

Sustainable space operations: Navigating emerging technologies, debris management, and governance challenges for the future.

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Business

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August 2025

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Acknowledgements

First and foremost, I thank God for granting me the opportunity, strength, and motivation to undertake and complete this thesis. Without His guidance and grace, this journey would not have been possible.

I would like to express my deepest gratitude to my Director of Studies, Dr Erez Yerushalmi, whose time, dedication, and encouragement were invaluable throughout this process. His continuous support, countless calls, and insights, particularly in shaping the mathematical model for my first paper, were instrumental in keeping me focused and moving forward.

I am also sincerely grateful to my co-supervisors, Dr. Stefania Paladini and Dr. Krish Saha. Stefania's patience and guidance, especially with coding, were essential to the progress of this work, while Krish's thoughtful input on the literature review and his ideas greatly enriched my second paper. Their combined expertise and encouragement provided both academic and personal reassurance along the way.

My heartfelt thanks also go to Dr. Sarah Mohamed and Dr. Navjot Sandhu for their support and sagacious guidance throughout the entire PhD journey. Their advice and perspectives helped me navigate the challenges of the doctoral lifecycle with clarity and purpose.

To my family, my parents and siblings, I owe deep gratitude for their constant encouragement, belief in me, and for always being a source of strength during the difficult times.

Finally, and most profoundly, I wish to thank my wife. She has been my rock, my unwavering source of love, patience, and support. Her encouragement and presence gave me the resilience to persevere and the assurance that I always had someone to lean on.

This thesis is as much a product of the generosity, wisdom, and kindness of all those mentioned as it is of my own efforts. Without their help, it would not have been possible.

I would also like to acknowledge the progress of the research conducted throughout my thesis. The first paper, which constitutes Chapter 2 of this thesis, has been published in the *Journal of Environmental Management*. The second paper, presented in Chapter 3, is currently under review with the *Journal of Transport Policy*. The third paper, forming Chapter 4, is intended for submission to the *Journal of Research Policy*.

I am grateful for the support and guidance received throughout this journey, which has enabled the development and advancement of these research contributions.

Declaration

I declare that this thesis is my own work and has not been submitted to another university for a degree.

Darrell Martin-Lawson

August 2025

Abstract

The sustainability of Earth's orbital environment has emerged as one of the defining challenges of 21st-century space activity. As space becomes increasingly commercialised, privatised, and accessible, our space orbits, once perceived as vast and inexhaustible, are showing signs of critical stress. This thesis investigates the multifaceted dynamics shaping sustainable orbital operations, examining the projected risks of orbital overcrowding, the future of space tourism, and the role of patent-driven technological innovation in addressing space debris. Together, these dimensions form an integrated framework for understanding how humanity can navigate the tensions between innovation, exploitation, and preservation in outer space.

This thesis is structured as three independent but related papers that explore the sustainability challenges of space, defined in this thesis as Earth's orbital environment rather than the practically infinite expanse of deep space. The sustainability challenges of space are explored, through the lens of emerging technologies, debris management, and governance challenges, this research aims to inform readers on the complexities and opportunities for sustainable space development. The first paper (chapter 2) focuses on the issue of orbital crowding and debris, presenting Earth's orbit as a finite, congested resource and a textbook example of an Area Beyond National Jurisdiction (ABNJ). A version of this paper was published as (Martin-Lawson et al., 2024). It employs a probability-based empirical model, this section forecasts the trajectory of orbital object accumulation and identifies the impending approach of a 'critical density' threshold beyond which chain-reaction collisions could render key orbital bands unusable. The model projects that, in the absence of comprehensive debris management strategies, this tipping point may be reached within the next decade, significantly endangering the usability our orbits and in particular the use of low Earth orbit (LEO). The analysis further estimates the economic costs of active debris removal (ADR) and evaluates the limited efficacy of current technical interventions when separated from legal and institutional reforms. It argues that technological advances, while essential, are insufficient on their own. Lasting sustainability will require a radical overhaul of fragmented international legal frameworks that were never designed to govern the complexities of a commercial and contested orbital domain.

The next paper (chapter 3) focuses on space tourism, a rapidly growing frontier that reflects both the potential up and downsides of commercial space access. Drawing on over two decades of scholarly literature, this section identifies conceptual, regulatory, and environmental blind spots that hinder the sector's sustainable development. Despite considerable enthusiasm and investment, space tourism lacks a cohesive theoretical foundation or robust sustainability framework. Through a network analysis and thematic synthesis, the research proposes four critical dimensions to guide future inquiry: 1) conceptual clarity on what constitutes space tourism, 2) the integration of environmental sustainability metrics, 3) risk mitigation strategies for spaceflight and infrastructure, and 4) affordability pathways for broader

accessibility. These findings call for a reimagining of space tourism not merely as a luxury enterprise, but as a component of a sustainable and inclusive space economy.

The final paper (chapter 4) provides a quantitative analysis of innovation trends in debris management technologies, using a custom-designed DBSCAN clustering algorithm applied to patent data from spacefaring nations. Patents were classified into three functional categories, prevention, mitigation, and removal, and clustered based on both textual and structural similarities. The results reveal a global innovation landscape dominated by removal and mitigation strategies, with prevention technologies notably underrepresented. Regional comparisons show differing technological emphases: China and the EU lead in hardware-intensive removal technologies, while the US focuses more heavily on tracking and shielding systems. This imbalance points to a structural misalignment between technological development and long-term sustainability goals, as preventing debris at its source remains the most cost-effective and scalable solution. The study underscores the need for international economic incentives, such as space sustainability-linked taxes, orbital access restrictions, or funding schemes, to stimulate innovation in underinvested areas and align private sector R&D with global public interests.

Across its three papers, this thesis makes the case that sustainable space operations cannot be achieved through technological advancement or policy reform in isolation. Instead, it argues for an integrated approach that recognises the interconnected nature of tourism, congestion, innovation, and governance. The thesis contributes to both theoretical and applied debates by combining foresight modelling, legal analysis, and empirical patent clustering, offering a multidisciplinary framework for future research and policymaking. It concludes that safeguarding Earth's orbital environment will require not only more effective regulation and international coordination, but also a shift in mindset from viewing space as an unlimited frontier to treating it as a fragile, shared ecosystem in need of careful stewardship.

Abbreviations

ABNJ - Areas Beyond National Jurisdiction

ADR - Active Debris Removal

AIS - Automatic Identification System

ASAT - Anti-satellite weapons

CI - Confidence Interval

COSPAR - Committee on Space Research

DBSCAN - Density-Based Spatial Clustering of Applications with Noise

EO - Executive Order

ESA - European Space Agency

GEO - Geosynchronous Orbit

GSE - Global Space Economy

IADC - Inter-Agency Space Debris Coordination Committee

LEO - Lower Earth Orbit

MEO - Medium Earth Orbit

NASA - National Aeronautics and Space Administration

OECD - Organisation for Economic Co-operation and Development

OST - Outer Space Treaty

PPP - Planetary Protection Policies

R&D - Research and Development

SSN - Space Surveillance Network

UN - United Nations

UNCLOS - United Nations Convention on the Law of the Sea

UNOOSA - United Nations Office for Outer Space Affairs

1 Chapter 1

Introduction: The need for sustainability in Space

Humanity's involvement in space has only intensified since landmark events such as the first orbital flight of Sputnik in 1957 and the ever-famous lunar landing of Apollo 11 in 1969. These achievements, set against the backdrop of the Cold War, represented more than symbolic demonstrations of geopolitical power; they catalysed a technological revolution that advanced computing, telecommunications, and materials science in ways that continue to shape modern societies (Reynolds, 2010). Space exploration during this era was primarily reserved for the powerful nations, where political rivalry and national prestige were as central as scientific discovery (Reynolds, 2010). However, as the twentieth century progressed, space activity began to evolve beyond competition into cooperation and commercialisation. Programmes such as the International Space Station (ISS) demonstrated the potential of multinational collaboration, while satellite systems have become embedded in the critical infrastructure of daily life (Jiang and Zhao, 2021; Bush, 2002). Satellites now underpin navigation, telecommunications, financial transactions, weather forecasting, climate monitoring, and disaster response, making the space industry a vital component of global economic, social, and security systems (Kim et al., 2021; Carneiro et al., 2023; Koutsias et al., 2024; Shutler et al., 2024). In this way, what was once an aspirational frontier, limited by technological constraints, has become an operational backbone supporting countless aspects of human activity on Earth.

In recent years, this trajectory has accelerated with the emergence of "Space 4.0," a phase characterised by private-sector innovation, reusable launch systems, and growing global participation, reflecting the increasing commercialisation of space (Köpping Athanasopoulos, 2019). Mega-constellations of satellites such as SpaceX's Starlink and OneWeb promise to expand global internet connectivity, while companies including Blue Origin and Virgin Galactic seek to pioneer commercial space tourism (Radtke et al., 2017; Seitzer and Tyson, 2021; Spector et al., 2017; Cohen and Spector, 2020b). Beyond these technological and commercial developments, outer space has become a strategic domain: nations increasingly view orbital assets as critical for security, surveillance, and resilience of essential infrastructure, and any disruption in space could have cascading impacts on Earth systems (Klimburg-Witjes, 2021).

These developments collectively illustrate that outer space is no longer simply a frontier of exploration. It has become a domain that underpins everyday life, national security, and economic growth, with the potential to generate trillions in economic value (Stanley, 2020). The rapid expansion of activity in orbit and the growing reliance on space-based services highlight both the opportunities and the emerging responsibilities of humanity as it navigates this increasingly industrialised and commercially driven domain.

While the expansion of human activity in space has unlocked unique opportunities, it has also introduced a set of emerging challenges that threaten the long-term sustainability of orbital operations, with “space” in this research referring specifically to Earth’s orbital environment, not the near-limitless expanse of deep space. One of the most significant shifts in recent decades has been the transition from a domain dominated by a small number of state-led missions to one increasingly populated by thousands of commercial satellites (Belward and Skøien, 2015; Poghosyan and Golkar, 2017). Private actors, motivated by both innovation and profit, are now launching constellations of satellites at a scale previously unimaginable. Mega-constellations such as SpaceX’s *Starlink* and OneWeb illustrate this trend, placing thousands of satellites in low Earth orbit (LEO) to deliver global connectivity (Michelle Yan Huang et al., 2021; Cui and Xu, 2022; Radtke et al., 2017).

This rapid expansion has led to growing congestion in LEO, where the density of operational satellites, defunct satellites, and other debris is increasing the likelihood of collisions. Space debris-ranging from spent rocket stages to fragments from prior collisions-represents a critical risk to both current and future space activity (Phipps and Bonnal, 2016; OECD, 2020; Heilala, 2023a). Without effective mitigation, the accumulation of debris could trigger a cascade of collisions, a scenario known as the Kessler Syndrome, which could render key orbital regions unusable for decades (Drmolá and Hubik, 2018; Kessler et al., 2010).

Compounding these technical and operational pressures is a lag in governance. Existing regulatory frameworks were designed for a time when space activity was largely state-led and limited in scale. Today, they struggle to keep pace with the speed, volume, and diversity of commercial and international operations (Freeland, 2020; Li, 2015). This misalignment creates uncertainty over responsibility, liability, and coordination, leaving critical gaps in oversight and risk management.

Taken together, these factors highlight that space is no longer an unconstrained frontier. The same orbital environments that enable vital services for life on Earth, such as navigation, telecommunications, and climate monitoring, are increasingly under stress. Addressing these emerging challenges requires a proactive, sustainability-focused approach that integrates technological innovation, commercial practices, and governance mechanisms to ensure that space remains usable for future generations.

The challenges emerging from the rapid expansion of space activity highlight a fundamental truth: our orbits, like Earth’s oceans or atmosphere, are a finite, vulnerable shared resource (Rebay, 2023; Eric James Currie and Müller, 2025; Hardin, 1968). The continued growth of orbital operations, if unmanaged, risks undermining the very infrastructure on which modern society depends-satellite-based communication, navigation, weather monitoring, and disaster response. Just as unsustainable practices on Earth can lead to environmental degradation and systemic risk, the accumulation of space debris and orbital congestion threatens the long-term usability of low Earth orbit and other critical regions of space (Seitzer and Tyson, 2021).

Recognising space as a limited and shared resource underscores the need for a guiding framework to ensure its long-term viability. This perspective positions sustainability not as an abstract concept, but

as an essential lens through which to evaluate, regulate, and plan space activity. It is this lens that informs the following discussion, framing space sustainability in conceptual, technical, and governance terms, and providing a foundation for understanding how emerging technologies and commercial pressures can be managed to safeguard space for future generations.

1.1 Framing Sustainability for Outer Space

Sustainability, as a guiding principle, has long shaped discussions across environmental science, economics, and industrial development and centred around the idea of continuity. Sustainability can be understood through a definition provided by the Brundtland Commission in its 1987 report, *Our Common Future*, which frames it as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” This definition, now foundational across disciplines, captures the essence of long-term thinking and intergenerational responsibility (Keeble, 1988). It reflects a shift from short-term exploitation of resources towards a balanced, equitable, and future-oriented model of development and decision-making.

Sustainability can be seen to comprise of three interrelated pillars: environmental, economic, and social. Environmental sustainability focuses on preserving natural ecosystems and reducing the degradation of planetary resources. Economic sustainability concerns the ability to support long-term economic growth without negatively impacting social or environmental systems. Social sustainability centres on equity, well-being, and the resilience of human communities (Purvis et al., 2019). These dimensions are deeply interconnected, and addressing sustainability challenges often requires navigating trade-offs between them. As such, sustainability is understood as a concept, one that calls for mixed approaches and long-term thinking rather than isolated or short-term solutions.

In recent decades, sustainability has become a global priority, driven by mounting challenges such as climate change (Desjardins, 2013). As a result, sustainability has evolved from being a primarily environmental concern to a cross-cutting agenda that shapes public policy, social agendas, industry practices, and innovation strategies. Governments, corporations, and organisations increasingly embed sustainability into their frameworks, not only to mitigate risk but to ensure long-term resilience and competitiveness in an uncertain future (Purvis et al., 2019; Fauzi et al., 2019).

To support its multidimensional nature, sustainability can be framed through a set of theoretical models that help guide both academic research and policy practice. These frameworks offer distinct yet complementary perspectives on what it means to sustain systems over time, how to evaluate progress, and where interventions might be needed. Some of the key theories are the Triple Bottom Line, the Planetary Boundaries framework, and the Sustainability Transitions theory.

The Triple Bottom Line framework (TBL), introduced by John Elkington in 1994, proposes that sustainable development must rest on the balanced integration of three core dimensions: people (social equity), planet (environmental stewardship), and profit (economic viability) (Goh et al., 2020; Ahi and

Searcy, 2015). This framework challenges the traditional view that economic growth should be the sole measure of success, instead promoting a holistic model in which social well-being and environmental health are given equal weight. TBL has become a widely used evaluative tool in corporate sustainability reporting, impact assessments, and development planning (Ahi and Searcy, 2015). An example of this is Patagonia, a company that applies the TBL by aligning its business practices with social responsibility, environmental stewardship, and sustained profitability (Singh and Sangal, 2025). TBL underscores the idea that sustainability cannot be achieved through environmental action alone, it must be embedded in the ways we organise economies and support human communities. While this model provides a useful lens for assessing trade-offs and synergies among the three pillars, its application is typically static and evaluative rather than forward-looking or transformational (Muñoz-Pascual et al., 2019).

The Planetary Boundaries framework adds a biophysical dimension to the sustainability discourse (Rockström et al., 2024, 2009). It identifies nine critical ecological thresholds, including climate change, biodiversity loss, ocean acidification, and atmospheric aerosol loading, within which humanity must operate to avoid destabilising the Earth system. The framework shifts focus away from individual actions or sectors and toward a systems-level understanding of Earth's resilience. It highlights the limits of natural systems and the urgent need to reduce human pressures to stay within "safe operating spaces." Though not originally intended to be regulatory, the framework has influenced global environmental governance by providing a scientifically grounded way to conceptualise environmental boundaries. However, its emphasis remains firmly rooted in Earth's biosphere, offering limited tools for analysing socio-technical or institutional transitions, particularly in emerging or frontier domains like space (Steffen et al., 2015).

Sustainability Transitions theory provides a more dynamic and systems-oriented approach to sustainability (Markard et al., 2012). It examines how large-scale socio-technical systems, such as energy, transport, water, or agriculture, undergo structural change over time toward more sustainable configurations. These transitions are typically long-term, non-linear, and shaped by the interplay of technological innovation, policy change, market dynamics, and social behaviour. Central to this theory is the idea that change is not only about developing new technologies, but about transforming the institutional, economic, and governance systems in which those technologies are embedded (Markard et al., 2012; Köhler et al., 2019). For this reason, the aim of this thesis is to examine the sustainability challenges associated with the rapid commercialisation of Earth's orbital environment, with particular attention to emerging technologies, space debris dynamics, and the adequacy of existing governance frameworks.

To achieve the stated research aim, this thesis pursues three key objectives.

(1) To quantify and model the growth of orbital debris and assess the risk of critical congestion thresholds, evaluating the implications for the long-term sustainability of Earth's orbital environment.

(2) To critically examine the role of emerging commercial activities, particularly space tourism, in accelerating orbital congestion, and to assess the associated environmental, ethical, and governance challenges from a sustainability perspective.

(3) To critically analyse the current innovation landscape and governance responses to space debris, with a focus on identifying gaps, opportunities, and the potential for active debris removal and preventative interventions to support sustainable space operations.

Each key objective is addressed in the 3 main body chapters of the thesis. Chapter 2 identifies a systemic risk (space debris) that threatens the viability of the orbital environment. Chapter 3 explores how emerging commercial sectors, such as space tourism, are adding pressure to this system, while Chapter 4 investigates the innovation landscape and the policy responses emerging around it. Together, these chapters reflect a transition-oriented perspective: understanding how a legacy governance structure is being disrupted by commercial and technological change and exploring how coordinated responses could steer the space sector toward a more sustainable trajectory. Unlike the Triple Bottom Line or Planetary Boundaries, sustainability transitions theory offers both a diagnostic and a strategic lens, capturing complexity, uncertainty, and the interdependence between technological and institutional change. It is within this conceptual framework that the thesis positions itself. While the concept of sustainability has traditionally focused on Earth-based systems, its relevance has extended beyond our planet, as human activity in outer space grows exponentially.

The growth of satellite constellations, commercial launches, and emerging ventures like space tourism has transformed outer space into a domain of rapid industrialisation. This growth, while promising, has introduced new and urgent sustainability challenges. One of the key challenges is the accumulation of space debris, redundant satellites, wasted rocket stages, and fragmentation debris, which now pose significant threats to the long-term viability of space operations.

In response to these concerns, international bodies have begun articulating frameworks for space sustainability. According to the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS), space sustainability can be defined 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”* (UN COPUOS, 2018). This definition underscores not only the technical and environmental dimensions of sustainability but also its ethical, economic, and geopolitical implications, with “outer space” here specifically understood to be the orbital environment surrounding Earth.

Despite growing recognition of the issue, the field of space sustainability remains underdeveloped in both policy and academic discourse (Martinez, 2019; Newman and Williamson, 2018). Many of the systems governing space activity were designed in a different era and are ill-equipped for today’s

volume of launches and commercial interests (Li, 2015; Listner, 2011; Dennerley, 2018). As new players and technologies emerge, the need to evaluate, forecast, and guide space activity through a sustainability lens, becomes increasingly critical. This thesis is a direct response to that need, offering three distinct analytical perspectives that together form a comprehensive exploration of the risks, drivers, and potential solutions related to sustainable space governance.

This research was initially driven by an interest in Space 4.0, the next phase of the space sector marked by growing commercialisation, global participation, and private-sector innovation. However, as the research progressed, a critical theme began to emerge, one that cut across commercial ambition and technological advancement: space debris. While space debris was frequently mentioned in literature and policy discussions, few studies had attempted to measure the scale of the threat or forecast its trajectory. It quickly became clear that without intervention, orbital congestion could spiral into a tipping point scenario, severely compromising the viability of future space activity. This realisation shifted the focus of the thesis from examining space growth in general to investigating whether that growth was sustainable.

Thus, the core research question that subsequently emerged was: How can we understand, anticipate, and address the sustainability risks posed by the growing use of our orbits? From this point, the thesis evolved into a staged investigation into space sustainability. This thesis, which is divided into three independent but related papers (chapters), examined three important themes within the core field of sustainability within space, as outlined in Figure 1-1. Chapter 2 (Paper 1) explored the growing sustainability risks of space debris, caused by technological limitations and inadequate policy reform, by using a Poisson probability model to quantify the severity and potential consequences of increased space activity. Chapter 3 (Paper 2) explored the accelerating role of space tourism, an emerging branch of space commercialisation (the growing market-driven use of space by private actors for profit and innovation), in compounding orbital congestion, using a systematic review to highlight sustainability risks and future research directions. Chapter 4 (Paper 3) investigated how the challenge of space debris is driving technological innovation, using patent analysis to map advances in debris management technologies and examining how policy can engage with and shape this evolving innovation landscape. While each chapter adopted a distinct methodological approach, they collectively contribute to a unified investigation into the sustainability of Earth's orbital environment. This integrated design reflects the central rationale of the research, which arises from the growing mismatch between the accelerating pace of space commercialisation and the relatively slow evolution of governance, regulation, and sustainability frameworks. Although Earth's orbits are finite and increasingly congested, policy and institutional responses remain fragmented and largely reactive. To address this gap, the thesis adopts an interdisciplinary approach, drawing on theories of common-pool resource governance, sustainability transitions, and innovation diffusion, which are introduced here and developed in later chapters. These theoretical perspectives provide a conceptual basis for analysing orbital congestion as a systemic sustainability challenge shaped by technological, economic, and institutional dynamics.

Each of the three papers in this thesis approaches the question of space sustainability from a different conceptual and methodological angle. Together, they offer a layered analysis of the risks, pressures, and potential responses related to the long-term usability of Earth’s orbital environment. While distinct in their entry points and research methods, all three papers are unified by their contributions to understanding and addressing the challenge of sustaining space activity amid growing congestion, commercialisation, and technological change. Figure 1-1, below, presents the structural logic of the thesis, illustrating how the central research question and associated aims introduced in Chapter 1 are addressed across the three core empirical chapters and synthesised in the conclusion.

Figure 1-1: Thesis structural flowchart

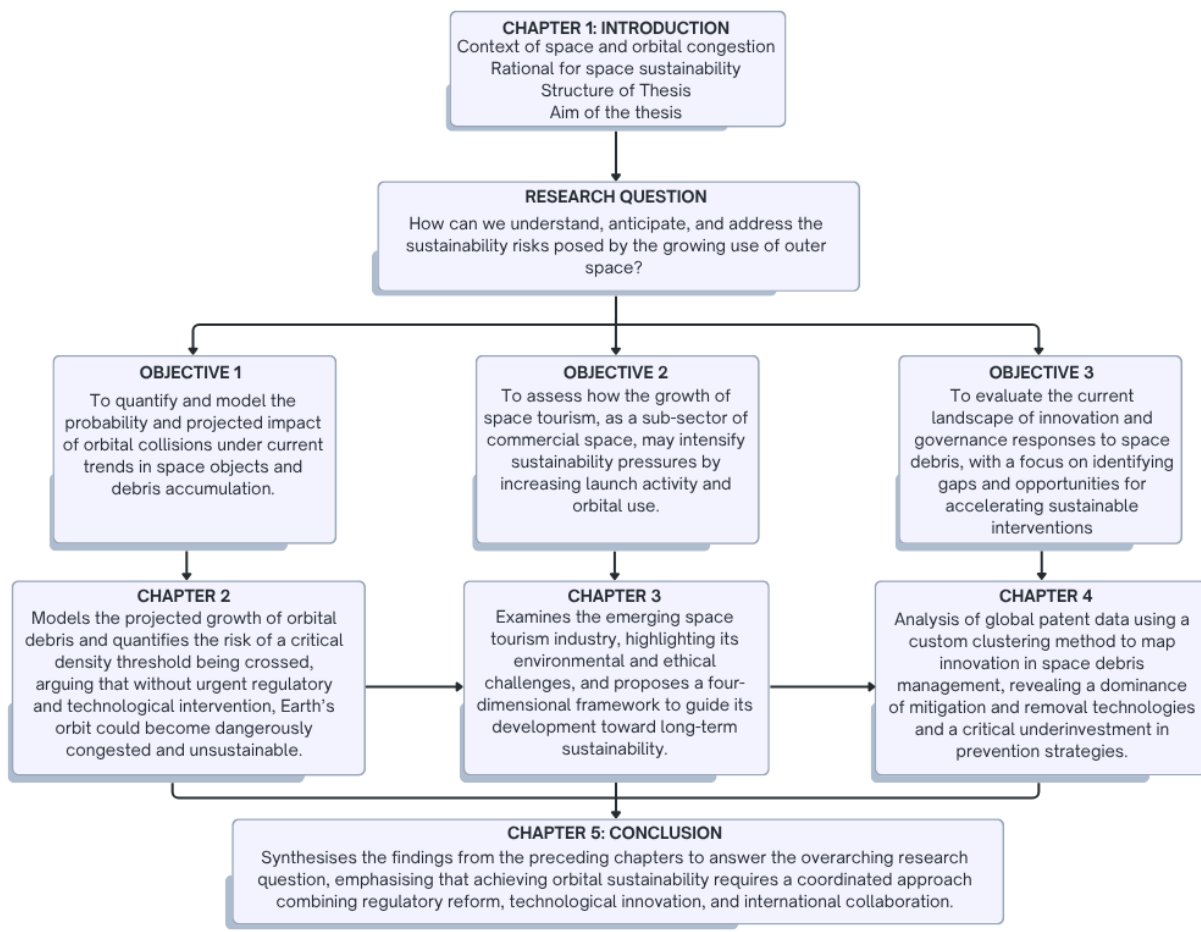


Figure 1-1: Thesis structure flowchart illustrating the progression from research context and objectives through to the three core studies and final synthesis in the conclusion.

1.2 Overview of Thesis Structure and Rationale

Addressing the sustainability of Earth’s orbital environment requires a methodological approach capable of capturing technical risk, commercial drivers, institutional and technological responses simultaneously. The research suggests that using a single method offers a limited analytical scope for

examining these dimensions. For this reason, the thesis adopts a mixed-method, multi-paper research design, with each methodological approach selected to address a specific aspect of the overarching research question: How can we understand, anticipate, and address the sustainability risks posed by the growing use of Earth's orbits?

The research design follows a staged logic. First, a quantitative modelling approach is required to establish whether orbital congestion constitutes a measurable and time-bound sustainability risk. Without such quantification, policy debates around space debris remain speculative. Second, understanding how commercial pressures contribute to this risk demands a systematic synthesis of existing knowledge, particularly in emerging sectors where empirical data remain limited. Finally, evaluating potential responses requires an examination of how technological innovation and policy frameworks are evolving in practice.

Accordingly, the thesis adopts a sequenced mixed-method design, in which each method is selected to address a distinct dimension of the sustainability challenge. Probabilistic modelling is used to quantify collision risk and project debris growth under existing governance conditions, providing an empirical diagnosis of systemic risk. A systematic literature review and bibliometric analysis are then employed to examine how emerging commercial activities, particularly space tourism, are shaping sustainability pressures and regulatory gaps. Finally, patent analysis and clustering techniques are applied to map innovation trajectories in debris mitigation and removal, offering insight into solution pathways and the alignment between technological development and policy response.

Together, these methods provide complementary perspectives that move from diagnosis, to contextualisation, to response analysis. This integrated methodological strategy ensures that the thesis does not examine space sustainability as a purely technical problem, but as a complex socio-technical challenge shaped by risk dynamics, market behaviour, and governance capacity.

1.2.1 The Cost of Un-regulation¹

Chapter 2 serves as a quantitative starting point, aiming to assess the severity and urgency of the space debris problem. In the initial stages of exploring commercial trends and industrial growth, one recurring issue kept surfacing: space debris. While it was widely referenced across reports and commentary, what stood out was the lack of concrete, quantitative research that attempted to model the future implications of debris accumulation. This gap in the literature became a compelling motivation, particularly given the growing number of satellite launches and the rapid entry of private actors into the orbital economy.

As the volume of objects in orbit increases, so too does the probability of collision. Left unchecked, these collisions can trigger a runaway cascade of further impacts, a scenario known as the Kessler Syndrome. Such a chain reaction could render low Earth orbit unusable for generations, posing a severe

¹ You can find the reference to the publication here: (Martin-Lawson et al., 2024)

threat not only to satellites and space-based services, but to the broader viability of space as an accessible domain. The issue of debris, therefore, is not simply a technical or operational concern; it is a fundamental barrier to long-term sustainability in space. In the absence of predictive tools, decision-makers are effectively navigating blind. Without a realistic estimate of risk, it becomes difficult to prioritise or justify investments in mitigation strategies or regulatory reform. There is an urgent need for methods that can quantify and visualise orbital risk to inform policy conversations and stimulate timely action.

This chapter (paper 1), a version of which has been officially published in the *Journal of Environmental Management* (Martin-Lawson et al., 2024), addresses this gap by developing a linear regression model combined with a Poisson probability model to forecast the potential growth of debris and objects in space over time, incorporating factors such as orbital collision probability, increasing satellite density, launch trends, and rising levels of space activity. The Poisson probability model calculates the probability of orbital collisions occurring each year. Each collision generates additional debris, which increases the overall debris population and, thus, the probability of future collisions increases year on year. This is then combined with a regression analysis of object growth in space year-on-year from satellite density, launch trends, and activity levels to quantify the escalating risk of space debris accumulation.

This model introduces a probabilistic understanding of risk, visualising the trajectory toward a worst-case scenario: a Kessler event, where cascading collisions make regions in space unusable. Strikingly, the model demonstrates that even if no new launches occur after a certain point, the existing debris environment could continue to self-propagate, rendering space inaccessible regardless of human intervention. This approach highlights that under current conditions; space operations are fundamentally unsustainable.

By transforming an abstract concern into a quantifiable and time-bound projection, the chapter builds a powerful argument for why orbital sustainability must become a policy and industry priority. The use of probabilistic modelling is especially effective in this context, as it allows for the projection of systemic risk at a scale that is often difficult to grasp without data analysis. In doing so, this chapter contributes to risk-based decision-making in orbital governance and situates itself within the broader literature on space policy, environmental risk management, and sustainability science.

1.2.2 Charting the Course of Space Tourism²

Chapter 3 shifts focus to the pressures accelerating orbital activity, investigating how the rapid rise of space commercialisation, and more specifically space tourism, will likely compound the sustainability challenge. Building on the risk quantified in Chapter 2 (paper 1), this chapter explores one of the contributors to the commercial space age, an industry that, while not the root cause of space

² You can find the reference to the publication here: (Martin-Lawson et al., 2026).

debris, acts as a pressure multiplier, intensifying orbital traffic, increasing launch frequency, and expanding demand for infrastructure in low Earth orbit. A version of this paper has been submitted for peer review in the *Journal of Transport Policy* and has been under review for over 6 months.

Space tourism, while not vividly defined, can refer to the commercial offering of suborbital and orbital travel experiences to private individuals (Crouch et al., 2009; Launius and Jenkins, 2006). Once viewed as speculative, it has quickly gained momentum, with major industry players such as SpaceX, Blue Origin, and Virgin Galactic making significant investments (Zhang and Wang, 2022). Market projections estimate the sector could be worth billions in the coming decades, signalling not only continued growth but the potential for widespread and sustained activity in orbit (Stanley, 2020). While this trajectory presents exciting opportunities, it also raises important concerns, ranging from environmental concerns for both near-earth orbit and Earth itself, debris generation, to equity, ethical considerations, and the absence of consistent regulatory oversight. In many ways, space tourism reflects the broader sustainability tensions emerging within the commercialisation of space: technological innovation and market expansion outpacing the governance frameworks meant to regulate them.

To better understand these dynamics, this chapter conducts a systematic literature review and thematic analysis of academic work on space tourism. The review identifies key themes and patterns, including the lack of regulatory cohesion, technological standards, and sustainability benchmarks, as well as gaps in research on environmental governance, consumer choice behaviour, and long-term policy planning. These findings reveal how the unchecked expansion of commercial space activity, exemplified by space tourism, risks straining shared orbital resources and compounding the debris problem.

Conceptually, this chapter contributes to ongoing discussions around commercial space governance and sustainability transitions, positioning space tourism as a critical node within this discourse. It argues that while space tourism is not inherently unsustainable, its development requires industry foresight and international coordination to ensure that it does not undermine long-term orbital viability. By situating space tourism within the broader trend of space commercialisation, the chapter reinforces the need for proactive, rather than reactive, policy design in emerging frontier domains.

1.2.3 Exploring the Dynamics of Innovation in Orbital Debris Management

Chapter 4 focuses on addressing the space debris challenge by analysing how technological innovation is emerging in response to mounting sustainability risks. Having quantified the scale of orbital risk in Chapter 2 (paper 1) and explored the commercial pressures compounding it in Chapter 3 (paper 2), this chapter (paper 3) asks a natural follow-up question: *What is being done to solve the problem?* Motivated by a broader interest in how innovation ecosystems develop in response to environmental crises, the chapter investigates the evolving landscape of debris-related technologies and the policy context that surrounds them. A final draft of paper 3 is being developed, soon to be submitted to a Chartered Associated Business School (CABS) ranked, peer-reviewed, journal.

While there is existing literature on both innovation policy and specific technological solutions for orbital debris, few studies bridge the gap between the two - which Chapter 4 seeks to fill. The analysis is based on patent data, using density-based clustering of applications with noise (DBSCAN), to examine innovation trends across three key debris technology types: prevention, mitigation, and removal. Patent analysis serves as a real-world proxy for tracking the direction and intensity of innovation across sectors, offering insights into where activity is concentrated, which technologies are being prioritised, and where significant gaps remain.

The findings reveal a growing volume of innovation in mitigation and removal technologies, including active debris removal missions, collision avoidance systems, and end-of-life strategies. However, preventative technologies, those designed to avoid debris generation in the first place, remain relatively underdeveloped. This suggests the sector remains largely reactive, a pattern that echoes broader sustainability challenges where innovation tends to follow, rather than anticipate, systemic risk.

Crucially, the chapter highlights a parallel issue: policy frameworks have not evolved at the same pace as technology. Without strategic alignment, there is a risk that emerging technologies will develop in isolation, lack interoperability, or fall short of meeting long-term sustainability goals. The chapter argues that technological advancement alone is insufficient; innovation must be shaped by informed, adaptive, and mission-oriented policy. Only then can a coherent and effective response to orbital debris take shape.

Conceptually, the chapter (paper 3) draws on sustainability transitions theory and mission-oriented innovation policy, framing space governance as a frontier case of innovation-led environmental change. By identifying where innovation is happening, and where it is not, this research provides a clearer picture for policymakers and industry leaders seeking to design interventions that foster sustainable progress. It contributes a forward-looking perspective on how innovation and regulation must co-evolve to support the transition toward a sustainable orbital environment. Finally, Chapter 5 concludes the Thesis.

1.3 The Unified Space Sustainability Framework

Sustainability is not a fixed or singular concept. It is dynamic and evolving, requiring the integration of multiple forms of knowledge to address complex and interdependent challenges. This thesis approaches sustainability through a multi-dimensional lens, applying distinct yet complementary methodologies to examine the risks, pressures, and potential responses to the growing problem of orbital debris.

Chapter 2 provides a measurement framework, using probabilistic modelling to quantify the scale and urgency of orbital collision risk. This approach makes the abstract threat of space debris tangible, offering a data-driven foundation for policy and planning. Chapter 3 introduces a contextual and institutional perspective, examining how commercial trends, particularly the rise of space tourism, are

reshaping orbital activity and intensifying sustainability pressures in the absence of coherent regulation. Chapter 4 adopts a forward-looking approach, mapping the global innovation landscape in debris mitigation through patent analysis and examining how technology and policy are, and are not, evolving to meet the sustainability challenge.

Each chapter employs a different methodological approach, but all are underpinned by a central question: how can we sustain orbital space in the face of growing use and risk? This shared focus on space sustainability serves as the conceptual thread linking the thesis together, with each method intentionally selected to explore a different facet of the problem.

This multi-method approach is not only pragmatic, but important. As scholars such as (Ostrom, 2009; Leach et al., 2010) have noted, complex systems problems, especially those concerning environmental risk and long-term governance, require interdisciplinary tools and frameworks. A single method is unlikely to adequately capture the scope of such challenges, particularly in a novel and rapidly evolving domain like outer space. By integrating modelling, review, and empirical analysis, this thesis delivers both breadth and depth, quantifying systemic risk, contextualising industry dynamics, and evaluating pathways for coordinated action.

In doing so, it embraces a systems perspective on space sustainability one that does not merely diagnose problems, but seeks to understand how risk, behaviour, and innovation interact, and where the most effective points of intervention may lie to safeguard the long-term usability of Earth's orbits.

This perspective directly aligns with the Sustainability Transitions Theory introduced above, providing a conceptual lens for understanding how the space sector can evolve toward more sustainable trajectories. While this overarching framework provides conceptual coherence, each empirical chapter draws on a complementary sub-framework tailored to its analytical aim: Chapter 2 applies probabilistic risk modelling to diagnose orbital collision threats; Chapter 3 employs a systematic review (PRISMA) to examine institutional and behavioural dynamics; and Chapter 4 uses innovation systems literature and mission-oriented policy frameworks to analyse solution-building.

This approach represents theoretical triangulation, where distinct frameworks are applied within a consistent lens to capture multiple dimensions of the sustainability challenge. It allows each chapter to employ the most appropriate tool for its research question, while maintaining conceptual consistency across the thesis. By anchoring technical risk, commercial pressures, and innovation-policy dynamics within a unifying transition perspective, this triangulated framework enables deeper, more nuanced insights than a single framework could provide.

