of OOS. Likewise, the Airbus O-Cubed project, presented in 2018, aims to develop a space vehicle that could operate in both low and geostationary orbits, on repair, maintenance and de-orbitation activities.

However, our results highlight certain specificities of ADR, which lead to a discussion of the hypothesis being a segment of OOS. We can indeed assume that the ADR sector, *a priori* riskier and therefore less profitable, should be less attractive to private actors. However, our results show that ADR still arouses the interest of firms that develop technologies (such as Terminator Tape from Tethers Unlimited or Dragnet from MMA Designs) using their own resources, without external funding from public actors (see Table 7.5, second column). We also observe forms of partnerships between different private actors, such as the ELSA-D demonstration project developed by the Japanese company Astroscale and which was carried out in partnership with Space Surrey Technology Limited, a company derived from the Space Surrey Center and specialised in the marketing of microsatellites (SSTL was responsible for constructing the satellite used as the target for the demonstration of the Astroscale de-orbitation service). In addition, OOS projects seem to give rise to fairly classic forms of public-private partnerships, in which an agency orders the development of a project (such as NASA’s Dragonfly or OSAM-1 projects or DARPA’s RSGS SIS Vehicle) or owns it (NASA’s RAVEN). In ADR projects, the forms of this co-operation also seem more innovative. Some agencies delegate the management of the entire project to a start-up in the hope that a market will be formed after the demonstration (CRD2 from JAXA or Clearspace-1 from ESA). This model is inspired by the NASA innovation policy, which delegates certain forms of R&D to private actors (Mazzucato and Robinson, 2018^[30]), but retains a strong involvement of space agencies in the development of the mission.

OOS therefore shares many features with ADR’s business. However, the way ADR projects are conducted differs from the strategies used for OOS in general. Although they evolve together and influence each other, these two segments do not seem to follow exactly the same dynamics.

Hypothesis 2: The specific dynamics of active debris removal projects

From this observation, it seemed necessary to study in more detail the multiplicity of forms of ADR projects to understand their specific dynamics. We find all the configurations: public, private, but also public/private and within this public/private category, varied degrees of involvement of the different actors. Thus, an agency can only be a sponsor or financial support, a firm can only develop a technology or position itself as a market creator. We successively explore three types of dynamics: temporal, geographic and inter-actor.

We first try to observe the dynamics of ADR projects from a time perspective. In general, this sector follows the overall development of the space sector, with the increasing involvement of private actors. This trend is visible, for example, within the ESA. The ROGER project, led by the agency and financed by it in 2002, gave way to the e.Deorbit programme, also financed by public funds but with a call for proposals from a service provider and the integration of actors from the industrial sector, and led to the Clearspace-1 programme, which delegated all development to the start-up Clearspace and whose objective was to create a new market. In addition, the number of projects fully developed by private actors represents half of ADR projects (12), the rest being divided between public projects (7), and public-private partnerships (5). Nevertheless, it would be hasty to conclude that a simple evolution of a model of public development by agencies to a prevalence of independent private projects. In fact, we have seen the development on a global scale over the past five years of private initiatives (such as Elsa-D in 2021 or Bulldog by Altius Space Machine in 2019) and public-private partnerships (such as the programme CRD2 in 2019 or Decommissioning Device – D-Orbit in 2020), as well as public initiatives (Tianyuan 1 in China in 2016) and university projects (CanX-7 in 2017).

We can also try to study the distribution of ADR projects according to the geographic dimension. The United States remains the country from which the majority of ADR projects originate (10 projects out of the 24 ADR projects listed here). In the United States, it is mainly private US actors that invest in ADR projects, independently or financially supported by public funds such as NASA scholarships. In Europe and Japan, on the contrary, space agencies are more involved in the support and development of services and the creation of an ADR market, with many public-private partnerships in which they mainly play the role of sponsors, whether for technologies or services. Other space powers, such as China, conduct this kind of research related to the defense sector at the institutional level only.

Finally, links can be made between different ADR projects. Indeed, some players are positioning themselves on several projects simultaneously, such as Astroscale, which is developing its own Elsa-d demonstration with private funds in order to develop a new commercial service. At the same time, it was selected by JAXA to spearhead the CRD2 project and demonstrate another de-orbitation. Likewise, some firms such as Airbus Defence and Space play a central role within certain industrial consortia (for example in the Remove Debris research project or for the Clearspace-1 demonstration mission), while also launching internal vehicle development projects intended to offer OOS (O-Cubed Services). On the other hand, some space agencies, notably the ESA, seem particularly active in creating an ADR market. Certain actors, public or private, seem to play a predominant role in constructing the conditions for the emergence of the market.

We can therefore observe certain major trends in the development of ADR projects: an evolution towards an activity increasingly developed by private actors, differences in strategies between geographic regions and in the importance of certain actors.

Conclusions

In this chapter, we tried to understand how an ADR market could tackle the “chicken and egg” problem. We set up a database gathering OOS and ADR projects developed over the past 25 years. Our analysis led to three main results.

First, our study highlights the different dynamics of OOS and ADR. We know that some players choose to develop projects covering OOS and ADR at the same time, such as space tugs. But despite the technological proximity between the two segments, ADR displays original features. Therefore, ADR cannot be expected to develop as a simple segment of OOS benefiting from OOS’ momentum. If ADR is to thrive, it has to deal with the chicken and egg problem itself.

Thus, we focused on the ADR market, which seems to be in an intermediate phase and still too underdeveloped to identify robust trends. Its evolution depends heavily on international regulations and geopolitical issues. We show that solving its “chicken and egg” problem will not be a linear process. There is no clear evolution starting with pure public initiatives, going through a phase of public-private partnerships and ending with solely private actors in a pure market. On the contrary, our second result, we find that public initiatives, private initiatives, more or less pure, as well as multiple forms of partnerships, tend to co-exist. Actors simultaneously explore different alternatives.

Finally, we believe that this diversity plays a key role in overcoming the “chicken and egg” issue. Public intervention will be central in fashioning an ADR market. Therefore, public actors should not seek to select a unique form of action but should, on the contrary, continue to favour flexible and diversified forms of action. They should go on trying to create new markets, but also keep supporting financially private actors in developing new technologies or missions, as well as developing their own R&D projects.

References

- Alver, J., A. Garza and C. May (2019), *An Analysis of the Potential Misuse of Active Debris Removal, On-orbit Servicing, and Rendezvous & Proximity Operations Technologies*, The George Washington University, Washington, DC. [24]
- Carioscia, S., B. Corbin and B. Lal (2018), *Roundtable Proceedings: Ways Forward for On-orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft*, Institute for Defense Analyses, <http://www.jstor.org/stable/resrep22845>. [19]
- Colmenarejo, P. et al. (n.d.), “On ground validation of debris removal technologies”, *Acta Astronautica*, Vol. 158, pp. 206-219, <https://doi.org/10.1016/j.actaastro.2018.01.026>. [27]
- Davis, J., J. Mayberry and J. Penn (2019), *On-orbit Servicing: Inspection, Repair, Refuel, Upgrade, and Assembly of Satellites in Space*, Aerospace, https://aerospace.org/sites/default/files/2019-05/Davis-Mayberry-Penn_OOS_04242019.pdf. [13]
- Delacrétaz, N., B. Lanz and J. van Dijk (2020), “The chicken or the egg: Technology adoption and network infrastructure in the market for electric vehicles”, *IRENE Working Paper*, No. 20-08, IRENE Institute of Economic Research. [7]
- Dumez, H. (2016), *Comprehensive Research: A Methodological and Epistemological Introduction to Qualitative Research*, Copenhagen Business School Press, Copenhagen. [12]
- Easdown, W. and L. Felicetti (2020), “A mission architecture and systems level design of navigation, robotics and grappling hardware for an on-orbit servicing spacecraft”, in *UKSEDS Student Space Symposium*, <http://dspace.lib.cranfield.ac.uk/handle/1826/16942>. [18]
- Fligstein, N. (2018), *The Architecture of Markets*, Princeton University Press, Princeton, NJ. [3]
- Gnann, T., P. Plötz and M. Wietschel (2015), “How to address the chicken-egg-problem of electric vehicles? Introducing an interaction market diffusion model for EVs and charging infrastructure”, *Proceedings of the 2015 ECEEE Summer Study on Energy Efficiency: First Fuel Now*, European Council for an Energy Efficient Economy, Stockholm, https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2015/4-mobility-transport-and-smart-and-sustainable-cities. [6]

- Graziano, M., A. Tomassini and J. Naudet (2017), “SBSS-DM and ANDROID: Two small missions for space-based space surveillance and active debris removal demonstrations”, 7th European Conference for Aeronautics and Space Sciences (EUCASS), <https://doi.org/10.13009/EUCASS2017-631>. [17]
- Helfat, C. and M. Lieberman (2002), “The birth of capabilities: Market entry and the importance of pre-history”, *Industrial and Corporate Change*, Vol. 11/4, pp. 725-760, <https://doi.org/10.1093/icc/11.4.725>. [10]
- Jacobides, M. (2016), “Industry architecture”, in Augier, M. and D. Teece (eds.), *The Palgrave Encyclopedia of Strategic Management*, pp. 1-5, Palgrave Macmillan, Basingstoke, <https://doi.org/10.1057/978-1-137-00772-8>. [2]
- Knudtson, P. and W. Peeters (2010), “The development of a technology prize to promote on-orbit servicing infrastructure”, IAC-10-D3.3.10, 61st International Astronautical Congress 2010. [20]
- Kreisel, J. (2003), “On-orbit servicing (OOS): Issues & commercial implications”, in *54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law*, <https://doi.org/10.2514/6.IAC-03-IAA.3.1.05>. [22]
- Krolikowski, A. and E. David (2013), “Commercial on-orbit satellite servicing: National and international policy considerations raised by industry proposals”, *New Space*, Vol. 1/1, pp. 29-41, <https://doi.org/10.1089/space.2013.0002>. [21]
- Li, W. et al. (2019), “On-orbit service (OOS) of spacecraft: A review of engineering developments”, *Progress in Aerospace Sciences*, Vol. 108, pp. 32-120, <https://doi.org/10.1016/j.paerosci.2019.01.004>. [14]
- Long, A., M. Richards and D. Hastings (2007), “On-orbit servicing: a new value proposition for satellite design and operation”, *Journal of Spacecraft and Rockets*, Vol. 44/4, pp. 964-976, <https://doi.org/10.2514/1.27117>. [23]
- Mark, C. and S. Kamath (2019), “Review of active space debris removal methods”, *Space Policy*, Vol. 47, pp. 194-206, <https://doi.org/10.1016/j.spacepol.2018.12.005>. [15]
- Martin, A. (2020), “Legal approach on the dual-use nature of on-orbit servicing programs”, in *On-orbit Servicing: Next Generation of Space Activities*, pp. 1-11, Springer, Cham, https://doi.org/10.1007/978-3-030-51559-1_1. [31]
- Mazzucato, M. and D. Robinson (2018), “Co-creating and directing Innovation Ecosystems? NASA’s changing approach to public-private partnerships in low-earth orbit”, *Technological Forecasting and Social Change*, Vol. 136, pp. 166-177, <https://doi.org/10.1016/j.techfore.2017.03.034>. [30]
- Mueller, R. and J. Kreisel (2006), “On-orbit servicing (OOS) concept trades based on the S@tMax System”, *Proceedings of the 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, ASTRA ESTEC, Noordwijk, Netherlands, <http://robotics.estec.esa.int/ASTRA/Astra2006/Papers/ASTRA2006-1.4.2.01.pdf>. [29]
- Navis, C. and M. Glynn (2010), “How new market categories emerge: Temporal dynamics of legitimacy, identity, and entrepreneurship in satellite radio, 1990-2005”, *Administrative Science Quarterly*, Vol. 55/3, pp. 439-471, <https://doi.org/10.2189/asqu.2010.55.3.439>. [4]

