Policy brief

Policy options to address collision risk from space debris

International Risk
Governance Center

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Executive summary

Decades of near-Earth space exploration and utilisation have resulted in an increasingly congested environment. As a by-product of space missions, a wide range of non-functional objects, from entire satellites to small bolts, have been deposited in orbit. These pieces of space debris are a growing threat to space assets, human spaceflight and future access to outer space. Making space activities sustainable, i.e., ensuring that benefits from access to and use of space meet the needs of the present without compromising the ability of future generations to meet their needs, requires informed policy discussion about matters related to space debris.

This policy brief provides a range of policy options to improve the assessment, evaluation and management of collision risk, as well as its communication. It draws on discussions held at a multi-disciplinary and multi-stakeholder expert workshop organised by the EPFL International Risk Governance Center (IRGC) in May 2021 and on follow-up exchanges with space debris experts. As low Earth orbit (LEO) is the region of space with the largest collision risk, it is the focus of this policy brief. However, some of the policy options proposed can be readily applied to other orbital regions.

There is insufficient evidence available necessary for a comprehensive scientific assessment of the risk. There is also an incomplete evaluation of the possible response strategies, which impedes the prioritisation of policy options to avoid, reduce or mitigate the risk. IRGC's opinion is that a complete evidence-based evaluation of the risk, response options and associated cost is still missing. Reasons for this include uncertainties about the future behaviour of space actors (such as the number and orbits of satellites launched), the implementation of non-binding guidelines (such as the rate of successful post-mission disposal), and the costs/benefits of mitigation and remediation approaches (such as the cost of active debris removal). However, IRGC's opinion is that incomplete assessment should not delay action. The development and deployment of technology to manage the risk and the implementation of best practices should be encouraged and rewarded, including through economic incentives.

We currently have a limited understanding of the maturity of certain technologies, as well as their capacity to scale up and be cost-effective under various possible policy and regulatory decisions. Moreover, the long timescale on which the issue unfolds makes the elaboration of cost-effective requirements and best practices difficult. Given the importance of the growing space economy and the extent of adverse consequences if certain risks materialise (e.g., cascading collisions in certain orbits limiting or preventing their use, the loss of particularly valuable spacecraft disrupting services on Earth), it would be a mistake to adopt a wait and see approach until much more granular evidence relevant to policy decisions becomes available. Governments should become more active, starting with incentives to produce the evidence needed for a more comprehensive risk assessment and the evaluation of possible response strategies.

This policy brief addresses the following four areas where policy decisions can support efforts to better address collision risk.

Risk assessment and evaluation

Improving the understanding of collision risk and the secondary consequences of collisions on Earth systems is of paramount importance. Studying the interconnections within Earth-space systems and integrating the perspectives of a larger set of stakeholders can help increase the knowledge surrounding collision risk, including its monetary and non-monetary aspects. Reaching a common agreement on management strategies requires consensus on evidence-based metrics that assess clearly defined objectives. A first step towards developing such metrics is to review the ones currently used to make their scope and objective transparent. Analysing stakeholders' concerns and behaviour in more depth would help unveil potential conflicts due to differences in risk perception, in objectives and values, and from inequities in the distribution of risk and benefits. This would help better tailor the response strategies and make progress at the international level.

Technology development and implementation

Availability of mature technologies for space debris mitigation and remediation is instrumental in making space activities safe and sustainable. Reducing collision risk can be achieved by (i) improving the tracking and cataloguing of objects to enhance the effectiveness of collision avoidance strategies, (ii) reducing the likelihood of explosion, (iii) making sure spacecraft are de-orbited at end-of-life and (iv) reducing the occurrence of debris-generating events involving existing debris. These four streams of activities not only rely on the implementation of best practices but also on the development and deployment of new technology, which can be incentivised through various policies.

Regulatory requirements and compliance

National regulatory authorities can mandate or incentivise the adoption of best practices and the use of cost-effective mature technologies. With current technology, the most promising options to reduce collision risk include organising the collection and sharing of data on space debris impacts and requirements on (i) manoeuvrability capabilities, (ii) trajectory information sharing (including planned manoeuvres) and independent tracking, and (iii) reduced post-mission orbital lifetime. Operators could directly apply these requirements, but they should eventually be incorporated in national licensing processes and international guidelines. In addition, regulatory authorities must continuously supervise the licensees and perform ex post monitoring to ensure that the requirements enacted are implemented and that operators respect the commitments made to obtain a license. Effective management of collision risk would require the implementation of these requirements and active supervision by every major spacefaring nation.

Multilevel governance of collision risk

Long-term effective global governance of risks related to space debris likely requires agreement among space actors on a management strategy, including sharing costs and benefits from space utilisation. Given that the prospect of reaching consensus in the short term is very low, governments are advised to take unilateral but coordinated action by improving their national regulations. Some plurilateral actions by several like-minded states should also be encouraged. This would improve the management of the issue in the short term and provide referenceable precedent as a foundation for building wider international agreements. However, if unilateral and plurilateral actions are not accompanied by transparent discussions at the international level, they will not help the development of an international management strategy as these actions could be perceived as attempts at imposing national rules onto the rest of the international community. Given impediments to reaching an international agreement, bottom-up initiatives led by non-state actors can also help in elaborating, disseminating and implementing best practices.

While this policy brief does not provide specific policy recommendations, which depend on national contexts, each chapter provides a menu of policy options related to technical aspects. It concludes with three overarching process recommendations to pave the way towards ensuring safe and sustainable space activities in the long term:

1. More collaborative work is needed to improve the framing and evaluation of the risk. This is due to scientific uncertainty about the consequences and likelihood of (cascading) collisions affecting the availability of space-based services and interconnected systems on Earth, and ambiguity regarding the role of different space actors and how they evaluate the risk.
2. A larger and more committed political involvement at the national and international level will be instrumental to any progress.
3. Addressing collision risk from space debris is necessary to avoid significant adverse consequences on the economy. In addition to space actors, other stakeholders that use or benefit from space-related activities should be involved in the discussion.

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Acronyms

ADR	Active debris removal
AMC	Advance market commitment
CAM	Collision avoidance manoeuvre
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COPUOS	[United Nations] Committee on the Peaceful Uses of Outer Space
ESA	European Space Agency
GEO	Geostationary Earth orbit
IRGC	[EPFL] International Risk Governance Center
ISS	International Space Station
JCA	Just-in-time collision avoidance
LEO	Low Earth orbit
LNT	Lethal non-trackable [object or debris]
NDCs	Nationally determined contributions
OST	Outer Space Treaty
PMD	Post-mission disposal
RPOs	Rendezvous and proximity operations
SDA	Space Data Association
SEM	Space environment management
SSA	Space situational awareness
SSR	Space Sustainability Rating
STM	Space traffic management

Introduction

Space debris—non-functional human-made objects—is a growing threat to space assets, human spaceflight and future access to outer space. The satellites on which our society increasingly relies face a growing collision risk from space debris and other operational spacecraft. Space debris also threatens astronauts and spaceflight participants. Low Earth orbit (LEO),[1] which is a highly valuable resource, notably used for Earth observation and communications, has become increasingly congested. Governance institutions and mechanisms to manage collision risk[2] have not kept pace with the rapid and ongoing changes in the space ecosystem. Increased efforts to ensure that space activities are safe and sustainable are required to preserve the current benefits and enable potential future benefits from space.

> *LOW EARTH ORBIT HAS BECOME INCREASINGLY CONGESTED, RESULTING IN A GROWING RISK OF COLLISION*

Collision risk is complex as it depends on both anthropogenic and natural factors. It is marked by reinforcing feedback loops where newly generated debris can create further debris. The risk is non-uniform across orbital regimes and has varying consequences on different space operations. It is difficult to assess the probability of occurrence, severity (monetary and non-monetary costs) and cascading effects. The space ecosystem in which the risk develops exhibits a complex pattern of interconnections, with numerous links to other systems on Earth, such as financial, transportation, telecommunications and emergency systems.[3] There is uncertainty regarding future activities in space, the economic and societal impacts of space debris, and the effects of policies to reduce risk. Furthermore, current and future behaviour of space actors are ambiguous, with divergent (and sometimes competing) values, interests and perspectives on the risk, complicating its assessment and management. The complexity, uncertainty and ambiguity surrounding collision risk have led

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[1] LEO, the orbital region ranging from the upper atmosphere to an altitude of about 2,000 km (depending on the definition), is the focus of this policy brief. However, some of the policy options proposed can be readily applied to other orbital regions.

[2] Collision risk not only encompasses the first order consequences of objects colliding in space but also the wider impacts on the interconnected systems on Earth. See section *Broaden the framing of the risk* on p. 07, for more details.

[3] The space ecosystem increasingly exhibits features of complex adaptive systems (CAS). See, e.g., IRGC's *Guidelines for the governance of systemic risks* (IRGC, 2018).

to governance deficits (i.e., gaps, deficiencies or failures in how the risk is assessed and managed). We note in particular the issues of compliance with or interpretation of international mitigation guidelines, the need to revise technical requirements as the landscape of technologies and satellite launches evolves, a lack of consensus about major principles for space governance,[4] and insufficient international collaboration.

This policy brief elaborates on the report *Collision risks from space debris: Current status, challenges and response strategies*, published by the EPFL International Risk Governance Center (IRGC) in June 2021 (Buchs, 2021a).[5] That report provides an overview of the current status of collision risk in LEO and highlights the challenges we face in addressing the risk. It gives the background for this policy brief by providing information about the context in which the risk develops, the state of collision risk assessment and evaluation,[6] and current and potential response strategies for the future. It takes into account broad principles and details technical, economic and regulatory solutions. We refer the reader to that report for basic facts and information about collision risk assessment, evaluation and management.

Discussions held at a multi-disciplinary and multi-stakeholder expert workshop organised by IRGC in May 2021 contributed to this policy brief, which provides a range of policy options and broad recommendations[7] that could be pursued to address collision risk from space debris. Policies described in this document aim at improving the assessment, evaluation and management of collision risk, as well as its communication.[8] We recommend adopting a step-by-step approach and focusing on measures that have the potential for rapid improvements.[9]

We highlight several policies to reduce collision risk in the short term that could be acceptable to stakeholders. However, we also include options that may prove to be the most cost-effective[10] in the longer term.

> *WE RECOMMEND ADOPTING A STEP-BY-STEP APPROACH AND FOCUSING ON MEASURES THAT HAVE THE POTENTIAL FOR RAPID IMPROVEMENTS*

In chapter 1, we offer proposals to improve the assessment and evaluation of the risk, including broadening the framing of the risk, developing new metrics, and analysing stakeholders' concerns, perceptions and behaviour. In chapter 2, we detail actions aimed at developing and implementing the necessary technologies for space debris mitigation and remediation. In chapter 3, we present technical requirements, which national regulators could implement, and approaches to improve the supervision of space actors. Finally, in chapter 4, we highlight the need to raise awareness at different levels and present approaches to make progress in governing collision risk at the national, multinational and global levels.

Although much progress has been made in the past few years towards collaboration in risk analysis, there are still divergences among experts on the best way forward. Some think that a more comprehensive risk assessment and in-depth cost-benefit analyses of all the proposed solutions are needed before making definitive recommendations. Others argue

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[4] For example, some spacefaring nations' declarations, current behaviour and future plans appear to contradict principles enshrined in the international treaties on outer space.

[5] Some of the content of this policy brief has been presented in two conference papers (Buchs et al., 2021; David et al., 2021).

[6] We use the term risk assessment to include factual, physical and measurable characteristics of the risk. In the context of this policy brief, this also includes an assessment of different stakeholders' perceptions, opinions and concerns. Risk evaluation takes into account broader value-based issues and aims at judging a risk's acceptability or tolerability. For more information, see *Appendix 4: Key concepts of risk analysis and governance* on p. 34.

[7] Specific recommendations are often context-dependent and can differ between countries.

[8] For a definition of these risk concepts, see *Appendix 4: Key concepts of risk analysis and governance* on p. 34.

[9] A major collision resulting in human casualties or substantial financial losses would be an impetus for a more drastic approach. Such an event would likely be a catalyst for change and open a window of opportunity to radically modify regulations.

[10] This policy brief adopts a broad definition of cost-effectiveness. Costs can be direct or indirect, monetary or non-monetary. They can be incurred by operators or by other entities to which the cost of the measure is transferred. Effectiveness is generally measured by reduction of the risk.

> *THE LACK OF A COMPLETE RISK ASSESSMENT SHOULD NOT BE A REASON TO POSTPONE ACTION, AS SUFFICIENT INFORMATION TO MAKE DECISIONS REGARDING SOME MANAGEMENT POLICIES IS AVAILABLE*

that the current risk assessment is sufficient to pursue low-hanging fruits[11] that can help reduce risk without waiting for more complete studies. While there is a need to improve risk assessment and conduct thorough cost-benefit analyses, achieving a complete picture is elusive, given the complexity of the problem and the range of response strategies available. However, the lack of a complete picture should not be a reason to postpone action, as sufficient information to make decisions regarding some management policies is available. Moreover, developing technologies that can help reduce risk gives information about their costs and benefits, which will help refine future recommendations.

Space debris is at the core of a network of risks that affect operations in space. Addressing this issue needs some form of coordination regarding the direction of policy decisions and vision about the future use of outer space. Policy decisions will determine much of the safety and sustainability of future space activities.

This publication is intended for space debris experts involved in policy discussions, as well as policy advisers, policymakers and decision-makers who are new to the topic. We hope it will be of particular interest to government-related and private organisations that have just started or are planning to engage in space activities and to organisations not directly involved in space activities that have an interest in safe and sustainable space activities. Newcomers to these discussions, in both government and industry, will find in this publication key policy aspects that affect the safety and sustainability of future space activities.

Today's situation regarding space debris calls for every country to participate in international discussions actively. This includes non-spacefaring nations, as they would also be affected by adverse consequences of collisions.