Having established the conceptual and theoretical framework, this thesis is situated within a clear philosophical and methodological context. This research adopts a pragmatic and positivist philosophy, reflecting a focus on both the observable realities of orbital space use and the practical implications for governance and innovation. Drawing on Saunders' Research Onion framework, the study is positioned within a pragmatic paradigm because it seeks to employ the methods most appropriate for addressing the research question: "How can we understand, anticipate, and address the sustainability risks posed

by the growing use of our orbits?” Pragmatism enables the integration of quantitative and qualitative methods, allowing the research to generate actionable insights for both scientific and policy spaces (Saunders et al., 2023). The positivist element of this research is evident in its reliance on empirical, measurable data, ensuring that findings are grounded in observable phenomena.

In terms of research approach, the thesis adopts a blend of deductive and inductive reasoning, with a stronger emphasis on induction overall. Chapter 2 begins deductively, testing the theoretical concern of space debris and the Kessler Syndrome through quantitative probabilistic modelling to establish that orbital environments are indeed becoming increasingly congested. Once this problem is confirmed, the subsequent studies take a more inductive stance. Chapter 3, which applies a systematic review and bibliometric analysis of space tourism, is largely inductive in that the data reveal the emerging patterns and research dynamics, though it originates from the deductive insight that tourism will likely be a future contributor of debris growth. Chapter 4 is also inductive in nature, using patent clustering to allow innovation data to shape an understanding of technological trajectories in debris management. In this way, the research approach evolves across the thesis, beginning with deduction to validate the problem before moving toward induction to explore pathways and solutions.

With respect to methodological choice, the thesis employs a mixed-methods design, combining both quantitative and qualitative tools across the three papers. At the level of research strategies, each chapter relies on the use of secondary data. The strategies employed include the systematic search, selection, and review of published literature (PRISMA), the analysis of bibliometric databases (Web of Science), the use of international patent databases (Lens/WIPO IPC codes), and the examination of institutional datasets (ESA space environment data, Space Foundation industry data). Although the specific analytical methods vary, from probabilistic modelling to bibliometric mapping and clustering techniques, the unifying strategy across all chapters is the secondary analysis of data originally collected by other organisations or researchers.

Regarding the time horizon, the research design is cross-sectional, in that each dataset was collected and analysed at a single point in time without revisiting or updating sources. However, the content of the data analysed is inherently longitudinal in scope. Chapter 2 examines the historical growth of orbital debris and forecasts future collision risks, Chapter 3 traces the evolution of research themes and sectoral dynamics in space tourism, and Chapter 4 maps the trajectory of patents relating to debris management from their inception to the present. This leads to a retrospective longitudinal analysis, which enables the thesis to identify patterns, shifts, and trends across time, even though the empirical work was conducted within a cross-sectional framework.

At the innermost layer of the Research Onion, the data collection and analysis techniques employed reflect the diverse methods required to address the multi-dimensional research question. These include probabilistic modelling and regression, systematic literature review protocols, bibliometric coupling, historiography, and patent clustering (DBSCAN) combined with innovation diffusion theory. By aligning these techniques with the broader philosophy, approach, strategy, and time horizon, the thesis

demonstrates a coherent and layered methodological design that is consistent with Saunders' Research Onion.

This thesis can be seen as a response to the increasingly urgent challenge of space sustainability, approached through three distinct yet interconnected papers, with each study contributing a different analytical perspective. While varied in methodology, all three papers are unified by a central concern, how to safeguard the long-term usability of orbital space in an era of rapid expansion and uncertain governance.

2 Chapter 2

Cost of un-regulation - Shrinking Earth Orbits and the Need for Sustainable Space Governance³

2.1 Introduction

2.1.1 The Space Industry, Sustainability, and Ethical Challenges

Over the past two decades, the global space industry has undergone rapid transformation, shifting from a predominantly state-led and exploration-focused domain toward a highly commercialised and increasingly congested operational environment (Paladini and Castellucci, 2022). Advances in launch systems, satellite miniaturisation, and private-sector participation have enabled a wide range of new applications, including global communications, navigation, Earth observation, and emerging commercial services (Li et al., 2021a). While these developments have generated substantial economic and societal benefits, they have also intensified pressures on Earth's orbital environment.

From a sustainability perspective, the expansion of space activities intersects with several of the United Nations Sustainable Development Goals (SDGs), most notably those related to innovation, economic development, climate action, and international cooperation (United Nations, 2025). The strongest and most frequently link is to SDG 9 (Industry, Innovation and Infrastructure), as space activities drive advanced manufacturing, high levels of research and development, and the deployment of complex technological infrastructures. A widely cited example of technological spillover from space research is the development of memory foam, originally created by NASA in 1966 as a cushioning and crash-protection material and later adopted in mainstream consumer products, particularly mattresses (Schmidt, 2009). Satellite systems underpin critical services such as digital connectivity, navigation, and Earth observation, while commercial launch systems and spaceports increasingly form part of broader industrial ecosystems that support innovation beyond the space sector (Shutler et al., 2024).

Space activities also contribute to SDG 8 (Decent Work and Economic Growth) through the creation of high-skilled employment in fields such as aerospace engineering, data science, and artificial intelligence, as well as through the growth of downstream markets, including telecommunications, geospatial analytics, and navigation services (Collins et al., 2006; OECD, 2020). However, these economic benefits are often accompanied by concerns regarding unequal access, geographic concentration of expertise, and the distribution of value across states and private actors, raising questions about the inclusiveness of space-enabled growth (Peeters, 2018).

³ This chapter has been published in the journal of *Environmental Management* see the reference: (Martin-Lawson et al., 2024)

In addition, space infrastructure plays a substantive, though largely indirect, role in advancing SDG 13 (Climate Action). Earth observation satellites are central to climate monitoring, carbon tracking, disaster prediction, and environmental management, providing the data required for evidence-based climate policy and international reporting (Shutler et al., 2024). At the same time, these contributions must be balanced against the environmental externalities associated with space activities themselves, including launch emissions and the accumulation of orbital debris, which may undermine the long-term availability of space-based climate services.

Finally, the governance and operation of space systems are closely linked to SDG 17 (Partnerships for the Goals), as space activities frequently depend on international cooperation, shared scientific infrastructure, and public–private partnerships (Jiang and Zhao, 2021; Crawford, 2021). The sustainability of the orbital environment, therefore, hinges not only on technological capability but also on the capacity of states and commercial actors to coordinate actions, share responsibilities, and collectively manage a finite and globally shared resource (Rebay, 2023).

Ethical considerations further complicate the sustainability of the orbital environment. Decisions regarding satellite deployment, debris mitigation, and end-of-life practices generate long-lasting consequences that extend far beyond the immediate interests of current operators, raising concerns of intergenerational equity. Actions taken today, such as inadequate disposal practices or the deliberate creation of debris, can constrain the ability of future generations to access and use orbital space safely, effectively transferring risk and cost forward in time (Freeland, 2020; Paladini, 2024).

Closely linked to this is the issue of responsibility for debris creation and management. While space activities are increasingly driven by private commercial actors, the consequences of debris accumulation are collective, affecting all space users regardless of who generated the risk (Salter, 2015). This asymmetry between private benefit and shared harm poses ethical challenges related to accountability, liability, and the allocation of remediation responsibilities, particularly in an environment where enforcement mechanisms remain weak and fragmented.

Ethical concerns also arise around fair access to finite orbital resources. Orbital slots and safe operating regions are increasingly occupied by early movers and large constellations, potentially disadvantaging late-entry states, emerging space nations, and non-commercial actors (Yang and Amongin, 2024). Without coordinated governance, the progressive congestion of key orbital regions risks entrenching inequalities in access to space-based services and benefits.

Together, these ethical dimensions reinforce the view that space debris is not merely a technical or economic externality, but a systemic sustainability challenge that requires collective restraint, shared responsibility, and governance arrangements capable of balancing innovation with long-term stewardship of the orbital environment.

Against this backdrop, Chapter 2 examines space debris as a critical risk to the sustainability of Earth’s orbital environment. By situating orbital congestion within the context of space industry growth,

sustainability objectives, and ethical responsibility, the chapter provides the foundation for the subsequent analysis of regulatory frameworks and debris growth dynamics.

2.1.2 Earth's Orbits as a Transboundary Commons

Transboundary resources, also referred to as Areas Beyond National Jurisdiction (ABNJ), are prone to depletion risks and conflicts over access. This widely recognised phenomenon, known as the 'tragedy of the commons' (Hardin, 1968), is evident in various areas, including outer space and specifically in Earth's orbits, due to self-interested behaviours and lack of regulation or ownership mechanisms that hinder coordination, exacerbate conflicting interests, and impede the establishment and enforcement of transnational regulations.

The current legal framework governing outer space, which consists of the Five UN Treaties from the 1960s to the 1970s (Migaud, 2020), is increasingly inadequate and outdated, and Earth's orbits in particular face mounting challenges (Paladini, 2023). The rise of objects in space, such as satellites, space stations, and non-operational objects like space junk and debris, has increased rapidly due to the commercialisation of space and the expansion of private companies in the sector. Consequently, the probability of a cascading chain of collisions has increased, commonly known as a Kessler Syndrome (Kessler and Cour-Palais, 1978; Bastida Virgili et al., 2016), and poses potential catastrophic environmental and economic consequences.

International agencies were the first to act, suggesting best practices, which, it is important to note, have no binding legal value. The Inter-Agency Space Debris Coordination Committee (IADC) recommended the implementation of end-of-life disposal measures for all LEO satellites, mandating their de-orbiting within a period of 25 years following their launch (Hakima and Emami, 2018); NASA has recently requested a far shorter 5-year window (NASA, 2022). GEO (Geosynchronous) satellites are typically deorbited according to standard procedures and moved into a 'graveyard' orbit above the protected zone. Debris are closely monitored by national and international space agencies.

Initiatives, such as the one proposed by the Committee of Space Research's (COSPAR) to promote Planetary Protection Policies (PPP), are a good starting point (COSPAR, 2017), though insufficient since they do not address thorny legal issues (e.g., ownership of space junk and debris alike).

There is a growing literature on the need for defining, addressing, and ensuring sustainability in outer space (Dobos and Prazak, 2019; Ledkov and Aslanov, 2023; Svitina and Cherkasova, 2023; Paladini et al., 2021) both in the sense of regulating human activities (ESA, 2022b; UN, 2013) and active debris removal. Strategies encompassing the regulation of satellite disposal and debris mitigation have emerged as crucial means of managing the space debris environment (Usovik, 2023), with a few initiatives already trialled to actively attempt cleaning up the orbits (Astroscale, 2023a; Biesbroek, 2015). However, although there are studies that estimates the likely growth of quantity of objects in space in terms of collision probability scenarios with the aim of costing its economic consequences and estimates the benefit of remediation initiatives (NASA, 2023a; OECD, 2020), there is still limited

research that connects the growing threat of debris and international regulations –or the lack of– that allowed this to happen.

The aim of this chapter (paper 1), therefore, is to fill this conceptual gap and link between debris mitigation and regulation. We develop a forecasting model to estimate how imminent, and costly, the debris crisis will be without the implementation of sustainable space governance and provide some suggestions.

With this aim in mind, we first analyse (Section 2.2) the regulatory framework of outer space, from the original outer space treaties to recent, and controversial, national regulations (the USA's 2020 EO- (Executive Order, 2020). We highlight the unique characteristics of the Earth's orbit(s) compared to other ABNJs, such as high seas and polar regions. We also discuss the current usage of Earth's orbits, showing the complexities of measuring and tracking space objects and the risks related to their rapid growth. Section 2.3 discusses the methodological choices made for the design of our empirical model, offering the rationale behind our projected growth of the number of trackable objects and the choice of the probabilistic function, while Section 2.4 presents the results from the forecasting exercises and compares its findings to alternative models, discussing the level of minimum mitigation strategies required to attain a sustainable level of space activities growth. Section 2.5 attempts a cost-benefit analysis and highlights that the real hurdle to mitigation measures is regulatory rather than technological. Section 2.6 takes stock of the article's findings, discusses limitations, and avenues of future research.

2.2 Earth's orbits as a unique example of Areas Beyond National Jurisdiction (ABNJ)

2.2.1 The regulatory framework of outer space

Areas Beyond National Jurisdiction (ABNJ) are regions for which no nation has sole responsibility for management, and which have been, over the decades, the object of international treaties aimed at regulating the access to the transboundary resources they contain. Formal provision has generally been derived from the customary international law (Scovazzi, 2015; Merkouris, 2020; Treves, 2005; Rebay, 2023; Scovazzi, 2021). Globalisation, the increasing complexity of economic activities, challenges from climate changes, and the call for sustainable growth are scrutinizing current regulatory frameworks (Rose, 2020; Toth, 2017). In recent years, calls are made for a 'global legal pluralism' (Sentz and Ferson, 2002) that is better suited to face these challenges (Moore, 1973; Griffiths, 1986; Tamanaha, 2008; Somos, 2020).

The American Society of International Law includes listed under the ABNJ acronym four areas, and namely, Oceans, Polar Regions, Cyberspace, and Outer Space (ASIL, 2023). There are important communalities among them, which explains why they have been historically regarded as examples of

‘global commons’ (UN, 2013), starting from their regulatory framework set through international treaties.

The most well-known among them, and a reference for all the others, is the United Nations Convention on the Law of the Sea, which built on, and replaced, the four treaties of the 1958 Convention of the High Seas. In the same way, the polar regions are regulated by the Antarctic Treaty System, and outer space by the Outer Space Treaty (OST, 1967) and the other four treaties stemming from it.

The most important characteristics that ABNJ have in common is that they are all considered a shared heritage, or ‘province of all mankind (e.g., Article (art) 1 OST; mirrored by art. 137 UNCLOS), which means they are not owned by any nation and must be used for the benefit of all and for peaceful purposes only (art 89 UNCLOS; art 2 OST). In the same way, they are recognized as global commons, open to all states and subject to specific legal regimes that govern their use. To ensure sustainable use and protection, this entails international cooperation and coordination to address common challenges.

Together with common characters, there are important distinctions among ABNJs, which is the reason why the current ‘international space law’ based on the Five UN Treaties of the 1960s–1970s and, particularly, the 1967 Outer Space Treaty (OST), developed on the customary laws of the high seas, have severe limitations. This is not, or not only, due to the overlapping areas of jurisdiction and the way national laws and existing treaties may clash in their provisions (Walton, 2017; Francioni, 2014; Francioni and Scovazzi, 1996; Hermida, 2004; Lucas-Rhimbassen, 2022). High seas, as much as outer space, are placed beyond the jurisdiction of any state, while the polar regions have limited sovereignty by certain states under specific treaties. Otherwise said, the clashes national-international regulations are a common and well-known problem for ABNJs.

What is uniquely problematic in the case of outer space is the fact that the existing regulatory framework makes no distinction in what comes under its remit. And, while there is no consensus about where space starts (the Karman line of 100 km above the sea level versus NASA’s lower limit of about 52 miles), once we cross that invisible line, the ‘outer space’ regime applies, regardless of whether it is Lower-Earth Orbit (LEO), a celestial body, or deep space. This is a problematic generalisation because each of them is a very different environment with its own characteristics and peculiarities (Paladini and Castellucci, 2022).

Even more concerning is the recent surge in regulatory activities targeting outer space, primarily driven by economic motivations. One notable example is the Executive Order (EO) 13914 issued by President Donald Trump on April 6, 2020. The EO explicitly rejects the longstanding notion of outer space as a ‘global commons’ established by historical UN treaties. According to the EO, “*Outer space is a legally and physically unique domain of human activity, and the United States does not view it as a global commons,*” (EO 13914, 2020). While the measure solely applies at the national level and lacks international binding effects, it originates from the leading country in the space sector and sets a significant and noteworthy precedent. It removes the previously ‘constraining concept’ associated to the exploitation of ‘global commons’ (Cogolati and Wouters, 2018; Tepper, 2019; Goehring, 2020),

along with any limitation previously implied by the UN Treaties. This situation presents a significant obstacle to achieving both equitable resource exploitation and a sustainable responsible growth.

Moreover, the Moon and other celestial bodies face similar challenges as those found in marine environment preservation zones (e.g., contamination avoidance and risks of resource depletion: Freestone, 2009; Costello et al., 2008; Fitzmaurice, 2017; Eisenbarth, 2022; von Rebay, 2023), offering valuable insights to draw upon. Earth's orbit, however, stands apart from these environments and offers little experiences thereby adding to the complexity of the situation. Furthermore, as we elaborate next and substantiate with our model, if prompt remedial actions are not taken, the orbit faces an imminent threat of excessive exploitation and could become unusable.

2.2.2 Earth's orbits and their threatened status

A good starting point to discuss 'space sustainability' is the United Nations' Committee on the Peaceful Uses of Outer Space (UN COPUOS) definition: *'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,'* (UN COPUOS, 2018).

This statement highlights the specific challenges the Earth's Orbit - or orbits - present. If outer space is infinite, by definition, the space around Earth's orbit that can be occupied by satellites is not. The Earth's division in various orbits is internationally accepted, and the three most used by satellites are Lower Earth Orbit (LEO) - the closest to the planet, Medium Earth Orbit (MEO) and geosynchronous orbit (GEO; (Iridium, 2018) as presented in Figure 2-1.

Figure 2-1: The Earth's Orbits

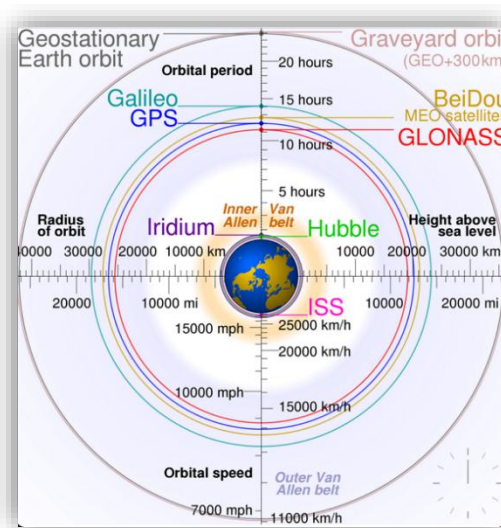


Figure 2-1: Illustrates the internationally recognised division of Earth's orbital environment into Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO), highlighting the finite and stratified nature of the orbital regions most heavily utilised by satellites. (source: Creative Common, 2023).

The division of Earth’s orbital environment into distinct orbital regions is internationally recognised, with the three most heavily utilised by satellites being Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO) (Iridium, 2018), as illustrated in Figure 2-1. Considering the number of objects sent to space, it is no surprise that overcrowding has quickly become an issue, with the ITU (International Telecommunication Union) issuing warnings about the overpopulation of GEO since the beginning of the 1970s (ITU, 1992). Monitoring has been historically challenging, and any discussion of sustainability in the Earth's orbits must consider two related but conceptually different issues: (i) the sheer number of objects sent into space and (ii) the consequences of their permanence creating further debris by collision.

A few international bodies track the number of objects sent to space, the European Space Agency (ESA) and United Nations Office for Outer Space Affairs (UNOOSA) among them. According to recent statistics (December 2022; European Space Agency, 2022) there were 14,450 objects sent to space in about 6300 successful rocket launches since 1957 (Sputnik 1 year), with more than 10,000 tonnes of materials. At the time of writing this article (July 2023), UNOOSA's Online Index of Objects Launched into Outer Space included 15,716 in their index (UNOOSA, 2023), the large majority of which in LEO. More importantly, this number includes ‘space junk,’ i.e., satellites no longer functioning that still orbit the Earth, but not space debris, which are classified and tracked adopting different metrics, as explained in the next section. Figure 2-2 gives a breakdown of the position of the space objects depending on their orbits and the timeline of their expansion.

Figure 2-2: Space Objects by Orbit (not including space debris)

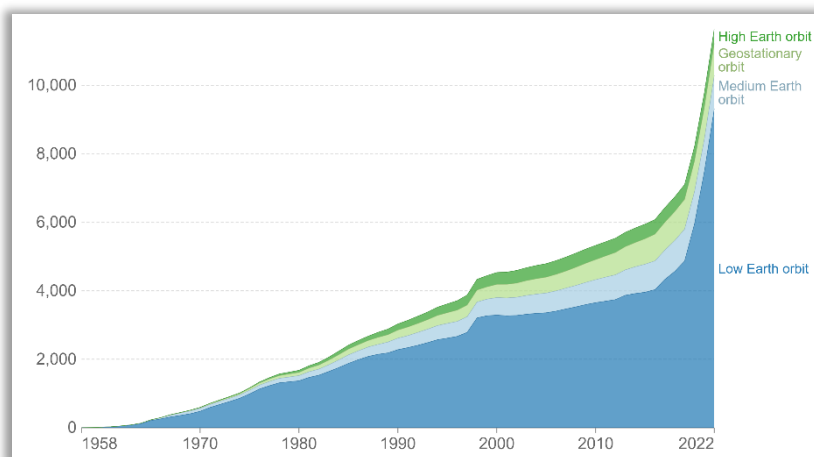


Figure 2.2: Cumulative growth of space objects by orbital regime (LEO, MEO, and GEO) from 1957 onwards, showing the rapid increase in orbital objects and their concentration in Low Earth Orbit. (Source: Our World In Data --MIT, CC-BY, 2023)

Figure 2-2 illustrates the cumulative growth of space objects across Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO) since 1957. The figure highlights both

the rapid increase in orbital objects over time and their pronounced concentration in LEO, underscoring the growing pressure on the most heavily utilised orbital region. This complicates the analysis and the development of mitigation measures aimed at addressing them because, for instance, the Inter-Agency Space Debris Coordination Committee (Kim, 2013) defines ‘space debris’ as non-functional man-made objects, including both space junk and satellites' fragments that are in the Earth's orbit. Differently from space junk, fragments are smaller pieces of the initial object that have broken up and are now orbiting at their trajectory without the ability to control them (Liou and Johnson, 2009).

The number of objects, excluding debris, is already high. But the future is even more worrying, a picture that is not fully conveyed by the number of launches (Figure 2-3) because of the change in the type of payload sent into orbit and the rate of growth. Figure 2-3 shows that the number of satellites launched grew from 120 to 1807 between 2011 and 2022, 1273 of which were smallsat constellations, such as Starlink and OneWeb (BryceTech, 2022; Mathieu and Roser, 2022).⁴ The constellations vary in type depending on their number and to the height of orbit. For example, by 1998, the Iridium Satellite network included 77 active satellites (Maine et al., 1995).

Figure 2-3: Annual number of launches by country (1957-2022)

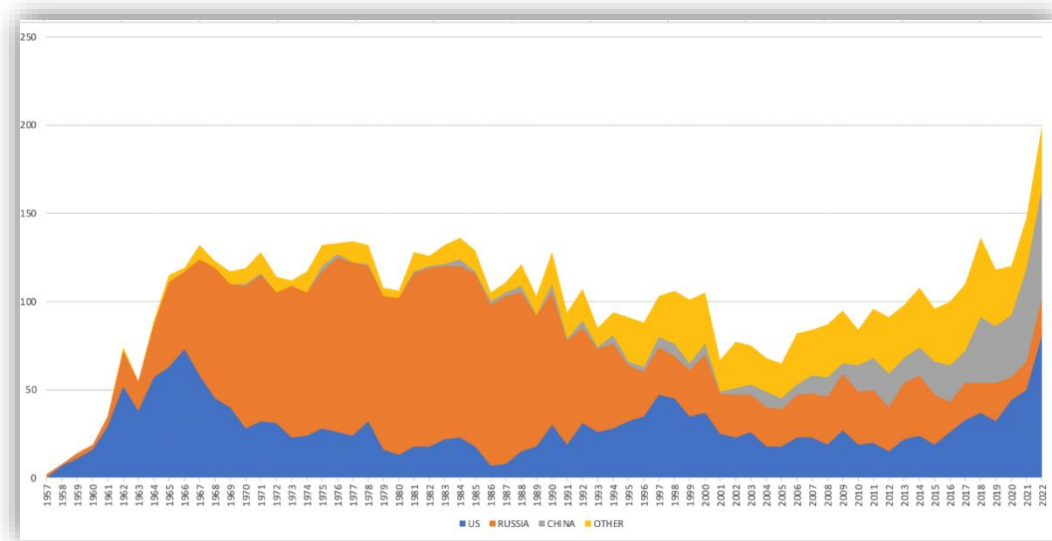


Figure 2-3: Annual number of orbital launches by country from 1957 to 2022, showing long-term growth in launch activity across major spacefaring nations. (source: Authors' elaboration on US Space Surveillance Network dataset, 2023).

Figure 2-3 presents the annual number of orbital launches by country between 1957 and 2022. The figure illustrates the long-term growth in global launch activity while also indicating that recent increases in orbital congestion cannot be explained by launch frequency alone, reflecting shifts in

⁴ A satellite constellation is generally defined as a group of satellites at a fixed orbit and distance from each other that have a single goal, be it navigational information or communication services (Abashidze et al., 2022; Wang and Li, 2023).

payload type, satellite density, and constellation-based deployment strategies. Also, alarming is the number of the newly proposed constellations, with projections indicating the launch of thousands of satellites that would increase traffic by more than fivefold in an already congested LEO (Polli et al., 2022). SpaceX's Starlink, the most advanced mega constellation project, currently includes over 2000 satellites in orbit, with Bernhard et al. (2023) estimating a total of 42,000 satellites once the constellation is completed. Other estimates give a smaller number for Starlink (29,988) but including also other operators - Astra (13,620), China SatNet (12,992), OneWeb (6,372) among them, the total number could read 76,606 (Tibor et al., 2022 as cited by NASA, 2023).

This push for large satellite constellations in LEO amplifies the risk of collisions, consequently contributing to the increase of space debris that threaten the sustainability of the space environment (Bastida Virgili et al., 2016). To assess the danger posed by space debris and build a projection model, we first begin with an explanation on how they are formed and monitored.

2.3 Methods and data

2.3.1 Debris formation and monitoring

The most comprehensive and long-serving tracking system is the one provided by the Department of Defence US Space Surveillance Network (SSN) that includes “*launch detection and tracking, conjunction assessment and collision avoidance, human spaceflight support, manoeuvre detection, breakup identification, and re-entry assessment*” (Joint Task Force-Space Defense, 2022).

By December 2021, more than 27 thousand (k) orbital debris were tracked which had a size greater than 4 inches in diameter (10 cm, cm). These include non-functional spacecraft, abandoned launch vehicle stages, and fragmentation debris. But the number of debris is far greater, and according to NASA, there are about half a million (m) fragments of 0.4 inches (1 cm) or larger, and approximately 100 m around 0.04 inches (1 mm, mm) and larger (NASA, 2021).

ESA's focus is slightly different and centres around debris creation and fragmentation events, although its estimates are comparable to NASA's. They report that since 1957, more than 630 events had occurred due to explosions, collisions, or other unplanned events that have provoked fragmentation, listing close to 33.5k tracked orbital debris of 10 cm or greater, and around 130 m untracked space debris of between 1 mm and 1 cm, defined as unidentified objects (UIs) (ESA, 2022b). These UIs are far more dangerous to existing satellites and space stations because they travel at extremely high speeds of up to 17,500 miles per hour (mph), and being untracked, collisions are difficult to predict and subsequently perform collision avoidance manoeuvres.

In terms of severity as cause of debris formation, propulsion, breakup events of various kind (for instance, during take-off), collision, and Anti-satellite weapons (ASAT) testing have been to date the largest contributors, with collision-related cause deemed to grow in severity in parallel with the increase

of the satellites launched into space (Le May et al., 2018). Figure 2-4 summarises the top 10 fragmentation events between 1957 and 2022.

Figure 2-4: Top 10 fragmentation events by number of fragments (1957-2022)

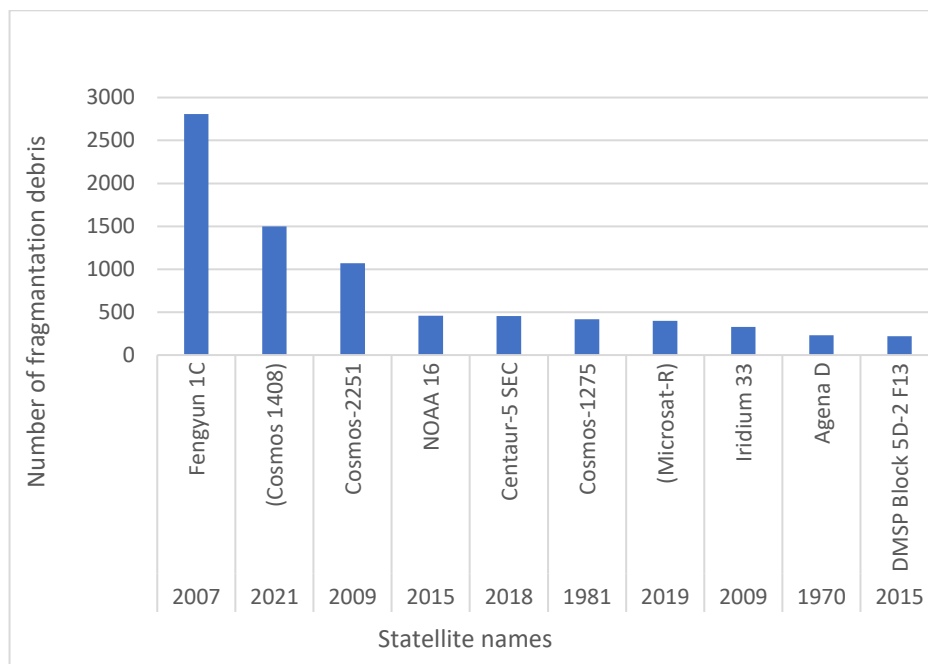


Figure 2-4 Top fragmentation events by number of trackable debris fragments (1957–2022), showing the highly skewed contribution of major break-up and collision incidents to the overall debris population. (Source: Elaboration on (Paladini, 2023). Original data from ESA and JAXA data, 2022)

Figure 2-4 illustrates the highly uneven contribution of major break-up and collision events to debris generation, with a small number of incidents producing a disproportionately large share of trackable orbital fragments. In 2018 alone, there were eight instances of breakup events in LEO that resulted in more than 1000 (now tracked) large new debris (Fattakhov, 2019; Baranov et al., 2021). And, although there is a substantial literature discussing major hypervelocity (high-speed) collisions as critical causes of debris formation (Zhang et al., 2016a; ESA, 2022b; Anselmo and Pardini, 2017; Pardini and Anselmo, 2021), ASAT tests are the ones causing the most damage in terms of fragment produced, as the 2007 Chinese Fengyun 1C event, which was high enough to slow down natural orbital decay (Weeden and Sankaran, 2010).

Collisions yield severe consequences too, as exemplified by the well-known incident in 2009 when the Soviet derelict Cosmos 2251 (a typical example of space junk) collided with the operational satellite Iridium 33. Even after seven years, a debris cloud of 1453 trackable objects remains in orbit, accounting for a significant proportion of fragments at an altitude of approximately 778 km. Notably, this altitude coincides with that of the Iridium constellation, and while no catastrophic collisions occurred between these fragments and the operational satellite constellation, it highlights the risks associated with a single collision in terms of potential long-term ramifications.

With plans for deploying additional mega-constellations, the likelihood of a hypervelocity collision increases. For example, on September 2, 2019, ESA was forced to execute a collision avoidance manoeuvre for its Aeolus satellite to avoid a potential collision with one of SpaceX's Starlink satellites. Space agencies send multiple collision risk alerts (Bernhard et al., 2023) with avoidance collision manoeuvres performed daily.

Le May et al. (2018) estimates the probability of a collision in LEO using 2018 SpaceX and OneWeb constellation data, adopting an empirical model based on Radtke et al. (2017) and ESA's MASTER software. They forecast *“a high probability for the occurrence of at least one collision for both the proposed OneWeb and SpaceX constellations during an operational phase of 5 years.”* (Le May et al., 2018:15). The probability of at least one catastrophic collision for either OneWeb and Space X was estimated 5.0% and 45.8%, respectively.

2.3.2 The model

To project the potential number of objects in orbit, we setup a model grounded in probabilistic economic theory (Ross, 2014). Orbital collisions are estimated drawing from models used in the transportation sector where a relationship exists between the number of unsafe events and their predictors. Different methods are used to model collision probabilities. For example, air traffic literature generally uses backpropagation neural networks (Chinatamby and Jewaratnam, 2023; Liao et al., 2021). Maritime transport is known to estimate and handle collision risks through an Automatic Identification System (AIS), which employs probabilistic methods to determine the future locations of ships (Sørensen et al., 2022), including deep neural network such as Bidirectional Long-Short-Term-Memory Mixture Density Network (BLSTM-MDN). The national highway in the UK adopts a non-homogeneous Poisson process to measure the occurrence of a collision, with the assumption that a collision does not influence the occurrence of another collision (Clements, 2021).

There are very few academic papers and reports that project the number of space objects and specifically debris and space junk. ESA (2023) use an inhouse generated tool called the Meteoroid and Space debris Terrestrial Environmental Reference (MASTER) to measure objects 0.0001 cm to 100m and uses ‘sophisticated’ mathematical techniques to predict the number of debris in the orbital environment. (NASA, 2023a), similarly to ESA, use the LEO-to-GEO Environmental Debris (LEGEND) Model to monitor and project the growth of debris in the orbital environment.

Academic studies such as Walker et al (2000) project the average number of space objects larger than 1 cm using the Integrated Debris Evolution Suite (IDES) for the period of 2000–2050. It differs from our model in that they include five satellite constellations rather than a single orbit Reynolds and Eichler (1995) used a mix of the Evolve and Chain models to estimate the number of debris from 1995 to 2090 in LEO. Neither study, however, link the potential impact of mitigation measures on the orbital environment. In a related study, Bongers and Torres (2023) project the maximum number of satellites in space prior to a Kessler event. In our model, we focus on debris rather than satellites. We also draw

upon two related theoretical papers: Maclay et al. (1996) that compares the Poisson and binomial distributions for modelling debris. They find that Poisson probability is a reasonable approximation of binomial distribution. Cament et al. (2021) used a mathematical Poisson labelled Multi-Bernoulli, multi-target tracking filter to predict the survival rate of space objects over time.

In our study, we develop an empirical accounting model to estimate the growth of trackable objects and subsequent debris from collisions. The model structure, overall, accounts for three main types of objects: currently tracked, new objects driven by technology, and additional satellites. As total objects rise, the probability of orbital collision rises - characterised by a Poisson distribution. Even though some objects decay into the atmosphere and removed, the net increase in objects is expected to increase the number of collision debris further and faster.

Our approach is similar to Clements (2021). However, Clements employs a disaggregated number of highways, while we have one “average” of all orbits. We do this to simplify the model and because this will not change our overall finding. Also, our assessment of the density parameter varies, and we discuss topics in line with others with emphasis on mitigating the shared space access domain (Grzelka and Wagner, 2019; Rao et al., 2020; Bernhard et al., 2023; Béal et al., 2020).

Our model is calibrated to ESA data, chosen their high level of reliability and timeliness, and relates to objects 10 cm or greater on average. We test three scenarios: low, base, and high, and have two model variants: commercialised (increased growth above business-as-usual) and an extension with small satellites (smallsats).

The total known objects in space T_0 is calibrated to the available data in Jan 2022, defined as $t = 0$. In period $t > 0$, the total objects in space A_t is equal to the trackable objects T_0 , with growth rate based on the past decade (i.e., a business-as-usual scenario). However, the projected growth in commercialisation activities and technological innovation in this sector, particularly in LEO, are expected to drive higher number of additional trackable objects ΔT_t (above the business-as-usual scenario). Moreover, ΔS_t specifically denotes the additional satellites that are anticipated to be launched due to commercialisation, which are not accounted for in ΔT . Finally, all objects contribute to the accumulation of debris resulting from collisions, represented by ΔC_t . We summarise the commercialised model below:

$$A_t = T_0(1 + g^T)^t + \Delta T_t + \Delta S_t + \Delta C_t \quad (1)$$

To pinpoint the growth rate of trackable objects g^T , we assume it follows the economic growth rate of the space sector. We compute an Ordinary Least Squares (OLS) regression whereby the dependant variable is the log of the known trackable objects (from January 2011 to January 2022), and the independent variable is the log of global space economy (GSE). The Space Foundation (2021) estimates GSE in terms of a revenue-base valuation that includes all commercial revenue from space products, services, infrastructure, and support industries as well as the space budgets of US and Non-US governments. The coefficient retrieved is the elasticity between the average growth rate of GSE and trackable objects, $\epsilon^T = 1.3$ (with 95% confidence interval (CI): 1.5 to 1.0).

Next, we compute the business-as-usual growth rate of known trackable objects as $g^T = \epsilon^T \cdot G^T = 1.3 \cdot 5.0\% = 6.3\%$, whereby the average growth rate of GSE between 2011 and 2022 was $G = 5.0\%$. The growth rate due to commercialisation $g^{Tc} = \epsilon^T \cdot G^{Tc} = 1.3 \cdot 8.2\% = 10.3\%$ is obtained by using the commercialised projected GSE growth of $G^{Tc} = 8.2\%$ from Crane et al. (2020). Finally, $\Delta T = T_0[(1 + g^{Tc})^t - (1 + g^T)^t]$.

Similarly, we estimate the additional launched satellites that are due to commercialisation:

$$\Delta S = S_0[(1 + g^{Sc})^t - (1 + g^S)^t] \quad (2)$$

whereby the business-as-usual growth rate $g^S = G^T \cdot \epsilon^S = 5.0\% \cdot 2.9 = 14.3\%$. The elasticity $\epsilon^S = 2.86$ (CI: 3.6 and 2.2) is computed by an OLS regression with log of satellites launched as the dependant variable and log of GSE as the independent variable. The same method is used to acquire the commercialised growth calibrated to $g^{Sc} = G^{Tc} \cdot \epsilon^S = 8.2\% \cdot 2.9 = 23.4\%$.

2.3.3 Collision debris

As total objects rise, the probability of a collision increases, given that the total volume of space (around Earth) remains fixed. To calculate the additional number of debris created by predicted collisions we estimated:

$$\Delta C_t = F \cdot P(k) \quad (3)$$

with $F = 2000$ being the average number of fragmentation debris generated by a collision (ESA, 2022a) and $P(k \geq 1)$ the probability of at least one collision k per year.