- Ozcan, P. and F. Santos (2015), “The market that never was: Turf wars and failed alliances in mobile payments”, *Strategic Management Journal*, Vol. 36/10, pp. 1486-1512, <https://doi.org/10.1002/smj.2292>. [5]
- Pelton, J. (2015), *New Solutions for the Space Debris Problem*, Springer International Publishing, Cham, <https://doi.org/10.1007/978-3-319-17151-7>. [26]
- Ribeiro, J. et al. (2018), “Evolution of policies and technologies for space debris mitigation based on bibliometric and patent analyses”, *Space Policy*, Vol. 44-45, pp. 40-56, <https://doi.org/10.1016/j.spacepol.2018.03.005>. [25]
- Schervan, T., M. Kortmann and J. Kriesel (2017), “iBOSS modular plug & play-standardised building block solutions for future space systems enhancing capabilities and flexibility, design, architecture and operations”, 68th International Astronautical Congress (IAC), International Astronautical Federation, <https://www.iboss.space/wp-content/uploads/2017/09/IAC-17D123x40674.pdf>. [16]
- Tziouras, J. (2020), “On-orbit servicing: Security and legal aspects”, in *On-orbit servicing: Next Generation of Space Activities*, pp. 55-68, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-030-51559-1_4. [32]
- Viola, F. (2021), “Electric vehicles and psychology”, *Sustainability*, Vol. 13/2, <https://doi.org/10.3390/su13020719>. [9]
- Williamson, O. (1975), *Markets and Hierarchies*, Free Press, New York, NY. [1]
- Yin, R. (2009), *Case Study Research: Design and Methods (Vol. 5)*, SAGE, Thousand Oaks, CA. [11]
- Zhao, P., J. Liu and C. Wu (2020), “Survey on research and development of on-orbit active debris removal methods”, *Science China Technological Sciences*, Vol. 63, pp. 2188-2210, <https://doi.org/10.1007/s11431-020-1661-7>. [28]
- Zink, R., J. Valdes and J. Wuth (2020), “Prioritizing the chicken or egg? Electric vehicle purchase and charging infrastructure subsidies in Germany”, *Politics and Governance*, Vol. 8/3, pp. 185-198, <https://doi.org/10.17645/pag.v8i3.3025>. [8]

Note

¹ We are aware of the importance of the legal and military issues (Martin, 2020^[31]; Tziouras, 2020^[32]; Alver, Garza and May, 2019^[24]), which condition the development of cleaning projects, but we have nevertheless chosen in this chapter to set aside these issues to deal with the issue from a market point of view alone.

8

Estimation of the costs and benefits of debris mitigation

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The uncertainties on property rights and other global governance issues related to space debris are market failures that call for public intervention. Inspired by other cases of negative externalities of production, this chapter models firm behaviour under different market structures for satellites and studies the effect of a policy intervention that can help reduce the new generation of mission-related debris.

Introduction

Space debris not only represent an environmental problem due to the emission of pollutants in outer space, they also challenge the development of the new space economy that must face escalating risks to spacecraft and new satellites.

It is a negative externality generated by human activity, and launchers and damaged satellites are already challenging the sustainability of outer space. The resulting situation can be characterised in terms of the tragedy of the commons, with the current regulation not being able to implement rigid systems of exclusion (Sandler, 2004^[1]; Salter, 2016^[2]). While resources seemed to be unlimited at the onset of space activity, nowadays the access and occupation of the limited geostationary (GEO) and low-earth (LEO) orbital slots are rival or subtractable. These orbits are immaterial resources of outer space and poor governance and overexploitation can lead to congestion and depletion due to space debris. Given the current governance of outer space, excludability is not feasible. Space exploitation is driven by technological reasons, with a finite but increasing number of agents having the technical capacity to launch and operate artefacts into orbit. This is also the case of material resources in outer space, where property rights are incomplete and access to the resource is open. Like international fisheries, asteroid mining could be challenged by the tragedy of the commons.

The problem of space debris is receiving increasing public attention and, probably because of this social awareness, public agents operating in space and researchers have intensified their efforts to quantify the magnitude of the problem. According to a study presented in April 2021, the problem had so far been underestimated and the amount of space junk in orbit could grow 50-fold by 2100 in a worst-case scenario. The number of debris objects estimated by statistical models to be in orbit (as of January 2021) is reported by the European Space Agency to be as follows: 34 000 objects greater than 10 cm, 900 000 objects from 1 cm to 10 cm and 128 million objects from 1 mm to 1 cm (Undseth, Jolly and Olivari, 2021^[3]).

Debris generation has a multiplicative effect: the more collision fragments there are, the more collisions will occur, with the risk that the entire population may be reduced to subcritical sizes. If the amount of space debris follows the tendency of recent years, it will eventually reach a tipping point, known as the Kessler Syndrome, that would prevent all space activity (Adilov, Alexander and Cunningham, 2018^[4]). Apart from the negative direct impact of space debris in terms of damage, other direct operational costs to avoid collisions are also affected, e.g. satellite design, operations cost, orbit clearance cost and insurance costs (Undseth, Jolly and Olivari, 2021^[3]). One could further argue that there are also indirect costs due to the impossibility to develop additional services provided by satellites, as the capacity of the orbits to host satellites would be reduced by debris.

So far, the contribution of economics to the understanding of the problem has been qualified as rather “thin” (Grzelka and Wagner, 2019^[5]), with few but remarkable analyses addressing this issue. Common property and control, taxes and markets have been considered by economists to achieve socially desirable outcomes (Adilov, Alexander and Cunningham, 2015^[6]; Béal, Deschamps and Moulin, 2020^[7]; Macauley, 2015^[8]; Rao, Burgess and Kaffine, 2020^[9]; Rouillon, 2020^[10]). However, further contributions from economics can bring new interesting insights, for instance the network structure of the co-operation between countries (Ateca-Amestoy et al., 2021^[11]; Eiriz, 2021^[12]). The modelling of strategic interaction between different firms that compete for a limited space but do not fully (or not even partially) account for the negative effects of their actions appears to be an adequate framework to study the outcomes in terms of space debris generation under different market structures. We follow this approach in this chapter.

The actual economic cost of space debris is multidimensional in the sense that it generates economic losses when incidents occur, hampering the normal functioning of satellites and further impeding the development of new opportunities, should a critical level of congestion be reached or if the capacity of orbits were to decrease. Our approach to this problem is to empirically approximate the cost of space debris when launching a satellite and to test the possibilities for policy intervention. We build a model to

analyse the impact of increasing space activity, estimate the parameters of the model and obtain the external costs imposed by space activity and the benefits of space debris mitigation. Our model introduces some relevant characteristics of the new space economy. The first is the entry of a growing number of agents competing in this market due to the development of downstream services. In this respect, it is necessary to acknowledge that, while satellite operation and services is not the most highly concentrated subsector of the space commercial activity, it is still far from being a competitive market (Giannopapa et al., 2018^[13]). The second is the evolution of the mass of space objects and the co-existence of bigger objects with constellations of smaller ones (Diserens, Lewis and Fliege, 2020^[14]). The third is the joint consideration of the direct effect of space debris (in terms of the expected cost of collision) and the indirect effect (in terms of the limit of the capacity of orbits to host operating satellites).

Contents

Model set-up

We build a theoretical framework to emphasise the importance of the increasing number of players in the satellite services market. We compare the outcome under different market structures for the provision of satellite services: monopoly, oligopoly and perfect competition.

The model provides an evaluation of the external costs imposed by each firm on the rest of the market in the absence of any intervention. We show that these external costs depend on the market structure. To assess these costs, we calibrate the model using values taken from the literature to highlight the importance of the different market structures. We use data on space satellite activity to estimate the parameters of the model and the external effects. Then we test some hypothetical policy interventions that can help to reduce the new generation of mission-related debris.

In our theoretical framework, part of the cost of space debris is the expected cost of replacing the damaged spacecraft or satellite (direct effect). A second (indirect) effect of space debris is that it affects the optimal number of operating satellites.

Table 8.1. The model's main variables

Variable	Name	Description
π	Profit by period of one satellite π	Profit of satellite owner
C	Cost of one satellite	
N	Number of active satellites	
N_j	Number of active satellites of firm j T	Satellite lifetime in years
p	Probability of destruction of a satellite due to collision $(1 - p)N$	Probability that no satellite is destroyed
$p(1 - p)^{N-1}$	Probability that exactly one satellite is destroyed	
$p^{N-1}(1 - p)$	Probability that exactly $N-1$ satellites are destroyed	
p^N	Probability that N satellites are destroyed	

Single provider of satellite services

When there is only one firm, the decision to launch an optimal number of satellites N^* accounts for the effect on the probability of collision, which increases with the number of satellites in orbit. Assume that the revenue that each satellite can generate is a decreasing linear function of the total number of satellites N :

$$\pi = a - bN \quad (1)$$

We assume that increasing space activity makes each additional satellite less profitable, since the more profitable activities are undertaken first. To simplify, we assume that satellites have an infinite lifespan and can only be destroyed by collision. In the case of a single satellite services provider, there are no external costs, since the impact on the probability of collision of the number of satellites launched is internalised. Profits are:

$$\Pi = D\pi N - CN - DC\rho(N) \quad (2)$$

where $D = \frac{\delta}{1-\delta}$ is the discount factor, C is the unitary cost of replacement and $\rho(N)$ is the expected number of spacecraft damaged by collisions in each period that must be replaced. It can be expressed as a function of the probability of collision, $p(N)$, and the number of operating satellites, N ,

$$\rho(N) = \sum_{j=1}^N \binom{N}{j} p(N)^j (1-p(N))^{N-j} \quad (3)$$

An increase in the number of satellites N produces more expected space debris and consequently raises the probability of collision. $C\rho(N)$ is the expected cost of replacement per period.

To maximise profits, the monopolist's optimal number of satellites (N^*) is defined by the following first order condition:

$$\frac{\partial \Pi}{\partial N} = \frac{\delta}{1-\delta} \left(a - 2bN - C \frac{d\rho(N)}{dN} \right) - C = 0 \quad (4)$$

The marginal revenue in terms of the satellite services provided has to be equal to the marginal cost, which includes not only the marginal cost of construction and launching, but also the indirect marginal expected cost of the replacement in case of collision.

Once the optimal level N^* is determined, the firm will maintain it, even in the case of collision. This implies that when a satellite is destroyed, it will be replaced so that the number of operating satellites is always at the optimal level. For a single provider, the decision to launch a new satellite depends on space debris, as it raises the probability of collision and therefore the expected number to be replaced and eventually the expected profits from satellite activity.

Competing providers of satellite services

We consider a duopolistic market. Assume two providers A and B choose simultaneously and independently the number of satellites to launch, N_A and N_B , respectively. The revenue per satellite is:

$$\pi = a - b(N_A + N_B) \quad (5)$$

The profits of providers A and B are, respectively:

$$\Pi_A = \frac{\delta}{1-\delta} [a - b(N_A + N_B)] N_A - CN_A - \frac{\delta}{1-\delta} C\rho(N, N_A) \quad (6)$$

$$\Pi_B = \frac{\delta}{1-\delta} [a - b(N_A + N_B)] N_B - CN_B - \frac{\delta}{1-\delta} C\rho(N, N_B) \quad (7)$$

where $N = N_A + N_B$, $\rho(N, N_A) = \sum_{j=1}^{N_A} j(p(N))^j (1-p(N))^{N_A-j}$, and $\rho(N, N_B) = \sum_{j=1}^{N_B} j(p(N))^j (1-p(N))^{N_B-j}$.

The first order conditions yield the optimal number of satellites each provider will launch depending on the satellites launched by the competitor and define response functions:

$$\frac{\partial \Pi}{\partial N_A} = \frac{\delta}{1-\delta} \left(a - 2bN - C \frac{d\rho(N, N_A)}{dN_A} \right) - C = 0 \quad (8)$$

$$\frac{\partial \Pi}{\partial N_B} = \frac{\delta}{1-\delta} \left(a - 2bN - C \frac{d\rho(N, N_B)}{dN_B} \right) - C = 0 \quad (9)$$

The optimal number of active satellites is characterised by the Nash equilibrium of the strategic situation. N_A depends implicitly on N_B , so firm A's decision of how many satellites to launch depends on the number of satellites launched by firm B and vice versa.