Debris can also result from deliberate destruction

On 15 November 2021, Russia conducted an anti-satellite (ASAT) weapon test targeting its satellite Kosmos 1408. The test resulted in the complete fragmentation of the Soviet-era spy satellite orbiting at about 500 km, producing more than 1,500 pieces of trackable debris. This event significantly increases the collision risk at these densely used orbits, threatening operational assets and humans in the International Space Station and the Tiangong space station (The Economist, 2021). Similar tests have been conducted in the past by the US, China and India.

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[11] See for example recommendations for "quick wins" in the RAND Corporation's report *Responsible space behavior for the New Space era* (McClintock et al., 2021).

Chapter 1

Risk assessment and evaluation

The first area where policy decisions can support efforts to better address collision risk is by supporting or mandating a more comprehensive evaluation of the risk. The development of effective management strategies requires a sound assessment and evaluation of collision risk. To this end, more research regarding the source, type and extent of the risk to assets and humans (including probability and severity of physical and economic consequences),[12] its broader ramifications and wider consequences on Earth would be beneficial. When assessing the risk, not only should the direct consequences of the risk for operational satellites be accounted for, but a wider perspective on the Earth-space system should be taken to include collision risk's cascading consequences on other interconnected systems.[13] A better understanding of the complex system into which the risk develops would allow for the development of strategies that not only address the risk at the source but also try to reduce its consequences on the risk absorbing systems.[14] First, broadening the framing of the risk would help take

> A WIDER PERSPECTIVE ON THE EARTH-SPACE SYSTEM SHOULD BE TAKEN TO INCLUDE CASCADING CONSEQUENCES OF COLLISION RISK ON INTERCONNECTED SYSTEMS ON EARTH

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[12] The sections *Space debris population* (p. 8) and *Risks to operational spacecraft and human spaceflight* (p. 11) in chapter 2 of IRGC's report *Collision risks from space debris: Current status, challenges and response strategies* give more details regarding our current understanding of collision risk and approaches developed to measure it. See also Kunstadter et al. (2021) for an overview of collision risk in LEO.

[13] Numerous systems on Earth depend on satellite services. For example, Earth observation satellites are used to monitor land use, atmospheric pollution, ocean health and the climate. Financial and transportation systems rely on global navigation satellite systems (GNSS) for position, navigation and timing. Satellites are also instrumental for early disaster warning and disaster management. These systems would be affected if the space assets on which they rely are damaged or destroyed by space debris.

[14] A risk absorbing system comprises the assets, ecosystems and individuals that could be impacted, directly or indirectly, by a risk source. This concept focuses on exposure and vulnerability of the system at risk. Since it adopts a systems view, rather than simply considering individual risks, this approach opens to considering resilience building as an appropriate strategy to face multiple interconnected risks.

into account these wider consequences. Second, developing simple yet sufficiently comprehensive metrics upon which common agreement can be reached would improve risk assessment and evaluation. Finally, conducting systematic analyses of space actors' behaviour and stakeholders' concerns would be instrumental in making progress at the international level.

Policymakers involved in decisions about the use of space need to know that stakeholder appreciation of the risk can vary widely due to the high uncertainty and ambiguity about collision risk, especially regarding its direct and indirect costs. Thus, designing policies that include capacity building and collaboration among stakeholders for improving risk assessment and evaluation is of utmost importance.

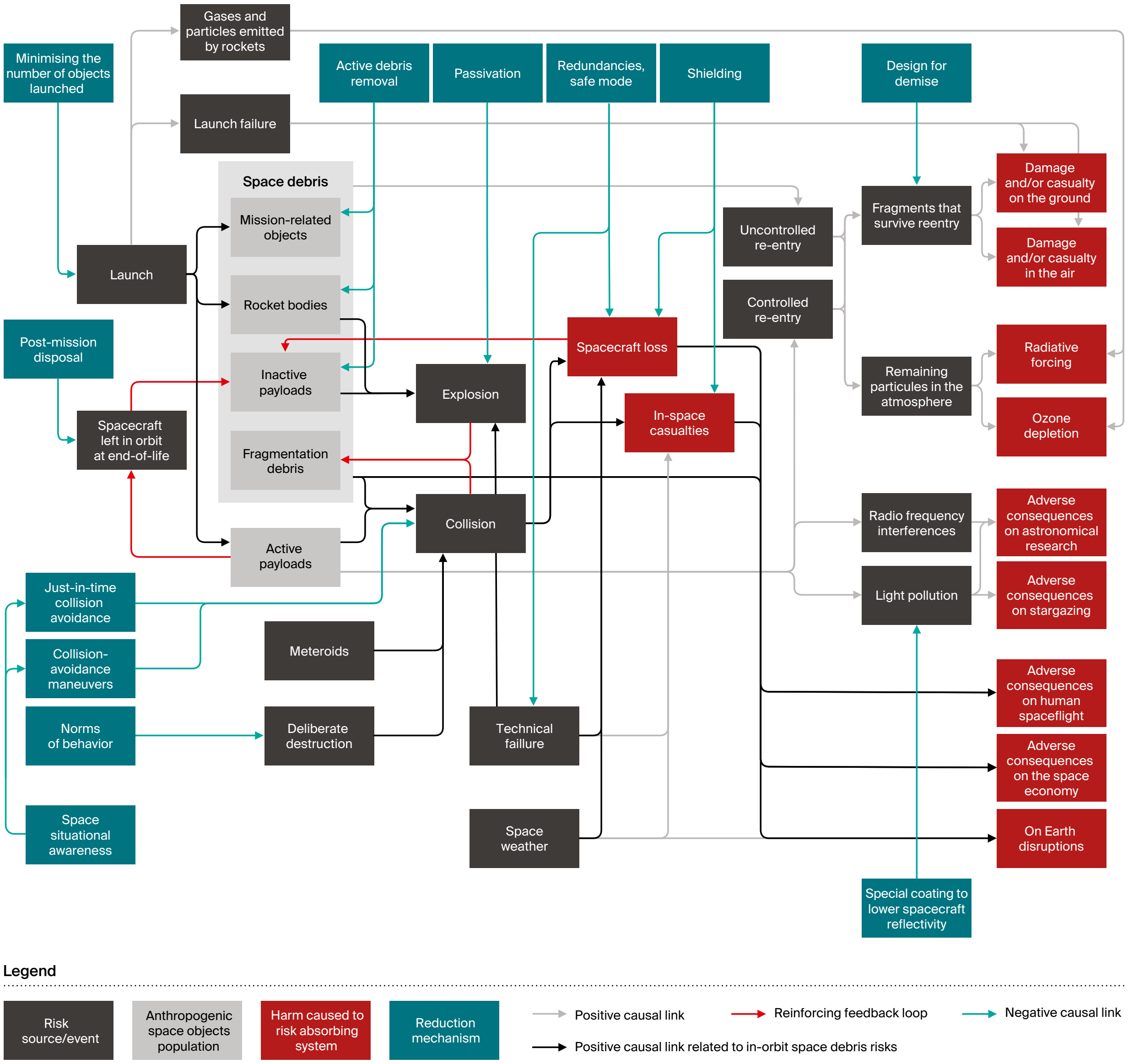

Figure 1: Risk landscape associated with human activities in near-Earth space (excluding risks particular to human spaceflight). The causal loop diagram highlights a pattern of complex interconnections characteristic of systemic risks (IRGC, 2018). See IRGC's Spotlight on risk article *Intensifying space activity calls for increased scrutiny of risks* (Buchs, 2021b) for more details.

1.

Broaden the framing of the risk

Improving the assessment and evaluation of the risk begins by taking a broader perspective on the context and system in which the risk develops to better understand the wider impacts on Earth (see Figure 1). Given the uncertainty regarding the evolution of the space ecosystem,[15] the ambiguity of space actors' future behaviour, and our limited knowledge of interconnections between space and Earth systems, integrating the perspectives of a larger set of stakeholders would help increase understanding of the wider ramifications of the risk, including monetary and non-monetary aspects. In addition, a broader understanding of the risk absorbing systems could help develop robustness to mitigate the risk and resilience strategies to enable the system to better cope with and recover from shocks, and adapt to new context conditions.[16]

A larger perspective on the consequences of collisions will help broaden the management strategies by addressing collision risk in the wider absorbing systems. To increase our understanding of the space ecosystem and the space-connected systems on Earth, including their physical and behavioural interconnections (see Figure 2 and Figure 3 for examples), we recommend:

- Analysing the interconnections within the Earth-space system to identify the key dependencies and alternative options if a space service is no longer available,[17] and time and costs to recover in the case of an accident. To this end, a wider set of realistic disaster scenarios should be conceived and investigated to evaluate the vulnerability of interconnected systems to space debris.
- Involving a wider set of stakeholders that contribute to space debris creation or that are or could be affected by the consequences of space debris to reach a more comprehensive understanding of the risk (see, e.g., IRGC, 2020). Larger stakeholder participation would help assess the severity of the risk, provide a better understanding of the costs and benefits of management strategies, and help reduce adverse consequences by various means, including risk transfer.[18]

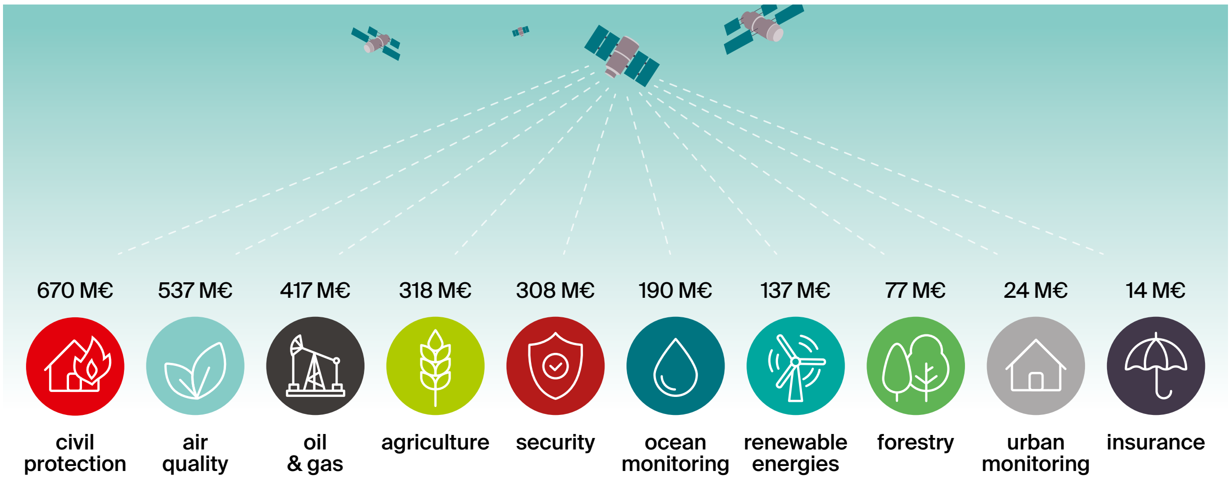

Figure 2: End-users revenues enabled by the European Earth observation program Copernicus in 2018 in EUR million (data from European Commission, 2019).

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[15] Forecasts of the space economy predict a significant growth in the coming years (e.g., OECD, 2019). However, there are still barriers to this growth (see, e.g., Daehnick et al., 2020, on cost reductions needed for large constellations to thrive). For example, in the case of large constellations, it is unclear which ones will be completed and when. Plans are ambiguous as constellations' settings (altitude, orbital planes, number of satellites, etc.) and deployment schedules constantly change.

[16] For an overview of risk management strategies and definition of robustness and resilience strategies, see *Appendix 4: Key concepts of risk analysis and governance* on p. 34.

[17] For example, analysing the alternative options if Earth observations used for a specific service are no longer available.

[18] Risk transfer consists of passing on some or all of the consequences of a risk to a third party (e.g., to an insurance company). A better understanding of the broader consequences of the risk would help potentially affected stakeholders to insure themselves against the risk.

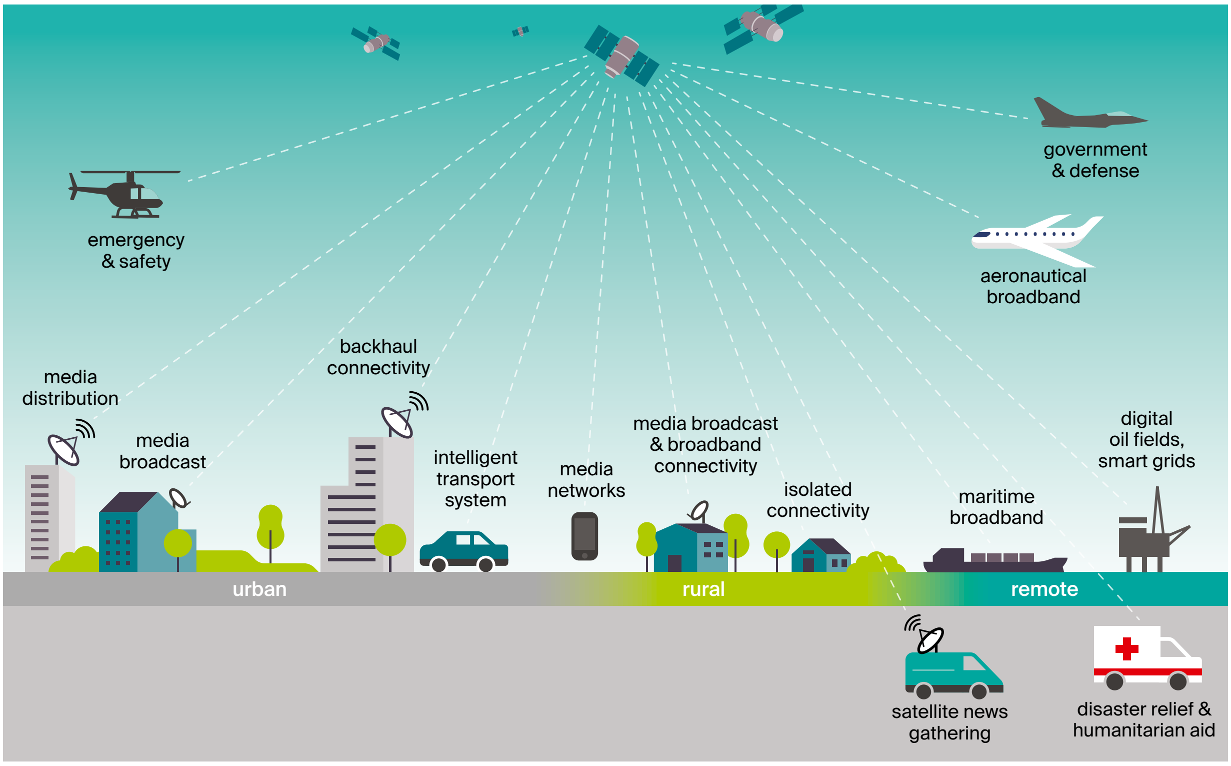

Figure 3: Interconnected satellite 5G network. Ground-based 5G services will rely on space infrastructure, including satellites in geostationary Earth orbit (GEO) and LEO (adapted from Giambene et al., 2018).