We drew here from a few models in transportation, which use variants of the Poisson process to characterise different aspects of probabilistic models (Maclay et al., 1996; Clements, 2021; Cament et al., 2021). For simplicity, we omit the time-period t and assume that collision probability follows a Poisson distribution $P(k) = \frac{\lambda^k e^{-\lambda}}{k!}$ with $\lambda = f(T)$ representing the mean number of collisions - a function of the number of trackable objects T at each given period t .

We assume at least one collision per year

$$P(k \geq 1) = 1 - \frac{\lambda^k e^{-\lambda}}{k!} \quad (4)$$

and that the growth rate of the mean collision per year λ follows the growth rate of trackable objects per year

$$\lambda_{t+1} = \lambda_t \frac{T_{t+1}}{T_t} \quad (5)$$

Therefore, the collision probability $P(k)$ rises as more trackable objects enter space as follows.

For the Poisson distribution to hold for the orbital collision model, several assumptions were made, i.e., within any given year, collisions are independent, homogeneous, and asynchronous. The assumption of independence restricts the variability of probabilities, as collisions tend to enhance the likelihood of subsequent collisions in nearby regions, even within a short time frame. The assumption

of homogeneity assumes a constant collision probability annually, disregarding potential fluctuations across different spatial regions, such as LEO, influenced by object density. Moreover, while simultaneous collisions are theoretically plausible, Aerospace (2021) estimates a frequency of approximately one significant collision every 7.5 years.

Table 2-1 provides a summary of the parameters used in the commercialised model. To assess the model's sensitivity, we include a high and low scenario at 10% around the baseline. In the results, we furthermore provide the 95% CI around the baseline.

Table 2-1: Model parameters

Description	Parameter	Scenarios			Reference
		Low	Base	High	
Trackable Objects					
<i>Initial trackable objects</i>	T_0	30,024	30,024	30,024	(ESA, 2022b)
<i>Elasticity of tracked objects and economic activity</i>	ϵ^T	1.14	1.26	1.39	OLS regression
<i>Growth rate of economic activity</i>	G^T	4.51%	5.01%	5.51%	(Space Foundation, 2022)
<i>Commercialised growth rate of economic activity</i>	G^{Tc}	7.35%	8.17%	8.98%	(Crane et al., 2020)
<i>Trackable objects growth rate</i>	$g^T = G^T \cdot \epsilon^T$	5.11%	6.33%	7.67%	
<i>Commercialised trackable objects growth rate</i>	$g^{Tc} = G^{Tc} \cdot \epsilon^T$	8.37%	10.33%	12.5%	
Collision Debris					
<i>Fragmentation parameter</i>	F	1,800	2,000	2,200	(ESA, 2022a)
<i>Average collisions per year</i>	λ_0	0.12	0.13	0.15	(Aerospace, 2021)
Satellites Launched					
<i>Initial satellites launched</i>	S_0	534	534	534	(Mathieu and Roser, 2022)
<i>Elasticity of satellites launched and tracked objects</i>	ϵ^S	2.57	2.86	3.14	OLS regression
<i>Growth rate of additional satellites launched</i>	$g^S = G^T \cdot \epsilon^S$	11.61%	14.33%	17.34%	
<i>Commercialised satellite launched growth rate</i>	$g^{Sc} = G^{Tc} \cdot \epsilon^S$	18.92%	23.36%	28.27%	

Table 2-1: outlines the core parameters used in the modelling framework, providing transparency over the assumptions underpinning the collision risk projections.

2.4 Results

Figure 2-5 shows the projected growth in the total number of trackable objects in Earth orbit, including operational satellites, non-operational satellites, and debris. The projections indicate that under the baseline scenario, the orbital population is expected to double within the next decade, highlighting the urgency of effective debris mitigation measures. The 95% confidence interval around the baseline projection suggests that a higher-growth trajectory is also highly plausible, with total trackable objects potentially reaching approximately 115,000 within ten years. This represents an increase of over 280%, driven primarily by the rapid commercialisation of space activities.

Figure 2-5: The number of projected objects in space

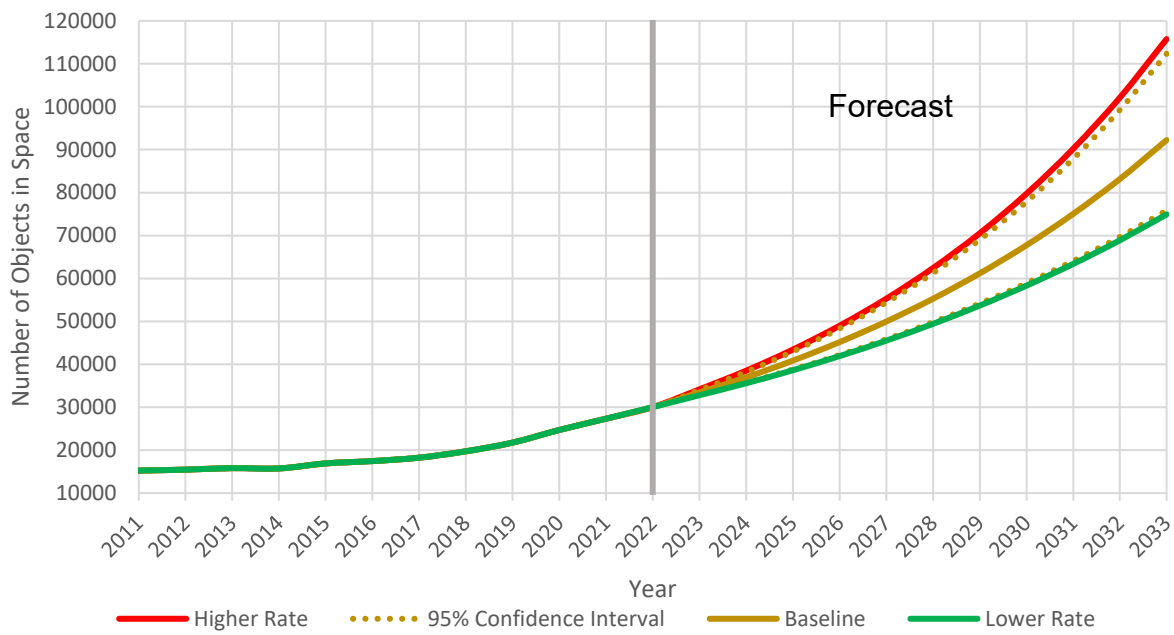


Figure 2-5 Ten-year projections of total trackable objects in Earth orbit (operational satellites, non-operational satellites, and debris) under baseline, lower-rate, and higher-rate growth scenarios.

Figure 2-6 shows the ten-year projected trend of satellite numbers in orbit. By the end of 2022, ESA (2022b) estimated a total of around 10,550 satellites in space, of which 7,900 of them classified as operational. Based on forecasts by Bongers and Torres (2023), a Kessler event would likely be triggered once the satellite count reaches approximately 72,000. Our findings indicate that this critical threshold is projected to be reached around mid-2035, in the high scenario, or shortly before 2037, in the base scenario.

Figure 2-6: The total number of satellites in space (all orbits)

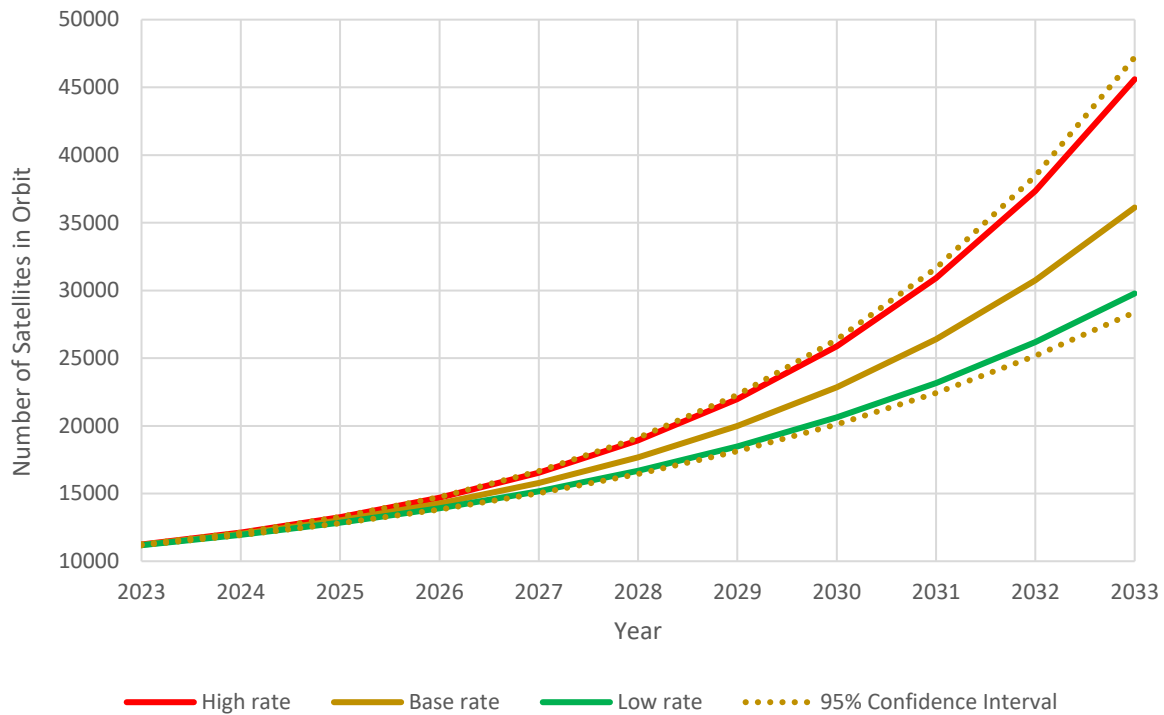


Figure 2-6 Projected growth in the total number of satellites in Earth orbit over a ten-year period under low, base, and high-rate deployment scenarios. .

The commercialised projection model, so far, does not incorporate additional nanosatellites (such as CubeSats⁵) primarily because most of them operate in low and self-decaying orbits within LEO, and thus unlikely to generate substantial debris formation. However, the expected growth in deployment of smallsat constellations, such as Starlink, due to commercialisation, pose substantially higher risk of debris formation.

However, precise forecasting of the growth rate of smallsats is challenging due to the rapid and uncertain pace in technological advancements, as well as the ambiguity surrounding smallsat mitigation policies (Bastida Virgili et al., 2016). Relying solely on historical data cannot accurately reflect the potential additional rise in smallsats launches, defined as ΔSS . These are in addition to those that have already been projected within the trackable objects A_t in the commercialised projection. We thus extend the commercialised model in Eq (1) by

$$A'_t = T_0(1 + g^T)^t + \Delta C_t + \Delta S_t + \Delta SS_t \quad (6)$$

The same method used to calculate ΔS is then used to calculate

$$\Delta SS = SS_0[(1 + g^{SS_e})^t - (1 + g^{SS})^t] \quad (7)$$

with a growth rate $g^{SS} = G^T \cdot \epsilon^{SS}$. Using a log-log OLS regression with GSE as the independent variable, we compute the elasticity $\epsilon^{SS} = 6.5$ (CI: 8.2 and 4.8) and use the average growth rate of

⁵ CubeSats –the most famous among the nanosatellite categories–are built to standard dimensions (“U”) of 10 cm × 10 cm × 10 cm and assembled into 1U, 2U, 3U, or 6U, with weights in between 1 and 10 kg

GSE $G^T = 5.0\%$. Thus, the business-as-usual growth rate is calibrated to $g^{SS} = 6.5 \cdot 5.0\% = 32.4\%$ and commercialised growth calibrated to $g^{SSc} = 6.5 \cdot 8.2\% = 52.8\%$.

Table 2-2 provides a summary of the key parameters and assumptions used in the extended orbital growth model, including initial satellite counts, elasticity estimates, and projected growth rates under different commercialisation scenarios.

Table 2-2: Parameters for the extended model

Description	Parameter	Scenarios			Reference
Smallsats Launched					
Initial satellites launched	SS_0	1743	1743	1743	(BryceTech, 2022)
Elasticity of satellites launched and tracked objects	ϵ^{SS}	6.40	7.11	7.82	OLS regression
Growth rate of additional satellites launched	$g^{SS} = G^T \cdot \epsilon^{SS}$	26.23%	32.38%	39.18%	
Commercialised growth rate of additional satellites launched	$g^{SSc} = G^{Tc} \cdot \epsilon^{SS}$	42.75%	52.78%	42.75%	

Table 2-2: Parameters and assumptions used in the extended orbital growth model, including initial satellite numbers, elasticity estimates, and growth-rate scenarios.

When incorporating additional smallsat deployments, Figure 2-7 indicates that the projected number of trackable objects in Earth orbit could reach approximately 240,000 by 2033 under the baseline scenario. This represents a substantial amplification of orbital congestion relative to projections that exclude smallsats. However, these projections are subject to greater uncertainty, given the unpredictable trajectory of the smallsat sector, rapid technological change, and evolving deployment strategies in low Earth orbit.

Figure 2-7: Forecasted number of objects in space including smallsats (95% CI)

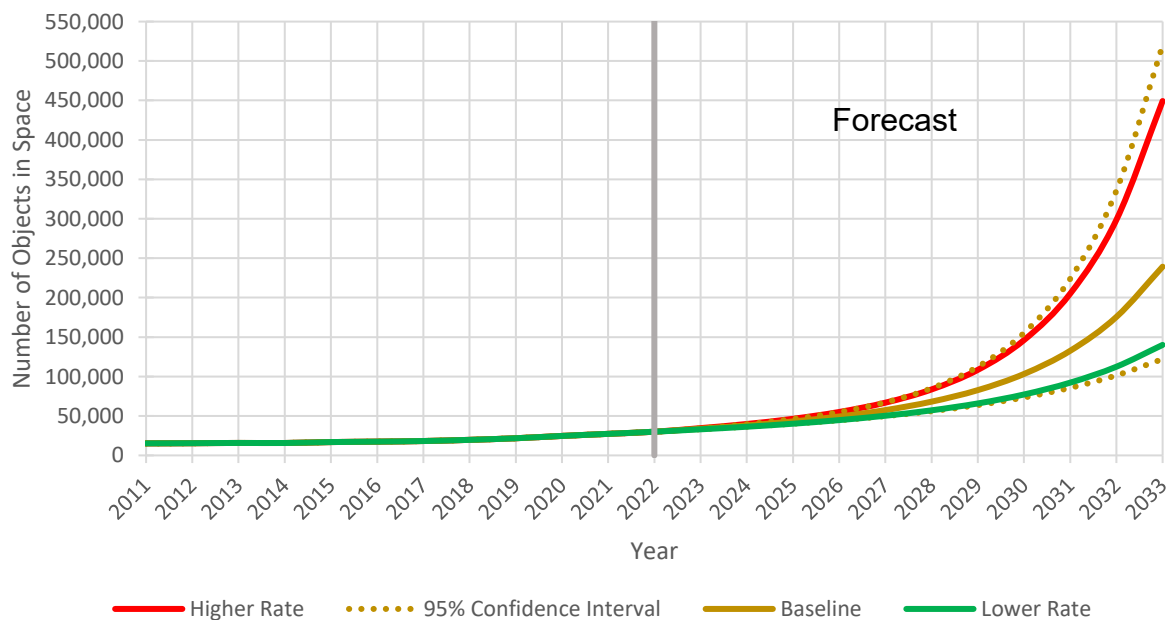


Figure 2-7: Projected growth in the total number of trackable objects in Earth orbit when smallsat deployments are included, under lower-rate, baseline, and higher-rate growth scenarios with associated confidence intervals.

2.4.1 Natural critical density

A common aspect shared by both model variants (i.e., commercialised and smallsats) is the ‘natural critical density.’ This is the rate at which collision-based fragments are naturally removed from space through atmospheric drag, pulling them into Earth's atmosphere where they are subsequently destroyed. If the debris population remains below this critical density, debris will eventually diminish when they re-enter the atmosphere and destroyed. However, if the population surpasses this critical density, and even after all space activities were ceased, the orbital population will continue to grow at a faster pace than atmospheric drag can eliminate objects, leading to exponential growth in orbital debris - referred as a Kessler Event (Krisko et al., 2001). It is important to note that this phenomenon is particularly relevant to LEO, which is the most densely populated orbital region. Other orbits, such as GEO, exhibit different conditions in terms of satellite positioning and active mitigation measures, reducing the likelihood of such conditions.

The National Oceanic and Atmospheric Administration (2018) estimates that 200 to 400 objects re-enter the Earth's atmosphere yearly, equivalent to around an object per day (i.e., 365 per year), 60%–70% of which from LEO (ESA, 2023). Combining this information into our basic model (from Figure 2-5), and assuming the proportion of objects in LEO is 65% (i.e., mid value), Figure 2-8 shows the number of LEO collisions made objects given that all new space activities are halted. The blue dotted line depicts the critical level.

Figure 2-8: Active collision-based fragmentation removal with re-entry (LEO)

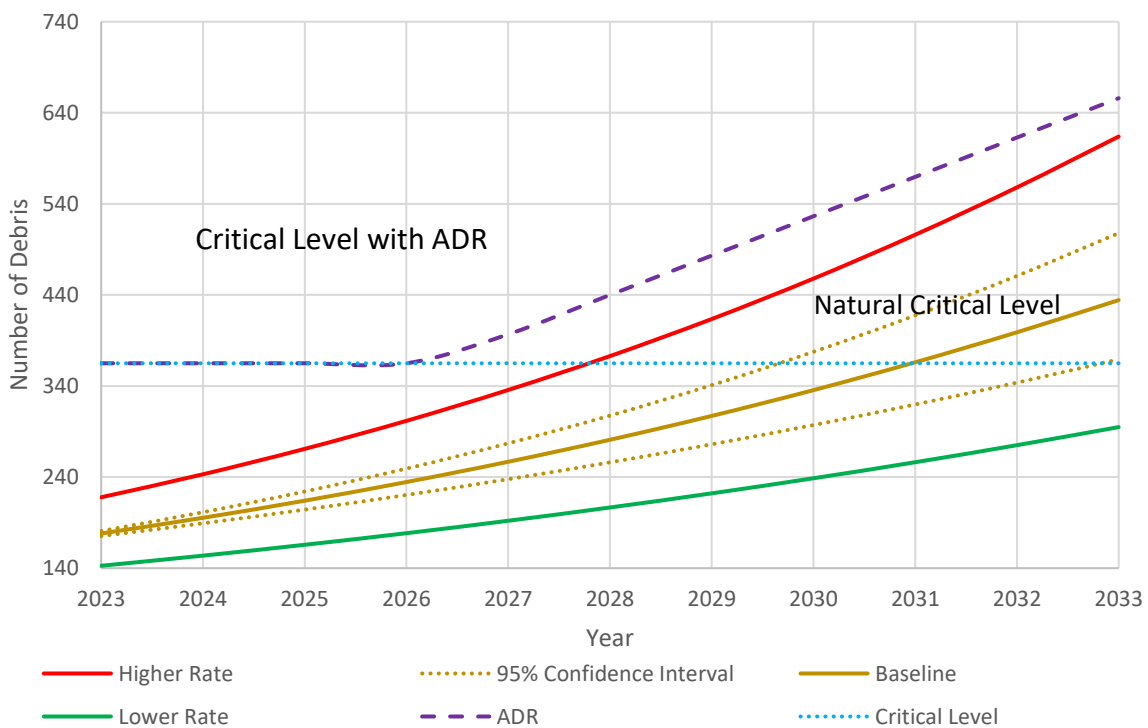


Figure 2-8: Annual projected collision-generated debris in Low Earth Orbit under lower-rate, baseline, and higher-rate scenarios, showing collision debris accumulation, natural atmospheric re-entry, active debris removal (ADR) trajectories, and a defined critical density threshold.

Figure 2-8 presents projected collision-generated debris in Low Earth Orbit under lower-rate, baseline, and higher-rate growth scenarios, alongside natural atmospheric re-entry, and active debris removal (ADR) trajectories relative to a defined critical density threshold. The results indicate that, under the baseline scenario, collision-generated debris reaches the critical density level by approximately 2031, while in the high-growth scenario this threshold is reached as early as late 2027. The inclusion of ADR trajectories demonstrates that active removal has the potential to delay the onset of a Kessler-type cascade, though it does not fully offset collision-driven debris growth under higher-rate scenarios. This gives a window of around 4–8 years to introduce debris mitigation and remediation solution, consistent with what the literature and industry studies report on this point. Some estimate that a Kessler Event has already started because the definition of the critical density varies depending on which LEO altitude is being considered. In any case, left unchecked, space activity could be forced to a grinding halt because of the increase in collision probability (Krisko et al., 2001; Adushkin et al., 2020). The longer we wait for ADR technologies, however, the more costly they become, as discussed in the next section.

2.5 Discussion: debris remediation costs, mitigation measures, and the need for a global regulatory framework

Sustainability in space is under increasing scrutiny, starting from what it means in this specific context, given the multiple interpretations it receives in literature (Purvis et al., 2019). If we adopt, as we did in this study, the UN COPUOS definition applied to the specific context of debris mitigation, it will then entail the maintenance, renewal, or restoration of the item we want to make ‘sustainable’ (Wilkinson et al., 2001). If collisions can be predicted and their consequences mitigated through the adoption of accurate probabilistic methods, this would make the sector more sustainable by increasing safety and reducing the cost of damages.

There is no shortage of mitigation programmes, and, although the market size for the debris removal segment is currently difficult to estimate, some studies have suggested a value of USD 100 m or more per year of activity (Zisk, 2022). ESA has, for instance, two ongoing programs: the *Clean Space Initiative* (set up in 2012 to address the problems related to both debris proliferation and crowded Earth's orbits), and the *Zero Debris approach* (launched in response to a scenario similar to the one we have modelled here, although based on different calculations; ESA 2023).

There are at present no standardised methods or technologies for what is called Active Debris Removal (ADR) technologies. Some of them are at an advanced development stage, while others remain more experimental, and it is unclear when they will be fully operational (Bonnal et al., 2013). A few are under testing (Hakima and Emami, 2018), such as electromagnetic tethers (Hoyt, 2011), nets (ESA, 2014), iron beams (Bombardelli and Peláez, 2012), ground-based lasers (Phipps and Bonnal,

2016; Phipps, 2018; Shen et al., 2014; Fang et al., 2019) and the use of robotic arms (Flores-Abad et al., 2014; Hirzinger et al., 2004).

Market leaders in this field are Clearspace (2023) and Astroscale, (2023b). ClearSpace, the Swiss-based leader of in-orbit servicing created in 2018, secured approximately \$28 m in funding from ESA and other partners to launch in 2026 its first space debris removal mission *ClearSpace-1*. The UK-based (Astroscale, 2023b) is another well-known presence into the ADR sector, with funding of around USD 376 m and both the support of JAXA (Japanese Space Agency) and ESA. Both are good examples of the rising market value predicted for this sector but also the space agencies' growing awareness of the severity of the debris issue. Initiatives such as (Net Zero Space, 2023) or ELSA-D orbital removal mission (Astroscale, 2022) will likely become more frequent in the next coming years.

Assuming the first object could be removed in January 2026, our model projects the possibility to delay a Kessler Event depending on the level of ADR technology. For example, in Figure 2-8, if ADR technology would rise by 10% per month (above the natural critical level), this would delay a Kessler syndrome event until approximately late 2041 (not shown in Figure 4-8) for the high rate. Implementing ADR soon could help achieve a sustainable orbital environment.

As previously discussed, we assumed that all future activity in space would halt, which is unlikely. Therefore, a much stronger ADR policy would need to be introduced to achieve a sustainable level of congestion in space. For example, targeting the high rate to achieve 10k objects in space³ within a decade (i.e., 7 years after starting ADR in January 2026), we would need to remove 3500 debris in 2026, rising at a 30% per year. Cumulatively, this means that approximately 61k debris would need to be removed in the next decade. The Figure 2-9 shows that the base and low scenarios could reach sustainability sooner because their debris growth is slower.

Figure 2-9: The total amount of debris in space with ADR implementation from 2026

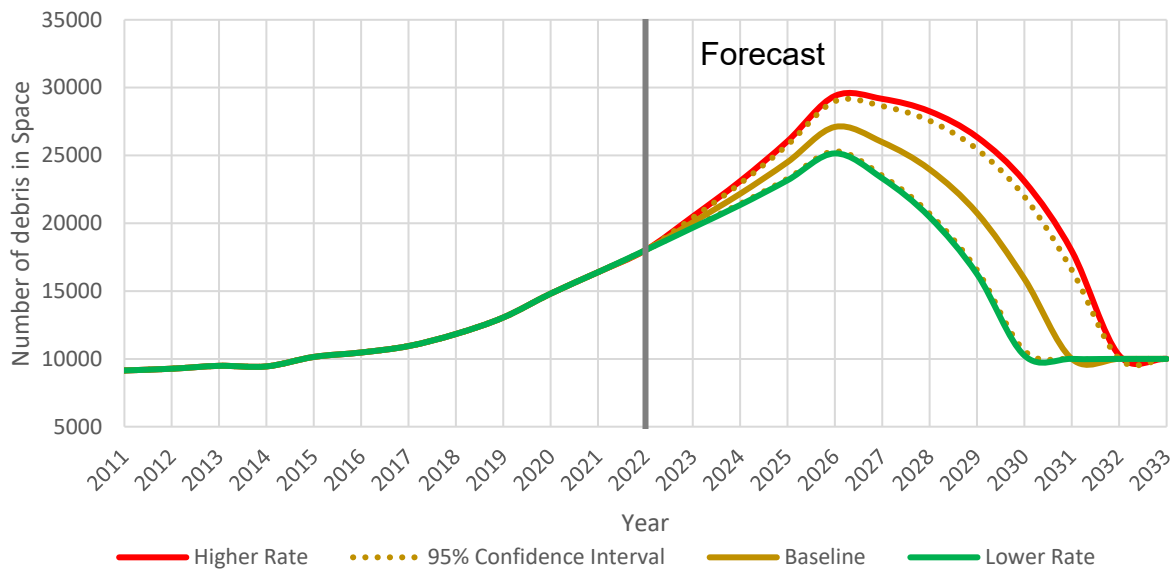


Figure 2-9: Projected total orbital debris trajectories under different active debris removal (ADR) rates, showing the removal intensity required to reduce the debris population to approximately 10,000 objects within a ten-year period.

Figure 2-9 presents projected debris trajectories under alternative active debris removal (ADR) rates, illustrating the scale and pace of removal required to reduce the total debris population toward a target level of approximately 10,000 objects within a ten-year horizon. The figure highlights that only sustained and relatively aggressive ADR rates are capable of reversing debris growth within this timeframe, underscoring the limited effectiveness of incremental removal strategies once critical density levels have been exceeded. A crucial point for the implementation of active measures of debris remediation and removal is, of course, the cost. There are surprisingly very few studies (see e.g., OECD, 2020; NASA, 2023b) that address this specific point, probably related to the high level of industrial operational secrecy. A general estimate of debris-associated costs in GEO has been reported to hover around 5–10% of mission costs (OECD, 2020). Comparable estimates in LEO are unknown, but they are believed to be far higher than that.

(NASA, 2023b) has published in Spring (2023) a cost-benefit analysis of debris remediation, based on an extensive survey among satellite and spacecraft operators. In this report, there are two alternative cost/benefit scenarios of debris removal. The first computes the benefits associated with the removal of top 50 most concerning debris, citing McKnight et al. (2021) estimates at an overall USD 3.5 m in the first year after removal, with a trade-off of several levels of costs depending on the various parameters (e.g., re-entry modalities). The second scenario considers the removal of 100k small fragments (1–10 cm) and provides far higher benefits (USD 23 m in the first year).

(NASA, 2023b) also address the limits of the few existing cost-benefit studies on debris remediation, being either purely qualitative (Schaub et al., 2015), theoretical (Adilov et al., 2018), or

unrealistic (Macauley, 2015) not without mentioning the weaknesses and constraints of their own model. The conclusion is that no-one (including satellite operators and space agencies) has a precise idea of the unit cost of debris and its remediation, a point also highlighted by the National Orbital Debris R&D Plan (National Science and Technology Council NSTC, 2021).

With these caveats in mind and acknowledging that this requires further research based on more extensive data, we attempted an initial cost-benefit estimate from debris removal in our model.

First, we calculated the annual total cost from debris impact at around USD 35 m in 2023 and doubling to USD 66 m by 2033, as the result of multiplying the total cost of replacing a satellite in LEO at around USD 253 m (Vance and Mense, 2013) by the mean annual collision of λ_t (from Eq. (5)). Second, we estimated that the number of LEO debris are around 12.5k in 2023 rising to 23.2k in 2033. This is obtained by multiplying the total trackable objects A_t (see Figure 2-5) by the proportion of LEO objects 65% and by their proportion of LEO debris 60% (ESA, 2023). Finally, by dividing the annual total cost by the number of debris in LEO, we reach a cost-saving per *unit* of debris de-orbited of USD 2,657 ⁶in 2023, which falls to USD 2350 by 2033 (plotted in Figure 2-10).

Figure 2-10: Cost-savings per debris de-orbited (US \$)

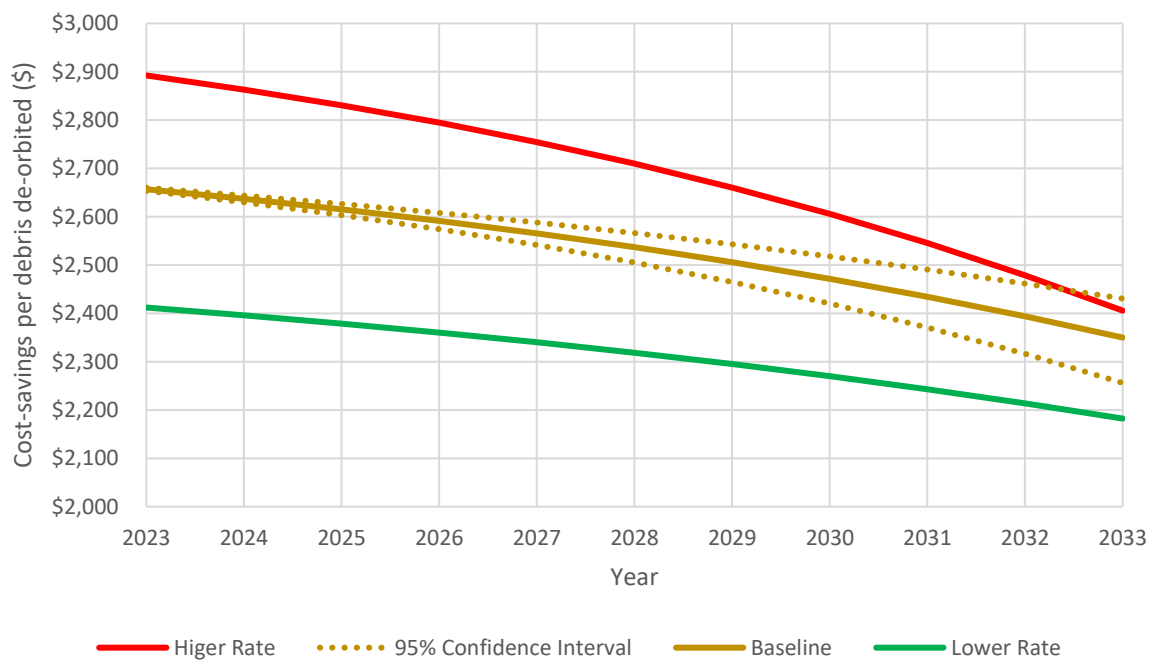


Figure 2-10: Projected cost savings per debris object de-orbited under low-, base-, and high-rate active debris removal scenarios over time.

⁶ A study for an ADR called Project Orion offered an estimate per unit varying in between USD 6000 to USD 300, depending on the power of the specific device used for debris removal (Phipps, 2010). This is overall consistent with our calculations.

Figure 2-10 presents projected cost savings per debris object de-orbited under low, base, and high-rate removal scenarios. The figure shows that while absolute removal costs remain broadly stable, the marginal cost savings per object decline over time as debris density increases and removal becomes more operationally complex. This trend highlights the economic implications of delayed intervention, as higher congestion reduces the efficiency gains achievable through active debris removal strategies. The fall in cost-savings happens because the total number of LEO debris rises faster than the number of LEO satellites launched to replace damaged ones (given that the total volume of LEO space is fixed). The longer ADR is delayed, the less cost-savings is achieved, a point all the studies reviewed here seem, unsurprisingly, to agree with.

However, progresses in space technology and ground-breaking ADR missions are only one side of the debris emergency solution. Underlying this discussion on the cost-benefit of the various technologies, there is the far more complex level of intervention that needs to be actioned to successfully address remediation and designing effective mitigation strategies. This level is not technical, but legal and (geo)political at the same time.

There is little doubt that addressing the debris crisis requires an international effort of coordination to modernise the existing regulatory framework of the space sector (Tronchetti, 2009). The lessons learned from the Cosmos 2251-Iridium 33 collision from 2009 and the protracted level dispute that followed is that the present regulatory framework (in that specific case, the UN Liability Convention of 1972) is not adapted to this 'new space age'. Because the responsibility for enacting space debris mitigation measures lies primarily with countries rather than private operators (Paladini, 2019; Listner, 2011; Kelso, 2012; Wang, 2010; Jakhu, 2010), private companies cannot even autonomously sue for eventual damages. Moreover, the ownership issue (the country that launches the space object retains ownership no matter its status; Baker, 1988; Christol, 1990) can, and already has, prevented any remediation at an international level (OECD, 2020) due to considerations of (i) risk of sovereign breach (Baker, 1988; Christol, 1990), (ii) residual value of the object although derelict (Perek, 2000, 2005), (iii) insurance claim, or even (iv) strategic considerations.

As in the case of other ABNJs, but in a fashion even more acute for the Earth's orbits, the international regulatory framework constitutes the beginning but also the eventual endpoint of many initiatives. Any serious attempt at a global intervention on active debris mitigation will require prioritising and harmonising international space law, beginning with addressing the unique characteristics of Earth's orbits' and distinguishing its 'normative' jurisdiction from the broader domain of outer space. As discussed in Section 2.2, and worryingly in terms of the consequences for the entire sector, satellite market operators and national space agencies likewise, the steps taken by the USA through the 2020 EO, although primarily focused on the exploration and resource extraction of celestial bodies rather than specifically addressing Earth's orbit (Goehring, 2020), appear to lead us in a contrary direction, further complicating the establishment of an effective and sustainable framework for space governance.

2.6 Conclusions

The space sector matters.

Its total valuation has been constantly and steadily growing, reaching USD 469 bln in 2022, from USD 277 bln in 2011 (Space Foundation, 2022), thanks to the increase in private sector involvement, in what used to be a largely government-controlled environment. The satellite market represents the lion share.

But it is important goes far beyond the numbers. What many fail to understand is that satellites are becoming crucial for what they contribute to the rest of the world economy and the civil society.

Their utilisation now spans over many sectors, and some of their services, such as Earth Observation to monitor natural and man-made phenomenon, have become crucial, from addressing climate changes and preventing natural disasters (Löv et al., 2021; Gao and Yuan, 2022; Telmer et al., 2006) to support agriculture and clean transition (Edwards et al., 2022; Hewson et al., 2020; Hill and Nassar, 2019):

The heightened level of attention given to the sustainability of the orbital environment is, therefore, of no surprise (Hakima and Emami, 2018; Usovik, 2023), considering the threat the debris crisis constitutes. NASA (2023a) warns that we may have already reached a critical point, particularly with the emergence of the proposed Starlink-like mega-constellations.

In this article, we contributed to the debate in two way, one empirical and the other theoretical.

Our empirical contribution to the discipline is a model that estimates the number of trackable objects and trackable debris objects based on the probability of collision. According to our estimates, within seven years, a Kessler Event is highly probable unless active mitigation measures (ADR) are introduced. We furthermore discussed the opportunity cost related to mitigation, a topic where research is still limited. Our model is calibrated to industry estimates, and it links the sector's economic growth as the main driver behind these projects. In this sense, the model differs from the others, which instead tend to focus on engineering parameters more than on economics. Our conclusions are in line with comparable studies and highlight the need for urgent action to address debris remediation. Further research on space debris is of the utmost importance, especially as it is technically still possible to delay a Kessler event by implementing ADR strategies.

Our model has a few limitations, some of which it shares with the existing literature and the prediction models discussed in Section 2.5. As it stands, the model provides a rough estimate because it only accounts for collision-based fragmentation and excludes ASAT tests, less frequent but far more damaging in terms of debris production. Furthermore, it only considers a single orbit, though different orbital altitudes have distinct critical densities (due to varying gravitational forces) and could lead to imbalances in population distribution and critical density levels. Limitations, nonetheless, we believe the results are still valid, if anything because they might lead to underestimate, not overestimate the phenomenon. Otherwise said, things can only turn out worse, not better, and contributions in the kind

of our study highlight the urgency of addressing the debris emergencies and highlight the dangers if no action is taken.

In terms of the theoretical contribution to the ongoing debate, this article identifies the root of the debris problem: outdated, overlapping, conflicting legal provisions no longer suitable for the current level of economic activity, and the overall lack of a regulatory framework specific to the Earth's orbits, affirming, instead of denying, their character of 'global commons' and their unique needs.

The centrality of this point cannot be stressed enough.

Unless this intractable conundrum is not addressed, maybe in a similar way of the upcoming High Sea Treaty (2023) adopted in June 2023 currently in ratification, it is unlikely substantial progress is made in time to avoid a Kessler event. As things stand now, the complexity around the orbits' transboundary status hinders achieving a sustainable usage of this resource. To make any international orbital management successful, the regulatory framework must legally allow for it first, starting with the establishment of a sustainable, equitable, internationally agreed space governance. There are no shortcuts.

3 Chapter 3

Charting the Course of Space Tourism toward a Sustainable Future. A cross-cluster thematic analysis⁷

3.1 Introduction and Background

Outer space is not an abstract or infinite frontier, but a finite, structured, and increasingly congested operational environment whose continued usability depends on collective restraint and effective governance (Rebay, 2023). Earth's orbital regions function as a shared socio-technical system, where actions taken by individual actors generate consequences that extend across users, time horizons, and national boundaries (UN COPUOS, 2018; Hardin, 1968). As space activity intensifies, particularly through commercialisation, this identity becomes critical: space is no longer defined solely by exploration or scientific endeavour, but by sustained, routine use under conditions of physical limitation.