This strategic interaction between providers comes, first, from the market of satellite services and the fact that revenues from a satellite depend on the number of those providing similar services and, second, from the externality generated by space debris. The optimal number of satellites decreases with the probability of collision and that probability is affected by the decisions of other providers. An important difference with the case of a single provider is that in this case, the external effects are not fully internalised.

A competitive market for satellite services

As the number of satellite services providers increases, the market becomes more competitive. In this section, we analyse the case when each provider is small compared to the market and may have a negligible impact on π , as well as on the probability of collision p . Each firm considers π (revenue per satellite) to be fixed, as well as the probability of collision, independent of its own decisions.

Thus, each firm decides N_i to maximise profits following a price-taking behaviour and collision probability-taking behaviour:

$$\Pi_i = \frac{\delta}{1-\delta} \pi N_i - C N_i - \frac{\delta}{1-\delta} C \rho(p, N_i) \quad (10)$$

where $\rho(p, N_i) = \sum_{j=1}^{N_i} j(p)^j (1-p)^{N_i-j}$

At the equilibrium of this market structure, demand equals supply and this requires the fixed probability of collision considered by firms in their optimisation problems to be consistent with the equilibrium number of active satellites N .

$$a - bN = C \left[1 + \frac{\delta \rho'(p, N)}{1-\delta} \right] \quad (11)$$

where $\rho'(p, N)$ is the derivative of $\rho(p, N) = \sum_{j=1}^N \binom{N}{j} p^j (1-p)^{N-j}$ with respect to N . Note that the private marginal cost does not take into account the effect of new launches on the probability of collision p , which is considered fixed.

Note that in this case, firms do not internalise the impact of their decisions on space debris. The supply curve for satellite services is the marginal cost of the industry. The fact that each provider i considers the probability of collision p as fixed (independent of N_i) implies that there is not even a partial internalisation.

Inefficiency and mitigation measures

We characterise the efficient solution then propose measures to implement it. The efficient solution corresponds to a level of N , such that the social marginal cost is equal to the social marginal value:

$$a - bN = C \left[1 + \frac{\delta \rho'(N)}{1 - \delta} \right] \quad (12)$$

where $\rho'(N)$ is the derivative of $\rho(N) = \sum_{j=1}^N \binom{N}{j} p(N)^j (1 - p(N))^{N-j}$ with respect to N .

Thus, the marginal social cost of a new satellite considers the impact on the probability of collision of new launches.

To implement the efficient solution, a fiscal policy could increase the firms' marginal cost up to the level of the social marginal cost, so that in equilibrium the number of satellites would be socially optimal.

$$\tau = C \frac{\delta}{1 - \delta} [\rho'(N) - \rho'(p, N)] \quad (13)$$

In this and the previous sections, we have emphasised the external effects imposed on other firms through the probability of collision and the need to replace the damaged spacecraft. However, note that if the probability of collision is high enough, the space economic activity may become unfeasible or unprofitable and the corresponding social surplus would be lost. The next section focuses on the social surplus that is lost due to space debris.

Value of space activity

To compute the loss of total surplus due to space debris, we assume a competitive market. Total surplus is the sum of consumers' surplus and producers' surplus

$$\int_0^{N^*} \left(a - bN - C - C \frac{\delta \rho'(p, N)}{1 - \delta} \right) dN \quad (14)$$

We compare the equilibrium total surplus to the total surplus that would be generated in the absence of space debris and, therefore, a negligible probability of collision. This comparison unveils the loss of value due to space debris, which has two parts: 1) the loss of space activity; and 2) the increase in cost for the replacement of the aircraft due to collision.

$$\int_0^{N^{**}} (a - bN - C) dN - \int_0^{N^*} \left(a - bN - C - C \frac{\delta \rho'(p, N)}{1 - \delta} \right) dN \quad (15)$$

To estimate the economic impact of specific space activities, previous empirical studies have based their valuation on four main indicators: 1) job creation; 2) gross domestic product/gross value added (GDP/GVA); 3) government revenues; and 4) spillover effects. Table 8.2 provides measures of impact. It estimates how much an investment of EUR 1 generates.

Table 8.2. Estimated returns on EUR 1 of investment in the European Space Agency's Future EO programme

GDP	Spillovers	Employment
EUR 1.9	EUR 1.9	EUR 2.3

Source: PwC (2019_[15]), "Socio-economic impact assessments and accompanying foresight study of selected ESA earth observation activities: Executive summary", https://esamultimedia.esa.int/docs/business_with_es/esa/ESA_EO_activites_Impact_Assessment_Executive_Summary.pdf.

Economic impact of space activities

In our model, space debris limits space activity to N^* , instead of N^{**} . The value of the additional space activity also translates into lower employment. Spillovers refer to impacts of space activity that are not captured by GDP or employment and include other indicators such as technology development, innovation

and data exploitation. The data generated are quite valuable, as they can be used by scientists, commercial users, development agencies and policy makers. Note that the spillovers vary depending on the nature of the satellites' activities. In the case of telecommunication satellites, the spillover effect is different from that of earth observation, since the downstream revenues are generated not by the data collected, but from the broadcasting and communication services, such as consumers' access to the Internet by satellite, communication with mobile phones, government communications, etc.

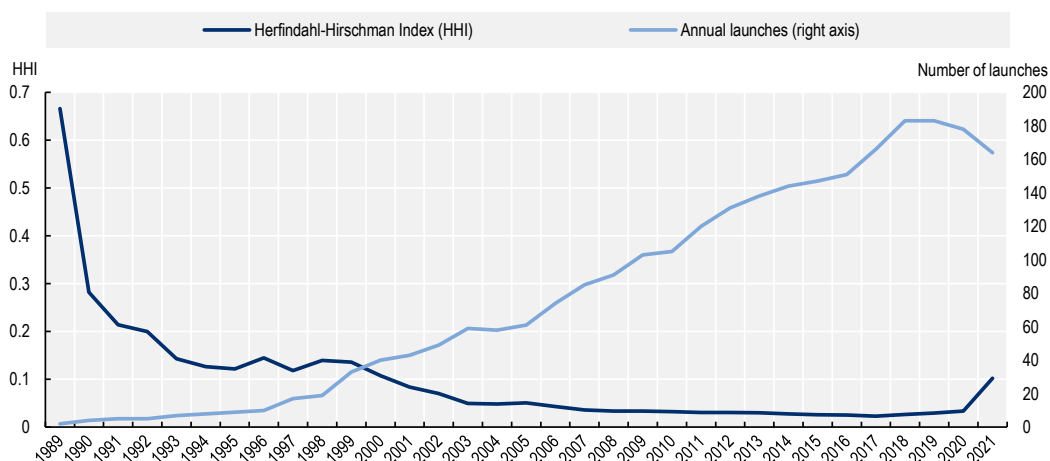
Taxes related to satellite production and launching are also part of the economic impact. Space activity generates direct government revenues for the participating countries through taxes on transactions, salaries and consumption. Several studies estimate that participating countries will indirectly recover through taxes more than 60% of the overall cost of the programmes. Adilov, Alexander and Cunningham (2015^[6]) found that perfect competition between firms results in a level of satellite launches that surpasses the social optimum and investment in debris mitigation that is below the social optimum. They derived a two-part Pigouvian tax for that specific type of market context, with taxes depending on debris creation and applied per launch, and tax revenue being used to fund new debris-removal technologies. Macauley (2015^[8]) also prescribed a system of launch taxes for the LEOs, the most populated orbits with the highest volume of debris. The taxes (at launch) would be refunded to companies that apply end-of life disposal measures to their satellites and spacecraft. Her approach includes rebates to satellite producers for incorporating certain *ex ante* debris mitigation technologies such as graveyarding, orbital manoeuvring and shielding, as these measures can also yield some spillover benefits. Rao, Burgess and Kaffine (2020^[9]) highlight the fact that the mere implementation of new mitigation technologies would not end with the problem of governance, as competitors would not have the incentive to internalise their negative externalities. Last, Béal, Deschamps and Moulin (2020^[7]) consider the effectiveness of different tax incentives, with more effective results in terms of recovering clean-up costs for centralised linear taxes.

According to Euroconsult (2019^[16]), it is estimated that EUR 8 billion of government revenues (taxes) will be generated over the full period of analysis (2007-32) in the 22 European Space Agency (ESA) member states, plus Canada and Slovenia.

Calibration of the model

In our empirical application, we use previous studies to define several scenarios of the probability of collision as a function of satellite activity (Patera, 2001^[17]; Adilov, Alexander and Cunningham, 2015^[6]). To better understand the implications of the market structure model and to justify our approach, we study the evolution of competition in the market over the past decades. Figure 8.1 represents the evolution of the concentration of space activity using the Herfindahl-Hirschman Index (HHI). The volume of satellites since the first spacecraft launch – Sputnik 1 in 1957 – has escalated from around one satellite launch per year to up to 70-90 launches a year and has witnessed an increasing number of launches injecting 30 or more small satellites into orbit at once (Undseth, Jolly and Olivari, 2020^[18]). This higher launch cadence and the decrease in manufacturing costs in the last two decades have affected market concentration. The market is now far more competitive with fewer entry barriers, as shown by the rise in the number of businesses, small and medium-sized, start-ups, and incubators.

Figure 8.1. Evolution in the number of satellites and concentration over the years



The concentration by orbit type represented in Figure 8.2 shows that, for the last two decades, there has been a higher concentration in all orbits.

Data and empirical results

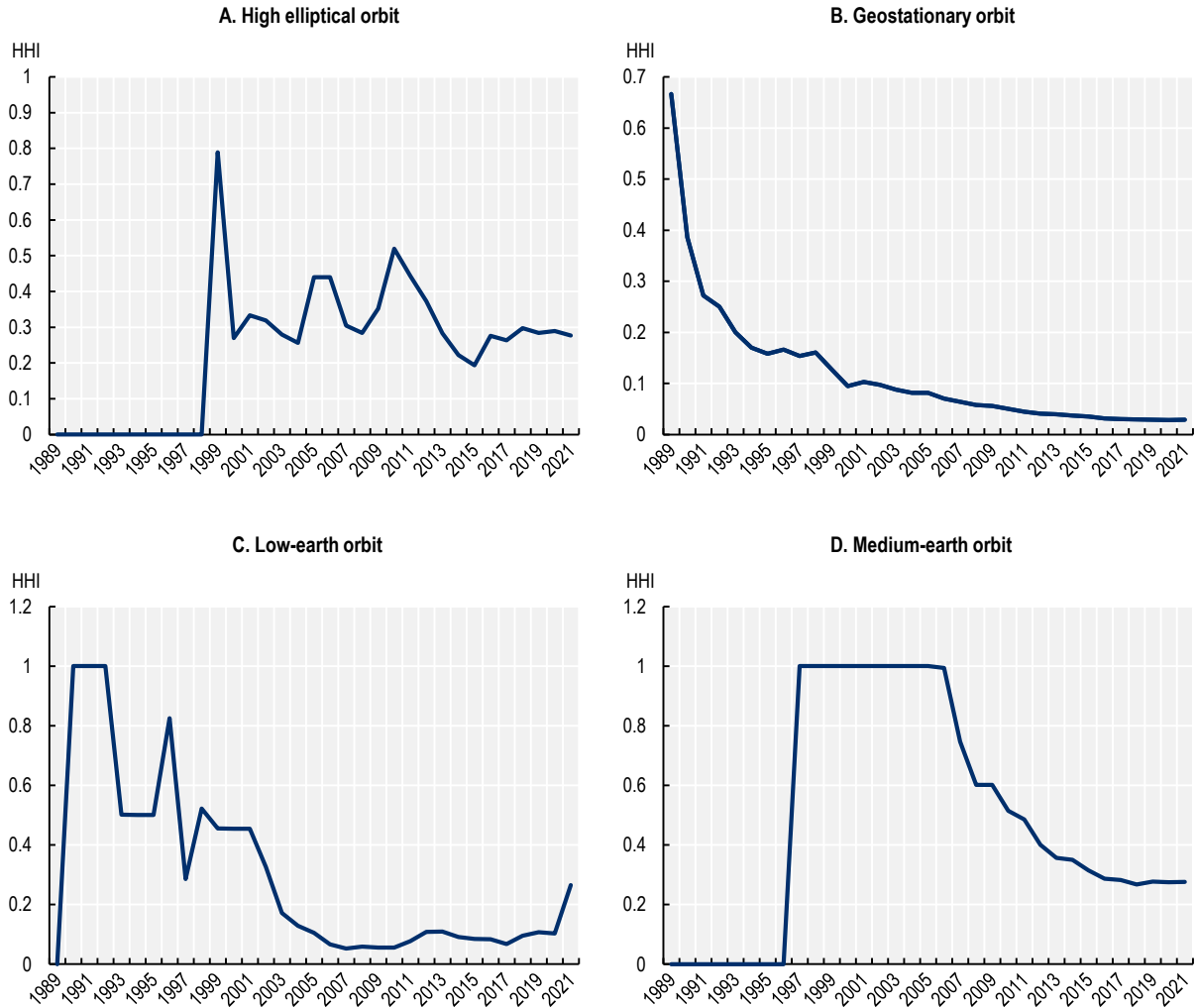
The data representing general information of the satellites launched in the past 40 years were collected from the Union of Concerned Scientists (UCS) Satellite Database, the usual source of information for this type of analysis. It includes more than 3 300 satellites launched since 1974. Table 8.3 represents the relevant variables, along with a brief description.