2.

Develop and use common metrics to measure the risk

The assessment of the risk level and its potential evolution in the future would benefit from the development of commonly agreed-upon evidence-based metrics.[19,20] This would help decision-makers evaluate the risk and the cost-effectiveness of various technology options, make better-informed decisions regarding the management of the risk and monitor the impact of new policies on the risk level.

Commonly used metrics

One way to assess the risk level and its potential evolution in the future is to use evolutionary simulations of the space environment. The number of large debris pieces and the cumulative number of catastrophic collisions in 100 or 200 years is generally compared between different scenarios (e.g., Liou et al., 2013, 2018; Somma et al., 2019). Another way is to consider near-Earth space as a resource used by active spacecraft and space debris, and measure the overall use of this resource. The European Space Agency (ESA) has developed a metric capturing the consumption of this resource by a space object, i.e., the collision risk induced by an object on orbital neighbours (Lemmens & Letizia,

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[19] Metrics are generally measures of quantitative assessment commonly used for comparing risks, tracking the performance of a management strategy or evaluating a risk level. They can be used to inform risk acceptance or tolerability, which determine from what level of risk managers are expected to take action. Appropriate and commonly agreed-upon metrics are thus stepping stones towards collaborative agreement on risk management.

[20] Various metrics exist to assess the collision risk faced by a single spacecraft and take decision regarding evasive manoeuvres. Here, we take a societal point of view and look at a general notion of risk that encompasses the first order consequences in space and the wider impacts on the interconnected systems on Earth.

2020; Letizia et al., 2019). Using this metric, the overall consumption of the resource under different scenarios can be computed, and environmental capacity thresholds derived (Letizia et al., 2021). This metric can also be used as a tool during the design of a space mission to facilitate the comparison of different mission architectures depending on their potential impact on the space debris environment (Letizia et al., 2020). Both types of metrics do not take into account direct (value of the assets) and indirect (value of the services provided by the assets) costs associated with collision risk.

Agree on objectives

Developing metrics requires clearly defining common objectives, such as space safety and sustainability, and what they entail. Metrics can be more or less aligned with different objectives. For example, measures that improve sustainability might not ensure short-term operational safety. Looking at the overall long-term growth of the large debris population might result in missing short-term effects (e.g., significant growth of the collision risk at certain altitudes during a limited period, increased operator conjunction assessment workloads), while focusing on short-term operational safety might result in missing long-term effects (e.g., consequences of collisions between large derelict objects). Making the objective transparent would enable working towards commonly agreed metrics, especially ones that encompass both long-term sustainability and short-term operational safety.

Clarify the meaning of space safety, security and sustainability

Space safety "refers to space mission hazards and relevant risk avoidance and mitigation measures" and "encompasses the safeguard of critical and/or high-value space systems and infrastructures, as well as the protection of orbital and planetary environments" (Pelton et al., 2020). It is often seen as the short-term minimisation of hazards for space assets and human spaceflight, and perceived as one of the prerequisites for space sustainability.

Space security is traditionally associated with the military security of states and encompasses the maintenance of peace and stability. However, its meaning has broadened to include the freedom of access to and utilisation of space. This concept can include "the security of satellites and spacecraft in orbit, the security of access to space, and also the contribution to the security of people on Earth made by various types of satellites" (Sheehan, 2014). States can interpret the terms space safety and security differently. While these concepts overlap, a greater distinction between them can help make progress at the international level, for example, by helping develop safety measures and avoid political blockage on security-related issues (Zarkan Cesari, n.d.).

There is no universal definition of space sustainability (or sustainable space activities), and many authors refer to this concept without defining it. The Guidelines for the Long-term Sustainability of Outer Space Activities developed by the UN Committee on the Peaceful Uses of Outer Space (COPUOS) define the sustainability of space activities as the "ability to maintain the conduct of space activities indefinitely into the future in a manner that realises 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" (UNCOPUOS, 2019). The Secure World Foundation (2018) defines space sustainability as "ensuring that all humanity can continue to use outer space for peaceful purposes and socioeconomic benefit now and in the long term." The Space Sustainability Rating (SSR), a composite metric assessing the sustainability of space missions, provides a de facto definition of space sustainability through the scope of the elements included in the rating (Rathnasabapathy et al., 2020).[21]

Global governance and international agreements are focused on sustainability. In contrast, the spacecraft operator's procedures are, unless mandated by a regulatory authority, typically focused on the individual operator's concerns and interests (as can be seen from the wide range of criteria used by operators to determine whether a collision avoidance manoeuvre is warranted; Alfano et al., 2021).

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[21] Note that the SSR does not cover every part of space sustainability, and the selection of indicators is driven by a variety of technical, logistical and strategic factors. See the World Economic Forum's SSR webpage for the latest updates on the SSR, www.weforum.org/projects/space-sustainability-rating.

Review current metrics and develop new ones

There has not been a systematic review of the currently used metrics for collision risk assessment.[22] Conducting such a review would make the scope and limitations of these metrics transparent, and would help foster agreement on an existing metric or develop new ones. The involvement of diverse stakeholders in the review and development process would help ensure that every relevant aspect of the risk is taken into account and general agreement on the relevance of the metric exists.[23] Work to broaden the framing of the risk, as described in the preceding section (p. 07), would also help include relevant actors in the design of more appropriate metrics. Developers of these metrics should strive to introduce costs associated with space debris – both direct and indirect – and make underlying values and preferences transparent.

3.

Analyse stakeholders' concerns and behaviour

The assessment of stakeholders' concerns regarding collision risk is largely incomplete. Drivers of their behaviour are often postulated but lack a systematic analysis. When undertaking such analysis, all stakeholder groups should be encouraged to express their objectives and concerns, and be transparent about what matters to them and drives their behaviour. For example, little public information is available about the exact motivations of governments, private companies and militaries regarding end-of-life disposal, as well as the level of concern of large constellation operators regarding collision risk. While there might be significant barriers to sharing this information, efforts are needed to require and incentivise more transparency. Increasing the understanding of space actors' behaviour and their drivers is instrumental in improving risk evaluation and selecting acceptable response strategies. In line with the first section of this chapter (p. 07), which calls for broadening the framing of the risk, the concerns of a wide range of potentially affected stakeholders should be taken into account.

This analysis would help unveil potential conflicts due to differences in risk perception, in stakeholder objectives and values, or from inequities in the distribution of benefits and risk. Only by making these aspects transparent can we achieve a mutual understanding and make further progress at the international level.

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[22] Such a review has been conducted previously for single spacecraft collision assessment (metrics used for go/no-go decision to manoeuvre; e.g., Oltrogge, 2020), and for indexes aimed at evaluating the criticality of an object to the space environment (Bombardelli et al., 2017). However, to the best of our knowledge there is no comprehensive review of metrics that holistically assess risk from a societal point of view and on which decisions regarding the management strategy can be based.

[23] Efforts similar to the ones conducted by ESA to engage with stakeholders to improve space debris modelling would be helpful (Braun et al., 2021).

Chapter 2

Technology development and implementation

The second area where policy decisions can support efforts to better address collision risk is by fostering or mandating the development of technologies for mitigation and remediation, which are key enablers of space safety and sustainability.[24] Space is a harsh and remote environment where assets cannot be easily maintained, refuelled or upgraded.[25] Innovative new technologies, along with best practices, can be instrumental in reducing the generation of debris and collision risk from existing debris. The availability of mature and cost-effective technologies raises the standard of care and enables regulatory authorities to adopt more stringent requirements or incentivise the use of these technologies.[26] However, the establishment of regulatory requirements and economic incentives must be based upon sound analyses of the technologies, including their effectiveness, costs, feasibility and risk-risk trade-offs.[27] Such analyses would also help channel public and private funds to the development and implementation of the technologies most likely to be cost-effective in the long term. The development

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[24] For details about the technical approaches, see *Appendix 1: Space debris related activitiess* on p. 31 and *Appendix 2: Main technical approaches* on p. 32.

[25] However, new technologies are being developed to enable on-orbit satellite servicing (e.g., Corbin et al., 2020; ESA, 2021; Mayfield, 2021; Rainbow, 2021). Some systems, e.g., to extend the life of a satellite (Northrop Grumman, 2020, 2021), have already been deployed.

[26] See chapter 3 on p. 17 and *Appendix 3: Policy instruments to incentivise technology development* on p. 34.

[27] A trade-off results from balancing two desirable but incompatible features, often requiring a compromise. Risk-risk trade-offs occur when interventions to reduce one risk can increase or create other risks, or shift risk to a new population. Resolving trade-offs between risks is one of the most challenging tasks of risk management and decision-making, and require appropriate metrics. For example, removing a large piece of debris from orbit decreases on-orbit collision risk, but generates a risk of damage to property and casualty on the ground when re-entering the atmosphere.

of cost-effective technologies to reduce risk is necessary to avoid implementing more radical solutions to decrease risk, such as reducing the number of launches or forbidding the use of certain orbits.[28]

Reducing collision risk can be achieved by (i) improving the tracking and cataloguing of objects to enhance the effectiveness of collision avoidance strategies, (ii) reducing the likelihood of explosion, (iii) making sure spacecraft are de-orbited at end-of-life and (iv) remediation activities. The latter consists of reducing debris-generating events involving existing debris by removing them from orbit or reducing the likelihood that they collide. These four streams of activities rely on the implementation of best practices and appropriate technology. Risk reduction potential, costs and feasibility of these different activities should be compared while keeping in mind that they might be complementary and help reduce different aspects of the risk.

Policymakers involved in decisions about space debris are advised to work collaboratively to coordinate their strategies towards the effective deployment of technologies for risk management. However, agreeing on common schemes remains a challenge because of differing perspectives, at least until there is more clarity about stakeholder preferences and behaviour.[29]

1.

Improve tracking, cataloguing and collision avoidance

The majority of active spacecraft are manoeuvrable[30] and can potentially dodge catalogued debris. Efforts described in this section to improve the tracking, cataloguing and avoidance of space debris only indirectly reduce collision risk for spacecraft lacking manoeuvrability capabilities, as they cannot react quickly in the case of an encounter with a piece of debris.[31] The rationale for requiring spacecraft to be manoeuvrable and ways to implement such a requirement are discussed in the section *Require manoeuvrability* on p. 19.

To reduce collision risk and its associated costs for manoeuvrable spacecraft,[32] efforts are needed on achieving five sub-goals:

1. **Reduce uncertainty on objects' predicted positions**. This decreases the number of conjunction alerts that space operators must analyse and act on, reducing the collision avoidance costs for operators. Reduced uncertainty also decreases the likelihood of a collision, as likely encounters will be detected far enough in advance to make the appropriate manoeuvre.
2. **Track smaller objects**. Tracking smaller objects allows spacecraft operators to avoid potentially lethal collisions because it decreases the number of lethal non-trackable (LNT) debris objects.
3. **Enable comprehensive data exchanges**. The higher quality data obtained through sub-goals 1

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[28] See, e.g., chapter 4, section 2 in Buchs (2021a).

[29] As seen in the section *Analyse stakeholders' concerns and behaviour* on p. 10.

[30] Bonnal et al. (2020) note that about 75% of the roughly 2,000 operational spacecraft were manoeuvrable at the time of their analysis. Since then, the number of operational satellites has more than doubled, mainly due to the launch of more than 1,700 Starlink satellites which are manoeuvrable, probably raising the share of manoeuvrable spacecraft in orbit.

[31] Some operators of spacecraft that lack manoeuvrability capabilities use attitude reorientation in order to incur drag perturbations that affect the orbit. When the outcome of such a procedure enables collision avoidance on a relevant time scale, this should be considered as an avoidance manoeuvre. The requirement proposed in the section *Require manoeuvrability* on p. 19 is performance-based and would take such a procedure into account.

[32] The proposals in this section would not only help reduce collision risk from space debris, but also collision risk between operational spacecraft.

and 2 must be accessible and trusted to enable efficient risk reduction from operators. This can be achieved through comprehensive data exchanges, particularly between spacecraft operators, state actors and commercial space situational awareness (SSA) service providers, using an internationally accepted standard (e.g., the orbit data message; Consultative Committee for Space Data Systems, 2009). Moreover, fusing government, commercial and satellite operator data with advanced data processing techniques can help improve accuracy and, as a result, flight safety (Oltrogge et al., 2021).

4. **Improve the processing of conjunction data messages**. A more comprehensive catalogue of tracked objects will result in a more complete set of conjunction data messages. Improving their processing and the decision-making regarding manoeuvres will reduce costs for operators.
5. **Reduce the time needed to manoeuvre**. The uncertainty of the predicted orbits increases with time due to intrinsic limits in physical models. Spacecraft need to be able to manoeuvre quickly to be able to avoid small objects.