This evolving identity has important implications for space tourism. Unlike traditional space activities, space tourism introduces repeated, market-driven demand for launches, orbital access, and supporting infrastructure, embedding tourism within an already strained orbital ecosystem. While tourism is not inherently incompatible with sustainability, its development within a finite and congested environment raises questions about environmental limits, governance adequacy, and equitable access. Understanding space as a shared, capacity-constrained system is therefore essential to assessing how space tourism may amplify sustainability risks and why its growth must be evaluated not only in economic terms, but in relation to the long-term viability of Earth's orbital environment.

The space industry has experienced substantial growth in the past two decades, and space tourism is no exception (Zhang and Wang, 2022), largely driven by private companies (Blue Origin, Virgin Galactic, SpaceX), with or without public funding and mirroring the aviation sector's trajectory, both in terms of technical innovation and industry competition. These dynamics contributed to enhancing safety records and reliability while reducing costs and widening the offering (Webber, 2013).

Space tourism is yet to assume a definite identity, reflecting its status as an emerging and rapidly evolving sector characterised by conceptual ambiguity and fragmented scholarly perspectives. The literature regards it either as a potential extension of commercial aviation (suborbital transportation

⁷ This chapter has been published in the journal of *Transport Policy* see the reference: (Martin-Lawson et al., 2026).

could more than halve travel distance between distance cities such as Singapore to London; Spector, 2020; Peeters, 2010) or as a form of ‘extreme tourism’, due to the risks associated with the process (Crouch et al., 2009; Launius and Jenkins, 2006). A few (Cohen and Spector, 2020c; Laing and Crouch, 2004; Chang and Chern, 2016; Musselman and Hampton, 2020) focus instead on its subcategories e.g., moon tourism, orbital tourism, suborbital tourism, ground tourism. Laing and Crouch (2004) identified six main categories within the space tourism market: (1) Virtual reality (gaining birds eye view to space), (2) Terrestrial (theme parks, space museums, etc), (3) Near-space (very high altitude short periods of weightlessness), (4) Sub-orbital (bringing people to high altitudes to see the earths curvature and blackness of space without leaving earth orbit), (5) Orbital (earth orbital experience lasting hours to days), (6) Interplanetary orbit (going to the moon and beyond).

In economic terms, space tourism has followed an ascending trajectory similar to the space sector. Despite space tourism’s revenue, at approximately \$747.1 million in 2023, representing less than 1% of the total commercial space industry evaluation, the pace has quickened: the projections give it at \$5.2 billion by 2034. This growth is driven by technological advancements and increasing demand (FMI, 2023), with suborbital space tourism expected to contribute to the space industry's projected growth (Musselman and Hampton, 2020).

As an emerging form of extreme/adventure tourism, space tourism faces formidable challenges (Giachino et al., 2023). While the literature in the field is rapidly expanding, there is still a lack of a coherent roadmap about where the sector is heading and how to identify first and subsequently address those challenges.

The present study intends to address the gaps in the literature by identifying the key themes and together suitable research methodologies. Using a SLR (systematic literature review) approach, we examined 291 primary and 9,481 secondary documents (2000-2023, clustered by historiography, document co-citation, bibliographic coupling) to capture past, present, and future dynamics of commercial space tourism (Donthu et al., 2021; Zhang and Wang, 2022).

Three research questions led the investigation:

1. What changes have occurred in the field of commercial space tourism research from 2000 to 2023?
2. What are the primary themes explored in the space tourism literature?
3. What areas are going to emerge as future directions for theoretical and practical research in space tourism that have the potential to steer it to a more sustainable trajectory?

Our study identified 21 key review articles up to 2024, divided into 4 main thematic clusters. The largest cluster (14 articles) focuses on medical and engineering aspects and the potential impact of space flights on the human body, such as: radiation risk (Ali et al., 2020; Grover, 2011), cardiovascular aspects (Krittanawong et al., 2023) human nervous system (Gupta et al., 2023; Van Ombergen et al., 2017).

The next largest cluster consists of four papers (Filatyev et al., 2009; Mazzetti et al., 2016; Knez and Khalilidermani, 2021; Musselman and Hampton, 2020), tackling technology advancements in space exploration (e.g., development of hybrid engines, off-Earth drilling).

Also represented is the psychology of space tourism. (Mehran et al., 2023) analyse tourists' behavioural responses to public opinion on space tourism as well as addressing ethical and environmental concerns; Zhang and Wang (2022) discuss the growing trend of space tourism publications highlighting the rise of studies in tourism-oriented journals.

Building on this assessment of space tourism literature and carrying out a gap analysis, we designed a roadmap for future researchers, identifying specific research directions in terms of insurance policies, cost reduction, environmental impact, and risk perception, and actions required to establish space tourism as a mainstream and sustainable industry.

Section 3.2 explains the methodological approach adopted for the SLR, PRISMA. Section 3.3 provides the explanation of the specific coding methods chosen for our analysis (historiography, document co-citation, bibliographic coupling) as well as content coding for our document selection. Section 3.4 discusses the results while Section 3.5 puts them in perspective, carrying out the gap analysis on the themes identified in each cluster and outlining future paths of the commercial space tourism sector. Section 3.6 summarises the main findings, discusses limitations and avenues for future work.

3.2 Constructing the PRISMA Methodology

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta- Analyse) is a widely recognised structured framework for carrying out systematic reviews and increasing their robustness, ensuring clarity and reliability (Page et al., 2021a, 2021b). Citation analysis, facilitated by technological advancements and databases (such as Web of Science and Scopus) and software tools (e.g., CiteNetExplorer and VOSviewer) has grown in use (Vogel et al., 2021) as it offers a systematic and quantifiable approach to measure impact, quality, and diffusion of research in a variety of fields (Vogel et al., 2021), including tourism sustainability (de Bruyn et al., 2023).

In our study, we use three methods (historiography, document co-citation, and bibliographic coupling) to screen the commercial space tourism field by analysing citation patterns in related documents (Wen et al., 2017). Table 3-1 shows the PRISMA method results, split into three sections: identification, screening and included. Figure 3-1 below summarises the PRISMA screening process applied in this study, illustrating how records were identified, screened, assessed for eligibility, and ultimately selected for inclusion in the systematic review. The diagram provides transparency around the exclusion criteria applied at each stage and demonstrates the systematic narrowing of the literature base used in the analysis.

Figure 3-1: PRISMA flow Diagram.

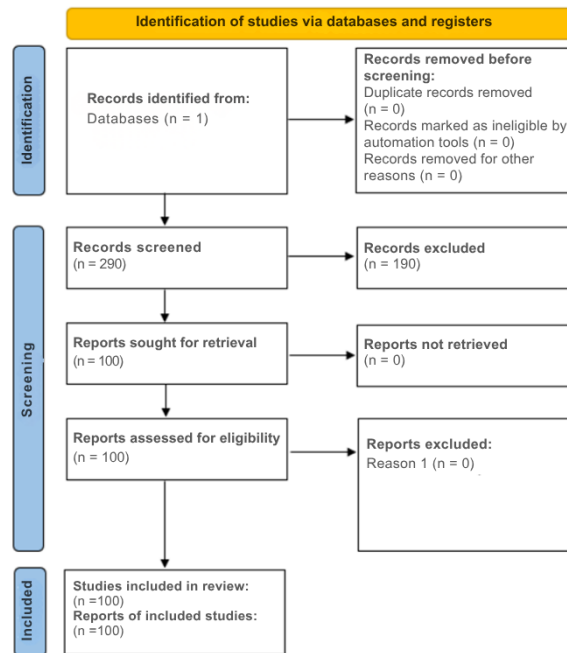


Figure 3-1: PRISMA flow diagram showing the identification, screening, eligibility assessment, and final inclusion of studies in the systematic literature review.

3.2.1 Identification

The pool of documents considered includes primary and secondary sources published in mainstream publishers, omitting working papers and blogs (not usually peer reviewed).

Primary documents are those directly identified through our search string, while secondary documents are those cited therein. To assemble the dataset of primary documents, we used Web of Science (WoS)' advanced search strings (Zupic and Čater, 2015)⁸, keywords: "space tourism," "space commerce," and "commercial space industry", date range of 2000-2023, roughly coinciding with the launch of the first space tourist, Dennis Tito, in 2001 (Chang, 2015a).

Our selection approach returned 291 primary documents and 9,481 secondary documents to be screened further.

3.2.2 Screening

Table 3-1 summarises the three bibliometric and network-based methods used to screen and classify the initial document set. Each method applies a different analytical lens to identify influential publications and structural relationships within the literature. The designation of "top documents" is based on citation strength and network position, allowing the analysis to capture both highly cited works

⁸ (((TS=("space tourism" OR "space commerce" OR "commercial space industry")) AND PY=(2000-2023) AND DT=(Article OR Book OR Book Chapter OR Review OR Editorial Material))) AND LA=(English)

and structurally important contributions within the research field. Together, these methods support a robust and transparent selection process for the subsequent cluster analysis.

Each method (historiography, document co-citation, and bibliographic coupling) serves a unique purpose in addressing different factors of the field's development. Thematic clusters were created based on citation data and relationships using software-powered elaboration (CitNetExplorer and VOSViewer). Historiography, based on citation scores and temporal analysis, traces the chronological evolution of commercial space tourism research, identifying changes over time. Document co-citation offers insights into the intellectual structure and primary themes within the field by revealing which secondary documents are frequently cited together. Finally, bibliometric coupling sheds light on emerging trends and future directions by identifying primary documents that cite the same secondary sources.

Table 3-1: Overview of three bibliometric techniques

HISTORIOGRAPHY	DOCUMENT CO-CITATION	BIBLIOMETRIC COUPLING
INDICATOR OF DOCUMENT STRENGTH		
Citation score = frequency of citations of a primary document by other primary documents	Co-citation strength = frequency two secondary documents are cited by primary documents	Coupling strength = frequency primary documents cite the same secondary document
Unique components		
Shows the evolution of the commercial space tourism field over time	Shows authors being cited together to show the roots of the commercial space tourism field	Shows the current trend of the commercial space tourism field and the emerging future topics
Focus		
Primary documents and their chronological citations with other primary documents	Secondary documents that are cited together in primary documents	Primary documents that cite the same secondary documents
Temporal Focus		
Past looking at field evolution	Past looking at intellectual structure and theoretical underpinning	Future looking at emerging topics and gap spotting
Research Question answered		
What changes have occurred in the field of commercial space tourism research from 2000 to 2023?	What are the primary themes explored in research related to commercial space tourism?	What are the promising directions for both theoretical and practical research in the future?
Software used		
<i>CitNetExplorer</i>	<i>VOSviewer</i>	<i>VOSviewer</i>

Table 3-1: Summary of bibliometric and network-based screening methods used to classify and prioritise documents for cluster analysis.

Historiography was the starting point to map the evolution of space tourism, using *CitNetExplorer* (Van Eck and Waltman, 2017; Liu et al., 2013). By defining two different documents as, e.g., document

A and B, historiography considers the link between two primary documents from our keyword search and establishes a link based on historical knowledge flow, and topic similarity (Liu et al., 2013) also enabling a transfer of knowledge. The level of significance of a primary document is determined by the number of citations it receives, with a cluster defined by three or more documents of thematic similarity. CiteNetExplorer visually depicts the network of all the documents with a cite score greater than or equal to 4⁹ representing the top 50 documents, with the Y-axis representing the publication year and document closeness illustrated on the X-axis (van Eck and Waltman, 2014; Van Eck and Waltman, 2017), showing changes over time in the sector.

Document co-citation highlights pairs of secondary documents cited together in primary documents, to emphasise semantic similarity, with two outcomes: (i) co-citation link-strength to measure a paper's significance to the field, and (ii) cluster visualisation highlights thematic similarities (Vogel, 2012), calculated by the number of the same secondary documents cited together in multiple primary documents. We used VOSviewer, a software tool to visualise citation data (Van Eck and Waltman, 2017), over a pool of 3,690 secondary documents, focussing on those cited at least 8 times by primary documents. The exercise returned 30 secondary documents in three clusters. It is important to notice that document co-citation is retrospective, limited by its focus on frequently cited secondary documents and potentially excluding newly created documents due to limited time in the academic space (Vogel et al., 2021).

Bibliometric coupling, which offers analytical insights into the current state of the field and facilitates the identification of trending priorities. The coupling link strength increases with the number of references two documents share. For instance, if primary documents A and B both cite secondary documents C, D, and E, they are considered "bibliometrically coupled," with a coupling link strength of three. Bibliometric coupling differs from document co-citation in that it focuses on primary documents in the visualisation. Secondary documents tend to be placed further in the past as secondary documents represent papers that have been published before the primary document that cites them. Due to this bibliometric coupling focuses on current themes that have been developed from past themes in significant secondary documents since the focus is on primary documents. However, document co-citation is different because the focus is now on the past (secondary documents) and the relevant papers from the past that were cited frequently. This means that those older documents (secondary documents) represent the thematic roots of the current field of space tourism. In this instance, we analysed all the documents with a citation threshold of 19 citations, to filter out documents with minimal citations and less likely to make a substantial impact on the analysis.

⁹ A cite score is a metric used by CiteNetExplorer to determine a documents level of influence on a field, i.e., the higher the number the stronger the influence of the document.

3.2.3 Inclusion: Content Coddng of the Top 100 Documents

The next step was to identify the “top 100 documents” through the combined results of the three different methods as discussed above, selected from the WoS-generated list of 291. To achieve this result, we consolidated the three top 100 lists made based on the document strength using the three different methods, ordered by the strongest document by list and ranked according to their presence in one, two or three. 35 documents appeared in all three, 32 documents in two, and the remaining 33 documents in just one list.

The breakdown of the document is 90 articles, 6 editorial, and 4 review papers, published between 2000 and 2023 with most of the publications (16) being in 2020. Dominant journals included *Acta Astronautica* (27 documents) *Space policy* (10), *Journal of British Interplanetary Society* (8), *Tourism Recreational Research* (8), with the other journals contributing less than 6 publications each. Of the top 100 documents, only 5 authors contributed more than 2 documents, Spector S (8), Collins P (5), Chang YW (4), Cohen E (4) and Higham J (3).

3.3 Data Presentation and Analysis

We have presented here the results visualised according to the three methods of analysis and their respective clusters, before discussing the final top 100 document diagram in the final visualisation. In chapter 3 clusters are discussed in numerical order as generated by the respective clustering algorithms. These numerical labels reflect software output rather than thematic importance, size, or hierarchy, and are retained for transparency and reproducibility. In the case of CiteNetExplorer, clusters are visualised to reflect historiographic significance, with clusters numbered from smallest to largest in ascending numerical order. By contrast, VOSviewer visualises clusters from largest to smallest while still assigning ascending numerical labels. Given these tool-specific differences, the chapter consistently follows the numerical cluster sequence in the discussion to maintain clarity and consistency between figures, tables, and text. The sequence of cluster presentation reflects the objective presentation of results and does not imply analytical priority or conceptual progression, as interpretation is developed in the subsequent sections.

3.3.1 Historiography

Figure 3-2, below visualises the historiographic network of the 100 most influential documents in commercial space tourism research. The figure illustrates the historical development of the field by mapping citation relationships between key publications over time, revealing four distinct thematic clusters that represent different strands of research. Together, these clusters show how the literature

has evolved from early conceptual discussions toward more recent debates on commercialisation, governance, and sustainability.

Figure 3-2: Visualisation of historiography clusters

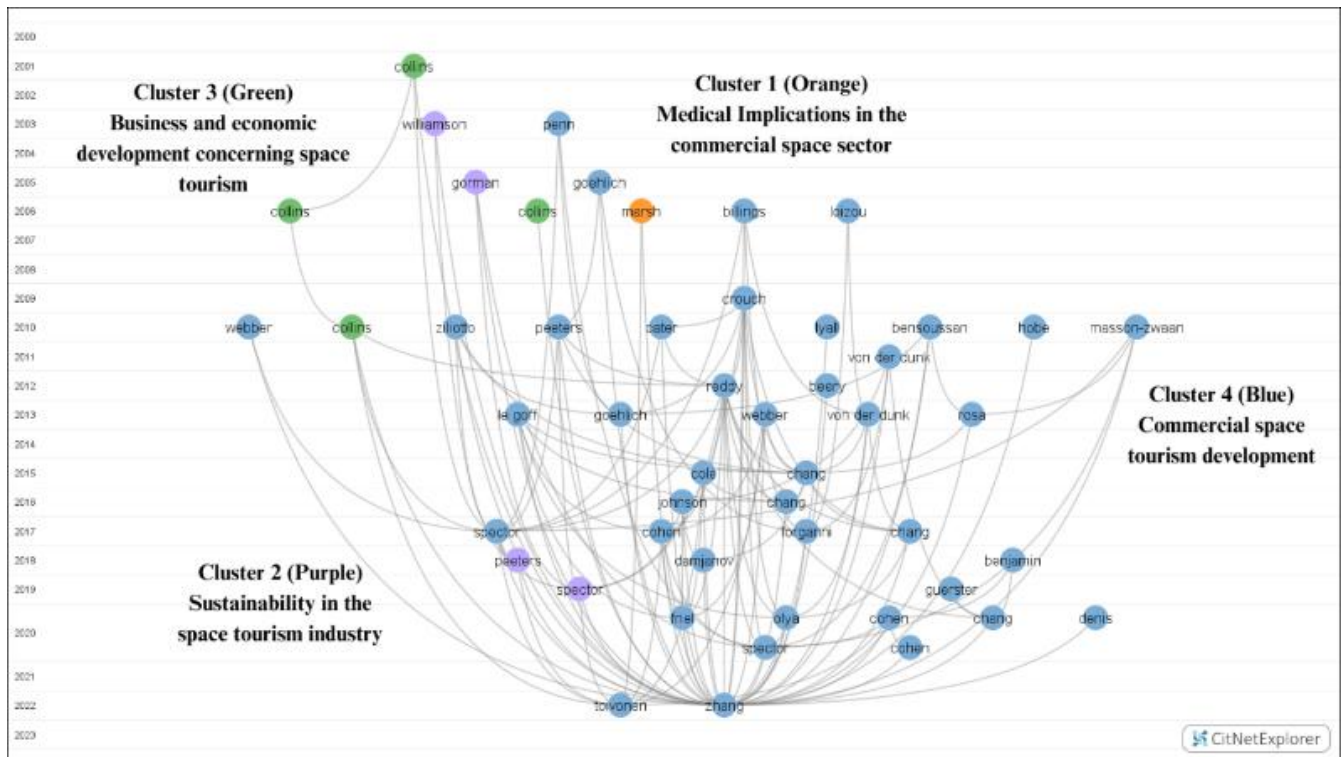


Figure 3-2: Historiographic network of the 100 most influential publications in commercial space tourism research. Nodes represent individual documents, lines indicate citation relationships, and colours denote thematic clusters (Cluster 1: orange; Cluster 2: purple; Cluster 3: green; Cluster 4: blue).

Table 3-2 summarises the four historiographic clusters identified in the commercial space tourism literature, outlining their dominant themes, key publications, and temporal focus. The table complements the historiographic network analysis by clarifying how distinct strands of research have developed and contributed to the evolution of the field over time.

Table 3-2: Summary of significant documents in each cluster (Top 100, historiography)

Author and Year	Document description	Citation Strength
Cluster 1 (orange) Medical implications in the commercial space sector		
(Marsh, 2006)	Explores emerging challenges in space tourism	6
Orme (2017)	Explores how space tourism poses challenges to traditional telemedicine	2
Cluster 2 (purple) Sustainability in the space tourism industry		
(Peeters, 2018)	Examines the sustainability space travel and outer-space migration	9
(Spector and Higham, 2019)	Explores the relationship between space tourism and the Anthropocene	9
Cluster 3 (green) Business and economic development concerning space tourism		
(Collins and Autino, 2010)	Argues that passenger space travel could have significant economic and social benefits	13
(Collins, 2001)	Explores how government space agencies are failing to promote the development of space tourism	8
Cluster 4 (blue) Commercial space tourism development		
(Reddy et al., 2012)	Proposes research dimensions for investigating the space tourism industry and examines the motivations of space travellers	27
(Crouch et al., 2009)	Uses stated preference experiments to explore how potential consumers react to different options in space tourism	24

Table 3-2: Summary of the four historiographic clusters in commercial space tourism research, including dominant themes, representative publications, and period of influence.

Cluster 1 (orange): Medical Implications in the commercial space sector: focuses on the medical implications in the commercial space sector and more specifically space tourism, highlighting potential issues such as, radiation exposure, decreased cardiovascular efficiency, increased risk of kidney stones, and immune system suppression (Orme, 2017; Tarzwell, 2000; Marsh, 2006). Medical space research faces constraints due to limited access to space research facilities (the ISS), and lack of data (Grigoriev et al., 2009). This would explain why the field has recently stalled: of the three papers, only one has a recent publication (2017) with the other two being in 2000, and 2006.

Cluster 2 (purple): Sustainability in the space tourism industry. According to some estimates (Peeters, 2018) if 1,000 spacecraft were launched in a year global temperature could increase up to 1°C. The focus of this cluster is on human space exploration beyond Earth rather than just on space tourism (Peeters, 2018; Cohen and Spector, 2020a; Spector, 2020). 4 papers were published in the last 5 years, signalling growth of a potential new topic in the field.

Cluster 3 (green): Business and economic development concerning space tourism: (Collins and Autino, 2010) emerged as a leading source and the first to publish on this topic with public choice

economics and space policy: realising space tourism, followed by 4 papers all on the macro and micro benefits of space tourism (Collins and Autino, 2010).

Cluster 4 (blue): Commercial space tourism development, the biggest one, and a sort of residual category. The high fragmentation here may be attributed to the novelty of the field itself and intensified by the tendency of most authors to contribute only 1 or 2 studies (Mora et al., 2017). This is a common occurrence, as emerging fields of research often encounter fragmentation as scholars strive to define the framework and fundamental principles within the discipline. Of the top three documents in this section, Reddy et al (2012) and Webber (2013) have different focuses. Reddy et al’ (2012) paper focuses on research dimensions for future research and the perception of space travel by potential consumers and Webber (2013) keeping a more general approach and focusing on the history and the potential direction of the sector.

3.3.2 Document Co-Citation

Figure 3-3 visualises the document co-citation network of the 30 most influential publications in space tourism research, grouped into three thematic clusters based on shared citation patterns. The clustering highlights how core strands of the literature are organised around closely related theoretical and empirical concerns within the field.

Figure 3-3: Visualisation of document co-citation clusters.

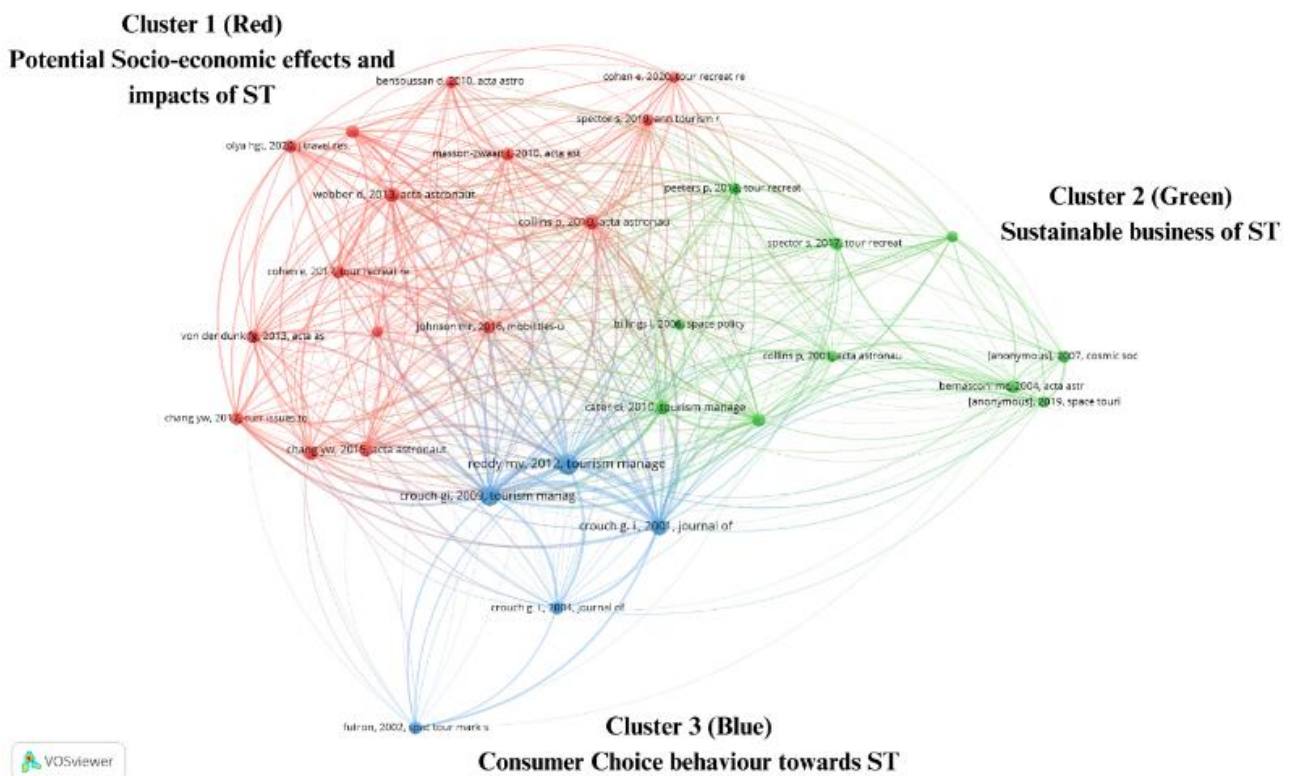


Figure 3-3: Document co-citation network of the 30 most influential publications in space tourism research, showing three thematic clusters based on shared citation relationships. Note: ST = Space tourism.

There are 15 documents in cluster 1 (red) which 157 citations between them, 10 documents in cluster 2 (green) and 92 citations and 5 documents in cluster 3 (blue) and 90 citations. Cluster 3 is the smallest but with the largest documents by citation number (Reddy et al., 2012; Crouch et al., 2009; Crouch, 2001). The document with the largest co-citation link strength (198) is Reddy et al (2012), a paper on space tourism research recommendations published in *Tourism Management*, addressing one crucial, early question to space tourism, “who will be the potential consumers?”. Instead of using economic trends to predict consumer choice behaviour, Reddy used quantitative questionnaires for residents as well as qualitative interviews with key industry informants in the UK, providing research recommendations for the space tourism field.

Below, Table 3-3 summarises the most significant documents within each co-citation cluster, highlighting key contributions and their relative importance within the network. Higher co-citation link strength values indicate documents that occupy more central positions in the literature and exert greater influence on the structure of space tourism research.

Table 3-3: Summary of significant documents in each cluster (Top 30, document co-citation)

Author and Year	Document description	Co-Citation link strength
Cluster 1 (red) Socio-economic effects and impacts of space tourism		
(Collins and Autino, 2010)	Explores macroeconomic impacts of the space tourism	136
(Cohen, 2016)	Explores the development of the space tourism: a sociological perspective	116
(Webber, 2013)	the history and future of space tourism	116
Cluster 2 (green) Sustainable business of space tourism		
(Cater, 2010)	Explores the developments of space tourism while defining astrotourism	125
(Peeters, 2010)	Explores the development of suborbital space flights to commercial personal spaceflights	112
(Peeters, 2018)	An article challenging sustainable space tourism	100
Cluster 2 (blue) Consumer Choice behaviour towards space tourism		
(Reddy et al., 2012)	Explores research dimensions as well as potential consumers of space tourism	198
(Crouch et al., 2009)	Explores consumer choice behaviour of space tourism	188
(Crouch, 2001)	Explores early indications of the space tourism	165

Table 3-3: Summary of the most influential documents within each document co-citation cluster in space tourism research, showing thematic focus and co-citation link strength.

Cluster 1 (red): Socio-economic effects and impact of space tourism. 46% of the documents were published in *Acta Astronautica*, a technical journal looking at the development of space science technology and space exploration.

These documents mainly focused on general macroeconomic components of the sector as well as regulatory mechanisms of space tourism. Collins and

(Collins and Autino, 2010), with the largest co-citation link strength, addresses macroeconomic benefits of commercial space tourism, including how the advancements in technology could lead to a carbon-neutral space environment. Other documents in the sub-group (Olya and Han, 2019) follow a similar approach while some deal with demand analysis for commercial space tourism. Olya and Han (2019) use cumulative prospect theory to investigate the motivation and risk concerning the demand for space tourism, whereas Le Goff and Moreau (2013) use interviews to estimate market size to draw conclusions.

Cluster 2 (green): Sustainable business of space tourism: the majority are older papers published before 2020, with only 30% of the documents were published between 2011-2020. Publications also show a lower co-citation link strength (smaller circles), signalling lower level of semantic similarity. Most of the documents in this cluster focus on the sustainability side of the space tourism industry, from negative expectations Peeters (2018) to more positive views (Spector et al., 2017).

More specifically, Peeters (2010) discusses sustainability of space travel in the long run, examining interior design as well as potential market trends that could lead to success or failure of the industry, concluding against its feasibility in sustainability terms Peeters (2018). Bernasconi and Bernasconi, (2004) argue that space tourism industry can facilitate the so-called 'space option' for society, i.e., the use of resources from space to address issues to life on earth (Bernasconi and Bernasconi, 2004). Space tourism is seen a 'makeshift' springboard to resource gathering in space through the advancement of technology. With the development of terms such as circular economy, sustainability has become an increasingly important topic relevant in industry, with the space tourism not being exempt (Newman and Williamson, 2018).

Cluster 3 (blue): Consumer Choice behaviour towards space tourism: this is related to cluster 1 but instead of focusing on consumer behaviour it specifically models the demand for space tourism. It is the smallest of the

clusters, with only 5 documents but with three of them with highest co-citation link strength (Crouch, 2001; Crouch et al., 2009; Reddy et al., 2012) and the highest level of significance.

Futron (2002) with a space tourism market study, is comparatively separated from the other in the cluster. This separation is seen with the gap between this paper and the other 4 documents. Reddy's contribution to the field, as mentioned above, underlies the link between Cluster 3 and Clusters 1 and 2, while Crouch et al (2009), the second highest, model consumer choice behaviour towards space tourism has a large contribution to the field having the second largest co-citation link strength. One of its conclusions is that people have different preferences and behaviours and understanding them will be a key ingredient in the industry's success. Moreover, Crouch's publication in 2001 predates the majority of the works found within cluster 2, making this paper a bridge connecting clusters 3 and 2.

Overall, this method shows that consumer behaviour towards space tourism is a key variable, represented by high co-citation link strength and showing a continuous presence in the historical development of the field.

3.3.3 Bibliometric Coupling

Figure 3-4 visualises the bibliometric coupling network of the ten most influential publications in space tourism research, grouping documents into three thematic clusters based on shared reference patterns. The analysis identifies three clusters with differing levels of influence within the field: Cluster 1 (red) comprises publications with a combined total of 185 citations, Cluster 2 (green) includes 94 citations, and Cluster 3 (blue) accounts for 55 citations. These differences reflect varying degrees of thematic centrality and scholarly impact within space tourism research.

Figure 3-4: Visualisation of bibliometric coupling clusters (Top 10 documents)

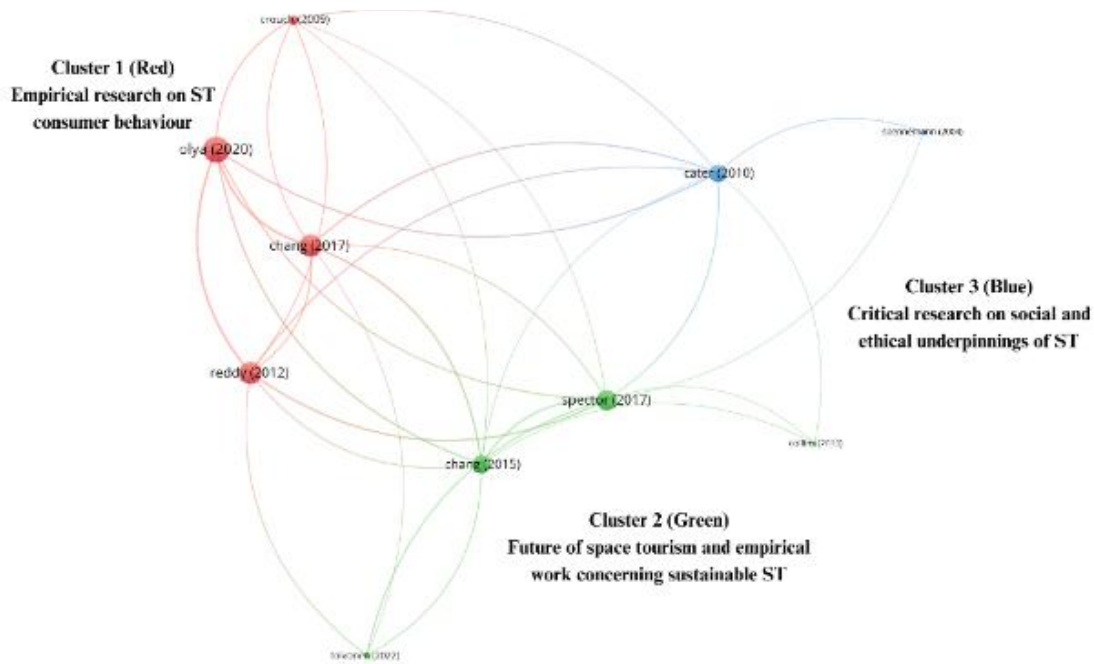


Figure 3-4: Bibliometric coupling network of the ten most influential publications in space tourism research, showing three thematic clusters based on shared reference patterns and citation strength. ST = Space tourism.

Table 3-4 disaggregates the bibliometric coupling network shown in Figure 3-4 by listing the most significant documents within each of the three identified clusters and their associated coupling strength. Higher bibliometric coupling values indicate stronger shared reference patterns and greater centrality of the document within its respective thematic cluster.

Table 3-4: Summary of significant documents in each cluster (Top 10, bibliometric coupling)

Author and Year	Document description	Bibliometric coupling strength
Cluster 1 (red) Empirical research on space tourism consumer behaviour		
(Olya and Han, 2019)	Explores behavioural intentions of space tourism consumers	28
(Reddy et al., 2012)	Explores research dimensions and potential consumers of space tourism	24
Cluster 2 (green) Future of space tourism and empirical work concerning sustainable space tourism		
(Spector et al., 2017)	Explores sustainability in space tourism development	22
(Chang, 2015b)	Explores the past and future prospects of space tourism	20
Cluster 2 (blue) Critical research on social and ethical underpinnings of space tourism		
(Cater, 2010)	Discusses the present and future of astrotourism	19
(Spennemann, 2004)	Explores the preservation of lunar heritage	3

Table 3-4: Summary of the most significant documents in each bibliometric coupling cluster (Top 10), including bibliometric coupling strength as an indicator of thematic relatedness and influence within the network.

Cluster 1 (red): Empirical research on space tourism consumer behaviour: of the top 10 documents, 4 of them belong to this cluster. (Olya and Han, 2019) has the largest contribution with a total coupling link strength of 28. These articles adopt cumulative prospect theory to explain associations and motivations behind space tourism from a consumer’s point of view, concluding that motivational factors (i.e. adventure, gratification, new experiences etc) contribute to consumer demand while risk factors (i.e. phycological, financial and safety) can weaken it. The other three documents also contribute to the consumer demand field with their own empirical approaches to understand the consumer mindset towards becoming an astrotourist.

Cluster 2 (green): Future of space tourism and empirical work concerning sustainable space tourism, includes 4 out of 10 documents with two focusing on sustainable space tourism and the other two focusing on what the field may look like in the future. One crucial element here is the macro-level approach, i.e., the broader landscape encompassing the industry, economy, and sustainability, in direct contrast to Cluster 1, which concentrates on micro-level analysis of consumer behaviour. Spector et al (2017) and (Chang, 2015b) contribute to the cluster evenly with coupling link strength of 22 and 20 respectively. Spector et al (2017) is an exploratory publication highlighting the importance of sustainable space tourism while (Chang, 2015b) discusses technical aspects in the history and future development of space tourism.

An attentive analysis of Figure 3-3. will show that Clusters 1 and 2 have merged in Cluster 2 of Figure 3-4, which means that the two clusters that represented around 83% of all past publications now represent only up to 40% of the sources included in the bibliometric analysis. This signals a saturation of papers discussing the future direction of space tourism, probably due to the scarcity of actual industry data available for forecasting and scenario analysis.

Cluster 3 (blue): Critical research on social and ethical underpinnings of space tourism: only consists of two publications of the two (Cater, 2010) has a much larger coupling link strength of 19 to (Spennemann, 2004) with only 3. The first discusses present-day and future advancements within the space tourism industry, including ethical issues. while the other leans heavily into the ethical standpoint of space tourism and heritage preservation, such as Neil Armstrong's footprints on the lunar soil.

3.4 Bringing all together. The top 100 documents in space tourism literature.

The analysis carried out in the previous section allows us to map out the field in the most relevant thematic clusters, which will prove essential to define, in the next section, the existing gaps and together the pathways for the future of space tourism as previously defined.

Figure 3-5 visualises the bibliometric coupling network of the 100 most influential publications in space tourism research, revealing eight thematic clusters based on shared reference patterns. The breadth of clusters highlights the conceptual fragmentation of the field. Although only a subset of documents met the citation threshold required for detailed coupling analysis, examining the wider set of influential publications provides a clearer overview of the intellectual structure and thematic diversity of space tourism research. The field's fragmentation is evident when considering that only 10 documents were retained from a pool of 100 for bibliometric coupling analysis, when a minimum of 19 citations was required for inclusion. Examining the ensemble of these 100 documents, however, still provides a clearer understanding of the field's overall landscape.