Table 8.3. Description of the variables

Variable label	Description
Name of satellites	Name
Country of origin	Country
Users	Type of users of the satellite (civil, military, ...)
Purpose	Nature of activity (surveillance, communication)
Type of orbit	Polar, equatorial or elliptical
Class of orbit	Low, medium or geostationary
Date of launch	Date of launching
Expected lifetime	Lifespan of the satellite in years
Dry mass	Mass of the rocket at full ascent (kg)
Launch mass	Mass of the launch vehicle upon takeoff (kg)
Perigee	Point in the orbit at which the satellite is nearest to the Earth
Apogee	Point at which the distance is greatest
Letters (AB, AC, ...)	Describe the sources of the launching information

Figure 8.2. Concentration index by orbit type

As measured by the Herfindahl-Hirschman Index

*Estimating the probability of collision*

The probability of collision is one of the most important metrics for collision avoidance measures. Alfano and Oltrogge (2018^[19]) provide a computational form for the probability of collision $p_c(N)$, which can be expressed as follows:

$$p_c(N) = \frac{1}{2\pi\sigma_x\sigma_y} \int_{-r}^r \int_{-\sqrt{r^2-x^2}}^{\sqrt{r^2-x^2}} e^{-\frac{1}{2} \left[\left(\frac{x-xm}{\sigma_x} \right)^2 + \left(\frac{y-ym}{\sigma_y} \right)^2 \right]} dy dx \quad (16)$$

where r is the combined object radius, x lies along the covariance ellipse minor axis, y lies along the major axis, xm and ym are the respective components of the projected miss distance, and σ_x and σ_y are the corresponding standard deviations. In this model, the probability of collision is very sensitive to inputs (object size, shape and orientation) and it is, therefore, crucial to determine the independent variables with precision, otherwise the model would yield high errors in the probability of collision. It further relies on the following assumptions: motion of the conjunction objects is fast enough (assumed linear); errors are

zero-mean, Gaussian and uncorrelated; the covariances (between size, shape, orientation) are assumed to be constant; and objects are modelled as spheres.

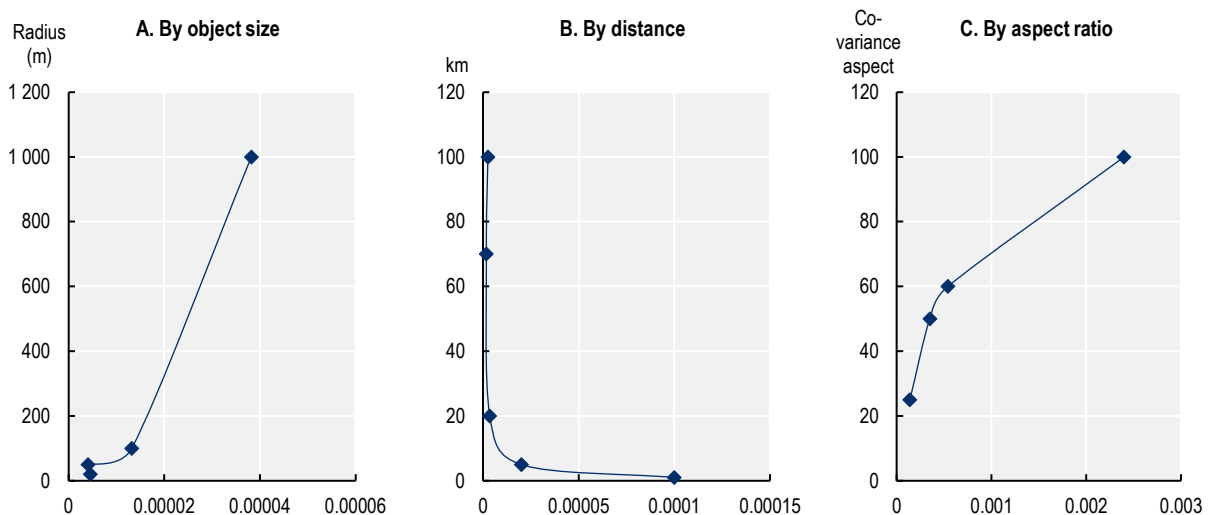
We estimate $p_c(N)$ as a function of volume (kg) and size, based on Alfano and Oltrogge (2018^[19]). We obtain:

$$p_{c,max} = \left[\left(\frac{\alpha}{1+\alpha} \right) + \left(\frac{1}{1+\alpha} \right)^{1/\alpha} \right] \quad (17)$$

where α includes the size of the object, represented by the following equation: $\alpha = \frac{r^2 AR}{d^2}$ with $AR > 1$

AR is the covariance aspect ratio (shape), d is the miss distance (the maximum distance at which the explosion of a missile head can be expected to damage a target, from Kumar, De Remer and Marshall (2005^[20])). Figure 8.3 shows the estimated probability of collision for different shapes, sizes and distances, based on the Alfano and Oltrogge (2018^[19]) nomogram. The centre panel illustrates how the lower the distance in kilometres (km) between the objects, the higher the probability of collision. For the second graph to show the impact of the AR (shape) and the size (r) of the objects on the probability of collision, we have fixed the distance at 1 km. With a fixed distance, we can conclude that the larger the size and the more sizeable the shape, the more likely the objects are to collide.

Figure 8.3. Probability of collision as a function of distance, size and covariance aspect ratio



Mitigation measures

Mitigation measures play an essential role in preserving the outer space environment and guaranteeing its sustainability. The debris present a menace to new launch missions and the functioning of existing spacecraft and satellites, and to some extent a high risk to crew safety and also a hazard to Earth in case of atmospheric re-entry. The debris technical mitigation measures could be broadly classified into two main categories: short-term and long-term measures. The short-term policies involve reducing the number of collisions and the generation of debris related to new missions (avoidance manoeuvres and passivation). The long-term measures are based, first, on deorbiting and removing spacecraft and launch vehicles that are no longer of use from very populated and operational orbits and, second, on compliance with guidelines. The United Nations Office for Outer Space Affairs has developed a framework (guidelines) that should be followed in the early stages of planning, manufacturing and design and later for launching and disposal. The guidelines can be summarised as: limiting space activity (spacecraft and launch vehicles) in

LEO and GEO; avoiding intentional destruction and minimising post-mission break-ups (stored energy); and limiting the debris released and collision in orbit (through separation mechanisms and deployment).

So far, according to data from the ESA, the only measures used are collision manoeuvres and passivation. The collision manoeuvres vary depending on the orbit type of the spacecraft. For instance, for LEO, the only possible and recommended disposal is re-entry into the Earth's atmosphere. For other orbits, the graveyarding technique is the most effective manoeuvre to date: a spacecraft has to re-orbit at an altitude no less than 300 km above the GEO ring to ensure that objects cannot collide or interfere. The passivation technique is implemented at the early stages of the manufacturing (energy reservoirs). It consists of removing all forms of energy sources to avert explosions while in the orbital stage. Such energy can be residual propellants and charged batteries.

Active debris removal brings about new concepts developed by space agencies to clean space at a rate of five to ten objects per year. Some of these concepts (based on the International Interdisciplinary Space Debris Congress Report (2012_[21])) are: momentum exchange or electrodynamics (LEO only) tether; attaching a deboost motor, a balloon (for LEO only) or adding a device to the object to increase drag; deploying a reusable tug that grapples and moves; and retrieval (return to Earth, recycling in space) of the object. The main constraint when it comes to active debris removal is that it should be cost-effective.

Based on our model under the perfect competition set-up, we consider a tax per launched satellite (equation 1.15) equal to:

$$\tau = C \frac{\delta}{1 - \delta} [\rho'(N) - \rho'(p, N)] \quad (18)$$

A tax set at this level would make the operators internalise the external effects they cause and therefore contribute to the mitigation of the space debris problem. Note that the tax is not fixed, but changes with the number of satellites already in orbit, with the cost of spacecraft replacement and the probability of collision. This last result derived from the model could be estimated for different values of the parameters, as done in the previous subsection to estimate the cost of replacement. Countries could use the revenue of such a tax to invest in R&D for effective technical mitigation measures, e.g. debris removal measures, or to pool collected taxes to provide resources for international research. In the case of already established international co-operative institutions, such as the ESA, these funds could be added to countries' voluntary contributions (see Ateca-Amestoy et al., (2020_[22]); Eiriz (2021_[12])).

Conclusions

A safe space, considered to be a global public good, and the market opportunities related to the exploitation and exploration of outer space, represented by the services derived from data, communications and navigation, must be made compatible by properly addressing the space debris problem. Human activity in outer space creates negative externalities, some of which are related to the use of the commons, others to the large fixed costs related to space activity and manufacturing leading to underinvestment; other problems are related to the limited spillover effects that only a few countries benefit from. In the limiting case, collision cascading could reduce the realised value of certain earth orbits to zero. Many scientists and space agencies estimate more debris generation and ultimately a non-accessible outer space due to the higher probability of collision that increases with every new launch mission.

This chapter studied the impact of increasing space activity under different market structures: monopoly, oligopoly and perfect competition, by valuating the debris in outer space and its cost. The model allows studying the effect of a policy intervention that can help reduce the new generation of mission-related debris. We illustrated an approach to quantify the cost of debris based on firm profits and the probability of collision under three market structures. The result is that there is no external cost in the case of a monopolistic satellite services provider, since the impact on the probability of collision of the number of

satellites launched is internalised. In contrast, in more fragmented market structures, the firms do not fully internalise the impact of their decisions on space debris. The internalisation of externalities related to space activity or debris can be represented by an enforced liability. On the basis of an (reformed) outer space treaty, the damages caused by debris could be assigned to the country or organisation responsible for launching and operating the satellite.

The debris mitigation measures already implemented have had little effect on the rate of debris generation and removal. The reason for this is that the guidelines that need to be followed only refer to the design, manufacturing and launching stages. However, the volume of debris from previous space activities needs to be eliminated. This chapter argued that a suitable approach would be a Pigouvian taxation system of *ex ante* launch taxes that would reduce debris per satellite launched. This fiscal policy could increase firms' marginal cost up to the level of the social marginal cost, so that in equilibrium, the number of satellites would be socially optimal.

The pervasiveness of technological risk, uncertainties on property rights and other global governance issues in outer space, which lead to the accumulation of space debris among other problems, are market failures that call for public intervention. As in other cases where negative externalities of production are involved, increased competition in the market for services provided by orbital satellites leads to a situation in which social welfare tends to decrease if the negative externality is not promptly addressed. Competition in this market has indeed increased a lot, as can be observed in the evolution of the market concentration (HHI) index.