Five streams of activities can help reach the aforementioned sub-goals:[33]

1. **Larger investments in SSA capabilities for data collection and processing**. Distributed sensors (radar and optical) across the globe[34] ensure more frequent observations of objects, resulting in reduced uncertainties. Processing capabilities to pool, fuse and interpret data from different sources are also instrumental in reducing uncertainty on orbital trajectories.[35] This stream of activity involves not only the deployment of operational systems but also research and development as there are many open questions and areas for improvement.
2. **More international collaboration**. This would help avoid the duplication of similar capabilities and efficiently allocate resources. An important aspect of this collaboration is the efficient sharing of data among public and private space actors, and among nations with SSA capabilities.[36] Enhanced sharing of data to build open-access consolidated catalogues would enable improved learning among stakeholders, third-party analysis and verification, and the competitive development of new models.
3. **Automation of conjunction data message processing and collision avoidance decision-making**. Automation would drastically reduce the burden for operators as the number of encounters involving debris will surge with new SSA sensors. However, safe autonomy requires sufficiently high-quality data and methods. It also requires a shared understanding of the operating environment, including the autonomous decision-making processes used by other space users. Moreover, sharing with other operators the autonomous manoeuvres conducted in a timely manner can enhance safety.
4. **Improved physical models**. Irrespective of the accuracy of the original tracking data, improved models are necessary to reduce the uncertainties of the predicted orbits.
5. **Routine assessment of sensitive parameters**. Complementary measurements (e.g., atmospheric density, object attitude states) of sensitive parameters in the models are also useful in reducing uncertainties.

In the best-case scenario, all spacecraft would be manoeuvrable, space debris would be tracked

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[33] This is similar to recommendations in the RAND Corporation's report *Responsible Space Behavior for the New Space Era* (McClintock et al., 2021).

[34] The deployment of space-based SSA capabilities could also help improve tracking and cataloguing (see, Ackermann et al., 2015, for a comparison of the approaches). A few countries currently have dedicated space-based SSA assets (Lal et al., 2018), and governments and private companies have plans to deploy networks of space-based sensors (e.g., Clark, 2020).

[35] Public and private capabilities in data collection are rapidly improving, notably with the deployment of new sensors (Lal et al., 2018). For example, the Space Fence, a radar system deployed by the US Space Force, could track debris as small as 5 cm (Erwin, 2020; Gruss, 2019), and LeoLabs' network of radars plans to catalogue objects down to 2 cm in size (Stevenson et al., 2020). Thus, the focus of policy might gradually shift towards improving data processing, collaboration and data sharing, with less attention given to developing the sensor infrastructure.

[36] Efficient sharing of data requires (i) compatible data formats, (ii) transparency on the acquisition method and processing performed, and (iii) trust among actors. National security concerns can be a barrier to achieving these goals.

down to the size where shielding is effective,[37] there would be low uncertainty on objects' predicted positions, and operators would share their predictive ephemerides, including planned manoeuvres.[38] This scenario would enable active spacecraft to avoid collisions with all objects that could cause severe damage. Cost-effective efforts to help current capabilities get closer to this best-case scenario, especially those requiring limited funding, should be pursued.[39]

2.

Develop technologies for passivation

Explosions of spacecraft in orbit caused by leftover energy (fuel and batteries) contribute significantly to the growth of the space debris population (Bonnal & McKnight, 2017). Although guidelines recommend that space systems should be designed and operated to prevent accidental explosions (IADC, 2021), there has been no decline in the number of explosions over the years (see, e.g., ESA Space Debris Office, 2021, Figure 5.3).

While satellite builders and operators have an incentive to reduce accidental explosions during operations, doing it after the end of a mission is more challenging. There is not only a lack of economic incentives but also inadequate technologies. Most currently used subsystems that store energy are not designed for passivation, i.e., the process of removing the internal energy from a spacecraft at the end of its mission or useful life to limit the probability of accidental explosion (Bonnal & McKnight, 2017). For example, it might not be possible to vent the remaining propellant or discharge the batteries. To carry out such tasks, the development of new technologies is required (ESA, 2016). Moreover, passivation is performed electronically, which, due to the harsh space environment, can fail. Therefore, it is also necessary to develop technologies to ensure that passivation can be completed even after a spacecraft has spent decades in space.[40]

Economic incentives can help ensure that newly developed technologies for passivation are implemented. Similar to de-orbiting requirements, passivation requirements can be implemented, monitored and their non-compliance sanctioned.

3.

Develop de-orbiting technologies

The post-mission disposal (PMD) of spacecraft is crucial to avoid increasing the population of derelict objects, thus limiting risk-generating events.[41] The exact causes for failing to achieve PMD are not well documented. Detailed analysis of unsuccessful PMDs and the lack of PMD attempts would help tailor the response.[42] Besides the absence of de-orbiting capabilities, possible causes of failure include technical issues (exacerbated by the use of satellites

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[37] Some external parts of spacecraft such as solar panels cannot be shielded. Moreover, even if the small objects are tracked, if they are too numerous, it is probably not feasible to dodge them all.

[38] Such data sharing has been done since 2010 among members of the Space Data Association (SDA). The data centre of the SDA now provides services to 30 operators and their 786 spacecraft spanning all orbital regimes (Wauthier, 2020).

[39] Some argue that a more comprehensive risk assessment and more complete cost-benefit analyses comparing investments in improving collision avoidance, reducing debris generation and remediation should be conducted before selecting the most cost-effective option(s). Given the complexity of the problem, conducting such a comprehensive analysis is probably unachievable. We see strengths in pursuing these three strands of action.

[40] Approaches to fostering the development of these technologies are detailed in *Appendix 3: Policy instruments to incentivise technology development* on p. 34.

[41] For LEO, the only viable PMD solution is to remove spacecraft from orbit with a destructive re-entry into the atmosphere. There is a trade-off between the post-mission orbital lifetime and its cost. We discuss it in the section *Reduce post-mission orbital lifetime* on p. 20.

[42] ESA's annual space environment report (ESA Space Debris Office, 2021) provides the most comprehensive public assessment of space objects' compliance with PMD standards. While ESA shares a growing amount of information, its reports still lack a fine-grained view on operators' practices. The most detailed data provided are the share of compliance in terms of clearing the LEO protected region by mission type (amateur, civil, commercial and defence; see Figure 6.2, p. 80) and constellation vs. non-constellation (Figure 6.3, p. 81). The lack of public databases highlights a hesitancy to name and shame.

beyond their design life; e.g., Ferrone, 2019) and operational culture. To ensure high PMD reliability, several options should be pursued in parallel. The following technical options have been proposed to address the problem:

- Use higher reliability qualification[43] standards for spacecraft components and systems.
- Add onboard redundancies.[44]
- Equip spacecraft with separate de-orbiting mechanisms (also known as de-orbiting kits) that are independent of the satellite and can function in case of satellite failure (see, e.g., Sánchez-Arriaga et al., 2020; Tarabini Castellani et al., 2020).[45]
- Organise the provision of end-of-life services (i.e., the removal of a failed or no longer operational satellite from orbit by a space tug).

Enhancing PMD reliability requires increased research and development funding for technologies necessary to deploy these options. Policymakers would be advised to consider mandating or incentivising the development of these technical options in view of deployment where appropriate.[46]

Efforts to develop standard procedures for rendezvous and proximity operations (RPOs) and de-orbiting to limit the risk associated with these activities are also needed.[47] RPOs involve operating spacecraft close to space debris or operational spacecraft, with the risk of unintended collision and debris generation. Deorbiting satellites, especially from upper altitudes in LEO, results in crossing paths with other satellites and space debris, creating a collision risk.

Regulatory requirements, sanctions or market-based instruments can incentivise the private sector to develop and implement these technologies (see chapter 3 on p. 17). The availability of these technologies will change the perception as to what is considered a best effort by an operator to achieve PMD and will allow regulators to enact more stringent requirements and put sanctions in place.

4.

Develop a portfolio approach to space debris remediation

While mitigation has been at the core of policy efforts, remediation, i.e., dealing with debris that has already been created, has received comparatively little attention. However, the debris-generating potential in LEO is largely driven by over one thousand derelict payloads and rocket bodies deposited in orbit, mainly between 1980 and 2005 (McKnight, Stevenson, et al., 2021). A collision between these derelict objects would create

> *WHILE MITIGATION HAS BEEN AT THE CORE OF POLICY EFFORTS, REMEDIATION HAS RECEIVED COMPARATIVELY LITTLE ATTENTION*

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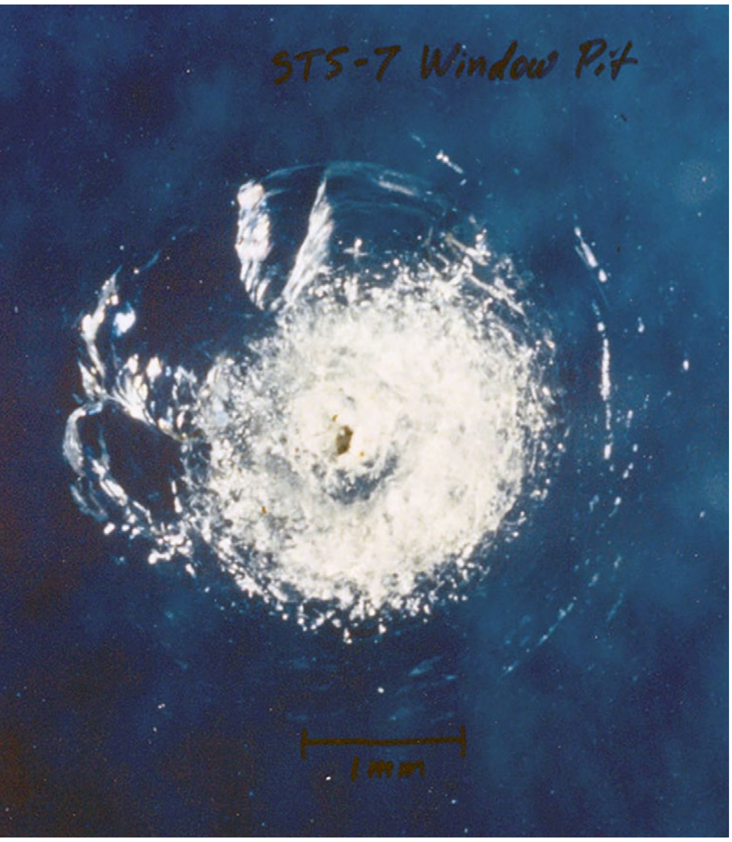
[43] A component or a system is tested under certain conditions to determine if it complies with specified reliability requirements.

[44] Redundancy is the use of more than one independent means to accomplish a given function. It is typically applied to systems critical to safety and mission success.

[45] This should be accompanied by the development of passive de-orbiting technologies such as drag augmentation devices and electrodynamic tethers which the de-orbiting kit would deploy (see, e.g., Sánchez-Arriaga et al., 2017, for a comparison of technologies for de-orbiting spacecraft). Drag augmentation devices such as drag sails increase a spacecraft's cross-sectional area to increase the aerodynamic drag and shorten its natural decay (see, Rhatigan & Lan, 2020, for a review). Electrodynamic tethers use the Earth's magnetic field to progressively decrease the orbital altitude of the spacecraft, causing it to re-enter the atmosphere (e.g., Sarego et al., 2021).

[46] See *Appendix 3: Policy instruments to incentivise technology development* on p. 34.

[47] Such efforts are underway, notably by the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS, 2021b), an industry-led initiative, and ESA (Swiatek et al., 2019). Development of a standard grappling interface for on-orbit servicing (including end-of-life services) is also discussed (e.g., Foust, 2020b).



thousands of large fragments and many more LNT objects. Reducing this risk requires developing and deploying an array of remediation technologies. Promising options for space debris remediation that policies could help organise, support, mandate or incentivise include:[48]

- **Active debris removal (ADR)** – Actively removing a certain number of large derelict objects from orbit to reduce the probability of major collisions (or removing small pieces of debris). The most advanced ADR mission concepts consist of sending a servicer satellite that would rendezvous with a piece of debris, capture it and lower its altitude to make it re-enter the atmosphere. Other proposed methods do not require capturing the target (e.g., ion-beam shepherd-based and laser-based methods).
- **Just-in-time collision avoidance (JCA)** – Lowering the collision probability between two non-manoeuvrable objects by deflecting the trajectory of one of them before the predicted collision time. The deflection is produced externally (e.g., using a laser, a cloud of gas) as the objects involved cannot manoeuvre.
- **Nanotugs** – Upgrading derelict objects with collision avoidance capabilities by attaching one or more cooperative microsatellites to them. Target objects remain in orbit but can avoid catalogued objects thanks to the attached nanotugs.

A portfolio approach (see, e.g., McKinsey & Company, 2017; Pacala & Socolow, 2004, in the context of climate change) would be useful to pursue the development of remediation options. It consists of pursuing and possibly testing several options, which will provide information about their relevance, contribution to risk reduction, cost, and other acceptability factors.[49] This approach is beneficial as it is not possible to know in advance which option should be prioritised. Furthermore, it is unlikely that there will be a one-size-fits-all option. Different options have particular strengths and weaknesses in specific situations. Thus, their parallel use might be an efficient way of reducing collision risk.[50]

The cost-effectiveness, risk-risk trade-offs, acceptability and legal feasibility of the different remediation options should be evaluated (see, e.g., Emanuelli et al., 2014; Way & Koller, 2021, for ADR). The development in parallel of mechanisms to finance and manage the options would increase their chances of deployment. In this evaluation, it is worth noting that:

- Different options might be used for different missions or targets, as they have different advantages and disadvantages in particular contexts.
- Different options might require different financing mechanisms.
- Involving a broad set of stakeholders could help mitigate the risk of conflict and concerns regarding the use of certain technologies.

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[48] See *Appendix 2: Main technical approaches* on p. 32, for more details.

[49] This approach could also include technologies for space debris mitigation and SSA (similar to the greenhouse-gas abatement cost curve, which includes both mitigation and remediation technologies). However, in the space debris context, comparison of the benefits from mitigation and remediation is more arduous.

[50] However, as conducting RPOs require strong capabilities and expertise, having various technologies and approaches may lead to an increased risk of operational mistakes.

Chapter 3

Regulatory requirements and compliance

The third area where policy decisions can support efforts to better address collision risk is by improving national regulations and the supervision of space activities. National regulatory authorities can mandate or incentivise the adoption of best-available cost-effective technologies for space debris mitigation and remediation. However, a prerequisite is the availability of mature and financially viable technologies. The policy options described in chapter 2 (p. 11) aim at developing these technologies and providing the necessary information to stakeholders, especially regulators, to assess their feasibility, costs, risks and benefits.