Figure 3-5: Visualisation of bibliometric coupling clusters (Top 100 documents)

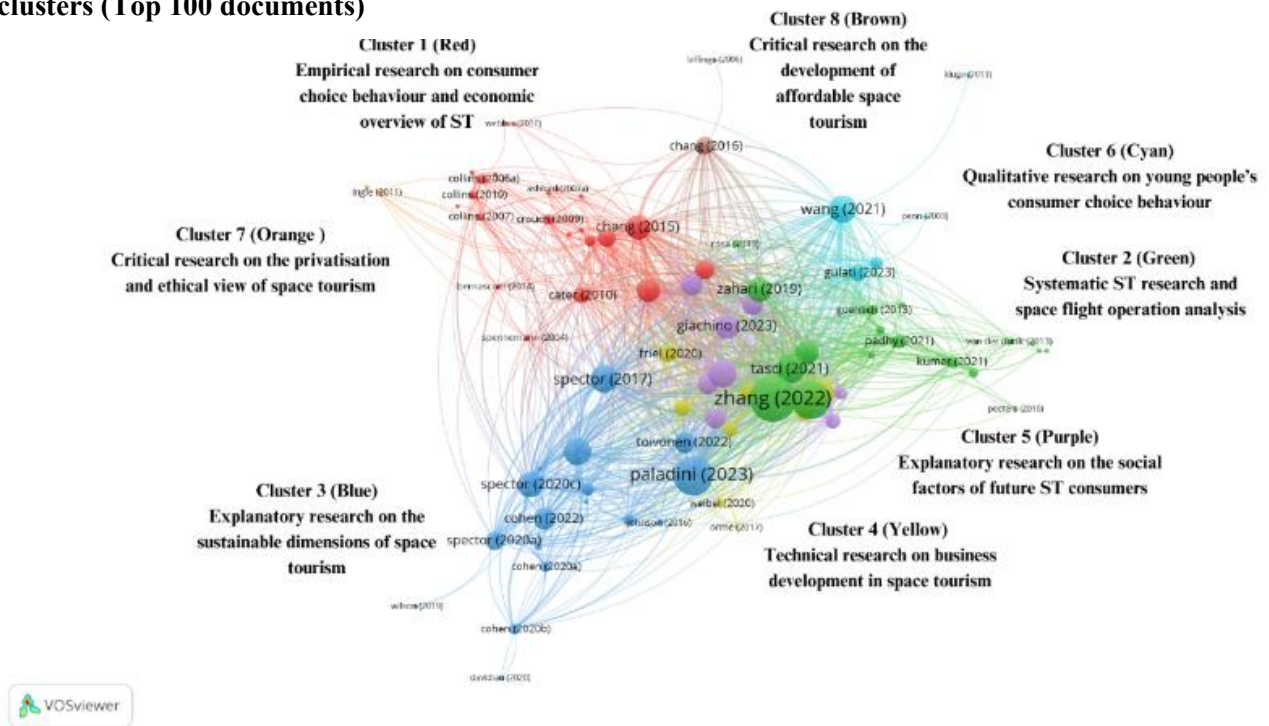


Figure 3-5: Citation network of the 100 most influential documents and eight clusters based on bibliometric coupling. Distinct colours are used to represent different clusters to which primary documents have been assigned (cluster 1 red, cluster 2 green, cluster 3 blue, cluster 4 yellow, cluster 5 purple, cluster 6 cyan, cluster 7 orange, and cluster 8 brown). Clusters represent closely related papers which share thematic similarities. ST = Space tourism.

Some of the documents have no links to any other documents and thus have been omitted from the visualisation, leaving 84 documents. Table 3-5 displays the link strength, which signifies the overall strength of bibliometric coupling connections for a specific document concerning other documents. A higher number signifies greater significance within the network for the document.

Table 3-5: Summary of significant documents in each cluster (Top 100, bibliometric coupling)

Author and Year	Document description	Bibliometric coupling strength
Cluster 1 (red) Empirical research on consumer choice behaviour and economic overview of space tourism		
(Chang, 2015b)	Examines space tourism's history, market demand and challenges,	154
(Río-Rama et al., 2022)	Explores tourists' preferences and willingness to pay for developing land resources for space tourism	148
Cluster 2 (green) Systematic space tourism research and suborbital flight operation analysis		
(Zhang and Wang, 2022)	Examines 109 space tourism papers showing the progress of space tourism	418
(Mehran et al., 2023)	Explores emerging space tourism market	371
Cluster 3 (blue) Empirical research on the sustainable dimensions of space tourism		
(Paladini and Saha, 2023)	Examines sustainable space tourism, and the industry's need for reconceptualising sustainability	330
(Spector and Higham, 2019)	Examines the link between space tourism and the Anthropocene	186
Cluster 4 (yellow) Technical research on business development in space tourism		
(Mesa-Arango et al., 2023)	Explores future U.S. space tourism demand, emphasising key missions and influencing factors	201
(Musselman and Hampton, 2020)	Evaluates demand, ticket cost, motivation, health risk, and policy in suborbital space tourism	97
Cluster 5 (purple) Explanatory research on the social factors of future space tourism consumers		
(Pásková et al., 2021)	Examines astrotourism, categorising as niche/mass tourism	198
(Giachino et al., 2023)	Examines commercial space travel's future	159
Cluster 6 (cyan) Qualitative research on young people's consumer choice behaviour		

(Wang et al., 2020)	Examines tech impact on space travel cost	191
(Gulati, 2023)	Explores space tourism research gap with analysis of Twitter data	89

Cluster 7 (orange) Critical research on the privatisation and ethical view of space tourism

(Ingle, 2011)	Explores space tourism history	13
(Marsh, 2006)	Examines medical and ethical issues in space tourism	1

Cluster 8 (brown) Critical research on the development of affordable space tourism

(Billings, 2006)	Explores space tourism's emergence, focusing on suborbital flights	99
(Chang and Chern, 2016)	Explores space tourism history	1

Table 3-5: Some of the documents have no links to any other documents and thus have been omitted from the visualisation, leaving 84 documents. Table 3-5 displays the link strength, which signifies the overall strength of bibliometric coupling connections for a specific document concerning other documents. A higher number signifies greater significance within the network for the document.

A total of 8 clusters (red, green, blue, yellow, purple, cyan, orange, and brown) are present, proving what already mentioned about the fragmentation of commercial space tourism research. Dennis Tito's historic journey in April 2001 marks the inception of commercial space tourist (Chang, 2015a), which, as a field of research is therefore only 23 years old as of the writing of this article.

Due to the novelty, key concepts are explored in conjunction with the technological developments of this industry. The medical research cluster discovered in historiography is a good example, limited as it is by the development and availability of laboratories and research facilities that can take advantage of zero gravity research and consistent space travel. This state of things explains both the slow evolution in the literature in space tourism but also the multiple concepts explored at the same time, instead of polarising around a couple of main concepts and directories.

Furthermore, there is a significant amount of overlap between clusters 4 (yellow) and 5 (purple) at the central intersection point, giving rise to what we have identified as 'indistinctive clusters.'

Cluster 4 (yellow) exist between the three main clusters, and it is due to which theme the cluster represents: *Technical research on business development in space tourism*. This topic is general and relates to all three of the main clusters (red, green and blue) represented by the links to each cluster and centrally located. In the case for the Cluster 5 (purple) what causes the overlap with Cluster 4 is likely due to the journals where these documents have been published, 62% being multidisciplinary outlets. As such, the two clusters are likely to have theoretical underpinnings that span a variety of disciplines.

3.5 Looking forward: where space tourism is heading to and how to make it sustainable.

One important result of the SLR analysis carried out in the previous section is that it enabled us to identify what we can call ‘cross-cutting clusters’, i.e., thematic clusters that were present in at least two of the three forms of bibliometric analysis and are therefore likely to represent not only the strong foundation of space tourism literature from inception but also the pathways to future research. There are three main cross-cutting clusters so identified: (i) sustainable space tourism, (ii) consumer choice behaviour, and (iii) socio- economic effect.

(i) Sustainable space tourism

Sustainable space tourism is the only cluster that spans over the findings of the three methods, due to the growing importance and debated around sustainability in the space sector.

The United Nations’ Committee of the Peaceful Uses of Outer Space (UN COPUOS) definition- *‘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,’* (UN COPUOS, 2018) -is merely the starting point of a theme that is now central in the space industry and that should include space tourism as a particularly problematic area of discussion, present and especially future.

If anything, this is a clear demonstration of the overall awareness of its centrality in terms of research but also that further efforts must be put to make sure to steer the sector in the right direction, as discussed in section 3.6.

(ii) Consumer choice behaviour

Consumer choice behaviour is the second cross-cutting cluster and, although the smallest cluster in document co-citation, it is the joint largest cluster in the bibliometric coupling analysis with the biggest contribution to the field, which highlights its growth in importance over time. Any business that provides goods or services usually considers the economic principle of supply and demand (Whelan et al., 2001). Significant importance is placed on the potential consumer demand and the ability to model and quantify this phenomenon. Consumer choice behaviour has become a key concept in the field represented Figure 3-4. and this is due to the importance of understanding what affects the decisions perspective customers make (Crouch et al., 2009). Like sustainable development, consumer choice behaviour is likely to remain a key theme in the field.

(iii) Socio-economic effects and impacts of space tourism.

Differently from the other two, the cross-cutting cluster of socio-economic effects of space tourism, initially prominent through document co-citation, has known a comparative decline, reflecting space tourism’s evolving focus on specialised topics instead of macro-level overviews. Although still relevant,

it is still matter of debate whether the socio-economic aspects remain central or become subsumed under broader concepts.

Based on these thematic clusters, we can now attempt a charting of where space tourism, and the academic debate about it is, or should be, heading next.

3.6 The next ten years: research gaps, future directions, and emerging themes

The evidence collected from our SLR and bibliometric analysis, together with the exploration of the cross-cutting clusters enable us to identify both existing gaps in the space tourism literature and define pathways to address them in future research.

There are the four dimensions (intended both as gaps and research directions) identified: (i) new theoretical paradigm, (ii) environmental impact,

(iii) risk mitigation and insurance, and (iv) affordability, each of them discussed in detail in the following sections.

Table 3-6 highlights the key future research directions identified in the literature, outlining their primary aims alongside potential methodological approaches. Each research direction is subsequently discussed in more detail in the following subsections.

Table 3-6 Summary of future research directions with specific research areas

Research Direction	Approach and aim	Method
Research Direction 1 Novel theoretical dimension.	Defining Space Tourism and Categorisation	- review and interviews to develop framework of space tourism
	Theoretical Dimension	-collaboration shapes a novel space tourism theory via consumer perceptions
	Conceptualisation	-extend Paladini and Saha's model, integrate tech advancements, refine metrics for sustainability.
Research Direction 2 Potential environmental impact of space tourism.	Addressing Environmental Issues	- assess environmental impact, analyse policies, explore collaboration for sustainable space tourism.
	Policy Development	-review policies, explore scenarios, engage experts for sustainable space tourism.
Research Direction 3 The role insurance and risk can play in space tourism.	Insurance and Risk Absorption	-study insurance strategies, adapt to space tourism challenges, assess consumer impact.
	Consumer Choice Behaviour	- use statistical models to understand factors driving space tourism participation.
Research Direction 4 Affordability and space tourism.	Affordable Space Tourism	-analyse cost factors, study market trends, enhance space tourism affordability.

Table 3-6: Summary of proposed future research directions in space tourism research. The table outlines key thematic research areas, their associated conceptual aims, and indicative methodological approaches for advancing scholarship on space tourism sustainability.

(i) New theoretical paradigm.

The most evident gap in space tourism literature is the lack of a comprehensive theoretical paradigm (Paladini and Saha, 2023) to serve as a foundation for this rapidly evolving field. If anything, our analysis showed as several researchers place their articles within the theoretical framework of extreme/adventure tourism. Researchers argue that prior participation in adventure tourism correlates positively with the inclination to participate in space tourism (Laing and Crouch, 2004; Crouch et al., 2009; Reddy et al., 2012; Spector, 2020).

However, this may be no longer the case now that the space industry has entered a new development phase (OECD, 2020), requiring the development of a unique theoretical dimension. The key limiting factor identified by Reddy et al (2012) is cost rather than risk, suggesting that the industry's growth depends on the establishment of an effective business model that can absorb costs, leading to increased customer demand. If this is correct, then future research will need to address the validity of existing and often competing definition of space tourism, and explore the relevance of factors such as purpose, destination, and duration of the experience.

It would be also crucial to determine how has the perception of danger associated with space tourism evolved over time, and what factors influence the theoretical placement of space tourism within the broader tourism landscape.

This is it likely to play an important role in shaping consumer perceptions of danger in space tourism and influence the development of a new theoretical dimension. As discussed in the conceptual model presented by Paladini and Saha, (2023) space tourism research could and should incorporate emerging technological advancements in space tourism as an inherent component of the field, especially if sustainability (discussed at length in ii) is what the sector intends, as it should achieve.

Finally, interdisciplinary collaborations can contribute to the creation of a unique theoretical dimension for space tourism, considering insights from psychology, sociology, and tourism studies, shaping the new theoretical paradigm in something substantially different.

There are various methodological approaches that could be used to achieve these aims, with longitudinal study to trace the evolution of various components, industry case studies, and cost-benefit analysis being the most suitable choices. However, the development ad-hoc metrics and expert opinion will also play an important role here.

(ii) Environmental impact

This is the most fundamental dimension of research in space tourism, and more in general, the space sector as a whole, plagued as it is now by increasingly crowded orbits (Martin-Lawson et al., 2024) and the debris crisis (Paladini, 2023).

Here the gap is not in the lack of sustainability literature in space tourism (Paladini et al., 2021), which as we have seen represents the most important cross-cutting clusters of our analysis. It is rather the actionable evidence for lack of specific data in this field. So far, most of all events we class as 'space tourism' have happened not in separation with existing space missions, as we have discussed at the

beginning, making the measurement of the specific environmental impact of those (still rare) events impossible. Once these events will occur in separation from others, and will likely become more common, a whole new area of analysis is likely to emerge.

Possible themes of investigation here abound: What are the specific environmental impacts linked to the escalating launches in the space tourism sector, and how can they be measured and mitigated; how do existing environmental policies and regulations apply to space tourism; what new policies may be required to address emerging environmental concerns; what

ways can collaboration between space tourism companies and environmental organisations contribute to minimising the environmental footprint of space travel, are only a few options.

Some considerations will be also given to study existing policies in high-risk industries contribute to the safety and sustainability of operations, and how can these insights be applied to the development of policies for the environmental impacts of space tourism.

To address these inquiries, an environmental impact assessment will have to be conducted to identify and measure specific environmental impacts associated with increased and targeted launches, while policy analysis will explore existing and potential remedies to mitigate environmental concerns.

Scenarios will be constructed to explore the potential impact of different policy frameworks on the growth and environmental sustainability of the space tourism industry, likely with the adoption of Delphi method to refine and validate policy recommendations. There will also be collaboration opportunities between space tourism companies and environmental organisations as a strategic approach to minimise the overall environmental footprint of space travel.

(iii) Risk mitigation and insurance

The novelty of space tourism, coupled with inherent risks in space activities and the imperative for technological advancements, underscores the absolute and real risks associated with the industry (Paladini and Saha, 2023). There is a need for further exploration through longitudinal studies tracking perceived space tourism risk over time, to determine the trajectory of space tourism in terms of potential demand. Future research needs to develop robust metrics to measure risk in space tourism and provide data-driven insights into potential market dynamics. The industry, currently associated with extreme/adventure tourism, must reduce all forms of risk, and enhance safety awareness to transition into mainstream tourism Reddy et al (2012). As such, both risk mitigation

measures and insurance play a crucial role in addressing risks inherent in space tourism. Here, the lack of clarity in defining commercial space tourism poses challenges for insurance. Laing and Crouch, (2004) identified six main categories¹⁰, each necessitating different insurance policies. Creating viable and affordable insurance market and procedures is imperative for the industry's establishment.

¹⁰ (1) Virtual reality (gaining birds eye view to space), (2) Terrestrial (theme parks, space museums, etc), (3) Near-space (very high altitude short periods of weightlessness), (4) Sub-orbital (bringing people to high altitudes to see the earth's curvature and blackness of space without leaving earth orbit), (5) Orbital (earth orbital experience lasting hours to days), (6) Interplanetary orbit (going to the moon and beyond).

In terms of perspective research objectives to pursue, there is the identification of key elements of successful insurance solutions in high-risk industries; how these elements can be adapted for space tourism; how consumer perceptions of risk in space tourism vary; how does insurance impact their willingness to participate in space travel, and, finally, which quantitative models can be developed to assess the effectiveness of insurance in mitigating consumer risk in the context of space tourism.

It will be also important to explore consumer choice behaviour in space tourism, as they are linked to risk and insurance, considering specifically, which factors shape consumer preferences in space tourism, and how do these factors vary among different demographic segments. Psychological and behavioural economics principles affect decision-making processes in space tourism, particularly regarding risk absorption, environmental impacts, cost considerations, and insurance.

Methodologies here vary, but the development of targeted statistical models to discern patterns and correlations in consumer behaviour, offering insights into the factors that either drive or inhibit participation in space tourism are going to be one method of choice.

Case studies will examine successful insurance strategies in industries with similarities, providing a foundation for adaptation to the unique challenges of space tourism, while expert interviews with insurance professionals will yield insights into effective risk absorption mechanisms. This multifaceted approach will offer a thorough understanding of how insurance is going to play a pivotal role in ensuring the success and safety of space tourism ventures, also shedding light on the diverse factors and principles that influence preferences and choices within the evolving landscape of space tourism.

(iv) Affordability

The very possibility of space tourism not limited to virtual reality or terrestrial exploration (e.g., launching sites, theme parks etc) is still a matter of debate. With Dennis Titos paying approximately US \$2 0M per seat, affordability remains one of the biggest barriers to consumers for participating in the industry (Peeters, 2010).

Advancements in technology helped reduced the price: Virgin Galactic setting prices hovers at US \$450,000 per seat on its SpaceShipTwo suborbital spaceplane. Zero G, another aerospace company, has been running its near- space operation for \$9,070 per seat (Pallini, 2021; Sankaran, 2021). The NSS (2017) predicted that if sub-orbital flight costs drop to \$100,000, this will allow the industry to sustain thousands of flights. Future researchers will likely model an “ideal asking price” for each form of space tourism to address the problem of affordability, uncovering significant variables that affect the cost of space tourism.

To achieve this, a set of research questions will have to be addressed first, for example, what factors contribute to the existing cost structures of space tourism, and how can they be optimised to improve affordability? How do diverse market segments perceive the value of space tourism, and what strategies can be employed to render space tourism more appealing to a broader audience? In what ways can collaborative efforts among industry stakeholders contribute to reducing the overall cost of space tourism experiences? The

methodology of choice here will be a cost-benefit analysis that considers all the factors influencing cost structures, analysing trends and discerning the perceptions of various market segments. The exploration of collaborative efforts among industry stakeholders will be facilitated through scenario planning, with the aim of identifying strategies to enhance the overall affordability of space tourism experiences. This approach will help to pave the way for making space tourism a more inclusive and accessible endeavour, ensuring broader participation in the evolving landscape of space exploration.

3.7 Conclusions

The findings from this investigation propose several key research directions for the future of space tourism, organised in a unified framework as presented in Section 3.4.

There is the need of a theoretical paradigm that better adapts to the rapidly evolving reality of a fast-growing industry and creates its own conceptual categories. In more practical terms, there is a pressing need for the establishment of robust space tourism insurance policies, essential to mitigate the industry's inherent risks, while the environmental impact of increased launches must be systematically addressed through environmental impact assessments and policy analyses. Research should also focus on affordability as an aspect of space tourism, examining factors contributing to current cost structures and exploring strategies, to enhance both environmental and social viability and broaden the appeal of space tourism.

The elaboration of this pathway framework was made possible by the approach we adopted in this study, systematically reviewing all the literature of space tourism between 2000-2023, collecting 291 primary documents and 9,481 secondary document and analysing them we three different methodological approaches. This led to the identification of three cross-cutting themes that served as the foundation of what proposed here.

We fully acknowledge the limitations of the analysis: Although keywords like "*space tourism*," "*space commerce*," and "*commercial space industry*," seems the correct choice, it is essential to acknowledge the potential influence they may have on our results (Batistič and van der Laken, 2019). As such we tested various combinations of keywords for responsiveness of WoS and data sample and fine-tuned the inclusion (or exclusion) of topics in adjacent fields,

e.g. reusable rockets, space debris and asteroid mining.

Also, the inclusion of a citation threshold for the top 100 documents, and for each form of bibliometric analysis, carries the potential to introduce bias to the results, particularly with small clusters (Batistič et al., 2017). To mitigate this impact, we followed recommendations from Batistič and van der Laken, (2019), comparing different citation thresholds for bibliometric analysis and finding no significant differences in the results. Still, our chosen citation thresholds were not based on thematic differences but on the number of documents. Citation analysis does not consider the significance of a link that has been established between documents, which affect potential differences in significance

among the links, as they are not addressed by current bibliometric analysis software. More limitations are linked to the selection process of certain documents for analysis. An example of this pertains to two recent publications Paladini and Saha (2023) and Zhang and Wang (2022), whose low citation counts fell below the minimum requirement of citations (19) to be included in the bibliometric coupling analysis, although having among the highest bibliometric coupling link strengths, respectively (330) and (418).

Despite these limitations, we believe our study fills a fundamental gap of mapping out the state of space tourism both in the historical evolution and in its current status, identifying essential components while outlining the most likely, and badly needed, areas for analysis and development. The framework developed here with its four research dimensions intends to serve both as insight tool and a research pathway for upcoming research, steering the sector toward a more environmentally sustainable future.

Of course, more research directions are likely to emerge over a longer time horizon, evolving in parallel to the growth and the expansion of the sector. Still, the framework proposed in this study provides a roadmap for future researchers over the next 5-10 years, pointing out where the knowledge gaps are and so are the opportunities. By addressing critical challenges and fostering sustainable practices, space tourism can steer toward mainstream accessibility, an ethical and responsible approach, and long-term viability.

4 Chapter 4

Dynamics of Innovation in Orbital Debris Management. A Patent-based Analysis.

4.1 Introduction

In the last decade, the dynamics of the space sector has first surprised and then amazed all the observers, given its continuous growth unaffected by all the downturns the world's economy has gone through; a dynamic that has involved all segments, from monitoring to navigation, communication, and space exploration (Kirchherr et al., 2017; Crane et al., 2020). In these conditions, ensuring sustainability, and not just in environmental terms, has become a concern for policymakers and industry stakeholders (Spector et al., 2017; Chang, 2015b). Governments and companies face escalating risks tied to orbital congestion, which increases the likelihood of orbital collisions and the creation of more debris in already critical conditions (Bensoussan, 2010; Liou and Johnson, 2006; Bastida Virgili et al., 2016; Paladini, 2019). Yet, as more satellites and entire constellations launch to meet growing industry demands, traditional regulations and liability frameworks appear ill-equipped to handle the perfect storm of orbital congestion and debris crisis (Schaub et al., 2015; Jakhu et al., 2017; Li, 2015; Paladini & Castellucci, 2021). Without more adapted guidelines on insurance coverage, emergency protocols, and debris mitigation measures, companies will struggle, if not fail altogether, to implement robust risk management strategies and adopt much-needed sustainable practices (Nassisi et al., 2018; Migaud, 2020; Newman and Williamson, 2018; Kishi, 2017).

From an innovation perspective, the ongoing space debris crisis represents a multifaceted, global 'market failure' in technological governance. Although some promising debris-management technologies have emerged (ADR measures such as robotic arms, harpoons, laser-based deorbiting, etc) they are still largely experimental, without mentioning the uncertain legal landscape that complicates an actual implementation (Froehlich, 2019; Emanuelli et al., 2014; Zhang et al., 2023; Li, 2015; Simmons, 2025; Paladini, 2019; 2025). The existing legal framework based on the Outer Space Treaty (1967) and Liability Convention (1971), does not address cross-border debris removal rights, creating legal ambiguities that discourage private investments in the technology and will likely delay its implementation once available (Li, 2015; Listner, 2011; Dennerley, 2018).

This inaction is not without risk; with LEO (Low Earth Orbit) increasingly congested, the growing density of space objects heightens the risk of a Kessler event (Kessler et al., 2010; Drmola and Hubik, 2018), i.e., a situation in which the density of objects in orbit reaches a critical threshold and collisions cause a chain reaction, further increasing the number of debris fragments and rendering parts of space unusable. Based on estimates (Bongers and Torres, 2023; Martin-Lawson et al, 2024), a Kessler event

would likely be triggered once the satellite count reaches approximately 72,000; the critical threshold could be reached as early as 2037, while crossing it would endanger any mission in space or, worse, result in a permanent loss of access to space. The financial implications are considerable as well, with projections estimating debris-related damage could cost as much as USD 66 million annually by 2033 (Martin-Lawson et al., 2024), threatening not just public agencies but commercial operators whose revenue depends on uninterrupted orbital services.

This is why debris-management innovation will soon represent a cornerstone of the space sector, supported by measures aimed at refining orbital access policies and licensing conditions for new satellite deployments, establishing compliance incentives (Bensoussan, 2010; Rumson and Hallett, 2019), encouraging investments with tax credits for collision-prevention hardware and region-wide agreements that facilitate active debris removal operations.

Despite growing concern over orbital debris, most research on space debris management falls into two distinct categories, i.e., technical studies focusing on the technical aspect of debris management and policy analysis addressing regulatory frameworks, none of which address the way policy shapes or constrains technological innovation in the field. This notable absence of a cohesive approach hinders the development, adoption, and diffusion of effective debris management technologies.

A modest research question guides this study: how do global patents in space debris management reflect technological priorities in prevention, mitigation, and removal?

This paper addresses sustainable space debris management and its interaction with the regulatory framework, reviewing emerging technologies in terms of prevention, mitigation, and removal strategies currently in development by analysing the patent landscape. As such, integrating patent clustering analysis with the innovation theory, it also provides a data-driven assessment of the innovation trajectory in space debris management and offers recommendations for policy-driven acceleration of sustainable space technologies.

Section 4.2 illustrates the literature on innovation theory and its link with patents, covering models such as the Patent Portfolio Model (PPM) and highlighting how it relates to the space industry in particular. Section 4.3 discusses the methodology choices made in this article, namely, the use of a custom Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm to categorise global space debris patents, on patent data sourced from the Lens database, filtering for structural and semantic similarities based on International Patent Classification (IPC) codes. It also demonstrates how, by clustering patents, it is possible to identify key areas of technological development, regional innovation trends, and gaps in R&D efforts. Section 4.4 presents the categories as resulting from the clustered patents and maps them against removal, prevention, and mitigation subcategories, to allow for a clearer analysis of innovation priorities in space debris management. Section 4.5, on the other hand, looks at the patent landscape in a longitudinal perspective, looking at historical trends and discussing the insights adopting the Innovation Theory and Diffusion of Innovation in the field of space debris management technologies. It then assesses whether the sector is in the early,

mid, or late adoption phase, estimating a timeline going forward in implementation terms that could possibly lead to long-term orbital sustainability.

The contribution to the field is twofold.

First of all, the analysis adds to the literature on innovation policy and technology management, showing how innovation, with patents as a proxy, can guide and support the elaboration of robust policy frameworks for space sustainability. Second, the methodological contribution of the adoption of clustering algorithms (namely, DBSCAN) to identify and categorise space-related patents, specifically focusing on debris management technologies; to our knowledge, this is the first study of its kind.

In more practical terms, our findings reveal an important trend, showing that removal (50%) and mitigation (45%) still dominate innovation efforts, while prevention (5%) remains underdeveloped, highlighting a critical gap in long-term debris reduction strategies. Important insights also come from a breakdown of regional patent applications, showing that while China prioritises active debris removal, the USA focuses on shielding and collision avoidance, with the EU somehow balancing mitigation and removal.

The conclusive Section 4.6 discusses how the now-outdated space regulatory framework continues to hinder the deployment of emerging debris management technologies, slowing their transition from concept to widespread adoption and that, without modernised legal frameworks and well-designed incentives, even the most advanced debris-control technologies remain on paper, delaying long-term orbital sustainability.

4.2 Patent Analysis in Driving Innovation

Innovation economics focuses on how innovation and technological progress drive economic and societal advancement (Mohamed et al., 2022), highlighting the importance of developing, adopting, and spreading new technologies for sustained economic development. Patents, especially in high-tech fields like aerospace, are key indicators of technological progress (Benson and Magee, 2015). The aerospace industry is characterised by high entry barriers, high risks, significant R&D investments, and rapid technological change, making patents crucial for maintaining a competitive advantage (Gurtuma, 2011; Pop et al., 2023). Studies have shown that the aerospace sector, with its high-tech nature, relies heavily on both public and private funding to support innovation especially in the initial stages, and patents are a key mechanism to protect and commercialise innovation efforts (Sydorenko and Poltavska, 2021; Belz and Giga, 2018).

Patents also facilitate the exchange of information, contributing in a substantial measure to the diffusion of knowledge, allowing other entities and researchers to build upon existing technologies and supporting further innovation (Seymore, 2010; Baruffaldi and Simeth, 2015). In high-tech sectors, the strategic use of patents influences the direction of technological development in different sectors. Companies in research-intensive markets (such as the aerospace industry) may use patents not only to

protect their inventions but also to shape the competitive landscape by securing key technologies and setting industry standards (Pohlmann and Blind, 2014; Holgersson and Granstrand, 2022).

The number of patents filed by a firm, industry, and country generally reflects its level of innovative activity (Linares et al., 2019; Pohlmann and Blind, 2014). While there are a few metrics available to gauge innovation efforts (Colovic et al., 2024), the Patent Portfolio Model (PPM) is especially suited to assess an organisation's technological strength through patent portfolio analysis (Li et al., 2020). This model helps in identifying technological advantages and guiding strategic decisions in R&D investments (Li et al., 2020). Additionally, patents can reveal the direction of technological developments and the emergence of new fields of innovation, making them a valuable resource for policymakers and business leaders (Jaffe and Trajtenberg, 2003; Li et al., 2021a).

Patents also actively drive innovation by securing the economic benefits of technological advancements (Holgersson and Granstrand, 2022). By granting inventors temporary monopolies on their innovations, patents ensure that innovators profit from their inventions (Barash, 1996). This financial security encourages continued investment in innovation, leading to a cycle of technological progress and economic growth. The relationship between patents and innovation is particularly evident in industries that rely heavily on R&D, such as healthcare, tech and aerospace (Huang et al., 2016; Lee et al., 2015).

Added to this, patents contribute to the diffusion of knowledge by requiring the disclosure of technical details about new inventions (Baruffaldi and Simeth, 2015). This disclosure facilitates the diffusion of innovation, allowing other researchers and companies to build upon existing knowledge (Baruffaldi and Simeth, 2015). The strategic use of patents can also influence the allocation of resources within companies and industries. For example, patents can guide companies in identifying and prioritising key areas for R&D investment (Miyashita et al., 2020).

The space sector relies on patents to protect intellectual property and incentivise the continuous development of technology. This is particularly true in areas critical to space sustainability, such as debris management (Jaffe and Trajtenberg, 2003). The accumulation of debris in Earth's orbit poses a growing threat to both current and future space operations (Allen et al., 2019; Smirnov et al., 2015; Martin-Lawson et al., 2024). Patents related to debris management technologies are critical in addressing these challenges, as they help secure the economic benefits of innovation while promoting the development of solutions to address space debris. For instance, recent studies have highlighted the importance advanced technologies such as autonomous systems, robotics, and AI play in integrated debris mitigation strategies (Newman and Williamson, 2018; Heilala, 2023b).

Through the analysis of patents, researchers and policymakers can identify emerging technologies that could significantly impact space sustainability. For example, a study on technology trends in New Space missions using a patent analytics approach identified key areas of innovation, including remote sensing, telecommunication systems, and space platforms (Garzaniti et al., 2021). Such analyses can

provide valuable insights into the types of technologies that are being prioritised in the debris management and the space sector.

Clustering analysis in patent analytics (as we use in this paper) groups patents based on similar characteristics such as keywords, classifications, or citations, enabling researchers and policymakers to identify emerging technologies, innovation hotspots, and key areas of focus (Oyelade et al., 2019), in all the three main phases of debris removal, namely, prevention, mitigation, and removal. Prevention reduces new debris creation through post-mission disposal, mitigation involves real-time monitoring and impact protection while, removal actively eliminates debris from orbits. By analysing patent data related to space debris, clustering techniques can reveal new approaches or innovations that are gaining traction within the field. This method has been used effectively to identify technological trends in various sectors, including space technology, where innovations are critical for addressing challenges such as debris management (Ribeiro et al., 2018; Altuntas et al., 2020).

Clustering analysis not only identifies emerging technologies but also highlights areas where research and technical innovation breakthroughs are likely to occur and where investment might be most effectively directed, and the space sector is no exception (Garzaniti et al's (2021). The insights gained from clustering analysis are invaluable, as policymakers can use the results to prioritise funding for research and development in areas identified as emerging or strategically important (Ribeiro et al., 2018), and so do investors (Suh et al., 2020).

Yet, recognising these trends is a first step. To ensure these innovations are effectively implemented and contribute to sustainable space activities, they must be supported by robust legal and regulatory frameworks, the absence can lead to fragmented efforts and ultimate failure to achieve their full potential (Biermann et al., 2009).

4.3 Methodology: The Clustering Algorithm

To carry out the patent cluster analysis, this study designed a custom clustering algorithm using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN; Hui and Liu, 2020; Ester et al., 1996), which classify patents into separate distinct clusters to uncover distinct themes and trends in the patent filing of the space industry.

The algorithm of choice was one of the key choices.

There is limited academic literature that systematically compiles space-related patents and applies clustering algorithms to identify groups representing emerging technologies, specifically those focused on debris management. While there is a growing body of work on patent analysis, most studies focus on specific aspects such as network analysis or citation patterns rather than clustering for technological categorisation, which makes the selection of the correct algorithm an important aspect of the research as well.

Chakraborty et al (2020) conduct a comprehensive patent citation network analysis using descriptive statistics and Exponential Random Graph Models to understand the structural properties of patent networks, while Jeon and Suh (2019) utilise multiple patent network analysis techniques to identify safety technology convergence, providing insights into how various technologies blend within patent networks. Pantoja et al (2022), on the other hand, explore graph representation learning for patent network analysis. Although powerful, the method illustrates the existing relationships within patent networks rather than identifying emergent technological clusters. Lei et al (2019) apply a feature vector space model for patent analytics in the context of IoT (Internet of Things), which is somewhat closer to our aim but lacks the focus on space-related patents and debris management's specific areas. Ribeiro et al (2018) conduct a bibliometric and patent analysis to explore the evolution of space debris mitigation technologies but primarily examine policy evolution rather than the clustering of emerging technologies.

DBSCAN defines clusters as areas of high density separated by areas of lower point density, allowing the algorithm to identify clusters of different shapes and effectively manage noise within the data (Ester et al., 1996). According to the literature (Schubert et al, 2017; Gan and Tao, 2015) the DBSCAN works by evaluating the density of points within a specified neighbourhood around each data point, defined by the parameter's *eps* (the radius of the neighbourhood) and *min_samples* (the minimum number of points required to form a dense region; see appendix 9.1.1 for technical details). Points that meet both density criteria are classified as core points, or border points. Points that do not fit either category are labelled as noise. The algorithm groups core and border points into clusters by expanding from each core point, thereby identifying clusters of varying shapes and size.

Due to its ability to handle clusters of irregular shapes, DBSCAN has been widely applied in various fields, from environmental monitoring to detect pollution hotspots to astronomy to classify celestial bodies, working effectively even in noisy datasets (Actkinson and Griffin, 2023; Bastien and Somanah, 2019).

In a study by Li (2021) the DBSCAN algorithm was employed to evaluate traditional Chinese medicine (TCM) patents. By clustering the TCM patents based on their legal evaluation indices, DBSCAN effectively identified clusters within the dataset, allowing for a detailed analysis of patent law evaluation. The algorithm's ability to manage noise and distinguish between dense and sparse areas in the data led to the creation of a model with an average accuracy of 91.97%, outperforming other domestic models used for similar purposes. Similarly, in the work by Han et al (2019), DBSCAN was applied to clarify inventor names in the USPTO patent database, clustering inventor records based on semantic fingerprinting, and facilitating the accurate identification of unique inventors, even in the presence of noise in the dataset.

Although powerful in clustering data, DBSCAN does have limitations.

The algorithm's effectiveness is highly dependent on the choice of *eps* and *min_samples* parameters, which can be difficult to determine without domain knowledge (Li et al., 2021b). Moreover,

DBSCAN struggles with datasets that have clusters of varying densities, as the algorithm assumes a uniform density threshold throughout the dataset, which can lead to the undesirable merger of distinct clusters (Fahim, 2022).

Still, DBSCAN was deemed preferable to other typical ML (machine learning) clustering algorithms (e.g., K-means, Hierarchical, Grid-based, Model-based) because its characteristics make it ideal for handling datasets with complex relationships and varying densities (Benabdellah et al., 2019), as is the case of patents, whose varying levels of similarity make traditional clustering methods like K-means less effective (Zhang et al., 2016). DBSCAN does not require specifying the number of clusters in advance (Ester et al., 1996) either, which added to the algorithm's robustness in handling noise made it the most suitable tool for the task (Schubert et al., 2017).

The implementation of DBSCAN clustering algorithm is often done with Python's extensive libraries, such as Scikit-learn, enabling efficient clustering of complex, high-dimensional patent data, along with flexibility, scalability, and reproducibility ¹¹ (Agapito et al., 2022).

Our study uses a patent database called LENS (Lens, 2025), which is a comprehensive open-access platform that provides access to patent data, the same one used for patent study in the World Intellectual Property Organisation (WIPO) patent analysis handbook (Oldham, 2022). The classification of patents is done with an International Patent Classification (IPC) code which is administered by WIPO. Two separate patent datasets were downloaded in excel format, the first including all the patents assigned to the IPC code B64G, '*Cosmonautics, Vehicles or Equipment therefor*', i.e., the science and technology of spaceflight (Gruntman, 2007). The second dataset employed instead a search query¹² of the Lens database based on the word search performed in chapter 3, the systematic literature review paper on space commercialisation.