Without a global regulatory intervention, the welfare loss will start to explode because of cascades of collisions and incidents created by objects launched. The main lesson from our analysis is that the best time to act is now, as the recent irruption of cubesats and mega-constellations of satellites can dramatically change the magnitude of the problem (Béal, Deschamps and Moulin, 2020^[7]). Twenty years ago the technology enabled the shift into a more competitive market, but still the number of countries and agencies that have access to the launch and operation of satellites is limited, which makes it relatively easy to implement a new governance system that introduces regulation. Such regulation should ensure that actors in this market have the proper incentives to internalise the negative externalities of their activity. This opens a window of opportunity. While the incentives and the tools to implement that new governance system should be negotiated and agreed upon, the urgency of the intervention is clear and past research suggests that we cannot only rely on the progress of technical solutions, such as improvement in deorbiting, to tackle the problem (Undseth, Jolly and Olivari, 2020^[18]; Rao, Burgess and Kaffine, 2020^[9]). If a new governance of satellite launches and space activity is not implemented, current actors and new entrants will still have the incentive to neglect the negative externality imposed on an increasing number of third parties. The proposed space governance will not be easy, but can we afford the welfare losses and the risk of depletion of the commons?

References

- Adilov, N., P. Alexander and B. Cunningham (2018), "An economic "Kessler Syndrome": A dynamic model of Earth orbit debris", *Economic Letters*, Vol. 166, pp. 79-82, <https://doi.org/10.1016/j.econlet.2018.02.025>. [4]
- Adilov, N., P. Alexander and B. Cunningham (2015), "An economic analysis of Earth orbit pollution", *Environmental and Resource Economics*, Vol. 60/1, pp. 81-98, <https://doi.org/10.1007/s10640-013-9758-4>. [6]

- Alfano, S. and D. Oltrogge (2018), "Probability of collision: Valuation, variability, visualisation, and validity", *Acta Astronautica*, Vol. 148, pp. 301-316, <https://doi.org/10.1016/j.actaastro.2018.04.023>. [19]
- Ateca-Amestoy, V. et al. (2021), "Network under H2020 space and knowledge diffusion", UPV/EHU mimeo. [11]
- Ateca-Amestoy, V. et al. (2020), "Contributions to the European Space Agency", UPV/EHU mimeo. [22]
- Béal, S., M. Deschamps and H. Moulin (2020), "Taxing congestion of the space commons", *Acta Astronautica*, Vol. 177, pp. 313-319, <https://doi.org/10.1016/j.actaastro.2020.07.036>. [7]
- Diserens, S., H. Lewis and J. Fliege (2020), "NewSpace and its implications for space debris models", *Journal of Space Safety Engineering*, Vol. 7/4, pp. 502-509, <https://doi.org/10.1016/j.jsse.2020.07.027>. [14]
- Eiriz, I. (2021), *An Economic Analysis of the European Space Economy*, Doctoral dissertation, University of the Basque Country UPV/EHU, https://addi.ehu.es/bitstream/handle/10810/51145/TESIS_IGNACIO_MAR%C3%8DA_EIRIZ_GERVAS.pdf?sequence=1. [12]
- Euroconsult (2019), "Socio-economic impact assessment of selected ESA telecommunication Partnership Projects", Study commissioned by the European Space Agency, https://esamultimedia.esa.int/docs/business_with_es/SEI_ARTES_PPP_Executive_Summary.pdf (accessed on 6 May 2022). [16]
- Giannopapa, C. et al. (2018), "Elements of ESA's policy on space and security", *Acta Astronautica*, Vol. 147, pp. 346-349, <https://doi.org/10.1016/j.actaastro.2018.02.044>. [13]
- Grzelka, Z. and J. Wagner (2019), "Managing satellite debris in low-Earth orbit: Incentivizing ex ante satellite quality and ex post take-back programs", *Environmental and Resource Economics*, Vol. 74/1, pp. 319-336, <https://doi.org/10.1007/s10640-019-00320-3>. [5]
- International Interdisciplinary Space Debris Congress (2012), "Active debris removal — an essential mechanism for ensuring the safety and sustainability of outer space", Presented at the 49th session of the UN COPUOS, Scientific and Technical Subcommittee, https://www.unoosa.org/pdf/limited/c1/AC105_C1_2012_CRP16E.pdf (accessed on 6 May 2022). [21]
- Kumar, B., D. De Remer and D. Marshall (2005), *An Illustrated Dictionary of Aviation*, McGraw-Hill, New York, NY. [20]
- Macauley, M. (2015), "The economics of space debris: Estimating the costs and benefits of debris mitigation", *Acta Astronautica*, Vol. 115, pp. 160-164, <https://doi.org/10.1016/j.actaastro.2015.05.006>. [8]
- Patera, R. (2001), "General method for calculating satellite collision probability", *Journal of Guidance, Control, and Dynamics*, Vol. 24/4, pp. 716-722, <https://doi.org/10.2514/2.4771>. [17]

- PwC (2019), “Socio-economic impact assessments and accompanying foresight study of selected ESA Earth observation activities: Executive summary”, Study commissioned by the European Space Agency, https://esamultimedia.esa.int/docs/business_with_es/ESA_EO_activites_Impact_Assessment_Executive_Summary.pdf (accessed on 6 May 2022). [15]
- Rao, A., M. Burgess and D. Kaffine (2020), “Orbital-use fees could more than quadruple the value of the space industry”, *Proceedings of the National Academy of Sciences*, Vol. 117/23, pp. 12756-12762, <https://doi.org/10.1073/pnas.1921260117>. [9]
- Rouillon, S. (2020), “A physico-economic model of low-Earth orbit management”, *Environmental and Resource Economics*, Vol. 77/4, pp. 695-723, <https://doi.org/10.1007/s10640-020-00515-Z>. [10]
- Salter, A. (2016), “Space debris: A law and economics analysis of the orbital commons”, *Stanford Technology Law Review*, Vol. 19, pp. 221-238, <https://law.stanford.edu/publications/space-debris-a-law-and-economics-analysis-of-the-orbital-commons>. [2]
- Sandler, T. (2004), *Global Collective Action*, Cambridge University Press. [1]
- Undseth, M., C. Jolly and M. Olivari (2021), “The economics of space debris in perspective”, *Proceedings of the 8th European Conference on Space Debris*, <https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/12/SDC8-paper12.pdf>. [3]
- Undseth, M., C. Jolly and M. Olivari (2020), “Space sustainability: The economics of space debris in perspective”, *OECD Science, Technology and Industry Policy Papers*, No. 87, OECD Publishing, Paris, <https://doi.org/10.1787/a339de43-en>. [18]

9

An efficiency analysis of space launch activities

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Investments in space programmes appear to bring significant economic benefits to society, but they pose new challenges. This chapter proposes the first methodological approach empirically investigating the efficiency of satellite launches. Specifically, it proposes a model for evaluating satellite launch activity and apply it to a sample of satellites.

Introduction

In the last few years, countries and commercial firms have become increasingly interested in space activities for civil, military and commercial purposes. As has been shown in the economic impact assessment study released by the US National Aeronautics and Space Administration (NASA) (NASA, 2019^[2]), investments in space programmes can bring substantial economic benefits to society. More directly, space activities positively affect gross domestic product, by creating employment and generating revenues (OECD, 2019^[3]). To put things in perspective, during fiscal year 2019, NASA's activities produced more than USD 64.3 billion in total economic output, supporting thousands of jobs nationwide (NASA, 2019^[2]).¹

Space-based infrastructures are essential for citizens' everyday lives. Data resulting from space observation are used for weather forecasting, climate monitoring (Cheng et al., 2006^[4]) and, above all, telecommunications. For all these reasons, starting from the launch of Sputnik 1, the use of Earth's orbits has expanded globally (Liou and Johnson, 2006^[5]), mainly boosted by lower launch costs and foreseen returns. Since 2010, NASA has recorded on average roughly 80 launches per year (Liou, 2017^[6]). Specifically, lower orbits are overpopulated due to a considerable rise in constellation satellites, replacing single satellites (Chrystal, Mcknight and Meredith, 2018^[7]). The accumulation of man-made objects, defined as orbital debris, dramatically challenges the long-term sustainability of space operations, posing considerable risks to human space flight and robotic missions (Liou and Johnson, 2006^[5]). Beyond the existing costs of satellites protection and mitigation (see, for example, Rossi et al. (2017^[8]), the costs resulting from accidental collisions with debris deserve special attention. First, collisions generate additional debris, leading to the so-called Kessler Syndrome of self-generating collisions (Rossi, Valsecchi and Farinella, 1999^[9]; Adilov, Alexander and Cunningham, 2020^[10]). In fact, projections to simulate the future debris patterns show that after 2055, even assuming no further satellites launches, the satellite population will increase due to the generation of new collision fragments, exceeding the quantity of decaying debris (Liou and Johnson, 2006^[5]). Second, satellites' random collisions with debris not only would require spacecraft replacement and trigger launch delays but, most importantly, it could result in data loss, with disastrous economic consequences for satellite communications (OECD, n.d.^[11]).

Given the importance of space activities in a variety of areas, assessing the balance between revenues and the costs related to launches of satellites might be of some interest. Specifically, estimating satellite efficiency could fill a notable gap in the research literature. At the base of each economic activity stands the relationship between revenue and cost, or, to put it differently, between input and output leading to efficiency analysis. The pursuit of high efficiency levels is the main goal of any organisation. In that regard, we believe that filling this knowledge gap in the space economy framework deserves attention.

We therefore propose a model to evaluate satellite launch activity and apply it to a sample of satellites. To assess the relative efficiency of satellite launch activity, we employ an estimation technique – data envelopment analysis (DEA) – which, due to its methodological properties, is one of the most common approaches for assessing the efficiency of organisations. In general terms, DEA is a mathematical programming technique designed to evaluate the relative efficiency for a group of comparable observations (decision-making units, DMUs), which is capable of handling multiple inputs and outputs without requiring *a priori* assumptions of a specific functional form on production technologies and the relative weighting scheme.

Following the DEA approach, we will consider launched satellites as DMUs to estimate the efficiency of their life cycle, satellite mass (i.e. a proxy for the satellite's dimensions and then for the number of debris objects it might generate following a collision) and mission costs as inputs, and expected life as an output. Though coping with a very limited amount of available data (i.e. 37 satellites on the whole), our results can inform interesting policy strategies. Our findings show that overall average efficiency is quite low and that it could significantly be improved by studying launches according to user, purpose and class of orbit, showing how they largely affect mission efficiency and, even more relevant, future debris creation.

Consequently, regulations on satellite composition (for instance reducing the launch mass) or on design could increase efficiency levels. Additionally, identifying market solutions to make reliable data available and accessible could help further improve the analysis.

Methods and data

Methodological framework

As previously mentioned, to perform our empirical exercise, we will employ the DEA approach, which is a non-parametric mathematical programming technique that can be oriented to minimise input values or maximise output (Coelli, 1998^[11]). DEA measures productive efficiency through the estimation of a frontier envelopment surface for all DMUs by using linear programming techniques. In doing so, it allows identifying best practices and comparing each DMU with the best possible performance among peers, rather than just with the average. Once the reference frontiers have been defined, it is possible to assess the potential efficiency improvements available to inefficient DMUs if they were producing according to the best practice of their benchmark peers. From an equivalent perspective, these estimates identify the necessary changes that each DMU needs to undertake to reach the efficiency level of the most successful DMU (Fried, Knox Lovell and Schmidt Shelton, 2008^[12]). In addition, whereas DEA is, at the beginning, run under the constant returns to scale, it can be reformulated to account for variable returns to scale as well (Banker et al., 1988^[13]).

The input-oriented approach fits our case study nicely, measuring the radial reduction in input for a given output as the distance (efficiency score) between the observed and most efficient DMU. Our data set calls for such an approach, where for a given output level, the efficiency can be reached minimising the inputs.