Promising options to reduce collision risk from space debris include organising the collection and sharing of data on space debris impacts and requirements on (i) manoeuvrability capabilities, (ii) trajectory information sharing (including planned manoeuvres) and independent tracking, and (iii) reduced post-mission orbital lifetime. While specific roles and responsibilities of various actors would need to be defined, we assume here that all major actors would have some role to play in each set of recommendations.[51]

> *NATIONAL REGULATORY AUTHORITIES CAN MANDATE OR INCENTIVISE THE ADOPTION OF BEST-AVAILABLE COST-EFFECTIVE TECHNOLOGIES FOR SPACE DEBRIS MITIGATION AND REMEDIATION*

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[51] See, for example, the recommendations from the EMEA Satellite Operators Association (ESOA, 2021), which propose specific options that regulators and industry should adopt and implement.

These requirements could be directly applied by operators but should eventually be incorporated in national regulations and international guidelines. Given the increasing complexity of the systems proposed, regulatory authorities could benefit from third-party analysis and verification.[52]

> REGULATORY AUTHORITIES MUST ENSURE THAT OPERATORS RESPECT THE COMMITMENTS MADE TO OBTAIN A LICENSE

Many observers note insufficient compliance with internationally agreed-upon standards and guidelines (see, e.g., ESA Space Debris Office, 2021), highlighting the need for continuous supervision.[53] Regulatory authorities must not only enact requirements, but they must also ensure that operators respect the commitments made to obtain a license. Without continuous supervision and ex post monitoring, there is a risk that ex ante requirements will not be implemented.

Although we highlight several technical requirements that would strengthen regulations to improve collision risk management, better regulation does not only involve stricter requirements. Regulations should be (i) technology-neutral, (ii) directly tied to clear governmental objectives, and (iii) adaptive, i.e., include a planned revision or adaptation mechanism to keep up with changes in the space environment, the evolution of our understanding of the risk and our experience with the regulation.[54]

Requirements discussed in this section are easier to implement for well-established spacefaring nations. However, aspiring space nations may face more difficulties in applying these requirements, given the nature of their space activities. To address this issue, two options can be pursued: (i) relax the requirements in very specific conditions, or (ii) keep the same requirements for every actor, but conduct capacity-building efforts, knowledge transfer, or economic support for technology access towards emerging actors. Decisions regarding which option to pursue should be based on the risk level. Given the current level of collision risk in LEO, pursuing the second option is preferred.

1.

Organise the collection and sharing of data on space debris impacts

Data regarding the population of untrackable debris and its consequences on operational spacecraft are limited. It is often difficult to disentangle technical failures from those caused by a collision with an LNT object. Given the large population of LNT objects, the current costs associated with them may be higher than generally assumed. To bridge this knowledge gap and improve technical risk assessment, it would be beneficial to incentivise spacecraft operators to generate and share data related to anomalies and contingencies, which contain information about potential space debris impacts.[55]

To obtain more data on LNT debris impacts and consequences, regulatory authorities can create the trusted environment needed to (i) help make public the data already collected by space actors, and (ii) incentivise the generation and sharing of new data. For example, regulators could encourage or require the disclosure of spacecraft anomaly information.[56] To prevent concerns regarding proprietary information this data might contain, the disclosure could be a private channel to a trusted agency that would only share aggregated data to

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[52] Regulatory bodies often do not have the necessary in-house expertise and can only rely on information provided by the company requesting a license. Independent and objective third-party analysis can support regulatory authorities in their task and enhance their assessment.

[53] See, e.g., Undseth et al. (2020) and Reesman et al. (2020), for a discussion of policies to raise compliance.

[54] See *Planned adaptive regulation* in *Appendix 4: Key concepts of risk analysis and governance* on p. 37.

[55] Higher transparency standards (protocols, technical disclosures, etc.) regarding accidents and anomalies in space, similar to the ones in the aviation sector (e.g., ICAO, 2020), could be developed.

[56] Identifying impact events and attributing failures to them is difficult. Although this requirement might only provide limited information on non-trackable objects and their costs, it would make use of available data to improve our knowledge, and would thus have negligible cost.

the public. Regulators could also incentivise data collection by rewarding operators who actively monitor their spacecraft (e.g., by adding dedicated sensors that monitor impacts). Operators who added dedicated sensors and provided their data to the agency would be rewarded by, for example, diminished licensing fees, accelerated licensing procedure or even direct subsidies.

2.

Require manoeuvrability

Satellites lacking manoeuvrability capabilities face a collision risk that cannot be easily mitigated.[57] Because they are unable to avoid catalogued debris and other non-manoeuvrable spacecraft, nothing can be done to reduce the risk of a potential collision that such satellites may encounter.[58] This risk is perceived as not tolerable by a significant share of the space community.[59] Moreover, when two active spacecraft conjunct, satellites lacking manoeuvrability capabilities transfer the costs of collision avoidance to other space users.[60] Manoeuvrability is a precious and expensive commodity for a spacecraft. The propellant used for collision avoidance manoeuvres is unavailable for later use towards the mission goals. A manoeuvrability requirement would help distribute the burden of collision avoidance among space users more equally. Regulators could thus require that all spacecraft above a defined altitude (e.g., 400 km) be manoeuvrable.[61] A performance-based requirement (e.g., a spacecraft should be able to move a certain distance in a certain amount of time), which does not require the use of specific technologies, would be more cost-effective and leave agency to operators.[62]

Regulators would also be advised to require operators to demonstrate their ability to process and decide upon conjunction data messages, which requires skilled staff and appropriate procedures to prevent collisions. These tasks can be performed in-house, subcontracted to a qualified entity, or done by a government entity on behalf of the operators. New entrants can underestimate the resources necessary to address conjunction data messages and take appropriate decisions.

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[57] Some satellites do not need manoeuvrability capabilities to meet their mission objectives (e.g., passive satellites used for geodesy and atmospheric measurements, CubeSats with a wide array of applications, chip-sized satellites). Due to the increase in CubeSat launches, there has been significant attention on the issues associated with their lack of manoeuvrability (see, e.g., ESPI, 2018; Finkleman, 2013; National Academies of Sciences, Engineering, and Medicine, 2016). Chip-sized satellites, which are cheap to manufacture and launch (e.g., Abate, 2019), are too small to be manoeuvrable. If they start being launched in significant quantities, it could become an issue as they would increase collision risk.

[58] Quantitative risk metrics (see section *Develop and use common metrics* on p. 08) could be used to quantify the risk reduction enabled by the manoeuvrability requirement. Such research would offer valuable information to policymakers.

[59] See, e.g., section 5.4.2.2 in Buchs (2020) for an overview of US stakeholders' positions regarding such requirement. The *Best Practices* of the Space Safety Coalition (2019), endorsed by about 50 operators and other organisations (including SES, OneWeb, Iridium, Planet, AXA XL), recommend collision avoidance capabilities above 400 km. However, the academic community, which builds and launches CubeSats, argue that the risk from such satellites is small and that a propulsion requirement would add unacceptable cost, size, weight and power burden given current technology (e.g., University Small-Satellite Researchers, 2019). Here we suggest a manoeuvrability requirement rather than a propulsion requirement which does not specify how the manoeuvrability should be achieved and would thus leave more room for compliance.

[60] If the assets of these space users are insured, the risk that is unmitigated by collision avoidance is ultimately transferred to their insurers.

[61] Determining the appropriate altitude above which this requirement applies is difficult. However, applying this requirement above the International Space Station (ISS) seems legitimate, as conducting of collision avoidance manoeuvres is a significant burden for the ISS and human lives are involved. Continuous human presence at a lower altitude than the ISS could be a reason for adapting the requirement. The size and mass of a spacecraft, and the debris density in the orbit used by the spacecraft, could influence the level of manoeuvrability required.

[62] As the requirement is performance-based, this would not prevent the use of any method or technology, as long as it can meet the performance required. For example, differential drag, which consists of changing the altitude of a spacecraft to affect its atmospheric drag and thus its trajectory, could potentially be used.

3.

Require trajectory information sharing and independent tracking

To facilitate the maintenance of spacecraft trajectory information, thus reducing uncertainties about their predicted positions and improving collision avoidance, operators could be required to:

1. Share real-time trajectory information (e.g., data from on-board equipment like GNSS receivers, data from operator's tracking stations, telemetry ranging) and predictive ephemerides with associated uncertainties, including planned and autonomous manoeuvres in a timely manner.[63]
2. Use an independent, active tracking system (e.g., an independent GNSS receiver and independent radio capable of transmitting that data to an independent communications provider; NASA, 2020a).[64]
3. Use passive (e.g., corner cube reflectors, Van Atta arrays) or active (e.g., devices that use coded light signals) tracking and identification aids (NASA, 2020a) when a spacecraft's radar cross-section (RCS) is not large enough to be reliably tracked with current SSA capabilities.

Requiring item 1 above would induce a very limited burden on operators as it makes use of available data.[65] Requiring item 2 would be the most effective as the spacecraft would keep being trackable in case of spacecraft failure (but not if the independent tracking system fails). However, this is the most complex option which constrains the spacecraft design as it is size, weight and power-intensive. The benefits of such a requirement compared to non-cooperative tracking using SSA sensors are unclear. Requiring item 3 is not as effective, but passive tracking aids work irrespective of spacecraft functionality.

4.

Reduce post-mission orbital lifetime

Satellites that are not promptly, properly and safely removed from orbit at their end-of-life are a major source of collision risk. For this reason, post-mission disposal (PMD) has been identified from the start of space debris mitigation efforts in the 1990s as a key action necessary to reduce risk. Cost-benefit trade-offs have led to the so-called "25-year rule," included in the guidelines of the Inter-Agency Space Debris Coordination Committee (IADC, 2021), which requires satellite operators to manoeuvre spacecraft terminating their mission into an orbit with an expected residual orbital lifetime of 25 years or shorter.[66] While some argue that these trade-offs are still valid, there have been increasing calls to reduce this orbital lifetime (see, e.g., section 5.4.3.2 in Buchs, 2020, for an overview of US stakeholders' positions regarding this rule; Foust, 2020a; Hitchens, 2020).[67] The extent of the long-term benefits from shortening this lifetime threshold is debated.[68] However, it can effectively reduce collision risk at low altitudes, the burden on tracking and conjunction assessment entities and operator collision avoidance workloads in the short term. The current rule encourages an accumulation of derelict objects in the lower portion

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[63] Operators could also be required to share spacecraft health information, including up to date manoeuvrability capabilities.

[64] The US Federal Communication Commission considered requiring the use of an independent tracking solution for all spacecraft in the last revision of its rules, but declined to adopt any requirement, arguing that it was premature (Federal Communications Commission, 2020).

[65] Involving operators in the development of an effective sharing architecture is key in dissipating their concerns regarding the sharing of these data.

[66] This rule is not present in the guidelines of the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS, 2007), which only provide high-level guidance without quantitative thresholds. This rule has been integrated in national regulations by a number of countries.

[67] Constellation operators SpaceX, OneWeb, and Iridium, as well as the Space Safety Coalition (2019) support shortening this lifetime while NASA and others believe the current rule is sufficient. In the last revision of the US Government Orbital Debris Mitigation Standard Practices (ODMSP), this rule was upheld (Liou et al., 2020).

[68] Using simulations, Liou (2020) shows that reducing the orbital lifetime from 25 to 5 years only reduces the number of objects larger than 10 cm in orbit in 200 years by a small amount. Lucken and Giolito (2019) show that reducing the orbital lifetime significantly decreases the collision risk for large constellations. The additional collision risk from spacecraft performing their PMD is often assessed by assuming perfect collision avoidance for all active spacecraft, which is far from being the case. Relaxing this assumption could affect the evaluation of the benefits from a reduction of the post-mission orbital lifetime.

of LEO, which is detrimental to the development of space activities and low-thrust orbit raising[69] in this increasingly used region. With current technologies, reducing the post-mission orbital lifetime to five years would induce a limited additional burden on operators. Off-the-shelf, flight-proven electric propulsion systems can be integrated into a range of satellite systems to meet a more stringent post-mission orbital lifetime (McKnight, Joe, et al., 2021). Integration of such a system would have a limited impact on the satellite mass but has a cost. However, that cost is quickly decreasing. The real necessity of allowing exceptions should be studied in detail by weighing the benefits from missions that would not fly with such a requirement against the collision risk they generate.

The current global compliance level with the 25-year rule is low (e.g., ESA Space Debris Office, 2021, Figure 6.10; in 2019, more than 80% of the non-naturally compliant payloads made no PMD attempt),[70] which complicates the discussions regarding shortening it. We concur with McKnight et al. (2021) that poor adherence to a rule should not be a rationale for not adopting a more stringent requirement. Implementation and enforcement issues need to be discussed further, as they are common to most current requirements or guidelines.

To reduce collision risk, the PMD success rate is more important than the post-mission orbital lifetime. IADC (2021) guidelines recommend that the probability of success of the disposal should be at least 90%. We do not discuss strengthening this requirement as its ex ante evaluation is difficult. There are significant barriers to introducing ex post sanctions for non-compliance with such a rule given the currently available technologies. However, pursuing technological developments described in the section *Develop de-orbiting technologies* (p. 14) would help improve PMD reliability. Once technologies are available, ex post sanctions for non-compliance with a defined PMD success rate should probably be implemented. Requirements regarding the expected success rate should scale with the risk a PMD failure would generate for other assets (i.e., the criticality of the object to the environment).

5.