The patent datasets were downloaded on the 18 July 2024, capturing all space related patents up to that date. The results were merged, checked, and cleaned for duplicate patents, which then returned 77,233 patents.

4.3.1 Debris dataset creation

The next step was to put out together the space debris patent dataset, filtering out patents that did not have the term "debris" in either the abstract, title or non-patent literature (NPL) citations of the patent. NPL citations matter, because they refer to non-patent sources like academic papers and technical reports, used to provide context and support for the invention's claims (Verbandt and Vadot, 2018). The filter reduced the full space patent dataset from 77,233 to 756 patents relating to space debris.

¹¹ Jupyter notebook containing data is available upon request.

¹² (Title: (astro* OR cosmo* OR spacecraft* OR ("space exploration" OR rocket* OR orbit*))) AND (Abstract: (astro* OR cosmo* OR spacecraft* OR "space exploration" OR rocket* OR orbit*)) OR Claims: (astro* OR cosmo* OR spacecraft* OR ("space exploration" OR rocket* OR orbit*)))

We calculated both textual and structural similarity for the analysis.

The textual similarity calculation involves comparing the semantic content of patents based on their abstracts, titles, NLP citations. The process begins with preprocessing the raw text through tokenization, which splits sentences into individual words, followed by the removal of stop words (commonly used words that hold minimal significance) and lemmatization, where words are reduced to their root forms for consistency in comparison. The cleaned text is converted into numerical vectors using a pre-trained Word2Vec model, where each word is represented as a 300-dimensional vector capturing its semantic meaning, to be then averaged to create a single vector representation for the text of each patent. Normalised cosine similarity is used to measure the similarity between two average vectors by calculating the angle between them, ranging from 1 (perfect similarity) to 0 (no similarity). This method quantifies how semantically similar two pieces of text are, making it useful for grouping patents with related content.

Structural similarity, on the other hand, leverages the International Patent Classification (IPC) codes assigned to patents. These codes categorically organise patents by their technical fields into hierarchical components: section, class, subclass, group, and subgroup. Each level is assigned a specific weight based on its contribution to the technical specificity of a patent. The similarity between two patents is calculated by comparing their IPC codes level by level. For exact matches, the similarity score is 1, and for partial matches, the score decreases proportionally based on the degree of overlap. Group and subgroup levels require additional calculations to measure how closely related the numerical values are, with differences being inversely proportional to similarity. The structural similarity score is normalised between 0 and 1, providing a measure of how closely two patents are aligned in their technical classifications. This method emphasises the importance of IPC-based categorisation in clustering patents within similar technological domains.

Textual and structural similarity scores are combined into a final similarity matrix, with a weighted contribution of 20% from textual similarity and 80% from structural similarity, chosen in this percentage after observing in preliminary experiments that prioritising the standardised, objective IPC codes produced effective groupings. This weighting also allowed the textual content to capture nuanced semantic details, balancing the robust formal classification system with finer-grained insights from natural language processing, and emphasising the importance of the structured IPC classifications, while still capturing the semantic content of the patents. This is an important factor: IPC codes represent the technological groupings represented by patents that carry more importance to the representation of the patent than its textual similarity, hence the importance and weight placed on structural similarity. In appendix 9.1.3 there is an example table from our distance matrix, while appendix 9.1.2 includes detailed explanation of how the similarity calculation is formulated.

4.3.2 Clustering Algorithm Application

On the resulting custom distance matrix, we applied the DBSCAN algorithm to identify clusters among the 756 patents (display keys). Dimensionality refers to how many variables, features or attributes each point in a dataset has (Del Giudice, 2021). In our analysis, each patent (display key) is described by 756 distinct attributes, resulting in a 756-dimensional dataset. We addressed the computational challenge of DBSCAN in high-dimensional (Chen et al, 2021) by performing principal component analysis¹³ (PCA). PCA was applied to the distance matrix to reduce dimensionality while retaining 90% of the variance. In this dataset, the 90% variance threshold corresponded to 7 principal components, which were retained to preserve key patterns while mitigating issues of high dimensionality. The PCA implementation in scikit-learn computes orthogonal principal components through eigen-decomposition of the covariance matrix. No additional rotation (e.g., varimax or promax) was applied; the analysis relies on the standard unrotated principal components, as the objective was dimensionality reduction for clustering rather than interpretability of the components (Lever et al., 2017).

With the reduced data from PCA, we computed the pairwise Euclidean¹⁴ distances to form a new distance matrix, which we then fed to the DBSCAN clustering algorithm, using a Multi-Verse Optimizer¹⁵ (MVO) to optimise the parameters for the DBSCAN clustering algorithm, i.e., eps and min_samples (Lai et al., 2019) and the silhouette score measuring how well-separated the resulting clusters were. We ran the MVO algorithm ten times to find the optimal eps and min_samples values, which were then averaged for stability, and applied Multidimensional Scaling (MDS)¹⁶ to reduce the dimensionality of the distance matrix, allowing us to visualise the clusters in a 2D space (Buja et al., 2008).

Next a network graph was constructed where each node represented a patent (display key), and edges were formed between nodes that shared IPC codes. Then, the nodes were color-coded based on their cluster assignment and filtered by country for the DBSCAN algorithm to generate the visualisation.

¹³ PCA is a well-known statistical and ML method, which basically works by identifying the directions (principal components) in which the data varies the most, and then projects the data along these directions, effectively reducing the number of dimensions while preserving as much variability as possible.

¹⁴ Pairwise Euclidean distances involve calculating the straight-line distance between each pair of points in a given set. This distance is determined by applying the Pythagorean theorem to the differences in their coordinates. When you compute these distances for every possible pair of points in a set, the result is a matrix where each element represents the distance between two points (Achlioptas, 2003).

¹⁵ The Multi-Verse Optimizer (MVO) works by treating each potential solution to an optimisation problem as a "universe." It improves solutions by simulating the exchange of information between universes: better solutions act like "white holes," sharing their attributes with others, while poorer solutions behave like "black holes," absorbing new characteristics. Additionally, random adjustments called "wormholes" allow universes to explore new areas of the solution space, helping the algorithm to balance the search between refining current solutions and discovering new ones (Mirjalili et al., 2016).

¹⁶ Multidimensional Scaling MDS is a technique used for dimensionality reduction, which aims to visualise the structure of high-dimensional data in a lower-dimensional space, typically two or three dimensions. The main goal of MDS is to preserve the pairwise distances between points in the high-dimensional space as much as possible in the reduced-dimensional representation (Buja et al., 2008).

4.4 Evidence from data analysis: Regional Technological Development Priorities

Once the patent data were clustered as resulting from the application of the algorithms, we structured the underlying technologies into three primary categories aligning with the typical classification's of space debris management approaches: prevention, mitigation, and removal (Ribeiro et al., 2018). Prevention aims at reducing instances leading to new debris by decommissioning satellites or planning post-mission disposal (e.g., bringing LEO satellites back within 25 years, or 5, following the new NASA recommendations, moving GEO satellites to graveyard orbits). Mitigation focuses on real-time monitoring (such as the NASA's CCD Debris Telescope) and protective measures like impact-resistant bumpers, helping spacecraft withstand debris encounters and avoid collisions. Removal (often referred to as ADR, active debris removal) seeks to physically capture and eliminate debris using a wide set of tools, among which nets, harpoons, or robotic arms.

Each cluster was assigned to one of three categories based on the most prevalent technology in its patents group. If no single technology dominated, the cluster was assigned to both relevant categories. While several removal methods are under development, none has yet achieved full operational deployment. These categories guided our analysis, ensuring that each patent's main purpose (e.g., preventing, mitigating, or removing debris) was clearly distinguished within the clustering results.

We first discuss the global, aggregate-level clustering outcome, highlighting overarching trends in debris-related patents. Subsequently, we zoom in on the three main spacefaring regions Europe, USA, and China to offer region-specific perspectives on patent clustering. For readers seeking further details, see the appendices, which present additional breakdowns of other regions (e.g., Japan, one of the strongest players in debris management; (Paladini, 2019, 2024).

In the next section we will present the tabular and visual summaries and clustering of the patent data clusters, with their primary debris management focus and the technological priorities driving the observed patterns.

4.4.1 Tabular summary

The first and most important output from the DBSCAN application is, of course, the diagram. Table 4-1 presents a summary of the clusters identified through DBSCAN, covering all countries Figure 4-1 in the dataset. Each cluster is assigned a unique number and colour to correspond with the network visualisations. The "Short Label" column provides a concise description of the technological focus of each cluster, enabling easier interpretation of the figures and tables.

For each cluster, the associated IPC codes are listed along with the number of patents corresponding to each code (shown in brackets), capturing the technological composition of the cluster. It should be noted that there are more IPC codes than patents, which is because each patent can be

associated with multiple IPC codes. The Main Patent Category column summarises the primary policy focus of the patents within each cluster, such as Removal, Mitigation, or Prevention, with counts in brackets to indicate the number of patents addressing each policy. The Patent Count column gives the total number of patents in the cluster, corresponding to the sum of the individual policy counts.

This table provides a compact overview linking the visualised clusters to their underlying technological and policy characteristics. For example, Cluster 1 (Red, GEO Debris Systems) focuses on geostationary orbit debris mitigation technologies, while Cluster 4 (Yellow, Braking/Energy Removal) contains patents predominantly addressing removal and mitigation strategies. The summary facilitates the identification of key clusters relevant for specific policy or technological objectives.

Table 4-1- Tabular summary of patent clusters from DBSCAN clustering of all countries.

Cluster Number	Colour	Short Label	IPC Codes	Main Patent Category	Patent Count
1	Red	GEO Debris Systems	B64G3 (18), B64G1 (22), A63F9 (4), A63F3 (4), G01S1 (4), G01S7 (1), G06Q1 (1), G06Q4 (1)	Mitigation (18)	18
2	Green	Removal Technologies	B64G1 (44)	Removal (15)	15
3	Blue	Active Removal/Stabilisation	B64G1 (42), H04N1 (1), H04N7 (1)	Removal (10), Mitigation (5)	15
4	Yellow	Braking/Energy Removal	B64G1 (56), G08G9 (1), F16D6 (2)	Removal (10), Mitigation (4)	14
5	Purple	Debris Capture & Recovery	B64G1 (42), B65H7 (3)	Removal (8), Mitigation (1)	9
6	Cyan	EM/Propulsive Removal	B64G1 (42), B65H7 (3)	Removal (6), Mitigation (3)	9
7	Pink	Active Capture/Deceleration	B64G1 (22)	Removal (5)	5
8	Orange	Capture/Transport/Management	B64G1 (20), B64C2 (1), F03H1 (1)	Removal (3), Mitigation (2)	5
9	Teal	Tethered Capture/Processing	B64G1 (5), B64G4 (5), B09B3 (1)	Removal (4), Mitigation (1)	5

Table 4-1: Summary of patent clusters identified through DBSCAN clustering across all countries. The table reports cluster identifiers, colour coding, dominant technological themes, associated IPC classifications, primary patent category (mitigation or removal), and the number of patents assigned to each cluster.

4.4.2 Cluster visualisation analysis

Key information can be inferred from the visualisation of the clusters themselves.

In the network visualisations, each node (represented as a circle) represents to a single patent, identified by its display key. Edges (represented as grey lines linking two nodes) indicate that two connected patents share IPC codes, reflecting technological similarity. The distance between nodes corresponds to their overall similarity: patents that are more similar (in terms of IPC codes and text features) are positioned closer together, while less similar patents are farther apart.

Nodes are color-coded according to the DBSCAN cluster to which they belong, highlighting groups of patents with similar technological characteristics. Patents not assigned to any cluster (DBSCAN noise points) are excluded from cluster visualisation.

Each visualisation also applied filtering parameters to determine which nodes were included and which were excluded, based on a minimum number of edges per node and a minimum number of nodes required to form a cluster. For example, if the minimum edges required was 30 and the minimum nodes to form a cluster was 10, a node with 50 edges but only 5 nodes would be omitted from the visualisation. These parameters vary between visualisations, and the specific values used for each figure are provided in the captions.

The visualisations were further filtered by country, allowing for comparison of patent activity and cluster composition across geographic regions. In the geographic network maps (Figure 4-2, Figure 4-3, Figure 4-4, Figure 9-1, Figure 9-2, Figure 9-2, Figure 9-3, Figure 9-4, Figure 9-5) differences in cluster density, number of patents, and cluster composition reveal country-specific technological focuses. Some countries show high concentrations in certain clusters, indicating targeted innovation areas, while others display a more even spread across clusters, reflecting diverse research activity.

These visualisations provide a comprehensive summary of the relationships between patents, helping to identify clusters of similar technologies, assess policy relevance, and understand national patterns in space debris management.

In contrast to Chapter 3, where clusters represent distinct bodies of literature and are therefore discussed individually and sequentially, the analytical focus of Chapter 4 is not on individual patents or standalone clusters, but on broader groups of clusters that represent related technological approaches to space debris management. The DBSCAN clusters are therefore interpreted as components of higher-level technology categories (e.g. removal, mitigation, prevention), rather than as isolated analytical units. As a result, clusters are discussed thematically and in grouped form, with numerical identifiers used only for traceability to the visualisations. This thematic structuring reflects the chapter's objective of analysing technological trajectories and innovation patterns, rather than comparing clusters as discrete entities. Clusters are presented to support systematic reporting of results, with analytical emphasis placed on cross-cluster technological patterns rather than the order of presentation.

The first visual output, Figure 4-1, presents the results of the DBSCAN clustering applied to the global dataset of space-debris-related patents. The figure visualises the emergent technology clusters derived from all available patent records, illustrating how distinct debris mitigation and removal technologies group together based on similarity, without country-level disaggregation.

Figure 4-1: Visualisation of All Countries Display Key Debris Patents Clusters with their Technological

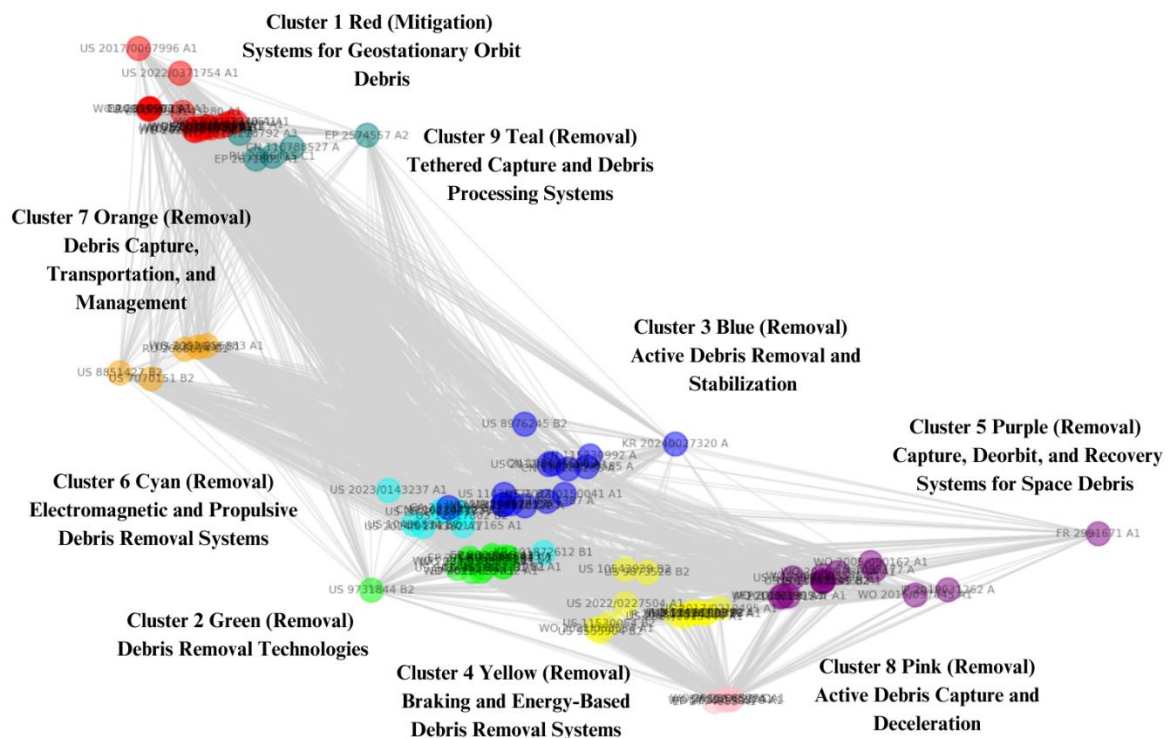


Figure 4-1: Displays technology clusters identified using density-based spatial clustering (DBSCAN), based on semantic and classification similarity across all patents in the dataset. Only clusters meeting a minimum threshold of five patents and sufficient network connectivity are shown. Colours indicate distinct technology clusters. (Source: author, generated from patent data.)

This visualisation highlights an evolving and rapidly expanding global response to space debris, where each cluster points to a distinct technological priority. Notably, the substantial number of removal-focused clusters (Clusters 2, 3, 4, 5, 6, 7, 8, 9) reflects the strong drive to develop practical ADR methods ranging from harpoon capture and tethers to electromagnetic deceleration. Simultaneously, the presence of significant mitigation-oriented patents (Cluster 1) underscores how spacefaring entities are also exploring alternative way to addressing the debris emergency, investing also in real-time tracking, collision avoidance, and software-based solutions.

A combination of hardware-heavy removal techniques and software-driven mitigation strategies suggests that while policymakers and industry are aware of the urgency to remove existing debris, they also recognise the value of situational awareness and management of new debris sources. Such complementary emphases tackling both the supply and stock of orbital debris signal a more holistic shift in how the global community is approaching space sustainability.

A notable trend was the emergence of a dedicated cluster of patents targeting geostationary orbit (GEO) satellites, which somehow deviates from the recently predominant LEO-centred conversation in debris management (Paladini, 2025; Martin-Lawson et al., 2024; (Seitzer and Tyson, 2021; Hakima and Emami, 2018; Istria et al., 2023). This is likely due to the fact that safeguard measures in GEO, an orbit

critical for telecommunications and weather observation, have long been a priority for space agencies, as historically one of the first orbit to become ‘scarce’ and ‘sensitive’ in management terms.

In terms of geographic distribution, the algorithm returned a detailed breakdown of the leading space faring nations’ patent landscape, three of which, the EU (European Union), USA and China, are discussed here, starting from the EU. Figure 4-2 visualises the DBSCAN clustering of space-debris-related patents filed within the European Union, highlighting technology clusters derived exclusively from EU patent data. The figure illustrates how European innovation activity concentrates around specific debris mitigation and removal technologies, allowing comparison with the global clustering patterns presented in Figure 4-1.

Figure 4-2: Visualisation of European Union Display Key Debris Patents Clusters with their

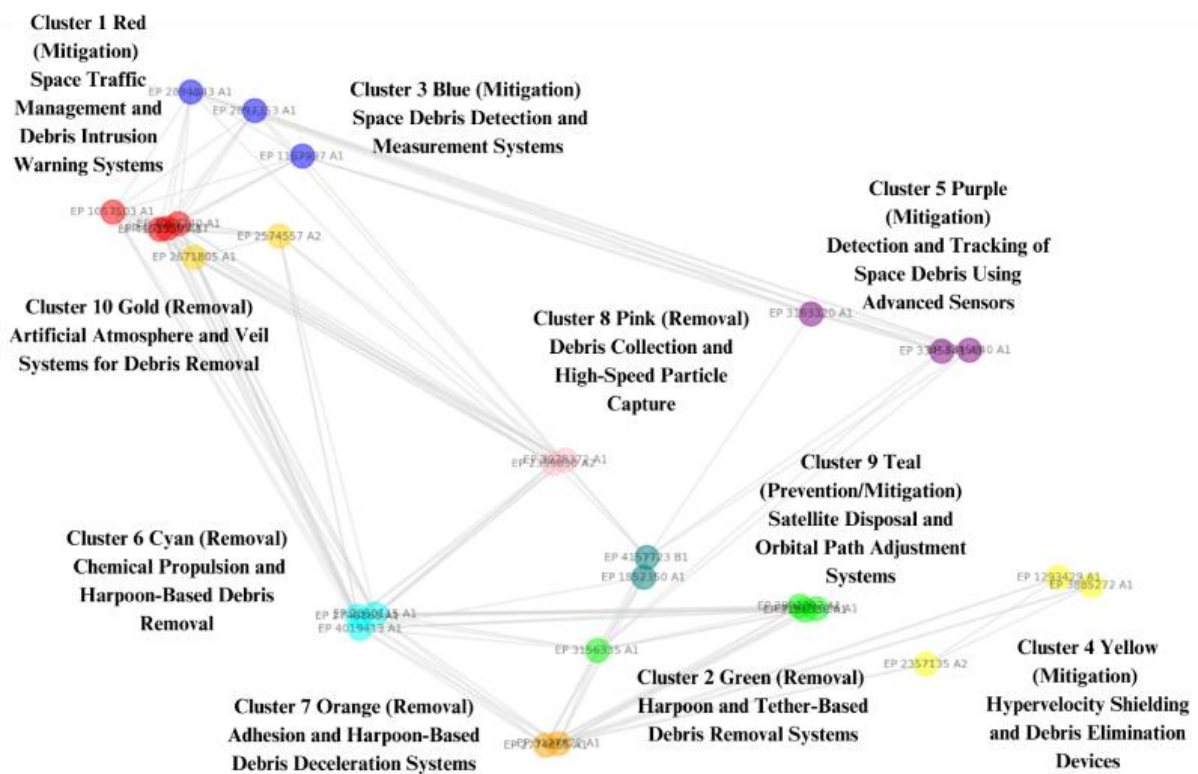


Figure 4-2 : Displays technology clusters identified using density-based spatial clustering (DBSCAN) applied to EU-filed patents only. Clusters are formed based on semantic and classification similarity, with a minimum threshold of two patents per cluster and sufficient network connectivity. Colours denote distinct technological groupings. (Source: author, generated from patent data.)

Within the European Union’s patent landscape, ten distinct clusters emerged each for a specific aspect of debris management, with several clusters on debris removal technologies such as harpoon-based capture (Clusters 2, 6, 7) and high-speed particle absorption (Cluster 8), indicating a strong focus on this segment. This is not surprising, when considering that ESA, the European Space Agency, is one of the most active space agencies in terms of investments in ADR companies, ClearSpace and

while still sharing some overlap with electromagnetic or atmospheric management methods seen in Cluster 5. Across all the US clusters, mitigation emerges as a dominant theme, more than in what observed in the EU case: Cluster 1 (Red) and Cluster 2 (Green) together account for over half of the U.S. patents, highlighting extensive work in shielding, collision avoidance, and real-time debris monitoring. On the other hand, Clusters 3, 4, 5, and 6, collectively intended as removal strategies, from tethers and harpoons to nuclear-powered spacecraft, fare relatively lower in the US innovation landscape, with fewer variety and lower number in patent count. Overall, the U.S. approach exhibits a heavy reliance on near-term resilience and collision avoidance solutions, supplemented by specialised removal concepts but lacking ClearSpace-type of companies and relative public investments in them.

Finally, China, whose patents are displayed in Figure 4-4 presents the DBSCAN clustering of space-debris-related patents filed in China, illustrating a distinct national innovation profile within debris mitigation and removal technologies. Compared to the EU and U.S. patent landscapes, the Chinese clustering reveals a concentrated set of technology groupings, suggesting a more targeted and state-directed approach to debris-related innovation. This pattern reflects China’s strategic emphasis on specific debris management capabilities rather than broad diversification across multiple technological pathways.

Figure 4-4: Visualisation of China Display Key Debris Patents Clusters with their Technological Splits

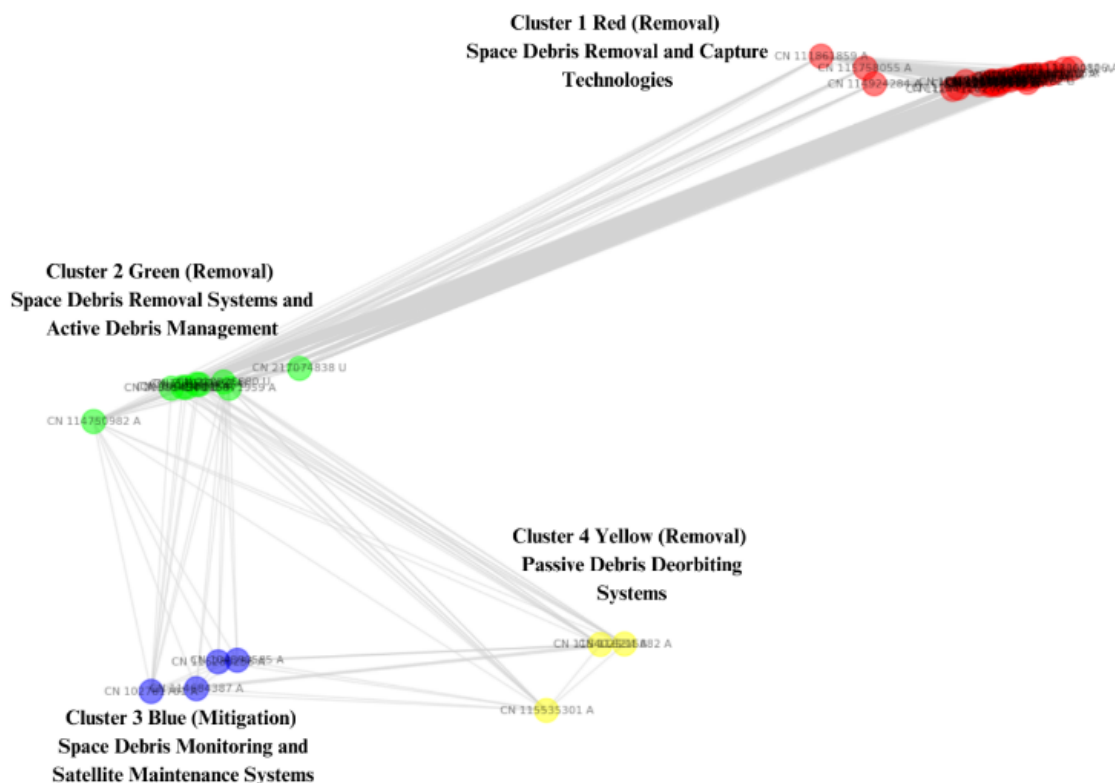


Figure 4-4: Displays technology clusters derived exclusively from patents filed in China using density-based spatial clustering (DBSCAN). Clusters are formed based on semantic similarity and IPC classification, applying thresholds of a minimum of three patents per cluster and at least 30 network edges to ensure statistically meaningful groupings. Colours indicate distinct technological clusters. (Source: author, generated from patent data.)

The Asian leading space country presents, like the US, a narrower range of patent profiles, but, differently from the States, the patent clusters reflect a strong emphasis on active debris removal, with Cluster 1 (Red), with 23 patent filings, dominating in areas such as laser or net-based capture. This cluster sits somewhat apart from the others, linking to Cluster 2 (Green), a “bridge” group of nine patents that combines removal methods (e.g., rocket-tail staging) with more general debris-management functions. By connecting to both Clusters 3 and 4, Cluster 2 highlights how China’s debris research extends beyond pure removal placing emphasis on monitoring (Cluster 3) and passive deorbiting (Cluster 4). Although Clusters 3 (with four patents) and 4 (three patents) are comparatively smaller, they underscore China’s interest in long-term orbital maintenance (e.g., micro-nano satellite tracking) and low energy deorbit solutions (e.g., inflatable drag sails). Notably, while there is no dedicated “prevention” cluster, a small set of patents propose preventing debris spread or further collisions (e.g., by rope-net capture or laser monitoring). These examples demonstrate that although removal dominates China’s debris-management strategies, prevention is also being addressed in select patents to enhance orbital sustainability. Overall, the patent distribution reveals a pronounced commitment to removal technologies, supported by a secondary focus on monitoring, maintenance, and passive deorbit strategies.

The breakdown in segments and clusters, however, can go even further, both in geographical terms that in terms of specific patent specification, as Figure 4-5 demonstrates.

And while the present article does not go into the technical specifications of the innovative technologies of the single clusters included, it is nonetheless significant to identify which countries specialises in manufacturing what, especially for complex realities such as the European Union with his composite state member’s space activities.

Figure 4-5: Flow Chart of Space Debris Protection Systems

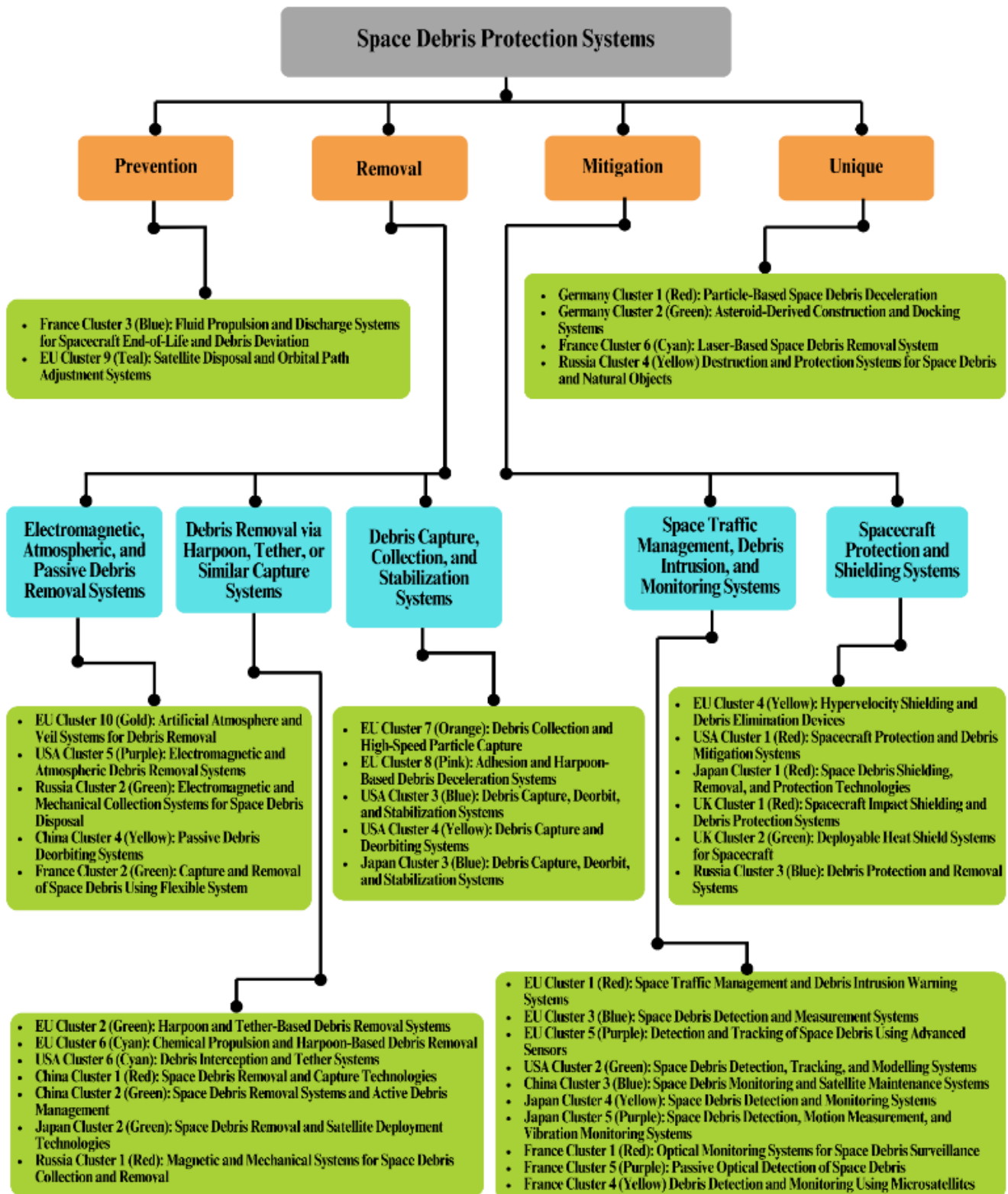


Figure 4-5: Illustrates how space-debris-related patent clusters can be grouped into three main technological approaches, prevention, mitigation, and removal, with an additional “unique” category capturing clusters that do not align closely with the primary pathways. The classification highlights the relative emphasis of innovation activity across different debris management strategies.

Figure 4-5 provides a schematic overview of the technological landscape of space debris management, grouping the patent clusters identified through DBSCAN into higher-level functional categories. Rather than treating clusters as isolated units, the figure synthesises them into prevention, mitigation, and removal approaches, alongside a residual “unique” category for technologies that do not align clearly with the dominant pathways. This aggregation enables a system-level interpretation of innovation priorities across the debris management ecosystem. Removal technologies target debris already in orbit and break down into three sub-sections: (1) electromagnetic, atmospheric, and passive removal systems (7 clusters), (2) harpoon, tether, and similar capture systems (5 clusters), and (3) debris capture, collection, and stabilisation (5 clusters). Among these, harpoon/tether-based systems form the largest cluster group, suggesting a strong technological focus on direct, mechanical capture methods.

Mitigation technologies aim to reduce the rate of debris generation, with the two sub-sections being: (1) space traffic management, debris identification, and monitoring (10 clusters, the single largest subgroup overall), and (2) spacecraft shielding and protection (7 clusters). The prominence of monitoring systems reflects their critical role in enabling collision avoidance and maintaining long-term orbital safety, particularly following major collision events such as the Iridium-Cosmos incident. Shielding complements this by addressing the persistent hazard of small, untrackable debris.

Prevention technologies, which aim to eliminate debris sources at the end of mission life, are comparatively under-represented, with only two clusters: one on fluid propulsion and another on orbital path adjustment for controlled re-entry. While there are some prevention focused patents within the removal branch, specifically in the electromagnetic, atmospheric, and passive removal systems sub-category, the clusters are still classified under removal technologies. This is because their dominant focus remains on removal rather than prevention, which highlights the relatively limited emphasis on prevention within the patent landscape.

Finally, the Unique category captures clusters important enough to appear in the DBSCAN outputs but do not sit within any of the main sub-categories. Examples include particle-based debris deceleration systems, which are conceptually related to removal but too distinct to group under existing sub-categories.

Overall, the clustering results show a patent landscape strongly weighted toward removal, followed by mitigation, with prevention emerging as the least developed domain. This suggests a technological emphasis on addressing debris as it accumulates rather than prioritising root-cause elimination.

4.4.3 Global Space Debris Trends

A more high-level visualisation offers insights into how varying countries potentially intend to invest in removal, mitigation, and prevention measures in their space debris. Figure 4-6 visualises the percentage of space patent technology types per region and disaggregates each region’s patent portfolio, revealing the strategic dominance of each segment (or lack of).

Figure 4-6: Regional Emphasis on Debris Management

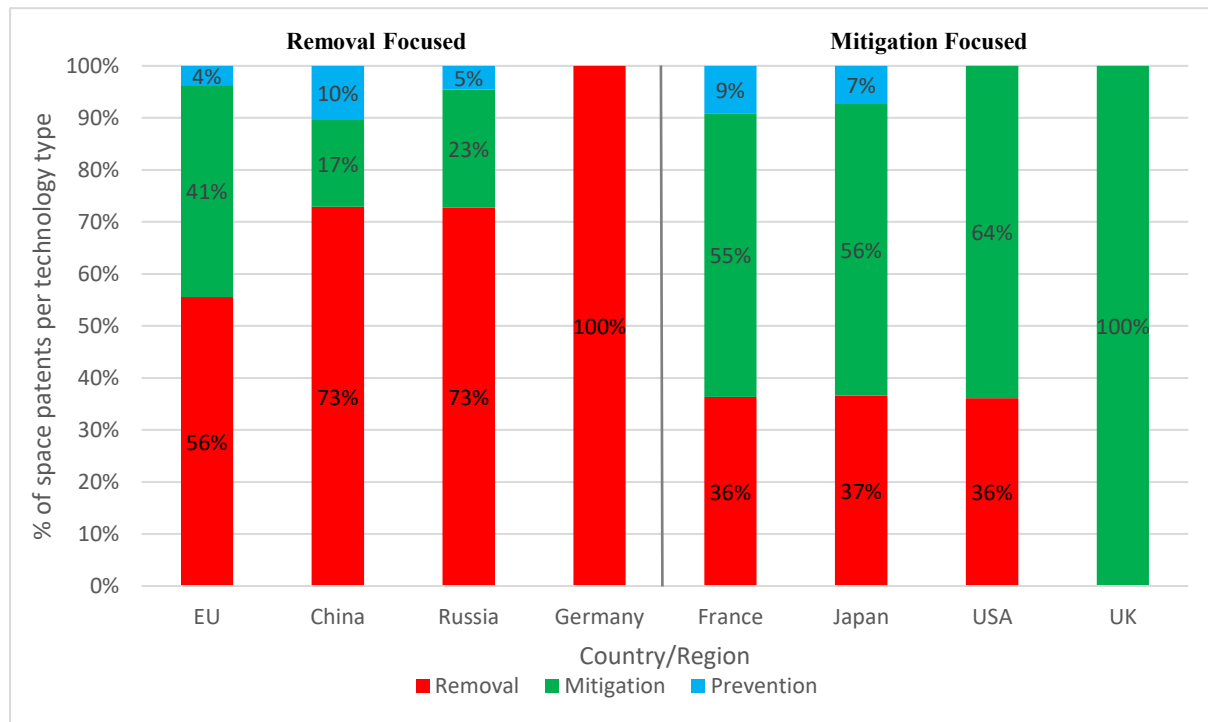


Figure 4-6: Presents the percentage share of space-debris-related patents allocated to removal, mitigation, and prevention technologies across different regions, enabling comparison of regional innovation priorities in debris management.

Figure 4-6 compares the regional distribution of space-debris-related patent technologies, illustrating how different regions prioritise removal, mitigation, and prevention within their respective patent portfolios. The figure highlights clear regional differences in strategic focus, revealing varying approaches to addressing orbital sustainability through innovation. China, Russia, Germany, and the EU all allocate over half their debris-focused patents to active debris removal, although the number of patents per country varies at times significantly (EU–27, China–48, Russia–22, Germany–2, France–11, Japan–41, USA–72, UK–3). It is important to note that these percentages are calculated relative to each country’s total number of patents, meaning that countries with smaller portfolios (e.g., Germany with only 2 patents, both in removal) can appear disproportionately skewed compared to regions with larger sample sizes (e.g., the EU with 27 total patents, of which 15 are removal).