Illustrating this point,² consider n DMUs for evaluation; a DEA input-oriented efficiency score h_i is calculated for each DMU, which solves the following programme for $i = 1, \dots, n$ using the constant returns to scale (CRS) assumption.³

$$\begin{array}{ll} \text{Min}_{\lambda, \theta_i} & \theta_i \\ \text{subject to} & Y\lambda - y_i \geq 0 \\ & \theta_i x_i - X\lambda \geq 0 \\ & \lambda \geq 0 \end{array} \quad (1)$$

x_i and y_i are the input and output, respectively, for the i^{th} DMU; X is the matrix for the input, Y is the matrix for the output, and λ is a $nx1$ vector of variables. The model (1) can be modified to account for variable returns to scale (VRS) by adding the convexity constraint $e\lambda = 1$ where e is a row vector with all elements unity, which distinguishes between technical efficiency (TE) and scale efficiency (SE).

DEA is a well-established and useful technique for measuring efficiency in several sector activities (for a comprehensive review, see (Liu et al., 2013^[14]). The reasons for the widespread use of DEA are summarised as follows: it can handle multiple inputs and outputs without *a priori* assumptions for a specific functional form of production technologies, it does not require *a priori* a relative weighting scheme for the input and output variables, it returns a simple summary efficiency measurement for each DMU, and it identifies the sources and levels of relative inefficiency for each DMU.

However, DEA is an estimation procedure that relies on extreme points: it may be extremely sensitive to data selection, aggregation and model specification. Typically, the selection of input and output variables is a major issue for efficiency measurements. The principal strengths of DEA, which include no *a priori* knowledge requirement for functional relationships, can be fully exploited under the premise that the input and output variables are relevant and sufficiently fair for all the DMUs considered.

Another problem common to DEA studies is the relatively small number, n , of DMU with respect to the space dimension d (i.e. the number of input and output variables in the efficiency analysis) and the reliability of the results from the DEA model. However, for a given sample size, the rate of convergence depends on the space dimension d .⁴ This issue clearly represents a potential limitation of our work that may be solved only when more data are available. Notwithstanding, we do believe that our analysis represents a first sound step to the analysis of launch efficiency.

Finally, since DEA does not allow for any statistical inference and measurement error, Simar and Wilson (2000^[15]; 1998^[16]) introduced a bootstrapping methodology to determine the statistical properties of DEA estimators.⁵ Thus, the bootstrapping algorithm (Simar and Wilson, 2000^[15]) is used in this chapter to control for consistency among the efficiency estimates.⁶

Data

Our sample has been built on the publicly accessible Union of Concerned Scientists (UCS) Satellite Database, which contained 4 550 entries on 1 September 2021 (UCS, 2022^[17]). First, we selected the launches with complete information on a satellite's expected lifetime (measured in years), *Expectedlifetimeyrs*, which represents our output. Once satellites with such missing data were removed, we searched for those variables chosen as input: the launch mass, *Launchmasskg*, and the mission cost, *Cost*. Whereas the launch mass was directly taken from the UCS *Satellite Database*, the cost was taken from different sources provided in the UCS data set (e.g. spaceflightnow.com).

Hence, we restricted our data set to 37 satellites, representing the DMUs under investigation. Table 9.1 provides a first description of a sample composition. At a first glance, it appears that launches span quite a wide period, ranging from 2006 to 2020, although most of the launches took place in the last five years and that several countries or multinational agencies have been involved in the launches forming the sample under study. In detail, eight countries (Argentina, Australia, Canada, France, Germany, India, Korea and the United States) and two international agencies (the European Space Agency [ESA] and the European Organisation for the Exploitation of Meteorological Satellites [EUMETSAT]) are listed as satellite registration countries/organisations.

Table 9.1. Sample composition

DMU	Name of satellite, alternate names	Current official name of satellite	Country/organisation of UN registry	Date of launch
1	Prox-1 (Nanosat 7)	Prox-1	United States	25/06/2019
2	Calipso (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation)	Calipso	France	28/04/2006
3	Aeolus	Aeolus	ESA	22/08/2018
4	Buccaneer RMM	Buccaneer RMM	Australia	18/11/2017
5	CSG-1 (COSMO-SkyMed Second Generation)	CSG-1	NR (12/20)	18/12/2019
6	FalconEye-2	FalconEye-2	NR (12/20)	02/12/2020
7	CSO-2 (Optical Space Component-2)	CSO-2	NR (12/20)	28/12/2020
8	Galileo FOC FM10 (0210, Galileo 13, PRN E01)	Galileo FOC FM10	NR	24/05/2016
9	Galileo FOC FM20 (0220, Galileo 24)	Galileo FOC FM20	NR	25/07/2018
10	Badr 7 (Arabsat 6B)	Badr 7	NR	10/11/2015
11	BulgariaSat-1	BulgariaSat-1	NR	23/06/2017
12	GEO-Kompsat-2B	GEO-Kompsat-2B	Korea	18/02/2020
13	GOES 17 (Geostationary Operational Environmental Satellite GOES-S)	GOES-S	United States	01/03/2018
14	Göktürk 1	Göktürk 1	NR	05/12/2016
15	Grace Follow-on-1 (Gravity Recovery and Climate Experiment Follow-on-1)	Grace Follow-on-1	United States	22/05/2018

DMU	Name of satellite, alternate names	Current official name of satellite	Country/organisation of UN registry	Date of launch
16	Grace Follow-on-2 (Gravity Recovery and Climate Experiment Follow-on-2)	Grace Follow-on-2	United States	22/05/2018
17	GSAT-11	GSAT-11	India	04/12/2018
18	GSAT-15	GSAT-15	India	10/01/2015
19	GSAT-18	GSAT-18	India	05/10/2016
20	Icesat-2	Icesat-2	United States	15/09/2018
21	Intelsat 30/DLA 1	Intelsat 30/DLA 1	NR	16/10/2014
22	Intelsat New Dawn (Intelsat 28)	Intelsat New Dawn	NR	22/04/2011
23	Iridium Next SV 102	Iridium Next 102	United States	14/01/2017
24	Jason 3	Jason 3	United States	17/01/2016
25	MetOp-C (Meteorological Operational satellite)	MetOp-C	EUMETSAT	06/11/2018
26	NOAA-20 (JPSS-1)	NOAA-20	United States	18/11/2017
27	PRISMA (PRecursore IperSpettrale della Missione Applicativa)	PRISMA	NR (12/20)	22/03/2019
28	RCM-1 (Radar Constellation Mission 1)	RCM-1	Canada	12/06/2019
29	SAOCOM-1A (Satélite Argentino de Observación Con Microondas)	SAOCOM-1A	Argentina	07/10/2018
30	Sentinel 1B	Sentinel 1B	ESA	25/04/2016
31	Sentinel 2B	Sentinel 2B	ESA	06/03/2017
32	Sentinel 5P (Sentinel 5 Precursor)	Sentinel 5P	ESA	13/10/2017
33	Sentinel 6 (Michael Freilich)	Sentinel 6	NR (12/20)	21/11/2020
34	Sky Muster 2 (NBN-1B)	Sky Muster 2	Australia	05/10/2016
35	South Asia Satellite (GSAT 9)	South Asia Satellite	India	06/05/2017
36	TerraSAR-X 1 (Terra Synthetic Aperture Radar X-Band)	TerraSAR X 1	Germany	15/06/2007
37	TESS (Transiting Exoplanet Survey Satellite)	TESS	United States	18/04/2018

Notes: DMU: decision-making unit; NR: the satellite has never been registered with the United Nations; ESA: European Space Agency; EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Moreover, the UCS data set includes additional basic information about the satellites and their orbits. Specifically, for each of the satellites, it provides the country of owner, the users and its purpose. Additional relevant satellite characteristics are reported in Table 9.2.

Table 9.2. Users, purpose and class of orbit

DMU	Users	Purpose	Class of orbit
1	Civil	Technology development	LEO
2	Government	Earth science	LEO
3	Government	Earth observation	LEO
4	Military/civil	Technology development	LEO
5	Military/government	Earth observation	LEO
6	Military	Earth observation	LEO
7	Military	Earth observation	LEO
8	Commercial	Navigation/global positioning	MEO
9	Commercial	Navigation/global positioning	MEO
10	Government	Communications	GEO
11	Commercial	Communications	GEO
12	Government	Earth observation	GEO
13	Government	Earth observation	GEO
14	Military	Earth observation	LEO
15	Government	Earth observation	LEO

DMU	Users	Purpose	Class of orbit
16	Government	Earth observation	LEO
17	Government	Communications	GEO
18	Government	Communications	GEO
19	Government	Communications	GEO
20	Government	Earth science	LEO
21	Commercial	Communications	GEO
22	Commercial	Communications	GEO
23	Government/commercial	Communications	LEO
24	Government	Earth observation	LEO
25	Government/civil	Earth observation	LEO
26	Government	Earth observation	LEO
27	Government	Earth observation	LEO
28	Government	Earth observation	LEO
29	Government	Earth observation	LEO
30	Government	Earth observation	LEO
31	Government	Earth observation	LEO
32	Government	Earth observation	LEO
33	Government	Earth observation	LEO
34	Commercial	Communications	GEO
35	Government	Communications	GEO
36	Government/commercial	Earth observation	LEO
37	Government	Space science	Elliptical

Note: DMU: decision-making unit; LEO: low-earth orbit; MEO: medium-earth orbit; GEO: geostationary earth orbit.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Data show that most of the satellites (62%) are in the low-earth orbit (LEO), 5% are in the medium-earth orbit, 30% in the geostationary Earth orbit (GEO) and the remaining 3% in the high elliptical orbit. Satellite use can be divided into governmental (59%), civil (3%), military (8%), commercial (16%) or mixed (13%). Regardless of the orbit (with the only exception of medium-earth orbit, where there are only commercial satellites) their largest employment is for governmental purposes. Finally, as far as their purpose is concerned, the largest share of the satellites localised in the LEO (78%) are developed for earth observation, whereas most of the satellites localised in the GEO (82%) are developed for communication.

Table 9.3 reports the values of the three variables included in our DEA model for each DMU. The DMUs are ordered according to their expected life from the smallest to the largest.

Table 9.3. Inputs and outputs

DMU	Inputs		Output
	Launch mass (kg)	Cost (USD million)	Expected lifetime (years)
1	70	185	0.25
2	587	298	3.00
3	1 367	550	3.00
4	1 515	1 000	3.00
5	4	11 300	5.00
6	2 205	110	5.00
7	1 180	407	5.00
8	600	430	5.00
9	600	430	5.00
10	553	364	5.00
11	4 084	4 000	5.00

DMU	Inputs		Output
	Launch mass (kg)	Cost (USD million)	Expected lifetime (years)
12	550	143	5.00
13	1 650	600	5.00
14	1 192	1 000	5.00
15	1 230	250	5.00
16	1 060	300	7.00
17	2 294	1 600	7.00
18	1 430	900	7.00
19	2 300	157	7.00
20	1 130	150	7.00
21	820	284	7.00
22	3 565	1 500	10.00
23	3 379	650	10.00
24	723	8 000	12.00
25	715	11 700	12.00
26	3 164	128	12.00
27	2 230	60	12.00
28	5 500	128	15.00
29	3 669	235	15.00
30	5 211	11 000	15.00
31	5 854	650	15.00
32	3 404	153	15.00
33	6 220	250	15.00
34	3 000	250	15.00
35	860	3 000	15.00
36	6 405	153	15.00
37	362	337	20.00

Note: DMU: decision-making unit.

Source: Calculations based on data provided by the Union of Concerned Scientists.

As we can observe, data are very heterogeneous across the DMUs. This issue can be also noted by looking at Table 9.4, referring to the average values of the sample. Launch mass (expressed in kilogrammes [kg]) ranges from 4 kg to 6 405 kg, mission costs (USD millions) go from USD 60 million to USD 11 700 million, while the expected lifetime varies from 4 months to 20 years. Data heterogeneity is also shown by the high standard deviations for both inputs and output.

Table 9.4. Sample statistics

Statistics	Inputs		Output
	Launch mass (kg)	Cost (USD million)	Expected lifetime (years)
Mean	2 180.59	1 693.30	8.90
Standard deviation	1 830.43	3 245.08	4.91
Maximum	6 405.00	11 700.00	20.00
Minimum	4.00	60.00	0.25

Source: Calculations based on data provided by the Union of Concerned Scientists.