Continuously supervise space activities

Article VI of the Outer Space Treaty (1966) provides that “activities of non-governmental entities in outer space [...] shall require authorisation and continuing supervision by the appropriate State Party to the Treaty.” To respect their obligations under the OST, states need to ensure that the enacted rules are applied. Continuous supervision of commercial activities would improve transparency, enhance the regulator's credibility and ensure that enacted policies are implemented. The supervision, where applicable,[71] could take the following forms:

- A periodic review of licensees (e.g., annual compliance check). The review should be sufficiently in-depth to allow the regulator to take appropriate measures. For example, the regulatory authority could request de-orbiting if it deems that the risk associated with the mission is unbearable (e.g., if some subsystems have failed).[72]
- A requirement to submit a licence extension request in case the operator wants to continue using a satellite beyond its design life (i.e., the time specified in the original licence). Operators would need to demonstrate that the risk of technical failure is minimal and that sufficient propellant is reserved for PMD (or, when it becomes feasible, that an end-of-life service has been planned).

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[69] Due to their efficiency, low-thrust propulsion technologies, such as electric propulsion, are increasingly used. Spacecraft can be deployed in lower orbits and raised to their operational altitude (e.g., Davis et al., 2018).

[70] Continuous supervision of space activities (see next section) and encouraging states to pass, implement and enforce national legislation aligned with international guidelines (see section *Pursue unilateral and multilateral efforts in parallel* on p. 25) would help improve compliance levels.

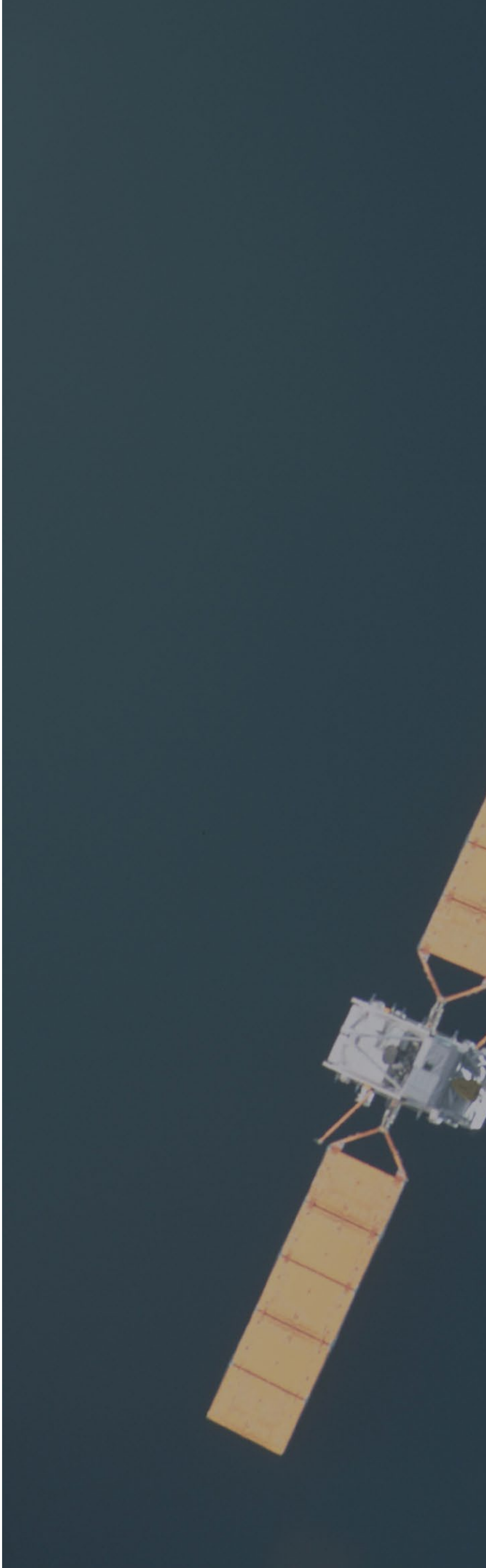
[71] In some countries, operators need a licence for the activity, while in other countries a licence for each satellite is necessary. Periodic supervision audits are already in place in some countries (e.g., the UK and the US require annual state-of-health reports). It would be useful to do a thorough review of existing regulatory practices.

[72] Operators could also be required to immediately report any anomaly, as suggested in the section *Organise the collection and sharing of data on space debris impacts* on p. 18. The consequences of theses anomalies could be reviewed continuously or periodically by the regulator. Instead of relying on a regulator’s judgement, there could be pre-established functional or performance criteria that, when no longer met, would raise the question of (or mandate) de-orbiting.

- A systematic ex post assessment, which could include sanctions for non-compliance with the rules. This could be coupled with quantitative risk metrics to create an adaptive regulatory regime and apportion additional risk to newly authorised missions as risk from previous missions is removed.

Continuous supervision can also be facilitated by regular low-key contacts between licence holders and authorities. Since governments may be worse offenders of internationally agreed-upon or national rules than private operators (e.g., ESA Space Debris Office, 2021, Figure 6.2), we recommend that an independent entity conducts periodic reviews of governmental space activities. National space legislations could create such independent entities and give them the necessary powers to review governmental activities. However, implementing this option might be difficult in specific contexts due to the unwillingness to give up power of national entities conducting space activities. Thus, a lighter review process that only involves collaboration among responsible entities and the adoption of organisational policies might be easier to implement.

> *WE RECOMMEND THAT AN INDEPENDENT ENTITY CONDUCTS PERIODIC REVIEWS OF GOVERNMENTAL SPACE ACTIVITIES*



Chapter 4

Multilevel governance of collision risk

The fourth way in which policy decisions can support efforts to better address collision risk is by fostering collaboration and building capacity across different governance levels. The pace of discussions around space debris at the international level is slow, and the international community is far from reaching a more detailed or binding agreement on the management of risks related to space debris. The UN Committee on the Peaceful Uses of Outer Space (COPUOS) took more than nine years to establish a set of 21 non-binding Guidelines for the Long-term Sustainability of Outer Space Activities (LTS guidelines), approved in 2019 (UNCOPUOS, 2019). Although there was general agreement among states that space sustainability is a pressing international issue, finding consensus for concrete guidelines was difficult.[73] The LTS guidelines are overarching high-level principles that provide a direction for space actors to follow. However, more detailed technical and operational guidelines (or preferably binding rules) addressing space debris mitigation and remediation would be welcome by many.

Building consensus around an international management strategy requires first raising awareness around the issue and bridging knowledge gaps between stakeholders. Building from unilateral decisions to multilateral agreements would be a step-by-step approach, which could help reach a shared vision of space and the risks, and recognise that near-Earth space is a limited shared resource. To reach a shared vision, it would also be useful to elaborate scenarios of possible mid- to long-term futures concerning the civilian use of space.

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[73] Progress is slow in the space safety and sustainability domain at the international level for similar reasons that it is slow for other global issues such as climate change (e.g., geopolitical interests, contested responsibilities, short-term economic impacts), but here these are compounded by a strong national security component.

1.

Raise awareness and build capacity around the issue

Space is a relatively novel field for policymakers and a wide variety of stakeholders. Space activities were once the purview of a narrow set of nations and were almost solely conducted by governments. Much of the common knowledge about space and how it can be safely used has become obsolete because of the rapid expansion of space activities, actors and stakeholders. The dissemination of up-to-date knowledge regarding space has not kept pace. The distant nature of space, the secrecy of some space activities and the complex technologies developed to use space have also been barriers to the transmission of knowledge surrounding space.

> *PARTICULAR ATTENTION MUST BE GIVEN TO NEW ENTRANTS AND STAKEHOLDERS MOST DEPENDENT ON SPACE-BASED SERVICES*

Academia, NGOs, governments, and international, intergovernmental and private organisations should strive to bridge the knowledge gaps between (i) advanced and emerging spacefaring nations, (ii) long-standing and new commercial space actors, (iii) regulatory authorities and space users, and (iv) space expert community and a broader set of stakeholders. Raising awareness and building capacity regarding the current use of space, especially the benefits and risks of space activities (see, e.g., Wilson et al., 2020, on the value of space), would help actors take informed decisions and make space debris appear higher in the political agenda of government officials. Particular attention must be given to new entrants (emerging space nations and new commercial operators), stakeholders most dependent on space-based services and a wider set of policymakers. To raise awareness, increase knowledge among these groups and build capacity around the issue, the following policy-led activities could be pursued:

- Reach out with timely and relevant evidence- and risk-based information about the issue and ways to address challenges. Prioritise efforts that target new space actors and increase exchanges between stakeholder groups.
- Increase accessibility of documentation on current rules and the issue by making documentation concise, timely and easily available online.[74] Organise workshops and webinars to disseminate this information.
- Organise capacity-building activities for space actors and other stakeholders to enhance knowledge sharing and build trust.
- Disseminate evidence-based information to society,[75] and engage with the wider public. This will contribute to shaping the discussions.

When raising awareness, it is worth bearing in mind that new actors might (i) not realise the risks or the costs associated with dealing with them, and (ii) underestimate the importance of successfully achieving the PMD and minimising the post-mission orbit lifetime. Therefore, preparing new entrants in space activities in advance can help them mitigate the risk and provide confidence to their investors. New space actors enter this field with a variety of prior experiences that can affect their perception of collision risk and their behaviour. Effective sharing of best practices and safety innovation would not just help the individual actors but also the rest of the space operations community.

It is also worth noting that some emerging spacefaring nations have concerns that established spacefaring nations will co-opt space traffic coordination and other efforts to reduce collision risk to limit access to space or exclude new entrants. Capacity-building efforts can help address these concerns and build broader acceptance. There is also a need to transparently address the equity concerns associated with the fact that established space nations, which created the current debris situation, are now insisting that new entrants adhere to higher standards than they did at the same stage in their development.

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[74] Publications such as NASA's best practices for conjunction assessment and collision avoidance (NASA, 2020b) and the Secure World Foundation's *Handbook for new actors in space* (Johnson, 2017) are helpful efforts to this end.

[75] The establishment of common evidence-based indicators, such as the SSR, can help disseminate information about the issue and ways to mitigate it.

2.

Pursue unilateral and multilateral efforts in parallel

Long-term effective global governance of risks related to space debris likely requires agreement among space actors on a management strategy, including on sharing costs and benefits from space utilisation. This includes a common vision of the expected norms of behaviour during operations and at end-of-life and agreement on remediation and the apportionment of its costs. Given that the prospect of reaching consensus in the short-term on a global management strategy is very low, two avenues can be pursued: (i) the development of consensus standards, best practices and guidelines, that could subsequently lead to national regulations where needed, and (ii) unilateral action (i.e., by one state) and some plurilateral actions (by several like-minded states).[76] Unilateral and plurilateral actions would avoid delaying action, which would worsen the problem and result in higher costs in the future, and would provide referenceable precedent as a foundation for building wider international agreements. Actions initiated at national, multinational and regional levels can create the basis on which global collaboration can be pursued.

> *STATES CAN UNILATERALLY ENACT NEW OR MORE STRINGENT RULES AND REQUIREMENTS IN THEIR NATIONAL REGULATIONS*

First, states can unilaterally enact new or more stringent rules and requirements in their national regulations.[77] To do so, they are advised to work with private actors operating from their jurisdiction, thus developing mutually satisfactory requirements that meet expectations from various actors. Then, groups of like-minded states can cooperate and coordinate to align their rules. This would enable rapid progress by effectively addressing the issue now (thus reducing overall costs) and would build the stepping stones on which international progress can be made. We list below several reasons to pursue this approach:

- Regulations enacted by larger states are often followed by other states.[78] Through this dissemination process, first movers can influence and drive the policy discussions on the international stage in their preferred direction. However, this must be accompanied by confidence-building and transparency measures at the international level to make sure it inspires others rather than raise objections.
- The risk of the national space industry moving to a jurisdiction with weaker rules is often mentioned and debated, but is probably overestimated. The risk of forum shopping can be adequately addressed using market entry requirements (especially if states with large markets pass stricter rules) and reputational aspects.
- Well-established and strong operators benefit from robust regulations. This provides them with legal certainty about the environment in which they operate and gives confidence to investors, underwriters and customers. Although robust regulations might increase barriers to entry, they should be proportional to safety and sustainability risks.
- The benefits of more responsible practices will only appear in the long term. Private actors sometimes do not have a decision-making structure that accounts for such long-term effects. Regulators must thus incentivise or force more sustainable operations.

Encouraging states to devise, adopt, implement and enforce national legislation is a difficult endeavour.[79] Raising awareness around the space debris issue among policy advisers, lawmakers and in broader

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[76] Actions at the national and international levels should be pursued in parallel, without a preference for one or the other. Most of the issues discussed in this policy brief cannot be entirely solved unilaterally (e.g., orbital data sharing, norms of behaviour, prevention of appropriation of orbital regions by single actors, remediation). However, at a technical level, a bottom-up approach can be effective (e.g., development of industry standards, implementation of requirements in national legislation).

[77] States from which launches are conducted have a particular responsibility and significant leverage as they are authorising launches. If they have appropriate requirements and oversight, they can significantly reduce risk.

[78] Only a small number of states have launch capabilities. Regulations from these states are thus very influential regarding collision risk.

[79] This is part of the mandate of the new COPUOS Working Group on the Long-term Sustainability of Outer Space Activities.

society would help the issue gain traction on the political agenda and put pressure on governments.

Efforts initiated by non-state actors to enhance space safety and sustainability can also help raise awareness in policymaking circles and lead to the development of more appropriate standards and regulations at national and international levels.[80] Given the impediments to reaching an agreement at the international level, bottom-up polycentric governance that includes non-state actors can have a significant role in developing and implementing best practices.

3.

Recognise that near-Earth space is a limited shared resource

Space debris is a global issue that requires a global response while recognising national contexts and sovereignty. Despite divergences among stakeholders, recognition that near-Earth is a limited shared resource with the characteristics of a common-pool resource[81] is a stepping stone to managing it effectively at the global level.[82]

The problem of space debris is global and complex, and actions to address it will be costly. This is similar to other global problems, like climate change, which require investments in technologies for mitigation (e.g., low-carbon energy to reduce the emission of CO_2) and remediation (e.g., negative emissions technologies to remove CO_2 already emitted). These efforts are a cost burden to those who undertake them but benefit everyone. Internationally binding agreements are almost impossible to pass and can be ineffective, as enforcement mechanisms are usually weak.[83] Therefore, the development of incentives and rewards to provide benefits to those who invest, at both national and international levels, is of paramount importance. Policy instruments implemented at the national or regional level to address global environmental issues such as climate change include marketable permits (e.g., the EU Emissions Trading System) and regulatory fees (e.g., carbon taxes). Similar instruments could be applied in the space debris context to incentivise risk-reducing behaviour, including the development and deployment of new technologies for space debris mitigation and remediation.[84]

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[80] Examples of such efforts include the *Best practices for the sustainability of space operations* of the Space Safety Coalition (2019), the *Guiding principles* (CONFERS, 2021b) and the *Recommended design and operational practices* (CONFERS, 2021a) of CONFERS, as well as the activities conducted by the Space Data Association (SDA). The call for more fit for purpose regulation by the EMEA Satellite Operators Association (ESOA, 2021) goes along these lines.