The insights are important. China’s emphasis on laser- or net-based capture (Cluster 1) aligns with an ambitious drive for comprehensive debris control, while Germany specialises in niche deceleration techniques (e.g., particle-based systems). The EU devotes substantial effort to advanced shielding and

tether-based collection, reflecting Europe's push for a broad range of removal capabilities, including hypervelocity shielding and targeted capture methods. By contrast, the USA, Japan, France and the UK show a stronger slant toward mitigation (green bars) tracking, collision avoidance, and protective hardware, indicating an immediate need to safeguard critical assets rather than invest predominantly in debris removal. The USA's reliance on space situational awareness (e.g., real-time tracking) and spacecraft protection underscores a near-term focus on shielding high-value satellites. Japan's technological focus on multilayer shielding reflects its approach to enhancing orbital safety. France's commitment to laser-based or optical detection similarly highlights the role of precision observation, while the UK's limited patent count revolves around impact shielding and deployable protective systems.

On the other hand, Figure 4-7 presents a consolidated global overview of space-debris-related patent activity, aggregating results from the country-level clustering analyses. By focusing on the 226 patents that met the clustering thresholds, the figure highlights the overall technological balance between removal, mitigation, and prevention approaches at the global level. This synthesis makes visible the dominant innovation pathways shaping debris management worldwide. Although 756 patents were initially identified as mentioned in section 4.3.1, only 226 appear in the visualisations. This reduction results from the clustering process and the filtering parameters applied. For a patent (node) to appear in a visualisation, it needed to have sufficient connections (edges) to other patents and belong to a cluster of a minimum size. Patents that were too weakly connected, too isolated, or did not meet the clustering thresholds were excluded. In total, 530 patents did not form part of any qualifying cluster and were therefore omitted from the visualisations, leaving the 226 patents that met the criteria which is what Figure 4-6 and Figure 4-7 are based on.

Figure 4-7: Global Share of patent technology

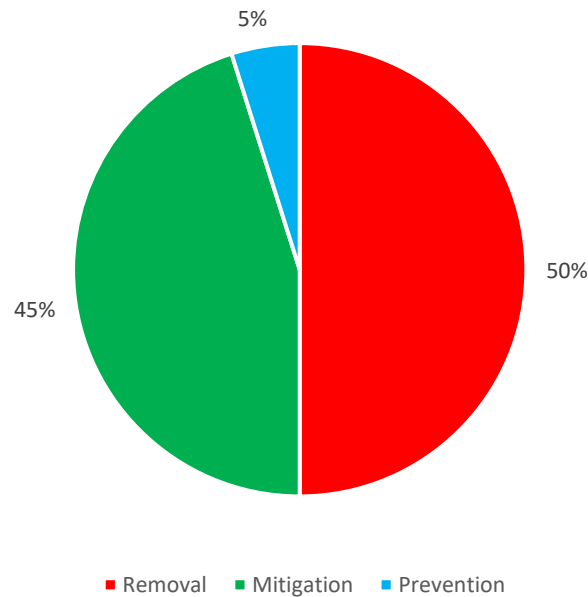


Figure 4-7: Shows the percentage share of removal, mitigation, and prevention technologies across the 226 patents that satisfied the DBSCAN clustering criteria, aggregated from eight country-level patent landscapes. The distribution highlights the dominant technological focus within the analysed global innovation ecosystem.

Figure 4-7 visualises a consolidated form of Figure 4-6 to represent global share of patent technology not just country wise. When aggregated across all the patent-holding countries, removal (50 percent) narrowly surpasses mitigation (45 percent), while prevention only accounts for 5 percent. Most of the leading space faring nation’s innovation initiatives target existing debris, either removing it altogether or mitigating its effects. Relatively few patents address prevention (e.g., satellite passivation or design practices that avert debris generation). Although the community recognises the gravity of current orbital debris, in practical terms comparatively less attention is directed to stopping debris creation at its source.

Overall, these figures confirm that, while the entire space community invests in ADR technologies, not all the players prioritise the same aspects in the debris management efforts. Countries such as Germany, Russia, and China push strongly toward hardware-intensive removal, whereas the USA, France, Japan and the UK emphasise shielding and detection systems.

Meanwhile, the lack of widespread prevention-focused patents highlights an underexplored frontier in long-term orbital sustainability.

4.5 Orbital sustainability: an historical trend. Past, present and future initiatives.

The ongoing commercialisation of outer space, driven by advancements in satellite technology and growing investment in orbital infrastructure, has made orbital sustainability (as defined by UN COPUOS, 2018) a priority, and debris management is the most urgent among all criticalities. With approximately 40,000 tracked pieces of orbital debris threatening operational satellites and future missions, and millions of them too tiny to be measured and accounted for but still dangerous to spacecrafts and probes the sustainability of Earth's orbital environment is at risk (Forshaw et al., 2016; ESA, 2025). Unchecked, this accumulation of debris could lead to a cascade of collisions, the well-known Kessler syndrome, making orbital regions unusable and eventually jeopardising the long-term viability of space.

To understand how orbital sustainability could be realistically achieved, it would be important to discover trends in the innovation research landscape of the last decades, at least from 1990s onwards. Such an analysis would offer insights on the industry's evolving innovation efforts and allow us to glimpse at future trends.

To frame these trends conceptually, this study applies the diffusion of innovation model explored by Rogers (2003) and Stoneman (1995). Rogers' model describes how technologies spread through populations via stages from innovators to early adopters, early majority, late majority, and laggards. Using this framework, the overall space debris technology landscape can be mapped along the diffusion curve to examine the general patterns of adoption, maturity, and potential for future uptake.

An historical examination of space debris-related patents reveals distinct patterns in how technological focus has evolved over the years. Like the network clustering analysis discussed in Section 4.4.2, the analysis done in this section is based on 226 patents from the DBSCAN, not the full set of 756 space debris patents.

Figure 4-8 presents the annual distribution of space-debris-related patent technologies by type, removal, mitigation, and prevention, illustrating how innovation priorities in debris management have evolved over time. The figure reveals clear shifts in technological emphasis across the period 1990–2024, reflecting changing perceptions of risk, feasibility, and governance needs within the space sector. Figure 4-8 shows that, from the 1990s to the early 2000s, mitigation technologies dominated the patent landscape; these technologies were the primary focus during the early period of the space industry. This reliance on mitigation highlights the industry's early prioritisation of mitigation-oriented measures potentially as a more feasible approach given the technology of the time.

Figure 4-8 Proportion of Debris technology type per year

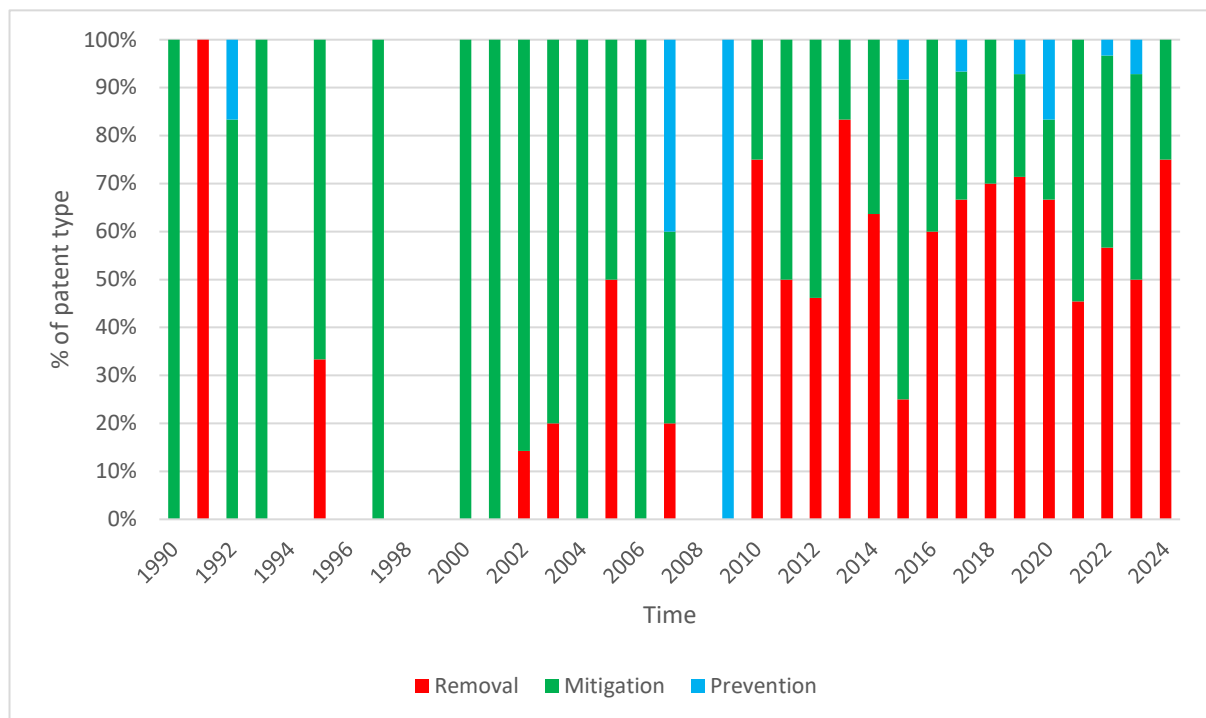


Figure 4-8: Shows the percentage share of patents published each year across removal, mitigation, and prevention technologies, highlighting how the relative focus of innovation in space debris management has shifted over time.

In Figure 4-8 a significant shift is observed starting around 2010, when there was a sharp surge towards patents for debris removal technologies. This shift occurs shortly after the period from 2007 to 2009, which marked a pivotal moment in the evolution of space debris management (Pardini and Anselmo, 2009; Lambert, 2018). There is a clear reason for this: two significant events during this time highlighted the risks posed by space debris and potentially accelerated the push for removal technologies. The 2007 Fengyun-1C anti-satellite test created thousands of pieces of debris, becoming one of the largest single debris-generating events in history (Paladini, 2024; Lambert, 2018; Pardini and Anselmo, 2009). This was followed in 2009 by the Iridium 33–Kosmos 2251 collision, which produced substantial debris clouds and underscored the increasing likelihood of orbital collisions (Jakhu, 2010; Brian Weeden, 2010). These events provided real-world examples of the threats posed by debris, potentially contributing to the need for removal technologies as a means of directly addressing the growing problem.

On the other hand, prevention technologies have emerged sporadically over time, with a slight rise in recent years. Their low patent numbers suggest they are either standardised in mission planning, requiring less innovation, or deprioritised in favour of more immediate benefits from removal i.e., ADR and mitigation. These observable shifts in technological focus over time raise the question of how such innovations emerge, gain traction, and diffuse across the industry. To better interpret these patterns, it is useful to situate them within established innovation theory.

The diffusion of innovation, as explored by (Rogers, 2003) and (Stoneman, 1995) provides a framework for understanding how new technologies evolve and spread through various phases. Rogers' diffusion model illustrates technology adoption through stages from innovators to laggards. This study applies the model to categorise space debris technologies, mitigation, removal, and prevention, along the diffusion curve, analysing their progression from 1990 to 2024. Figure 4-9 visualises this process by plotting the cumulative number of space-debris-related patents published between 1990 and 2024 alongside a fitted logistic growth curve, offering an empirical representation of innovation diffusion within the debris management domain.

Figure 4-9 Fitted Logistic Growth Curve

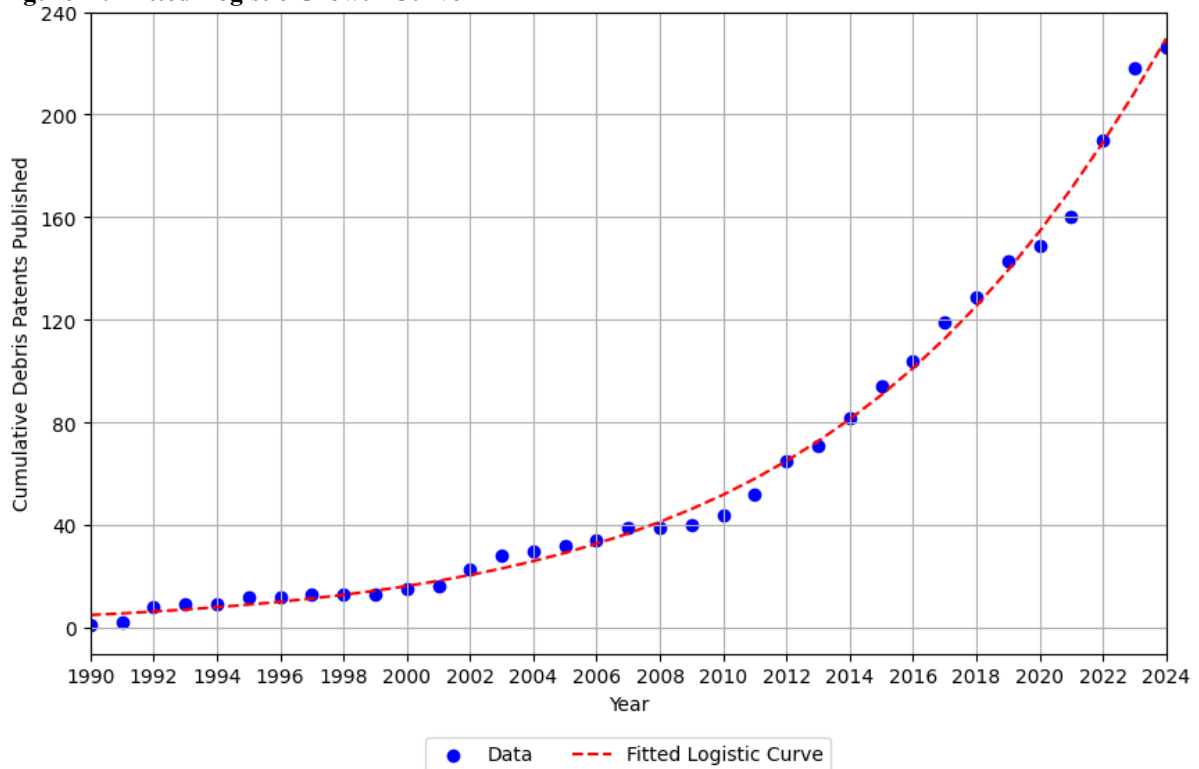


Figure 4-9: Shows the cumulative number of space-debris-related patents published between 1990 and 2024 (raw data), fitted with a logistic growth curve to represent the diffusion of innovation over time. The model is parameterised with a carrying capacity $K = 1123.833K$, growth rate $r = 0.11923$, and inflection point $t_0 = 2035.401$.

We fit a logistic growth curve to the historical data on the 226 cumulative debris-related patents to using the equation $f(t) = \frac{K}{1+e^{-r(t-t_0)}}$ with $f(t)$ the adoption rate (cumulative adoption) at time t , with K the maximum possible adoption level (i.e., a saturation point), r the growth rate and t_0 is the inflection point at which the adoption rate is 50% of K so that $f(t) = \frac{K}{2}$.¹⁷

¹⁷ The curve-fitting process was executed using the SciPy `curve_fit` function in python, which estimates the optimal parameters K (saturation level), r (growth rate), and t_0 (inflection point) by minimising the difference between the model and observed data. The initial estimations for these parameters were derived from the dataset itself, with K set to the maximum cumulative total of 226, r initialised to 0.1, and t_0 estimated using the median year of the dataset, 2007. The final fitted

As an illustrative extension of the diffusion analysis, Figure 4-10 applies the fitted logistic growth function to project the long-term adoption trajectory of space-debris-related technologies beyond the historical period. By extending the curve forward in time, the figure illustrates how innovation activity is expected to evolve as the sector approaches technological saturation. This projection suggests that space debris technology is currently in the early majority phase of innovation diffusion.

Figure 4-10: Logistic Growth Curve Fit with Forecast

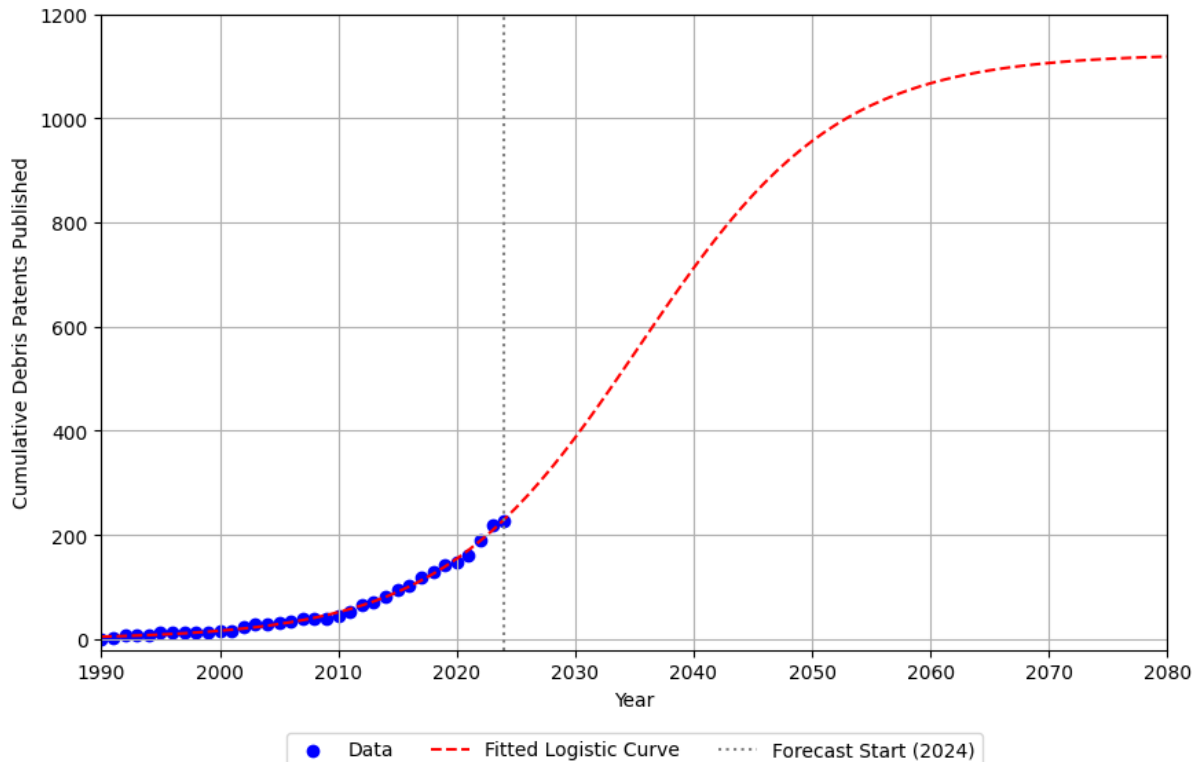


Figure 4-10: Shows the cumulative number of space-debris-related patents (1990–2024) fitted with a logistic growth curve and extended into a long-term forecast to the point of 99% adoption. Historical patent data are shown as points, with the fitted and projected diffusion curve shown as a dashed line. The model is parameterised with $K = 1123.833K$, $r = 0.11923$, $t_0 = 2035.401$.

Figure 4-10 is the fitted logistic curve (dashed red line) which extends from historical data (blue points) into the future, illustrating a trajectory where patent activity is projected to slow down as it approaches technological saturation around 2080, crossing 99% adoption between 2074 and 2075. The inflection point ($t_0 \approx 2035$) suggests that as of 2024 we are still in the early majority phase of 16% – 50% adoption but will be transitioning into the late majority phase of the innovation cycle in the next decade, where adoption expands more rapidly but remains constrained by economic and regulatory factors.

parameters were then used to generate a smooth logistic curve that overlays the historical data, illustrating the adoption trend over time.

Though experimental, this visualisation highlights how space debris management technology may evolve. The steady rise in patents suggests growing investment, potentially influenced by past debris events. However, the logistic curve's slow growth and high inflection point suggests systemic barriers, such as regulatory fragmentation, high R&D costs, and technological complexity (Markard et al., 2012; Martin-Lawson et al., 2024). Unlike consumer-driven innovation, space debris management relies on government funding and policy incentives, slowing adoption (Pelton, 2019). As the sector nears the late majority phase, economic incentives and regulatory frameworks will be key to accelerating growth. The high K value signals potential for expansion, but overcoming adoption barriers through policy, funding, and international collaboration is crucial for full-scale deployment and long-term sustainability.

Using Rogers (2003) Diffusion of Innovation Theory, our analysis shows that space debris technologies, mitigation, removal, and prevention, are still in their early adoption phase, with about 22% diffusion based on patent activity. While patents indicate technological progress, they do not necessarily mean widespread operational use. The gap between innovation and deployment needs to be bridged through policies that lower entry barriers, increase economic incentives, and establish clearer regulations.

One approach to doing this is through the Technology-Push approach which focuses on driving innovation through R&D funding, tax breaks, and grants. Some examples of these initiatives are executed by NASA and ESA supporting companies like Astroscale and ClearSpace-1. But technical readiness alone is not enough. Demand-Pull measures, such as orbital usage fees (charging satellite operators based on lifespan) and debris removal credits (tradable permits that offset debris creation), help align market incentives with sustainability. Together, these strategies can ensure patented innovations do not just remain on paper but turn into real-world solutions.

Added to this, our patent trends show an imbalance, most focus on debris removal, while prevention lags due to inadequate financial returns. (Mowery and Rosenberg, 1979) framework helps to explain this phenomenon from our patent analysis: prevention and removal benefit the collective rather than generating direct profits. To shift this dynamic, policies like orbital access fees (tiered based on collision risk) and tax breaks for sustainable end-of-life satellite disposal could encourage adoption. A “remove-as-you-launch” mandate could also make accountability a standard industry practice, turning sustainability from a goodwill effort into a business norm.

Moreover, Mazzucato's (2018) theory highlights the importance of public-sector leadership in reducing risk for high-cost innovations. Prize-based initiatives such as XPRIZE, a global innovation competition driving breakthrough solutions, and public-private partnerships (like ESA's Clean Space Initiative) could accelerate breakthroughs in both ADR and prevention. Patent pools promoting collaboration among governments, academia, and industry would help avoid redundant R&D efforts and fast-track commercialisation of new technologies.

By integrating these approaches, Technology-Push for R&D, Demand-Pull to shape market behaviour, regulatory updates for legal certainty, and public-sector leadership to de-risk investment, we

can embed debris prevention, mitigation and removal into standard industry practice. This strategy not only tackles the immediate challenge of space debris but also serves as a model for using innovation policy to address broader sustainability challenges.

4.6 Conclusions and future research.

The increasing commercialisation of space and rising orbital congestion present urgent challenges for sustainable space operations. The accumulation of space debris threatens satellite-dependent industries, increases collision risks, and highlights gaps in existing legal frameworks that fail to regulate debris management effectively. Without technological innovation and coordinated policy intervention, the long-term sustainability of Earth's orbital environment remains at risk.

This study analysed the landscape of space debris innovation and its interaction with regulatory frameworks. Using a custom DBSCAN clustering algorithm, we categorised global patents related to space debris management into prevention, mitigation, and removal technologies, providing a data-driven assessment of innovation trends. Additionally, we applied the principle of Diffusion of Innovation Theory to assess the adoption trajectory of these technologies, identifying where progress is concentrated and where policy gaps may hinder adoption.

To sustain and accelerate the growth of space debris mitigation, removal, and prevention technologies, policymakers will need to align regulatory, financial, and market-based incentives with current adoption trends. By implementing market-pull mechanisms, such as orbital-use fees, sustainability-linked tax reductions, and mission-driven funding programs, governments can create economic incentives that push patented technologies toward real-world deployment. Standardising regulations across spacefaring nations, establishing clearer liability frameworks for debris removal, and supporting ADR initiatives through targeted subsidies will be critical in ensuring that commercial entities actively engage in debris management.

Beyond the policy and regulatory dimension, it is also important to acknowledge considerations that may influence the robustness of the findings. One notable limitation is the reliance on our custom DBSCAN clustering algorithm, created in Python for this analysis. While DBSCAN is widely recognised for its effectiveness in density-based clustering, the custom nature of our implementation opens it to potential scrutiny. Experts with a technical background in clustering mechanics may argue against its robustness, as the custom adjustments may not align with best practices in some contexts. Additionally, the high-dimensionality of the 756-dimensional display key data posed challenges, as redundant distance calculations could impact clustering accuracy (Chen et al., 2021). To mitigate this, we applied PCA, reducing the data to seven components while retaining 90% of the variance. This improved accuracy but also highlights potential limitations in generalising our results due to the structure of the dataset.

Another limitation is the method used to capture space-related patents. Despite rigorous efforts, there remains the possibility that not all relevant patents were included due to classification inconsistencies or variations in keyword use, which could influence the final dataset and impact the conclusions drawn from the analysis. Furthermore, this study focused primarily on the leading spacefaring nations, countries with the largest investments in space exploration and technology development. This approach, while necessary for capturing dominant trends, may have overlooked emerging contributions from smaller or developing space industries, limiting the diversity of technological insights. Future research could benefit from expanding the dataset to include a broader range of spacefaring entities.

Additionally, the logistic growth curve used to model space debris innovation assumes a predictable trajectory of technology adoption. However, space technology diffusion is influenced by geopolitical events, regulatory shifts, and international policy interventions, leading to irregular adoption patterns. Unlike consumer-driven markets, where innovation diffusion follows a relatively steady progression, space technology adoption is highly dependent on government funding and policy-driven incentives, making it susceptible to sudden accelerations or stagnation. The model may also overlook disruptive technological breakthroughs, such as AI-driven debris tracking, in-orbit recycling, or novel propulsion systems, which could dramatically alter the innovation landscape. Unexpected space events, such as catastrophic satellite collisions or major regulatory overhauls, could rapidly shift investment and research priorities, making traditional forecasting methods less reliable.

To improve accuracy, future studies could explore alternative modelling techniques such as scenario analysis or agent-based modelling to account for these uncertainties. Future research could also extend this work by incorporating a more detailed examination of applicant and inventor information in patent data, offering a granular view of how innovation is distributed across institutions, private companies, and governmental agencies. This could help uncover patterns in collaboration, funding structures, and regional innovation priorities that remain hidden in aggregate-level analyses.

International cooperation will also be essential in addressing the transboundary nature of space debris. While treaties like the Outer Space Treaty provide foundational principles, they lack enforceability mechanisms to regulate debris management efforts at scale. An organised governance framework, potentially incorporating licensing requirements, sustainability-linked permits, and coordinated debris removal mandates, could create a structured path toward a cleaner orbital environment. By fostering collaboration among space agencies, private industry, and international regulatory bodies, spacefaring nations can transition from fragmented, voluntary compliance to a unified strategy for long-term orbital sustainability.

While technological advancements in space debris prevention, mitigation, and removal are progressing, their widespread adoption depends on strategic policy interventions.

By mapping an emerging field that spans satellite operators, national agencies, and insurance markets, this study provides data-driven insights to inform future policy interventions, from orbital-use

fees to internationally recognised ADR authorisation, ensuring a safer and more economically resilient space economy. Leveraging economic incentives, regulatory enforcement, and international cooperation, governments can and will transform patent innovation into real-world implementation. Ensuring that emerging technologies move beyond conceptual development and into industry-wide deployment will be critical in securing a sustainable and accessible space environment for future generations.

5 Chapter 5

Conclusion

5.1 Key Findings

This section synthesises the key empirical findings of the thesis in relation to orbital sustainability. The sustainability of Earth's orbital environment has appeared as one of the defining global challenges of the 21st century. Over the past two decades, outer space, defined in this research as the region surrounding Earth where satellites and debris accumulate, rather than deep or interplanetary space, has undergone a profound transformation: evolving from a sparsely populated environment primarily used for scientific exploration and state-driven projects into a congested, commercially vibrant, and strategically contested domain (Tinoco et al., 2021; Peeters, 2010; Denis et al., 2020).

This exponential expansion, driven by the proliferation of satellite mega-constellations, a surge in private-sector investment, and the expected rise of new space markets such as space tourism and in-orbit servicing, has dramatically increased the density and complexity of orbital activity (Abashidze et al., 2022; Radtke et al., 2017; Svitina and Cherkasova, 2023). While these developments promise a wealth of benefits, including enhanced connectivity, global monitoring capabilities, and new economic opportunities, they also carry significant risks: chief among them is the rapid accumulation of space debris. The issue of orbital debris now occupies a central position in discussions about planetary governance, environmental resilience, and long-term socioeconomic stability.

Unlike other environmental concerns, the degradation of orbital space is not easily observable or intuitively understood by the general public, yet its impacts are no less severe. The cascading effects of debris collisions, the threat of Kessler Syndrome, and the presence of orbital congestion present substantial risks to the very infrastructure on which modern society increasingly relies on, from global telecommunications and satellite navigation to weather prediction, climate monitoring, and national security. In this context, the sustainability of orbital space is no longer a narrow technical concern, it is a systemic risk that intersects with economic growth models, legal regimes, innovation trajectories, and international regulations. This thesis was conceived as a response to this evolving threat, guided by the overarching research question: How can we understand, anticipate, and address the sustainability risks posed by the growing use of outer space?

In seeking to answer this question, the research deliberately adopts a systems-level perspective, moving beyond isolated treatments of space debris as either an engineering problem or a regulatory oversight. Instead, it synthesises insights from environmental risk modelling, systematic space economics research, and innovation studies to construct a multi-layered understanding of the orbital sustainability challenge. In doing so, the thesis contributes to an emerging but increasingly urgent body

of interdisciplinary work that aims to develop robust frameworks for safeguarding the orbital commons. By framing orbital sustainability as a socio-technical issue, one that is shaped by the interplay between commercial ambition, technological innovation, and fragmented governance, this research lays the foundation for more coherent, forward-looking approaches to managing the risks associated with Earth's orbits.

The first empirical paper, chapter 2, presents a novel approach to quantifying the systemic risks associated with orbital debris by integrating probabilistic modelling with economic growth data from the commercial space sector. The central theoretical contribution of this paper lies in its reframing of the orbital debris problem as a dynamic, feedback-driven risk system, one in which commercial growth, technological capacity, and physical environmental degradation are linked. By situating orbital debris within the broader literature on systemic environmental risks and applying the lens of sustainability transitions, this study moves beyond the conventional treatment of debris as an isolated technical challenge. Instead, it theorises the accumulation of debris as a compounding threat that, if left unaddressed, could trigger a Kessler-like cascade effect, rendering key orbital bands unusable within a matter of decades.

Methodologically, Chapter 2 introduces a hybrid model combining a Poisson-based probabilistic framework with linear regression to estimate the growth trajectory of collision risks in low Earth orbit. By linking satellite launches and industry growth to collision probability, the model dynamically simulates how commercial expansion accelerates orbital congestion. Scenario forecasting under varying launch and debris management assumptions provides a transparent and replicable tool for both quantitative analysis and policy evaluation. Although constrained to a single orbital altitude and excluding externalities such as anti-satellite (ASAT) testing, the model offers a robust, data-driven basis for informing regulatory action. Under business-as-usual projections, collision risk becomes self-reinforcing, potentially reaching a critical tipping point by the mid-2030s. These findings underscore the urgency of proactive debris removal and regulatory interventions, and support integrating sustainability assessments into mission planning and launch approval processes.

The second empirical paper undertakes a systematic literature review to examine how commercialisation, specifically the rise of space tourism, functions as a multiplier of sustainability risk in orbital space. Theoretically, this paper extends the concept of environmental pressure multipliers, typically used in planetary sustainability studies, to the orbital domain. It argues that, although space tourism is not yet a primary contributor to debris generation, it is likely to significantly amplify existing risks by accelerating traffic growth in the future, straining governance frameworks, and heightening the symbolic and political pressures to maintain unconstrained access to space. By positioning space tourism as both a market disruptor and a regulatory challenge, the chapter contributes a new conceptual lens for understanding how emerging commercial activities intersect with sustainability transitions in space.

Chapter 3 employs a structured synthesis of 291 primary documents spanning 2000–2023, using a systematic review to categorise empirical and theoretical concerns around the commercialisation of space. This approach clarifies a field often marked by fragmented policy debates and disconnected technical discussions. The chapter also develops a framework of four interrelated domains, environmental impact, affordability and access, risk and liability, and regulatory coherence, highlighting gaps such as the lack of insurance standards for tourist missions and liability protocols in mixed-use orbital environments. Practically, the chapter reveals that current governance structures are ill-equipped to manage the rapid rise of space tourism. Legal ambiguities, unclear environmental standards for suborbital flights, and fragmented international coordination pose concrete risks to orbital sustainability, including intensified congestion and reduced manoeuvring flexibility. The chapter concludes by advocating a proactive governance model that anticipates rather than reacts to commercial growth, recommending adaptive legal frameworks, international policy harmonisation, and the integration of sustainability assessments into the licensing of all commercial launches, including tourism.

The third empirical paper shifts focus to the technological dimension of orbital sustainability, offering a detailed analysis of global innovation patterns in space debris management. Theoretically, this chapter contributes to the literature on sustainability transitions and socio-technical systems by showing how innovation in orbital debris technologies is currently skewed towards reactive measures (mitigation and removal) rather than proactive strategies (prevention). The paper positions this trend as indicative of a broader misalignment between innovation incentives and long-term sustainability goals. Drawing on innovation systems theory, it argues that the current focus on active debris removal, while necessary, reflects a crisis-response logic rather than a preventive or stewardship-oriented approach. This insight opens new space for critical reflection on how technology pathways are shaped by institutional, financial, and geopolitical factors.

Chapter 4 applies a DBSCAN clustering algorithm to 756 space debris-related patents, using a dual-layer similarity matrix that combines semantic (textual) and structural (IPC classification) data. This unsupervised machine learning approach, complemented by dimensionality reduction (PCA), silhouette scoring, and network visualisation, enables the mapping of debris management technological trajectories across prevention, mitigation, and removal technologies. Practically, the analysis reveals a strongly imbalanced innovation ecosystem: prevention technologies are severely underrepresented, while mitigation and removal dominate. Regional trends further highlight disparities, with China and Russia investing heavily in capture and deorbit systems, and the US and EU focusing on shielding and situational awareness. The chapter also identifies a disconnect between technological development and regulatory frameworks, which remain fragmented or outdated. Without coordinated international standards and enforceable legal instruments, even advanced technologies risk failing to achieve their sustainability goals. The chapter concludes by calling for a global innovation strategy, supported by

incentives for preventive design, sustainability-linked financing, and institutionalisation of best practices through multilateral frameworks.

As a whole, this thesis offers a cohesive and interdisciplinary response to the increasingly urgent challenge of orbital sustainability. The empirical analysis of this thesis shows that orbital congestion and debris accumulation are accelerating, that emerging commercial sectors such as space tourism act as pressure multipliers within an already constrained system, and that technological innovation in debris mitigation and removal, while growing, remains largely reactive rather than preventative.

These findings align closely with sustainability transitions theory, which conceptualises sustainability challenges as the outcome of misalignment between technological innovation, market dynamics, and institutional frameworks. In the case of Earth's orbital environment, niche innovations in launch systems, satellite miniaturisation, and commercial services are advancing more rapidly than the governance regimes designed to manage them. This creates conditions of institutional lock-in and path dependency, increasing the risk that unsustainable practices become entrenched before effective regulatory adaptation can occur.

From a sustainability perspective, the results also reveal inherent tensions between several United Nations Sustainable Development Goals. The expansion of space activity strongly supports SDG 9 (Industry, Innovation and Infrastructure) and SDG 8 (Decent Work and Economic Growth) through technological advancement, high-skill employment, and downstream economic benefits. However, the same growth dynamics place increasing strain on the long-term delivery of SDG 13 (Climate Action), which depends on reliable and sustainable space-based Earth observation and launch systems, as well as SDG 17 (Partnerships for the Goals), which requires effective international coordination in managing shared resources. The empirical findings illustrate how, in the absence of adequate governance, progress toward certain SDGs may inadvertently undermine others.

Overall, the findings can be situated within broader debates on global and polycentric governance, highlighting the fragmented and adaptive nature of contemporary space governance. The expansion of commercial activity illustrates clear patterns of institutional lag and regulatory fragmentation, while simultaneously pointing towards emerging forms of networked public-private governance. Collectively, these dynamics underscore the challenge of managing outer space as a shared and increasingly congested domain, and the need for governance frameworks capable of coordinating diverse actors while balancing innovation with long-term sustainability.

5.2 Achievement of Objectives

The overarching aim of this thesis was to understand, anticipate, and assess the sustainability risks posed by the growing use of Earth's orbital environment. This aim was achieved through the completion of three interconnected research objectives, each addressed in a dedicated chapter.

The first objective was to quantify and model the growth of orbital debris and assess the risk

of critical congestion thresholds for Earth's orbits. This objective was achieved in Chapter 2 through the development of a probabilistic modelling framework combining regression analysis and Poisson collision probability modelling. The results demonstrate that, under current governance conditions, collision risk and debris accumulation are likely to reach critical levels within a relatively short time horizon.

The second objective was to examine the role of emerging commercial activities, particularly space tourism, in accelerating orbital congestion and to assess the associated sustainability and governance challenges. Chapter 3 fulfilled this objective through a systematic literature review and bibliometric analysis, which revealed that commercial space activities act as pressure multipliers within an already constrained orbital system, while regulatory and sustainability considerations remain underdeveloped in the literature.

The third objective was to analyse the innovation landscape and governance responses related to space debris mitigation and removal. This objective was achieved in Chapter 4 through patent analysis and clustering techniques, which mapped technological trajectories across prevention, mitigation, and removal strategies. The findings highlight a growing but uneven innovation response, with a strong emphasis on reactive mitigation and comparatively limited focus on preventative approaches.

Collectively, these three objectives were met and together provide a comprehensive assessment of the technical, commercial, and governance dimensions of space sustainability, directly addressing the central research aim of the thesis.