Results

Unfortunately, the available data are quite incomplete, and we acknowledge that this represents a potential limitation to our analysis. As mentioned above, the available data moved us to choose satellite mass and mission cost as inputs and satellite expected life as output. Thus, it is reasonable to opt for an input-oriented estimation model, which is more consistent with the objective of the analysis. The rationale for such a choice is: for a given expected lifetime, the less resources in terms of mass launched into space and mission economic resources employed, the more efficient the satellite is.

This feature is relevant under a different perspective. A smaller mass implies less debris caused in the event of a collision. Hence, minimising satellites' mass may positively affect efforts to reduce the number of debris objects, and increase the satellites' expected lifetime. In all our estimates, each satellite represents our DMU. Furthermore, we will employ the well-known DEA estimator, put forward by Charnes, Cooper and Rhodes (1978^[18]), measuring the efficiency in terms of Farrell (1957^[19]) input distance functions, which are the reciprocals of the Shephard (1970^[20]) input efficiency measures. Then, for a point contained within the convex hull of the reference observations, the returned efficiency scores will be between 0 and 1. The larger the efficiency score, the higher the efficiency of the DMU. Furthermore, we assume constant returns to scale. To account for possible bias in the estimates and the presence of outliers, we will also perform the bootstrap confidence interval for efficiency estimates (Simar and Wilson, 2000^[15]). Table 9.5 reports the efficiency estimates for each DMU. Column 2 shows the original efficiency scores; Columns 3 and 4 provide the bias and bias-corrected efficiency scores. Columns 5 and 6 report the 95% confidence intervals for the bias-corrected efficiency scores. As can be seen, the value reported in the second column falls beyond the upper bound of the confidence intervals, revealing the presence of bias in the estimates. Both the levels of bias and bias-corrected estimates vary significantly across the DMUs. The greatest difference between the original and the bias-corrected efficiency scores is 0.40525 (DMU 4).

Table 9.5. Efficiency estimates

DMU	DEA efficiency scores	Bias	Bias-corrected efficiency scores	Lower bound (95% confidence)	Upper bound (95% confidence)
1	0.06381	0.01591	0.04790	0.03948	0.06177
2	0.16021	0.03106	0.12915	0.10548	0.15665
3	0.08411	0.01490	0.06922	0.05634	0.08217
4	1.00000	0.40525	0.59475	0.51151	0.89707
5	0.34105	0.07630	0.26475	0.21726	0.32728
6	0.18485	0.03132	0.15353	0.12564	0.18092
7	0.10348	0.01863	0.08485	0.06914	0.10101
8	0.27878	0.06706	0.21172	0.17453	0.26373
9	0.27167	0.06618	0.20549	0.16951	0.25740
10	0.58594	0.17058	0.41536	0.34434	0.56186
11	0.55024	0.11220	0.43804	0.36269	0.52920
12	0.20399	0.03367	0.17031	0.14224	0.19874
13	0.05163	0.01320	0.03843	0.03181	0.04971
14	0.33851	0.05608	0.28243	0.23162	0.33092
15	0.19188	0.04381	0.14807	0.12079	0.18571
16	0.19188	0.04381	0.14807	0.12079	0.18571
17	0.25568	0.04556	0.21011	0.17811	0.24680
18	0.61885	0.15163	0.46722	0.38364	0.59014
19	0.69108	0.16137	0.52971	0.43423	0.66144
20	0.04913	0.01058	0.03855	0.03140	0.04819
21	0.39443	0.09698	0.29745	0.24427	0.37546

DMU	DEA efficiency scores	Bias	Bias-corrected efficiency scores	Lower bound (95% confidence)	Upper bound (95% confidence)
22	0.58867	0.11165	0.47702	0.40156	0.56604
23	0.30963	0.07575	0.23389	0.19239	0.30032
24	0.22488	0.04835	0.17653	0.14378	0.22055
25	0.02215	0.00619	0.01596	0.01338	0.02096
26	0.07202	0.01610	0.05592	0.04555	0.07024
27	0.49844	0.08212	0.41632	0.34228	0.48623
28	0.12677	0.02671	0.10006	0.08149	0.12443
29	0.12650	0.02171	0.10479	0.08568	0.12356
30	0.39720	0.07933	0.31787	0.26422	0.38336
31	0.55215	0.09545	0.45670	0.38665	0.53406
32	0.37113	0.06292	0.30821	0.25219	0.36302
33	0.08360	0.02183	0.06177	0.05143	0.07903
34	0.49020	0.14310	0.34710	0.28808	0.46826
35	1.00000	0.29892	0.70108	0.58762	0.92050
36	0.26905	0.04427	0.22478	0.18719	0.26184
37	1.00000	0.28250	0.71750	0.60350	0.92805

Note: DMU: decision-making unit; DEA: data envelopment analysis.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Table 9.6 displays the average values. The bias-corrected efficiency scores range from 0.71750 to 0.01596, showing a remarkably high degree of heterogeneity among the DMUs. Also, the mean efficiency score across the sample is 0.2611, showing that, on average, inputs could be reduced altogether by roughly 74% to get full efficiency. Overall, the efficiency decreased slightly with a mean drop of slightly more than 8%.

Table 9.6. Summary statistics of the efficiency estimates

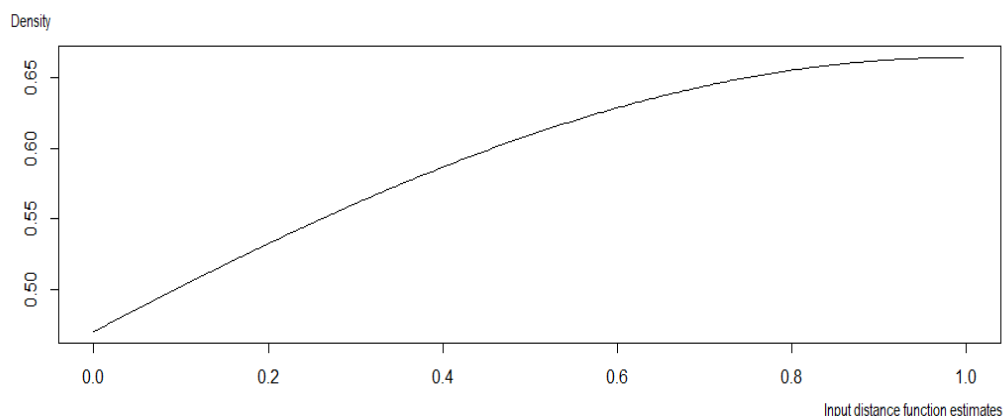
Statistics	DEA efficiency scores	Bias-corrected efficiency scores	Lower bound (95% confidence)	Upper bound (95% confidence)
Mean	0.34442	0.26110	0.21681	0.32817
Standard deviation	0.26621	0.18682	0.15709	0.24635
Minimum	0.02215	0.01596	0.01338	0.02096
Maximum	1.00000	0.71750	0.60350	0.92805

Note: DEA: data envelopment analysis.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Figure 9.1 reports the Kernel density estimates of the efficiency scores that rely on the reflection method (Simar and Wilson, 2008^[21]). The results are not significantly different from those reported in Table 9.6.

The presence of bias in the original efficiency scores reported in Table 9.6 could be further investigated by decomposing the sample according to the homogeneous characteristics of satellites. To do so, the following tables cluster the efficiency estimates according to user, purpose and class of orbit. Table 9.7 reports the DMUs clustered by user. In more than half of the observations, governments are the user, with an average bias-corrected efficiency score of 0.2628, with a small bias of 0.0798.

Figure 9.1. Kernel density of the data envelopment analysis efficiency estimates**Table 9.7. Efficiency estimates by user**

User	Obs.	Mean DEA efficiency scores	Standard deviation	Mean bias-corrected efficiency scores	Standard deviation
Civil	1.0000	0.0638		0.0479	
Commercial	6.0000	0.4290	0.1360	0.3295	0.1133
Government	22.0000	0.3426	0.2915	0.2628	0.2112
Government/civil	1.0000	0.0222		0.0160	
Government/commercial	2.0000	0.2893	0.0287	0.2293	0.0064
Military	3.0000	0.2089	0.1193	0.1736	0.1003
Military/civil	1.0000	1.0000		0.5947	
Military/government	1.0000	0.3410		0.2648	
Whole sample	37.0000	0.3444	0.2699	0.2611	0.1894

Note: DEA: data envelopment analysis.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Inversely, Table 9.8 refers to the clustering by satellites' purpose. In this case, there are two main groups. The first and more numerous is related to Earth observation (54% of the sample), showing an average bias-corrected efficiency score of 0.1799, with a very small bias of 0.0419. The second group refers to communications, showing an average bias-corrected efficiency score of 0.4117, with a quite significant bias of 0.1368.

Table 9.8. Efficiency estimates by purpose

Purpose	Obs.	Mean DEA efficiency scores	Standard deviation	Mean bias-corrected efficiency scores	Standard deviation
Communications	10.0000	0.5485	0.2114	0.4117	0.1473
Earth observation	20.0000	0.2218	0.1511	0.1799	0.1257
Earth science	2.0000	0.1047	0.0785	0.0839	0.0641
Navigation/global positioning	2.0000	0.2752	0.0050	0.2086	0.0044
Space science	1.0000	1.0000		0.7175	
Technology development	2.0000	0.5319	0.6620	0.3213	0.3867
Whole sample	37.0000	0.3444	0.2699	0.2611	0.1894

Note: DEA: data envelopment analysis.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Finally, Table 9.9 regards the cluster according to the class of orbit of the satellites. In this cluster, there are also two main groups. The first refers to LEO, showing an average bias-corrected efficiency score of 0.1928, with a quite small bias of 0.0577, whereas the second cluster refers to GEO, reporting an average bias-corrected efficiency score of 0.3720, with a remarkable bias of 0.1217.

Table 9.9. Efficiency estimates by class of orbit

Class of orbit	Obs.	Mean DEA efficiency scores	Standard deviation	Mean bias-corrected efficiency scores	Standard deviation
GEO	11.0000	0.4937	0.2603	0.3720	0.1854
LEO	23.0000	0.2505	0.2192	0.1928	0.1494
MEO	2.0000	0.2752	0.0050	0.2086	0.0044
Elliptical	1.0000	1.0000	x	0.7175	x
Whole sample	37.0000	0.3444	0.2699	0.2611	0.1894

Notes: DEA: data envelopment analysis; x = Not applicable.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Looking in depth at the results reported in the previous tables, it seems reasonable to perform new estimates focusing only on the most homogeneous groups of DMUs to mitigate the bias. Thus, the following tables report the efficiency estimates for the subsamples referring to earth observation and communications.

Table 9.10 reports the efficiency estimates for the subsample of communications satellites. The results show a quite remarkable increase in the average bias-corrected efficiency scores of the subsample, as compared to the results for communications satellites in Table 9.8 moving from 0.4117 to 0.5275. Also, the bias has significantly decreased, from 0.1368 to 0.0970. It thus appears that we have been able to somehow mitigate the negative effect of the DMUs' heterogeneity on efficiency levels.

Table 9.10. Efficiency estimates for the subsample of communications satellites

DMU	DEA efficiency scores	Bias	Bias-corrected efficiency scores	Lower bound (95% confidence)	Upper bound (95% confidence)
10	0.58594	0.08253	0.50341	0.41777	0.58131
11	0.74190	0.06870	0.67320	0.59130	0.73556
17	0.45157	0.04037	0.41120	0.36209	0.44631
18	0.69867	0.07830	0.62037	0.53771	0.69188
19	0.80943	0.08465	0.72479	0.62933	0.80406
21	0.44433	0.05018	0.39415	0.34126	0.43950
22	0.89641	0.07965	0.81676	0.71793	0.88714
23	1.00000	0.24053	0.75947	0.62411	0.97554
34	0.49020	0.07069	0.41950	0.34904	0.48502
35	1.00000	0.17386	0.82614	0.70412	0.98085
Mean	0.71185	0.09695	0.61490	0.52747	0.70272
Standard deviation	0.20372	0.05866	0.16205	0.14045	0.19860
Minimum	0.44433	0.04037	0.39415	0.34126	0.43950
Maximum	1.00000	0.24053	0.82614	0.71793	0.98085

Note: DMU: decision-making unit; DEA: data envelopment analysis.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Inversely, Table 9.11 shows the efficiency estimates for the subsample of earth observation satellites. In this case, the average bias-corrected efficiency score has tripled, from 0.1799, as reported in Table 9.8, to

0.5401, while keeping the bias at a very low level (0.0835). As said before, running estimates on a subsample to keep heterogeneity at a minimum has dramatically helped boost bias-corrected efficiency levels.