[81] Orbital space in LEO and GEO is rivalrous and non-excludable (in the future, this could extend to other orbits, if their use intensifies). It is rivalrous, as a space actor's use of a particular orbit prevents others from using it, and its use is non-excludable, as it is costly to exclude actors from enjoying the benefits of orbital space. Common-pool resources are found in global commons, a broader concept that refers to the nature of the common good, but not to the type of arrangement that can be made to sustainably use the resource and avoid a tragedy of the commons. See chapter 2, section 5 in *Collision risks from space debris: Current status, challenges and response strategies* (Buchs, 2021a) on the tragedy of the space commons.

[82] Recognition (at least partial) by the international community that GEO is a limited shared resource has helped its management.

[83] However, in certain cases, even with weak enforcement mechanisms, international agreements can be sufficient to motivate signatory states to adopt incentive or enforcement mechanisms at the national level.

[84] See chapter 4, section 2 of IRGC's report *Collision risk from space debris: Current status, challenges and response strategies* (Buchs, 2021a) and chapter 6 of Buchs (2020) for more details on these two instruments.

> *WORK TOWARDS GLOBAL MANAGEMENT STRATEGIES THAT NOT ONLY ADDRESS MITIGATION BUT ALSO ENCOMPASS REMEDIATION*

An initial step, which is probably a low-hanging fruit for the international community, is to work on coordinating space traffic. This is important because of the increase in space assets and debris tracked. Establishing coordination rules or protocols would be a Pareto improvement to all space actors and should not be insurmountable.[85] As suggested by McClintock et al. (2021), increasing awareness around the issue through enhanced communication and engagement activities, increasing SSA transparency for all, and focusing on safety rather than security aspects are key to establishing space traffic coordination and more broadly responsible space behaviour.[86]

A second step is to work towards global management strategies that not only address mitigation but also encompass remediation. Initial exploration of mechanisms to allocate mitigation and remediation costs should be pursued. Mechanisms that let actors decide their contribution to addressing the issue, similar to the nationally determined contributions (NDCs) of the Paris Agreement on climate change, could be a way of addressing issues regarding the allocation of costs. Each spacefaring nation would have to set its target, aligned with the agreement's goals, and revise it periodically to make it more ambitious. Under such an agreement, the parties would agree to have an independent review to assess their achievement towards the NDCs. Implementation of the agreement would be performed through national policies.

4.

Elaborate scenarios of plausible futures

The elaboration of qualitative scenarios of possible mid- to long-term futures of space use for civilian purposes would help drive the development of policies. Such scenarios, or narratives, would serve to (i) visualise extreme case scenarios, (ii) identify those that are desirable and those that are not desirable, and (iii) help various stakeholders position themselves vis-à-vis those scenarios and take steps to reach the one they prefer and avoid the least favourable to their interests. The output of such an exercise would also be helpful to grab the attention of high-level policymakers and decision-makers, and enable them to elaborate a coherent roadmap towards effective management of collision risk. Developing narratives of plausible futures requires an approach of openness, creativity, analytical rigour and inclusion. A scientific institution acting as a neutral convening place could take the initiative of facilitating the process.[87]

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[85] A Pareto improvement is an alteration in the allocation of resources in a system which harms no one and benefits at least one actor. Coordination would be (almost) costless to space actors but would provide significant benefits.

[86] Suggested readings on space traffic coordination and how to build it include: Blount (2021), Dickey (2021), Dominguez et al. (2020), ESPI (2020), Lal et al. (2018) and Muelhaupt et al. (2019).

[87] For more detailed recommendations on developing scenarios, see section 2.4 in IRGC's *Guidelines for emerging risk governance* (IRGC, 2015) and section 5.4 in IRGC's *Guidelines for the governance of systemic risks* (IRGC, 2018).

Conclusion

Improving risk assessment and conducting thorough cost-benefit analyses of the different proposed management options are of paramount importance to making informed decisions. However, getting a comprehensive picture of a complex, ambiguous and uncertain risk is likely unachievable, and the lack thereof should not be a reason to postpone action. The numerous risk analyses conducted so far have produced actionable information, and steps can be taken to reduce risk, as shown with the policy options presented in this document. As technologies mature, more information regarding their costs and benefits will be available to decision-makers.

In conclusion, we offer three major process recommendations to create an appropriate context for developing improved response strategies. First, due to uncertainty and ambiguity surrounding collision risk, more collaborative work is needed to improve the framing and evaluation of the risk. Risk evaluation by different space actors vary and can be improved by capturing the knowledge and concerns of a broader set of stakeholders.

> *IMPLEMENT THE G7'S COMMITMENT TO THE "SAFE AND SUSTAINABLE USE OF SPACE"*

Second, greater and more committed political involvement at the national and international levels is instrumental to reducing collision risk from space debris and enabling sustainable space activities. An important step in this regard is the G7's commitment to the "safe and sustainable use of space" and its recognition of "the growing hazard of space debris" in June 2021 (UK Space Agency, 2021). At the national level, governments should now declare this as an issue of high importance to them. For example, in many states, this could start with a request from the parliament that the government produces an assessment of the country's exposure and vulnerability to risks from space debris. These national efforts could help foster international discussions and work towards a consensus on the need for enhanced mitigation action and the start of remediation activities. Voluntary commitments by spacefaring nations, accompanied by independent reviews of achievements, could also be the way forward.

BROADEN THE RISK ANALYSIS TO INCLUDE SYSTEMIC INTERCONNECTIONS WITH CRITICAL INFRASTRUCTURE ON EARTH

Third, it is necessary to broaden the risk analysis to include systemic interconnections with critical infrastructure on Earth. Appropriate action to address collision risk from space debris is necessary to avoid significant adverse consequences on the economy. While the space debris community has been discussing this issue for a very long time focusing on space activities, there is a need to more strongly involve a broader range of stakeholders, in particular the private sector that launches and operates satellites and organisations that purchase, use or benefit from satellite-based services.[88] Raising awareness around the issue in the broader society would also help create more acknowledgement of the risk in wider policy-making circles. More transparency regarding space operations and greater monitoring of space activities would allow a more tailored response and incentivise responsible behaviour in space. Involving more actors, including satellite operators, satellite services users and NGOs, would create a critical mass of involved stakeholders. It is important that both those who generate the risk and those who could be impacted by the risk take part in policy discussions. With many new private actors and new spacefaring nations, a wider set of stakeholders should participate in the discussions.

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[88] While the private sector is very involved in these discussions in the US (e.g., comments to the Federal Communications Commissions proposed rulemakings, industry-led initiatives such as CONFERS or the Space Safety Coalition), it seems less so in other jurisdictions and on the international stage.

Appendices

Appendix 1

Space debris related activities

Three sets of activities are aimed at reducing the space debris growth and the negative impact debris has on space operations (see Figure 4):

- **Space situational awareness (SSA)** – SSA "includes perceiving orbital anomalies or threats, maintaining an inventory of objects as completely as possible, and developing and providing timely information for collision avoidance and safe operation" (Bonnal & McKnight, 2017). SSA consists of collecting and processing data, and generating data products. It involves detecting and tracking space objects using ground- and space-based sensors (optical, radar, radio-frequency and laser ranging), creating databases using the observations (pooling and fusing data), and analysing the data to create data products (e.g., conjunction warnings). Determining orbits requires powerful algorithms and significant computer resources. Monitoring of near-Earth asteroids and space weather are sometimes included in SSA. For more details on what SSA entails and global trends, see Lal et al. (2018).
- **Space traffic management (STM)** – There is no commonly agreed definition of STM, with different studies developing their own definition (see, Verspieren, 2021, for a discussion of the evolution of this concept). It can be defined as "the planning, coordination, and on-orbit synchronisation of activities to enhance the safety, stability, and sustainability of operations in the space environment" (The White House, 2018), or more broadly as "the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference" (Contant-Jorgenson et al., 2006). The aim of STM activities is to ensure safe operations within the existing space environment by avoiding collisions with known objects.
- **Space environment management (SEM)** – SEM encompasses activities aimed at ensuring the near-term safety of operations and the long-term stability of the environment (Maclay &

McKnight, 2020). It comprises mitigation, aimed at preventing the creation of new debris, and remediation, aimed at reducing risk once debris has been created.

As there is no commonly agreed-upon definition of these concepts, the exact wording and scope of these three sets of activities can differ among actors (e.g., Blount, 2021).

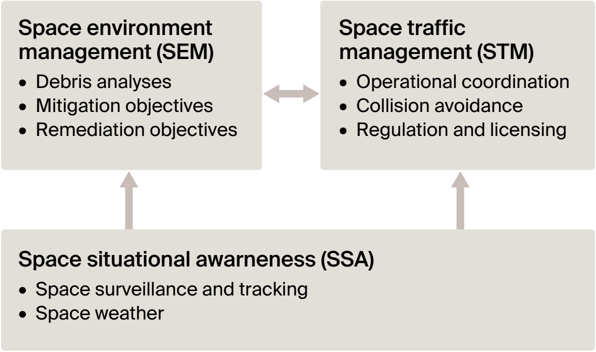

Figure 4: Relationships between space debris related actions (adapted from Bonnal et al., 2020, Figure 1).

Appendix 2

Main technical approaches

This appendix briefly presents the technical approaches mentioned in this policy brief. For more details, we refer the reader to our report *Collision risk from space debris: Current status, challenges and response strategies* (Buchs, 2021a) and references therein.

Mitigation

Debris mitigation refers to technical procedures or requirements for operational spacecraft aimed at reducing the risk that they become debris or generate debris. Models of the future space environment highlight the need for compliance with strict mitigation standards (see, e.g., chapter 2, section 2 in Buchs, 2021a). When a spacecraft is in orbit, the following mitigation activities can be conducted:

- **Collision avoidance manoeuvre (CAM)** – A CAM consists of modifying a spacecraft's orbit to avoid a predicted collision with a piece of debris or another active spacecraft. It requires the ability to manoeuvre, which some active spacecraft lack. Operators receive conjunction warnings provided by government systems and private services. As the trajectories of catalogued objects have uncertainties, only a probability of collision can be derived. Operators then decide if a CAM should be conducted. CAMs are costly as they require staff to monitor the conjunctions, assess the risk and conduct the manoeuvres, and result in system downtime and propellant use.
- **Post-mission disposal (PMD)** – The PMD consists of removing spacecraft from orbit once they are no longer useful. In LEO, this involves manoeuvring spacecraft into an orbit where, due to atmospheric drag, they will re-enter the atmosphere in a certain amount of time. The less the amount of time, the smaller the collision risk. International guidelines recommend that spacecraft re-enter the atmosphere no more than 25 years after the end of operations (IADC, 2021). If a spacecraft can no longer be controlled or has no more propellant, its PMD cannot be achieved. To remediate this problem, independent deorbiting kits are being developed (see section *Develop de-orbiting technologies* on p. 14).
- **Passivation** – It consists of limiting the probability of accidental explosion by removing the internal energy contained in a spacecraft at the end of its mission or the end of its useful life. To avoid explosions, the remaining propellant should be vented and batteries completely discharged.

These activities can only be performed if they have been planned in the design phase of a spacecraft, as they require particular capabilities. In the design phase, several passive approaches to mitigate the risk of debris creation can be pursued. They include inserting spacecraft at a low altitude and performing functionality checks before raising the orbit to the operational altitude,[89] choosing operational orbits with low debris density (especially LNT debris), and shielding. Spacecraft can be protected from hypervelocity impacts of small pieces of debris using shielding. However, above some impact energy, spacecraft cannot be protected. Critical parts of spacecraft are more heavily shielded, but external

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[89] This ensures that dead-on-arrival satellites will re-enter the atmosphere in a short amount of time. The majority of satellite failures happen in the first months of operation.

parts such as solar panels cannot be protected. Thus, impacts from small pieces of debris can degrade satellite performances.

Remediation

Remediation refers to methods aimed at reducing risk once debris has been created. If mitigation actions are taken too late or are insufficient, remediation becomes necessary. Remediation can target large objects which have a significant risk-generating potential. Collisions or explosions involving large derelict objects can generate tens of thousands of LNT debris, which are a significant threat for operational spacecraft as they cannot be dodged. Remediation can also directly target these LNT debris fragments. However, as it is technically easier and less costly to address the risk from large debris before they generate smaller debris, efforts have focused on remediating risk from large debris (see, e.g., McKnight, 2010). Reducing the risk of debris-generating events from large derelict objects take three broad forms:

- **Active debris removal (ADR)** – This approach involves actively removing a certain number of derelict objects from orbit to reduce the probability of major collisions (or removing small pieces of debris). Numerous methods to perform ADR missions have been envisioned (see Mark & Kamath, 2019; Shan et al., 2016, for a review). A typical ADR mission involves the launch of a servicer spacecraft that will rendezvous with the target object, capture it and remove it from orbit through a destructive re-entry into the atmosphere. The capture is a crucial part of the mission. Mechanisms proposed to perform it include tentacles, a robotic arm, a net or a harpoon. The de-orbiting can be performed by the servicer spacecraft, which lowers the orbital altitude of the target. It can also be performed by an autonomous de-orbiting kit which is attached to the target by the servicer.[90] This kit can consist, for example, of an electrodynamic tether, which is a long conducting wire that pulls down the target using Earth's magnetic field (e.g., Pardini et al., 2009; Shan et al., 2017).[91] However, not all proposed methods require the capture of the target. For example, in ion-beam shepherd-based methods, the servicer spacecraft projects a beam of ions onto a piece of debris to push and deorbit it (e.g., Bombardelli & Pelaez, 2011), and laser-based methods use high-power lasers, on the ground or in space, to sublimate pieces of space debris and slow them down (e.g., Phipps, 2014; Phipps et al., 2012; Wen et al., 2017).
- **Just-in-time collision avoidance (JCA)** – This approach consists of lowering the collision probability between non-manoeuvrable objects by acting on one of them. Prior to the predicted collision time, the trajectory of one of the objects involved is deflected to reduce the probability of collision. Various JCA methods have been proposed and are currently under study. They include using radiation pressure from ground-based lasers to nudge debris, generating a cloud of gas and particles using a sounding rocket to deflect a debris trajectory, and using a space-based laser to vaporise the surface of a piece of debris, generating a recoil effect (e.g., Bonnal et al., 2020; Phipps & Bonnal, 2016).
- **Nanotugs** – Derelict objects could be upgraded with collision avoidance capabilities, drastically reducing the risk of a catastrophic collision involving them (Marchionne et al., 2021; McKnight et al., 2020). One or more microsatellites (i.e., 3U to 14U CubeSats) would be deployed close to a derelict object and attach to its surface. These nano-tugs could cooperatively determine their orientation and then use their propulsion system to detumble[92] the object and perform CAMs.