Table 9.11. Efficiency estimates for the subsample of earth observation satellites

DMU	DEA efficiency scores	Bias	Bias-corrected efficiency scores	Lower bound (95% confidence)	Upper bound (95% confidence)
3	0.24140	0.02644	0.21497	0.18596	0.24009
5	0.97403	0.17063	0.80339	0.65915	0.96499
6	0.46610	0.05916	0.40694	0.35063	0.46197
7	0.30856	0.03278	0.27577	0.23897	0.30728
12	0.39190	0.06996	0.32194	0.27273	0.38185
13	0.31664	0.02223	0.29440	0.25893	0.31592
14	0.72642	0.12025	0.60616	0.52385	0.71503
15	0.91667	0.07035	0.84631	0.74029	0.91419
16	0.91667	0.07035	0.84631	0.74029	0.91419
24	0.99458	0.08024	0.91434	0.80185	0.99104
25	0.13467	0.00976	0.12492	0.11003	0.13436
26	0.33566	0.02612	0.30954	0.27073	0.33462
27	1.00000	0.18481	0.81519	0.70669	0.96590
28	0.53846	0.04489	0.49357	0.43385	0.53635
29	0.33333	0.03989	0.29345	0.25283	0.33127
30	0.95541	0.17755	0.77787	0.64491	0.93983
31	1.00000	0.21967	0.78033	0.66558	0.97141
32	0.93902	0.11851	0.82052	0.70647	0.93146
33	0.46141	0.03417	0.42724	0.37609	0.46021
36	0.52120	0.09186	0.42934	0.36444	0.50687
Mean	0.62361	0.08348	0.54012	0.46521	0.61594
Standard deviation	0.30033	0.06048	0.25344	0.21734	0.29523
Minimum	0.13467	0.00976	0.12492	0.11003	0.13436
Maximum	1.00000	0.21967	0.91434	0.80185	0.99104

Note: DMU: decision-making unit; DEA: data envelopment analysis.

Source: Calculations based on data provided by the Union of Concerned Scientists.

Conclusions

Space activities are becoming crucial for many areas such as meteorology, navigation, communication and earth observation. For this reason, most countries are increasingly investing in the space sector to improve their space-launching capabilities.

Considering the growing importance of the space sector in everyday life, especially in the long and medium terms, assessing the efficiency of space activities could be of interest to policy makers. Thus, we aimed to fill the gap in the space literature by providing an efficiency analysis using the DEA technique. Specifically, by using a subsample of the *UCS Satellite Database*, we considered 37 satellites, launched between 2006 and 2020, as our decision-making units, their launch mass and mission cost as inputs and their expected life expressed in years as output, for our input-oriented approach. Also, the mean efficiency score across the sample is 0.2611, showing that on average, inputs could be reduced altogether by roughly 74% to reach full efficiency. In a second step, satellites were clustered according to their users, purposes and class of orbit respectively, to account for data heterogeneity. Then, the efficiency analysis was conducted for two subsamples based on their purposes: Earth observation and communications. For earth observation, the results show a quite remarkable increase in the average bias-corrected efficiency scores

of the subsample, moving from 0.4117 to 0.5275. Also, the bias significantly decreased, from 0.1368 to 0.0970. Focusing on communications, the average bias-corrected efficiency score tripled, from 0.1799 to 0.5401, while keeping the bias at a very low level (0.0835). Hence, it appears that the communications satellites are those where inputs are more efficiently employed, keeping the expected lifetime constant.

From a policy perspective, it could be worth designing interventions that improve satellite efficiency by working on the launch mass which, in its turn, can affect the mission cost. To incentivise the space sector to focus on mission design, policy makers could introduce soft regulatory tools such as guidelines on satellite composition, driving agents to conform to standards on the dimensions or on the materials used to build the satellites, for example. Debris mitigation and remediation policies, which have been very inconclusive so far (Hall, 2014^[22]), could benefit from similar regulatory mechanisms.

However, our results should be interpreted with caution. Several limitations affect our study, the main problem being the limited available sample set due to multiple missing variables in the UCS *Satellite Database*. Market mechanisms that make such information available would not only make the analysis more robust, but could support the sector in detecting strategies to improve efficiency levels.

Notwithstanding, we believe that our analysis represents the first step in the efficiency analysis of satellites' launches, placing attention on the problem of future debris creation.

References

- Adilov, N., P. Alexander and B. Cunningham (2020), "The economics of orbital debris generation, accumulation, mitigation, and remediation", *Journal of Space Safety Engineering*, Vol. 7/3, pp. 447-450, <https://doi.org/10.1016/j.jsse.2020.07.016>. [10]
- Banker, R. et al. (1988), "A comparison of DEA and translog estimates of production frontiers using simulated observations from a known technology", in *Applications of Modern Production Theory: Efficiency and Productivity*, pp. 33-35, Springer, Dordrecht, https://doi.org/10.1007/978-94-009-3253-1_2. [13]
- Charnes, A., W. Cooper and E. Rhodes (1978), "Measuring the efficiency of decision making units", *European Journal of Operational Research*, Vol. 2/6, pp. 429-444, [https://doi.org/10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8). [18]
- Cheng, C. et al. (2006), "Satellite constellation monitors global and space weather", *EOS Transactions American Geophysical Union*, Vol. 87/17, p. 166, <https://doi.org/10.1029/2006EO170003>. [4]
- Chrystal, P., D. Mcknight and P. Meredith (2018), *New Space, New Dimensions, New Challenges: How Satellite Constellations Impact Space Risk*, Swiss Re Corporate Solutions Ltd, Zurich. [7]
- Coelli, T. (1998), "A multi-stage methodology for the solution of orientated DEA models", *Operations Research Letters*, Vol. 23/3-5, pp. 143-149, [https://doi.org/10.1016/S0167-6377\(98\)00036-4](https://doi.org/10.1016/S0167-6377(98)00036-4). [11]
- Farrell, M. (1957), "The measurement of productive efficiency", *Journal of the Royal Statistical Society: Series A (General)*, Vol. 120/3, pp. 253-281, <https://doi.org/10.2307/2343100>. [19]
- Fried, H., C. Knox Lovell and S. Schmidt Shelton (2008), *The Measurement of Productive Efficiency and Productivity Growth*, Oxford University Press, New York, NY. [12]

- Hall, L. (2014), "The history of space debris", Space Traffic Management Conference, 16-18 November 2014, paper 19. [22]
- Liou, J. (2017), *USA Space Debris Environment, Operations, and Research Updates*, 54th Session of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space, United Nations, 30 January-10 February, Vienna, <https://www.unoosa.org/pdf/pres/stsc2012/tech-26E.pdf>. [6]
- Liou, J. and N. Johnson (2006), "Risks in space from orbiting debris", *Science*, Vol. 311/5759, pp. 340-341, <https://doi.org/10.1126/science.1121337>. [5]
- Liu, J. et al. (2013), "A survey of DEA applications", *Omega*, Vol. 41/5, pp. 893-902, <https://doi.org/10.1016/j.omega.2012.11.004>. [14]
- NASA (2019), *Economic Impact Report FY19*, National Aeronautics and Space Administration, <https://www.nasa.gov/press-release/nasa-report-details-how-agency-significantly-benefits-us-economy>. [2]
- OECD (2019), *The Space Economy in Figures: How Space Contributes to the Global Economy*, OECD Publishing, Paris, <https://doi.org/10.1787/c5996201-en>. [3]
- OECD (n.d.), *OECD Science, Technology and Industry Policy Papers*, OECD Publishing, Paris, <https://doi.org/10.1787/23074957>. [1]
- Rossi, A. et al. (2017), "The H2020 project ReDSHIFT: Overview, first results and perspectives", *Proceedings of the 7th European Conference on Space Debris*, <https://elib.dlr.de/121525>. [8]
- Rossi, A., G. Valsecchi and P. Farinella (1999), "Risk of collisions for constellation satellites", *Nature*, Vol. 399/6738, p. 743, <https://doi.org/10.1016/j.omega.2012.11.004>. [9]
- Shephard, R. (1970), *Theory of Cost and Production Functions*, Princeton University Press, Princeton, NJ. [20]
- Simar, L. and P. Wilson (2008), "Statistical inference in nonparametric frontier models: Recent developments and perspectives", in Fried, H., C. Knox Lovell and S. Schmidt Shelton (eds.), *The Measurement of Productive Efficiency and Productivity Growth*, <https://doi.org/10.1093/acprof:oso/9780195183528.003.0004>. [21]
- Simar, L. and P. Wilson (2000), "A general methodology for bootstrapping in non-parametric frontier models", *Journal of Applied Statistics*, Vol. 27/6, pp. 779-802, <https://doi.org/10.1080/02664760050081951>. [15]
- Simar, L. and P. Wilson (1998), "Sensitivity Analysis of Efficiency Scores: How to Bootstrap in Nonparametric Frontier Models", *Management Science*, Vol. 44/1, pp. 49-61, <https://doi.org/10.1287/mnsc.44.1.49>. [16]
- UCS (2022), *UCS Satellite Database*, <https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database> (accessed on 20 March 2019). [17]

Notes

¹ The Moon to Mars exploration programme alone generated 69 000 jobs nationwide (NASA, 2019^[2]).

² For more details, see Coelli (1998^[11]) and Fried, Know Lovell and Schmidt Shelton (2008^[12]).

³ The acronyms CRS and VRS are often used with reference to the CCR and BCC models from the initials of the authors, Charnes, Cooper and Rhodes (1978^[18]), Banker et al. (1988^[13]).

⁴ For a numerical example of the trade-off between sample size and number of inputs and outputs used for consistency, see Simar and Wilson (2008, p. 439^[21]).

⁵ The idea is to simulate a true sampling distribution by mimicking their DGP – here the outputs from DEA (Simar and Wilson, 2008^[21]) – by constructing a pseudo-data set and re-estimating the DEA model with this new data set. Repeating the process many times to achieve a good approximation of the true distribution of the sampling. The Simar and Wilson (1998^[16]) bootstrap procedure gives an estimated bias and the variance, which in turn provide confidence intervals. Later, Simar and Wilson (2000^[15]) provided an improved and more flexible procedure that automatically corrects for biases without explicit use of a noisy bias estimator. See Simar and Wilson (2008^[21]) for the technical details on the bootstrap procedures.

⁶ This procedure is also adopted because it does not assume homogeneity on the distribution of efficiency, which may be too restrictive for this analysis and may invalidate the inference on the efficiency estimates.

Earth's Orbits at Risk

THE ECONOMICS OF SPACE SUSTAINABILITY

Society's dependence on space infrastructure is at a critical juncture. Public and private actors worldwide are planning to launch tens of thousands of satellites into Earth's orbit in the next five years. This will greatly expand and enrich the use of space resources, but it will also result in more crowded orbits and greater risk of damage from satellite collision and space debris. As satellite launches continue to multiply and concerns grow, the long-term sustainability of space-based infrastructure on orbit and beyond is set to emerge as an increasingly important space policy issue of the 21st century. This publication takes stock of the growing socio-economic dependence of our modern societies on space assets, and the general threats to space-based infrastructure from debris in particular. Notably, it provides fresh insights into the value of space-based infrastructure and the potential costs generated by space debris, drawing on new academic research developed especially for the OECD project on the economics of space sustainability.



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