While JCA and nanotugs are at an early development stage, technologies for ADR are currently being tested. In March 2021, Astroscale launched its End-of-Life Service by Astroscale demonstration (ELSA-d) mission to test the technologies necessary for debris docking and removal (Astroscale, 2021; Forshaw et al., 2019). Astroscale has also been selected for the first phase of an ADR mission funded by the Japan Aerospace Exploration Agency (JAXA) to inspect a discarded Japanese rocket upper stage to enable its removal in a subsequent mission (Henry, 2020). ClearSpace will conduct the first uncrewed removal of a derelict object with its ClearSpace-1 mission, scheduled for launch in 2025. This mission, which received about €120 million in funding from ESA, targets a payload adapter weighing 120 kg (ESA, 2019).

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[90] This can be particularly advantageous for multiple target missions under certain circumstances (e.g., Bérend & Olive, 2016).

[91] See the discussion on de-orbiting kits mounted on spacecraft prior to launch in the section *Develop de-orbiting technologies* on p.14.

[92] Derelict objects can have complex rotations which need to be removed to control and manoeuvre them.

Appendix 3

Policy instruments to incentivise technology development

Policy interventions to incentivise the development and adoption of technologies can rely on different policy instruments. Technology-push and demand-pull policies have been used to foster innovation in environmental technologies (e.g., Peters et al., 2012; Rennings, 2000). Technology-push policies aim to augment the supply of technologies by providing incentives that reduce the cost to firms of producing innovation. Examples of such policies include "government sponsored [research and development] R&D, tax credits for companies to invest in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects" (Nemet, 2009). Demand-pull policies aim to foster the development of new technologies by increasing the payoff from successful innovation and thus stimulate their demand. Examples of such policies include "intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, regulatory standards, and taxes on competing technologies" (Nemet, 2009).

To foster the deployment of space debris remediation technologies, different demand-pull policies have been suggested, such as advanced market commitment (AMC) and bounty schemes to help develop and deploy ADR:

- The AMC is a "binding commitment to purchase a certain number of units of a product at a premium price in return for a guarantee by the seller(s) to offer some additional subsequent quantity at near marginal cost" (Lifson & Linares, 2021). Thus, AMC incentivises "market entry by firms who might otherwise not consider a potential market sufficiently lucrative to justify research and development (R&D) investment, and it avoids the deadweight loss associated with firms exerting market power to extract profits above marginal cost" (Lifson & Linares, 2021).
- Bounty schemes offer a reward for the retrieval of space debris (e.g., Carroll, 2019). A value needs to be assigned to all pieces of debris based on their collision risk with operational spacecraft and their debris-generating potential. Such bounty payment could also encompass other activities that quantifiably reduce future debris-related costs (e.g., JCA, nanotugs, better SSA). However, this would make the scheme very complex and could limit political support.

Both policies are technology-neutral and would foster innovation that provides the best cost-benefit ratios.

Marketable permits and regulatory fees can also incentivise the development and deployment of new technologies for space debris mitigation and remediation. See chapter 4, section 2 of IRGC's report *Collision risk from space debris: Current status, challenges and response strategies* (Buchs, 2021a) and chapter 6 of Buchs (2020) for more details on these two instruments.

Appendix 4

Key concepts of risk analysis and governance

This appendix briefly presents some risk concepts that are particularly relevant when addressing the risk of collision with space debris. These concepts are drawn from the *Introduction to the IRGC Risk Governance Framework* (IRGC, 2017) and *Risk governance: Towards an integrative approach* (Renn, 2005). We refer the reader to these references for more details.

Risk

Risk results from uncertainty about the consequences of an activity or an event with respect to something valuable to the economy, society or individuals.[93] Risks include two components: the likelihood and the severity of potential consequences of human activities, natural events or a combination of both. The consequences can be positive or negative, depending on the values that people

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[93] According to ISO 31000 (International Organization for Standardization, 2018), risk is the "effect of uncertainty on objectives" and an effect is a positive or negative deviation from what is expected.

associate with them. Uncertainty can pertain to the type of consequences, the likelihood of these occurring (often expressed in probabilities), the severity of the consequences or the time or location where and when these consequences may occur.

A **hazard** (also referred to as a risk agent or risk source; e.g., a piece of space debris) is any source of potential harm or other consequences of interest. These potentials may never materialise if, for example, people are not exposed to the hazards or if the targets are made less vulnerable against the hazardous effect.

Exposure refers to the contact of the hazardous agent with the target (e.g., individuals, ecosystems, infrastructure). **Vulnerability** describes the various degrees to which a system can be affected by a hazard and able to withstand specific loads (e.g., if structural deficiencies in critical networks reduce the ability of that system to absorb a shock if a risk materialises). A **risk absorbing system** comprises the assets, ecosystems and individuals that could be impacted, directly or indirectly, by a hazard.

Systemic risk

Conventional risks are characterised by a well-known probability distribution over a limited scope of adverse effects. In contrast, the concept of systemic risk refers to the risk or probability of breakdowns in an entire system because of high levels of connectivity, major uncertainties and ambiguities, and non-linear cause-effect relationships. Systemic risks are embedded in the larger context of societal, financial and economic change. Such risks cannot be managed through the actions of a single sector but require the involvement of different stakeholders, including governments, industry, academia and members of civil society.

Governance

Governance refers to the actions, processes, traditions and institutions by which authority is exercised, and collective decisions are taken and implemented. It involves both public actors (governments and governmental organisations, at the national, regional and international levels) and private actors. There are various forms of governance, including public and private regulation.

Risk governance

Risk governance applies the principles of governance to the identification, assessment, management, evaluation and communication of risks in the context of plural values and distributed authority. It includes all important actors involved, considering their rules, conventions and processes. It is thus concerned with how relevant risk information is collected, analysed, understood and communicated, and how management decisions are taken and communicated. Risk governance mobilises both descriptive issues (how decisions are made) and normative concepts (how decisions should be made).

A **risk governance deficit** is a failure or deficiency in the assessment, management or communication of a risk, which hinders or prevents effective management.

Risk assessment

Risk assessment in the context of comprehensive (multi-stakeholder and multidisciplinary) risk governance includes both:

- An assessment of the risk's factual, physical and measurable characteristics, which aims to identify and describe the possibility of occurrence or a probability distribution over a range of negative consequences, considering the hazard as well as the exposure and vulnerability of the values or assets that must be protected.
- An assessment of different stakeholders' opinions, perceptions, concerns and attitudes about the risk, including a systematic analysis of the associations and perceived consequences (benefits and risks) that stakeholders may associate with a hazard, its cause(s) and its consequence(s).

Involving stakeholders in risk assessment is a fundamental element to ensure the relevance and acceptability of the measures taken to address the risk.

In the context of this policy brief, we use risk assessment to refer to both the technical risk assessment and the assessment of concerns, perceptions and opinions.

Risk evaluation

Risk evaluation is the process of comparing the outcome of the risk assessment with specific criteria to determine the significance and acceptability of the risk, and to prepare decisions. To be effective, risk management requires not only an assessment of the scientific evidence about a risk but also a careful judgement of whether or not a risk is acceptable to decision-makers and stakeholders. If it is not acceptable, risk reduction measures may make it more tolerable. To make this judgement, the evidence on the risk and the concern assessment must be combined with a thorough evaluation of other factors such as economic interests, societal preferences and political considerations. Risk evaluation thus results in a strategic decision that informs risk management.

Risk management

Risk management is a process that involves the design and implementation of the actions and remedies required to avoid, reduce (prevent, adapt, mitigate), transfer or retain the risks. Risk management includes the generation, assessment, evaluation and selection of appropriate management options, the decision about specific options, and implementation.

Decisions about risk are made on the basis of risk assessment but also of non-scientific aspects, such as political or economic priorities and interests, which result from a judgement made by a decision-maker. Overall, the decision-makers balance between various benefits expected from an activity and various risks incurred during this activity. Effective management of issues marked by uncertainty and ambiguity requires the involvement of both the stakeholders who are creating the risks and those who are adversely affected by the risk.

Risk management strategies (see Figure 5 for an overview) can target the risk at the source by acting on hazards (e.g., reducing space debris creation, removing derelict objects) or at the risk absorbing system by reducing exposure and vulnerability to the risk (e.g., spacecraft shielding, orbit selection). **Robustness** and **resilience** strategies are aimed at reducing the impact of the risk on the absorbing system. Robustness increases the resistance of the system at risk under normal circumstances. Resilience is a strategy to help systems cope with uncertain but potentially severe risks that cause large-scale accidents. It includes a suite of approaches to assess and understand the risk, prepare for it, rebound after an accident and recover critical systems functions, and finally adapt to new context conditions (e.g., Florin & Sachs, 2019). In contrast to robustness, where potential threats are known in advance and the absorbing system needs to be prepared to face these threats, resilience is a protective strategy against unknown or highly uncertain hazards.

A **risk-risk trade-off** is the phenomenon that interventions to reduce one risk can increase other risks or shift risk to a new population.

	Risk characteristic			
Target of the management strategy	Simplicity	Complexity	Uncertainty	Ambiguity
Risk absorbing system Goal: reduce exposure and vulnerability	Routine-based Apply traditional decision-making (e.g., introducing a law or regulation)	Robustness-focused Improve buffer capacity of risk target (build stronger, contain)	Resilience-focused Improve capability to cope with surprises	Discourse-based Apply conflict resolution methods for reaching consensus or building tolerance for risk evaluation results and management option selection
Risk source Goal: reduce hazards		Risk- informed Avoid, reduce, transfer, retain	Precaution-based Be prudent and do not make irreversible decisions	

Figure 5: Risk management strategies (adapted from IRGC, 2017; Renn, 2005).

Planned adaptive regulation

Planned adaptive regulation (PAR) is an approach in which a regulation is designed from its inception to be revised over time based on experience (see, e.g., IRGC, 2016). This requires: (i) planning for future review and revision of the governance arrangements, (ii) funding of targeted research, (iii) monitoring of performance and impact of existing arrangements, (iv) review and revision, (v) a vision of what the goal of adaptability is, (vi) the ability to respond to rapid changes, and (vii) trustworthiness between the actors who want to adapt the rules.

Regulations regarding space debris could be organised along the principles of PAR. It is suitable when the presence of large scientific uncertainties and fast-moving technology development makes it impossible to fix into law certain requirements that may become obsolete if the subject of the regulation changes quickly. This can be the case with plans to launch large constellations of small satellites in LEO, often by new space actors, and technology for collision risk mitigation and remediation that develops quickly, thus changing the kind and level of requirements that regulation can set. PAR is performance-based. It is flexible and adapts to reach a certain objective, such as reducing collisions or debris. Regulatory requirements are revised at regular intervals according to progress made towards meeting the objective.

Risk communication

Risk communication is the process of exchanging or sharing risk-related data, information and knowledge between and among different groups. It enables risk assessors and managers to develop a common understanding of their tasks and responsibilities. In addition, it empowers stakeholders and civil society to understand the risk and the rationale for risk management.

Appropriate communication about the risk is an important success factor for an effective risk management outcome. Communication creates awareness and, together with consultation, contributes to knowledge-sharing about the issue, committing stakeholders to the management process and eventually building trust.

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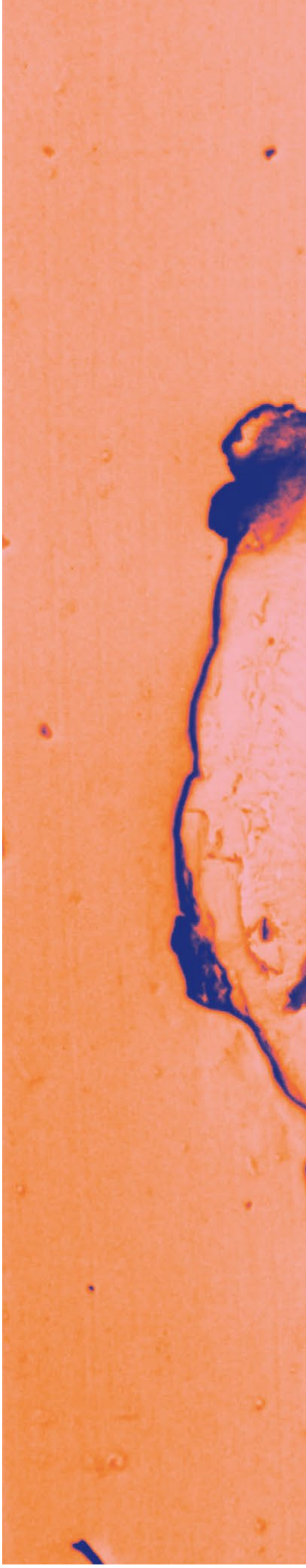

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