5.3 Key Contributions to the Body of Knowledge

In light of these achieved objectives, the thesis makes several important contributions to the existing body of knowledge. A central contribution of this thesis lies in reframing space sustainability as a governance challenge embedded within a complex socio-technical system, rather than as a purely technical or economic problem. While existing scholarship frequently identifies deficiencies in space governance, this research advances understanding by empirically demonstrating how regulatory fragmentation, institutional lag, and rapid commercialisation interact to shape sustainability outcomes in Earth's orbital environment.

Across the three empirical chapters, the findings consistently reveal tensions between national sovereignty, commercial incentives, and the collective management of shared orbital resources. Chapter 2 shows how the absence of coordinated and enforceable governance mechanisms allows collision risk and debris accumulation to escalate despite widespread recognition of the problem. Chapter 3 demonstrates that emerging commercial activities, including space tourism, act as pressure multipliers, expanding orbital use faster than governance frameworks can adapt. Chapter 4 further reveals that although technological innovation in debris mitigation and removal is accelerating, it remains uneven

and insufficiently aligned with regulatory and institutional structures, with a strong bias toward reactive rather than preventive solutions.

Rather than advocating a specific governance design, the thesis contributes a grounded assessment of which governance characteristics appear most consistent with empirical realities. The evidence suggests that neither a fully centralised global authority nor purely decentralised national regulation adequately addresses the sustainability challenge. A single unified authority, while theoretically appealing, faces significant political and institutional barriers, whereas fragmented national approaches risk exacerbating collective action failures in a shared orbital environment. Instead, the findings align most closely with a hybrid, polycentric governance logic, characterised by central coordination functions operating alongside decentralised national, regional, and sector-specific actors. This interpretation is offered as an analytical insight derived from observed governance dynamics, rather than as a prescriptive recommendation.

By situating orbital congestion and space debris within broader theories of global governance, commons governance, and sustainability transitions, the thesis contributes to reframing space governance as an evolving socio-technical system. This perspective helps explain why existing arrangements struggle to deliver sustainability outcomes and clarifies the conditions under which more coordinated, adaptive, and forward-looking governance responses may emerge. The comparison with international aviation governance further underscores this point, highlighting how the absence of binding international authority in space, unlike aviation, contributes to persistent fragmentation despite the presence of global coordinating institutions.

Overall, the thesis advances three interconnected contributions. First, it offers a systems-level perspective linking physical orbital risk with commercial behaviour and innovation trajectories. Second, it demonstrates that current technological and regulatory responses to orbital sustainability remain fragmented, reactive, and unevenly distributed. Third, it contributes methodologically by demonstrating the value of integrated, multi-method research for analysing complex sustainability challenges in frontier domains. Together, these contributions position orbital sustainability as a governance problem requiring coordinated institutional evolution alongside technological and commercial change.

Ultimately, the thesis contributes to an emerging discourse that positions outer space as a global common, an environment whose stewardship must be collective, forward-looking, and grounded in principles of sustainability. The central message is that preserving the usability of Earth's orbits is not simply about reducing debris; it is about rethinking how we govern, innovate, and commercialise in space. Readers are invited to see orbital sustainability not as a constraint on progress, but as the precondition for it. The thesis underscores the need for proactive governance models, realigned innovation incentives, and systemic foresight, without which, the promise of space risks being eclipsed by its own consequences.

5.4 Limitations and Directions for Future Research

While this thesis makes several empirical and conceptual contributions, its findings should be interpreted within the boundaries of the methodological and data-related choices made. These limitations reflect trade-offs present in the quest to contribute to a complex domain. In Chapter 2, the probabilistic modelling of orbital collision risk involved simplifying assumptions, including a focus on LEO and a reduced representation of satellite operational diversity. These choices were made to ensure analytical tractability and transparency, but they constrain the precision of long-term risk projections. Future research could address these limitations by expanding the model to account for planned mega-constellation deployments and other upcoming satellite launches, incorporating multiple altitude levels to reflect the array of orbital regimes. On top of this deploying Monte Carlo simulations would also allow for richer scenario analysis, offering deeper insights into the distribution of collision risks and the resilience of debris management strategies under varying growth trajectories.

Chapter 3 relied primarily on academic literature to examine the sustainability dynamics of space tourism. Although this approach enabled a rigorous synthesis of scholarship, it did not incorporate the perspectives of stakeholders such as policymakers, industry actors, and investors, whose insights are critical for understanding practical challenges and decision-making processes within the sector. Future work could build on this foundation by conducting interviews or surveys with these communities, enabling a comparison between academic narratives and real-world priorities. This would provide a more complete understanding of how emerging commercial activities intersect with sustainability transitions in orbital space.

Similarly, Chapter 4 examined technological innovation through patent analysis. While patents serve as a valuable proxy for inventive activity, they represent only one aspect of the broader innovation ecosystem. Informal knowledge, organisational capabilities, and the allocation of funding are not captured, limiting the completeness of the analysis. Future research could link patent clusters to venture capital investments, government grants, or major institutional contracts (e.g., ESA and NASA) to explore how innovation pathways follow financial and institutional incentives. Such work would provide a deeper understanding of how resources shape the development and deployment of sustainable debris management technologies.

At a broader level, the thesis is deliberately wide-ranging and systems-oriented, integrating multiple perspectives across risk, commercial pressures, and governance. While this breadth enables a general perspective, it comes at the cost of depth within each individual domain. Additionally, all empirical chapters rely exclusively on secondary data, which, while analytically tractable, restricts validation through first-hand evidence. Collectively, these limitations delineate the scope of the thesis' contribution. The research is not intended to provide precise operational forecasts, exhaustive sectoral coverage, or policy prescriptions. Rather, it aims to identify systemic risk patterns, governance mismatches, and innovation trajectories that shape the sustainability of Earth's orbital environment.

Future research could address these broader limitations by combining secondary and primary data sources, allowing for richer, empirically grounded insights and more actionable guidance for policymakers, industry actors, and the scientific community.

5.5 Implications for the Future of Space Governance

This thesis concludes with a recognition that the sustainability of Earth's orbits is not solely a technical or regulatory concern, but a defining challenge of planetary governance in the space age. The problem of orbital debris is both a practical risk to essential infrastructure and a symbolic indicator of how emerging domains are managed in the face of rapid technological change. What this research has shown is that without deliberate and coordinated intervention, the expansion of orbital activity risks undermining the very systems it seeks to enhance. The prospect of congested, inaccessible orbital environments is no longer speculative; it is the likely trajectory if current trends in launch activity, innovation incentives, and regulatory fragmentation continue unchecked.

Yet, the findings presented here also underscore the fact that the space sector remains at a unique inflection point. Unlike other environmental crises, which have often been recognised too late, the orbital sustainability challenge is still in a phase where preventive measures can meaningfully alter the course of development. This presents a rare policy and governance opportunity, to act before irreversible thresholds are crossed. It also places a clear responsibility on the scientific, commercial, and policymaking communities to ensure that Earth's orbits are not treated as expendable infrastructure, but as shared strategic resources requiring long-term stewardship.

The thesis contributes to this effort by providing a multi-level analysis that bridges risk forecasting, technological innovation patterns, and commercial drivers. Its central message is that orbital sustainability cannot be achieved through isolated interventions. Rather, it demands a systems-oriented approach that links regulation, economic incentives, and innovation governance under a coherent and forward-looking framework. The preservation of orbital space is not only a technical goal but a prerequisite for the stability of global systems that depend on it for, communications, environmental monitoring, disaster response, and defence, among others.

As such, this research aims to leave readers with a broader reflection: the governance of space must evolve in step with its commercial and technological transformation. It is insufficient to approach the issue reactively. The challenge is not only to remove debris, track satellites, or update treaties, but to anticipate the societal role space will play over the coming decades and design governance systems that reflect its criticality. This includes viewing orbital sustainability not as a barrier to growth, but as a foundation for it.

In sum, this thesis calls for renewed attention to the strategic and ethical dimensions of space governance. The future accessibility and functionality of orbital space depends on the decisions being made today. By framing orbital sustainability as a shared global resource good requiring

interdisciplinary coordination, this research contributes to a growing body of scholarship committed to shaping space not only as a domain of opportunity, but one of long-term responsibility. I believe this thesis has laid the foundation for such efforts, and it is hoped that its insights will contribute to a future where space remains open, safe, and accessible for generations to come.

6 Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7 Data availability

Data will be made available on request.

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9 Appendix

9.1 Appendices for Chapter 4

9.1.1 DBSCAN Parameters

Table 9-1: Parameter descriptions for the DBSCAN

Parameter	Description
Epsilon (EPS, ϵ)	a parameter that defines the maximum distance between two points for one to be considered as in the neighbourhood of the other. Essentially, it sets the radius around a data point.
Minimum Samples	a parameter that specifies the minimum number of points that must exist within an EPS-radius neighbourhood for a point to be considered a core point (a point that is at the core of a cluster)
Minimum number of Edges	a parameter that specifies the minimum number of connections (lines) to other points that a node requires to be visualised
Minimum Number of Nodes per Cluster	a parameter that specifies the minimum number of nodes that must be present in a cluster for it to be considered a valid cluster in the analysis.

This table summarises the key parameters applied in the DBSCAN algorithm, including neighbourhood distance (ϵ), minimum samples, and minimum connectivity thresholds used to identify valid patent clusters (Lai et al., 2019).

9.1.2 Similarity Calculation Breakdown

9.1.2.1 Textual Similarity Calculation

To break down the process we will use the example input text "Membrane seal assembly for a pulsed rocket motor" from the title of patent GB 2367605 A.

We begin with the raw input text representing patent GB 2367605 A:

Input Text: "Membrane seal assembly for a pulsed rocket motor" ()

This sentence describes a component of a rocket motor. It will undergo several processing steps to prepare it for semantic comparison with other patents. The first step is for the text to go through tokenization, the process of splitting the input text into individual words (tokens). We used the *TreebankWordTokenizer* from the Natural Language Toolkit (NLTK) in python to break down the text into individual tokens which is done to allow us to process each word individually.

Input Text: "Membrane seal assembly for a pulsed rocket motor" ()

Tokens: ["Membrane", "seal", "assembly", "for", "a", "pulsed", "rocket", "motor"] ()

Next the stop words¹⁸ are removed from the tokenised text. These words, which typically carry little semantic significance, are excluded to enhance the focus on meaningful and impactful terms, thereby improving the quality of the analysis.

¹⁸ common words (e.g., "and," "the," "is")

Input Tokens: "Membrane seal assembly for a pulsed rocket motor" ()

Stop Words: ["for", "a"] ()

Filtered Tokens: ["Membrane", "seal", "assembly", "pulsed", "rocket", "motor"] ()

Next the tokens are then processed using lemmatization, which reduces the words to their root forms to ensuring consistency when comparing different patents. For example, “running” and “ran” both become “run.”

Input Tokens: ["Membrane", "seal", "assembly", "pulsed", "rocket", "motor"] ()

Lemmatized Tokens: ["membrane", "seal", "assembly", "pulse", "rocket", "motor"] ()

To capture and quantify the semantic meaning of each token and therefore text relating to each patent we used the Word2Vec model. The Word2Vec is a pre-trained machine learning model that converts each token (word) into a 300-dimensional vector (Eshetu et al., 2020). This means each token is therefore converted into a vector of 300 numbers. These vectors capture and quantify the semantic meaning of words based on their usage in a large corpus¹⁹ of text, words with similar meaning have closer vectors.

Lemmatized Tokens: ["membrane", "seal", "assembly", "pulse", "rocket", "motor"] ()

Below is an example of word vectors conversion (subscript represents vector number):

vector("membrane") = [0.12₁, -0.34₂, 0.56₃, ..., 0.45₃₀₀] ()

vector("seal") = [-0.21₁, 0.67₂, -0.12₃, ..., -0.31₃₀₀] ()

vector("assembly") = [0.03₁, -0.45₂, 0.78₃, ..., 0.10₃₀₀] ()

vector("pulse") = [0.34₁, 0.89₂, -0.56₃, ..., -0.12₃₀₀] ()

vector("rocket") = [-0.56₁, 0.23₂, -0.45₃, ..., 0.67₃₀₀] ()

vector("motor") = [0.78₁, -0.67₂, 0.12₃, ..., -0.34₃₀₀] ()

Each dimension in the vector, for example 0.12₃, corresponds to a feature learning during the Word2Vec training process. Individually each dimension does not provide much information, collectively they encode relationship between different words. The reason why 300 dimensions are used is to help capture more complex relationships between words, balancing model richness with computational efficiency.

To measure how similar two texts of a patent are we compute the cosine similarity of their average vectors. To compute the average vector for the text, we sum the 300-dimensional vectors by element.

¹⁹ a large and structured collection of texts or language data used for linguistic analysis or natural language processing (NLP) (Son et al., 2025).

Below is an example of the summation process for the vectors (subscript represents vector number):

$$\begin{aligned}
 \text{vector}(\text{"membrane"}) &= [0.12_1, -0.34_2, 0.56_3, \dots, 0.45_{300}] & () \\
 \text{vector}(\text{"seal"}) &= [-0.21_1, 0.67_2, -0.12_3, \dots, -0.31_{300}] & () \\
 \text{vector}(\text{"assembly"}) &= [0.03_1, -0.45_2, 0.78_3, \dots, 0.10_{300}] & () \\
 \text{vector}(\text{"pulse"}) &= [0.34_1, 0.89_2, -0.56_3, \dots, -0.12_{300}] & () \\
 \text{vector}(\text{"rocket"}) &= [-0.56_1, 0.23_2, -0.45_3, \dots, 0.67_{300}] & () \\
 \text{vector}(\text{"motor"}) &= [0.78_1, -0.67_2, 0.12_3, \dots, -0.34_{300}] & ()
 \end{aligned}$$

Below is an example of the summation process for the vectors (subscript represents vector number):

$$\begin{aligned}
 \text{Summed vector}_1 &= [0.12_1 - 0.21_1 + 0.03_1 + 0.34_1 - 0.56_1 + 0.78_1] = 0.50_1 & () \\
 \text{Summed vector}_2 &= [-0.34_2 + 0.67_2 - 0.45_2 + 0.89_2 + 0.23_2 - 0.67_2] = 0.33_2 & () \\
 \text{Summed vector}_3 &= [0.56_3 - 0.12_3 + 0.78_3 - 0.56_3 - 0.45_3 + 0.12_3] = 0.33_3 & () \\
 \text{Summed vector}_{300} &= [0.45_{300} - 0.31_{300} + 0.10_{300} - 0.12_{300} + 0.67_{300} - 0.34_{300}] & () \\
 &= 0.45_{300}
 \end{aligned}$$

Therefore, the summed vector is:

$$\text{Summed vector} = [0.50_1, 0.33_2, 0.33_3, \dots, 0.45_{300}] \quad ()$$

Next, we computed the average vector:

$$\begin{aligned}
 \text{Average vector} &= \frac{\text{Summed Vector}}{\text{Number of Tokens}} & () \\
 \text{Average vector} &= \frac{[0.50_1, 0.33_2, 0.33_3, \dots, 0.45_{300}]}{6} & () \\
 \text{Average vector} &= [0.083_1, 0.055_2, 0.055_3, \dots, 0.075_{300}] & ()
 \end{aligned}$$

After this we can then start to calculate the cosine similarity which is represented by:

$$\text{Cosine Similarity} = \frac{A \cdot B}{\|A\| \|B\|} \quad ()$$

Where $A \cdot B$ represents the dot product of the two vectors taken from patent A and patent B , while $\|A\| \|B\|$ represents the product of their magnitudes.

To compute the dot product, we used the average vector of each patent text. For the vectors:

$$\begin{aligned}
 A \text{ (average vector)} &= [0.083_1, 0.055_2, 0.055_3, \dots, 0.075_{300}] & () \\
 B \text{ (average vector)} &= [-0.015_1, 0.055_2, 0.073_3, \dots, 0.112_{300}] & ()
 \end{aligned}$$

For the sake of this example, B represents fictitious data. Computing the dot product is as follows:

$$A \cdot B = \sum_{i=1}^n A_i \cdot B_i \quad ()$$

$$A \cdot B = (0.083_1 \cdot -0.015_1) + (0.055_2 \cdot 0.055_2) \quad ()$$

$$+ (0.055_3 \cdot 0.073_3) + \dots + (0.075_{300} \cdot 0.112_{300})$$

$$A \cdot B = -0.001245 + 0.003025 + 0.004015 + \dots + 0.0084 = 0.0071 \quad ()$$

To compute the magnitude of each vector the example is as follows:

$$\|A\| = \sqrt{\sum_{i=1}^n A_i^2} \quad ()$$

$$\|A\| = \sqrt{(0.083_1)^2 + (0.055_2)^2 + (0.055_3)^2 + \dots + (0.075_{300})^2} = 0.136 \quad ()$$

$$\|B\| = \sqrt{(-0.015_1)^2 + (0.055_2)^2 + (0.073_3)^2 + \dots + (0.112_{300})^2} = 0.145 \quad ()$$

Going back to our cosine formula this means that:

$$\text{Cosine Similarity} = \frac{A \cdot B}{\|A\| \|B\|} \quad ()$$

$$\text{Cosine Similarity} = \frac{0.0071}{0.136 \cdot 0.145} = 0.36 \quad ()$$

Next, we normalised the cosine similarity to a range of [0,1]. Cosine similarity figures range from [-1,1] where:

$$\text{Cosine Similarity} = 1 \text{ (Identical Words)} \quad ()$$

$$\text{Cosine Similarity} = 0 \text{ (Unrelated Words)} \quad ()$$

$$\text{Cosine Similarity} = -1 \text{ (Opposite Words)} \quad ()$$

This is to prevent the occurrence of a negative cosine similarity, leading to a negative distance in the matrix which would produce a calculation error for the DBSCAN algorithm:

$$\text{Normalized Cosine Similarity} = \frac{\text{Cosine Similarity} + 1}{2} \quad ()$$

$$\text{Normalized Cosine Similarity} = \frac{0.36 + 1}{2} = 0.68 \quad ()$$

9.1.2.2 Structural Similarity Calculation

In parallel, to calculate the structural similarity between patents, the WIPO IPC system assigns a structured code to patents, categorising them by technical fields. To quantify the similarity between two patents, the IPC similarity score evaluates the hierarchical similarity of their IPC codes. IPC codes have a structured format which splits the code into five separate components. See **B64G1/10 in Table 2 for an example break down**).

Table 2: Breakdown of International Patent Classification (IPC) code structure

Component	Symbol	Description	Example
Section	B	The first character represents the section.	Mechanical Engineering; Lighting; Heating; Weapons.
Class	64	The next two digits represent the class within the section.	Aeronautics or Astronautics.
Subclass	G	A letter indicates the subclass.	Astronautics.
Group	1	The digits before the slash indicate the main group.	Devices for launching, re-entry, or recovery of spacecraft.
Subgroup	10	The digits after the slash represent finer details of the group.	Further specialisation within the group.

Table 2: Illustrates how IPC codes are hierarchically organised into section, class, subclass, group, and subgroup components, which are used to assess structural similarity between patents.

The similarity between two IPC codes is computed based on their shared level where:

Section (Weight = 0.1)

Class (Weight = 0.15)

Subclass (Weight = 0.2)

Group (Weight = 0.25)

Subgroup (Weight = 0.3)

The weighting scheme reflects the hierarchical significance of the IPC code components, with increasing specificity as we move from section to subgroup. Section, being the broadest category, contribute the least weight (0.1) as they group technologies into large domains, while subgroups (weight 0.3) capture the most detailed technical aspects of the patent and contribute more heavily to the similarity score. The specific weights (0.1, 0.15, 0.2, 0.25, 0.3) increase incrementally by 0.05 to ensure proportional contribution, as more precise components (e.g., Group and Subgroup) are more significant in distinguishing patents. This progression strikes a balance between lower weighted categories, which provide a foundation for similarity, and higher weighted categories, which add technical specificity, aligning with the purpose of IPC codes to capture both broad categorisations and specific technical innovations. The total weights sum to 1.0, ensuring a normalised and interpretable similarity score.

In working towards the total similarity score, we first need to calculate the structural similarity for each component between patents. For this example, we will use the IPC code B64G1/1250 and tests its similarity to B64G10/1250 and B64G1/1221. The algorithm checks each component and assigns value depending on a match or no match where:

1 = *Perfect match*

0 = *(No match)*

Using the examples above the comparison is as follows:

Level 1: Section Similarity

B64G1/1250 = B

B64G10/1250 = B = match, score = 1

B64G1/1221 = B = match, score = 1

Level 2: Class Similarity

B64G1/1250 = 64

B64G10/1250 = 64 = match, score = 1

B64G1/1221 = 64 = match, score = 1

Level 3: Subclass Similarity

B64G1/1250 = G

B64G10/1250 = G = match, score = 1

B64G1/1221 = G = match, score = 1

The calculation of the group and subgroup similarity scores involves more computation. This is because most patents do not have IPC codes with the exact same group and subgroup. To separate patents that do have a link, although not exact at group level, we aimed to quantify how closely related two groups and subgroups are. With this in mind:

$$\text{Group Similarity} = \max\left(1 - \frac{|G_1 - G_2|}{\max(G_1, G_2)}\right)$$

Where:

G_1 : *Group number from the first IPC code*

G_2 : *Group number from the second IPC code*

$|G_1 - G_2|$: *The absolute difference between the group numbers*

$\max(G_1, G_2)$: *The larger of the two group numbers (used to normalize the difference)*

The way it works is that if $G_1 = G_2$, the difference is 0, and therefore similarity = 1. If the groups differ slightly, the similarity score decreases proportionally. If there is no match in the group, the similarity score is 0.

Level 4: Group Similarity:

Comparing B64G1/1250 with B64G10/1250

$$G_1 = 1, G_2 = 10$$

$$\text{Group Similarity} = \max\left(1 - \frac{|1 - 10|}{10}\right) = 0.1$$

Followed by the second comparison:

Comparing B64G1/1250 with B64G1/1221

$$G_1 = 1, G_2 = 1$$

$$\text{Group Similarity} = \max\left(1 - \frac{|1 - 1|}{1}\right) = 1$$

To calculate the subgroup similarity the code works digit by digit, with a weighted similarity approach.

$$\text{Subgroup Similarity} = \frac{\text{Number of Matching Digits}}{\text{Total Digits in the Longer Subgroup}}$$

Similar to the group calculation if the subgroup numbers are identical the similarity = 1. If the groups differ slightly, the similarity score is proportional to the overlap. If there is no match in the group, the similarity score is 0.

Level 5: Subgroup Similarity

Comparing B64G1/1250 with B64G10/1250

First digit: 1 vs 1 = match

Second digit: 2 vs 2 = match

Third digit: 5 vs 5 = match

Forth digit: 0 vs 0 = match

Therefore:

$$\text{Subgroup Similarity} = \frac{4}{4} = 1$$

Comparing B64G1/1250 with B64G1/1212

First digit: 1 vs 1 = match

Second digit: 2 vs 2 = match

Third digit: 5 vs 1 = no match

Forth digit: 0 vs 2 = no match

Therefore:

$$\text{Subgroup Similarity} = \frac{2}{4} = 0.50$$

Finally, we calculate the aggregate scores:

Comparing B64G1/1250 with B64G10/1250

Similarity score

$$= (\textit{section} \cdot \textit{Weight}) + (\textit{class} \cdot \textit{Weight}) + (\textit{subclass} \cdot \textit{Weight}) \\ + (\textit{group} \cdot \textit{Weight}) + (\textit{subgroup} \cdot \textit{Weight})$$

$$\textit{Similarity score} = (1 \cdot 0.1) + (1 \cdot 0.15) + (1 \cdot 0.2) + (0.1 \cdot 0.25) + (1 \cdot 0.3) \\ = 0.775$$

Comparing B64G1/1250 with B64G1/1212

$$\textit{Similarity score} = (1 \cdot 0.1) + (1 \cdot 0.15) + (1 \cdot 0.2) + (1 \cdot 0.25) + (0.50 \cdot 0.3) \\ = 0.85$$

From this example we can see that when B64G1/1250 is more similar to B64G1/1221 (0.85) than B64G10/1250 (0.775). Finally, the IPC similarity provides a score between [0,1] where:

$$\textit{IPC Similarity} = 1 \textit{ (Identical fields)}$$

$$\textit{IPC Similarity} = 0 \textit{ (Unrelated fields)}$$

The final similarity score between two patents was a weighted combination of their textual and structural similarities. Structural similarity contributed 80% to the final score, while textual similarity accounted for the remaining 20%.

$$\textit{Total Similarity} = (\textit{IPC Similarity} \cdot 0.8) + (\textit{Normalized Cosine Similarity} \cdot 0.2)$$

$$\textit{Total Similarity} = (0.85 \cdot 0.8) + (0.68 \cdot 0.2) = 0.82$$

The similarity scores were used to construct a similarity matrix, where each patent was compared to every other patent in the dataset. This matrix was then converted into a distance matrix by subtracting the similarity scores from 1, where a higher distance value indicates lower similarity between patents.

$$\textit{Total Similarity} = (\textit{IPC Similarity} \cdot 0.8) + (\textit{Normalized Cosine Similarity} \cdot 0.2)$$

$$\textit{Total Similarity} = (0.85 \cdot 0.8) + (0.68 \cdot 0.2) = 0.82$$

$$\textit{Distance} = 1 - \textit{total similarity}$$

$$\textit{Distance} = 1 - 0.82 = 0.18$$

9.1.3 Sample from Distance Matrix

Table 9-3: Sample Distance Matrix

	US 12033519 B2	WO 2024/137555 A1	US 12017803 B2	US 12017802 B2	WO 2024/126529 A1
US 12033519 B2		0.5808	0.580645161	0.581954887	0.568888889
WO 2024/137555 A1	0.5808		0.57	0.573913043	0.567123288
US 12017803 B2	0.580645161	0.57		0.564179104	0.548571429
US 12017802 B2	0.581954887	0.573913043	0.564179104		0.5625
WO 2024/126529 A1	0.568888889	0.567123288	0.548571429	0.5625	

Table 9-3: Presents an excerpt from the distance matrix used in the DBSCAN clustering process, where values represent combined semantic and structural similarity between patent documents based on text embeddings and IPC code similarity. Lower distances indicate higher similarity between patents.

9.1.4 Visualisation of Reginal Debris Patents Clusters

Figure 9-1: Visualisation of Japan Display Key Debris Patents Clusters with their Technological Splits

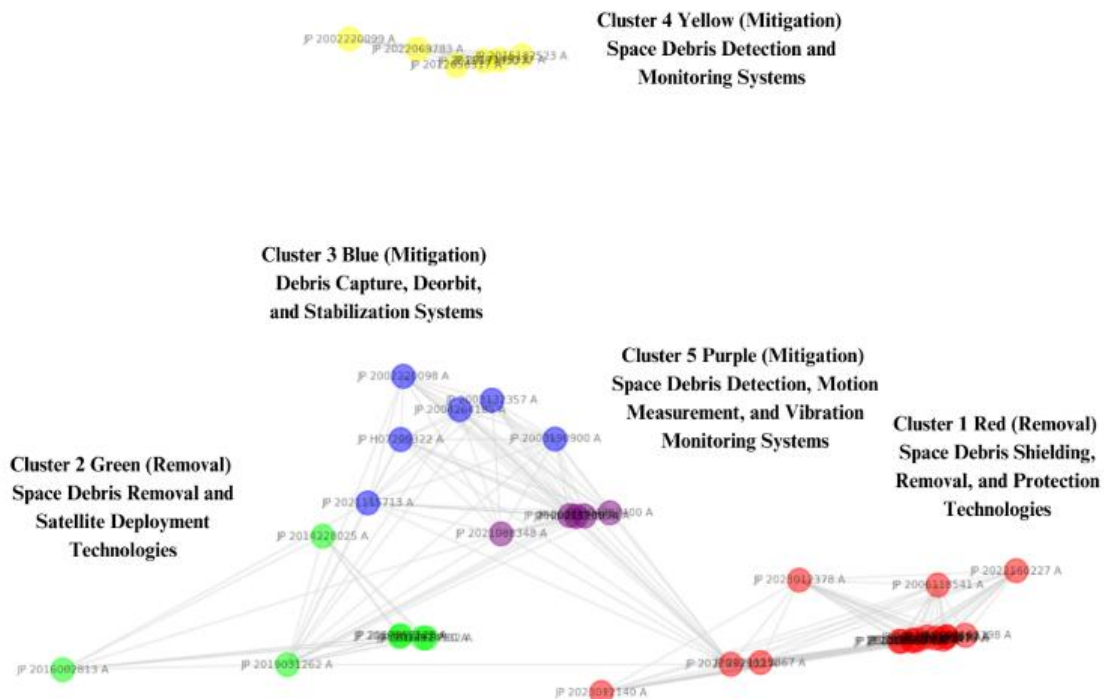


Figure 9-1: Visualisation that comprises clusters formed from Japanese patents. The criteria for the patents to be on the visualisation were a minimum of 10 edges and at least 5 nodes per to make a cluster. (Source: author, generated from patent data.)

The visualisation identifies five key clusters of space debris technologies, highlighting their roles in removal, mitigation, and prevention. Cluster 1 (Red) focuses on shielding and active debris removal, with strong connectivity showcasing its central role in debris management. Cluster 2 (Green) addresses debris removal and satellite deployment using harpoons and tethers, emphasizing sustainable space operations. Cluster 3 (Blue) integrates debris detection, motion, and vibration monitoring to provide essential data for collision avoidance. Cluster 4 (Yellow) and Cluster 5 (Purple) specialize in detection and monitoring systems using advanced sensors, lasers, and imaging, reflecting their importance in real-time tracking and collision assessment. Together, these clusters illustrate diverse but interconnected strategies for managing space debris.

Figure 9-3: Visualisation of France Display Key Debris Patents Clusters with their Technological

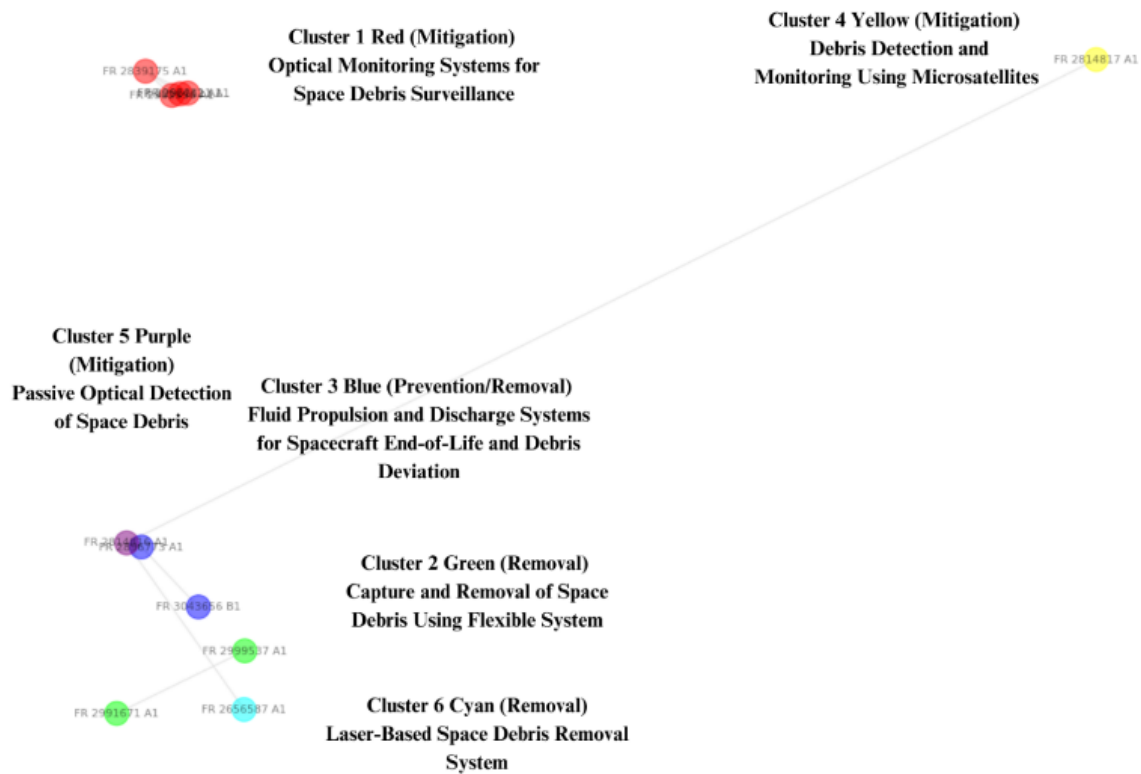


Figure 9-3: Visualisation that comprises clusters formed from Russian patents. The criteria for the patents to be on the visualisation were a minimum of 1 edge and at least 1 node per to make a cluster. (Source: author, generated from patent data.)

The clusters highlight varied approaches to space debris management. Cluster 1 (Red) focuses on optical monitoring systems using telescopes and imaging technologies for precise debris tracking in LEO. Cluster 2 (Green) emphasizes flexible capture systems like nets and harpoons for safe debris removal. Cluster 3 (Blue) integrates fluid propulsion and discharge systems for end-of-life spacecraft management and debris deviation, bridging active removal and prevention strategies. Cluster 4 (Yellow) and Cluster 5 (Purple) specialize in satellite-based and passive optical detection methods, using microsatellites and low-power CCD cameras for debris observation. Cluster 6 (Cyan) explores cutting-edge laser-based removal systems, vaporising debris to alter its orbit. Together, these clusters showcase specialised and integrative methods for tackling space debris challenges.

Figure 9-4: Visualisation of UK Display Key Debris Patents Clusters with their Technological

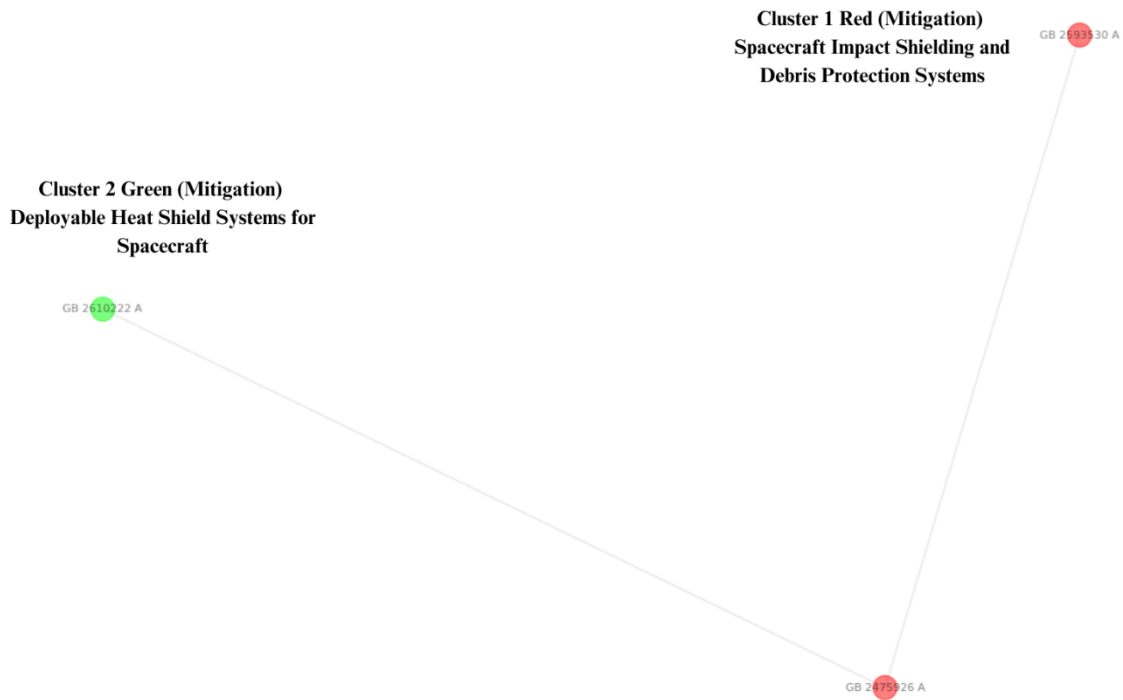


Figure 9-4 Visualisation that comprises clusters formed from UK patents. The criteria for the patents to be on the visualisation were a minimum of 1 edge and at least 1 node per to make a cluster. (Source: author, generated from patent data.)

The clusters highlight specialised approaches to spacecraft protection and debris mitigation. Cluster 1 (Red) focuses on impact shielding using materials like graphene foam and ceramic powder, along with deployable shields, to protect spacecraft in debris-filled orbits. Cluster 2 (Green) emphasises deployable heat shields, featuring an origami-inspired design that provides thermal protection during re-entry and mitigates debris impacts. Both clusters showcase unique, technology-driven solutions aimed at enhancing spacecraft resilience in high-risk environments.

Figure 9-5: Visualisation of Germany Display Key Debris Patents Clusters with their Technological

DE 102044004543 A1

Cluster 2 Green (Removal)
Asteroid-Derived Construction and
Docking Systems

Cluster 1 Red (Removal)
Particle-Based Space Debris
Deceleration

DE 102011001229 A

Figure 9-5: Represents the results of the DBSCAN clustering algorithm visualisation as well as the technological split of each cluster for Germany.

The clusters present distinct, innovative approaches to space debris and infrastructure management. Cluster 1 (Red) focuses on particle-based deceleration, a method to slow debris for easier management without fragmentation, reducing the risk of additional debris. Cluster 2 (Green) explores asteroid-derived construction and docking systems, leveraging asteroid materials for building infrastructure while indirectly addressing debris disposal. Both clusters highlight niche; forward-looking strategies aimed at improving space safety and sustainability.

9.1.5 Space Debris Protection Systems

Table 9-4: Space Debris Protection Systems

Space Debris Protection Systems			
Category	Country/Region	Cluster	Description
Mitigation			
Space Traffic Management, Debris Intrusion, and Monitoring Systems	EU	Cluster 1 (Red)	Space Traffic Management and Debris Intrusion Warning Systems
	EU	Cluster 3 (Blue)	Space Debris Detection and Measurement Systems
	EU	Cluster 5 (Purple)	Detection and Tracking of Space Debris Using Advanced Sensors
	USA	Cluster 2 (Green)	Space Debris Detection, Tracking, and Modelling Systems
	China	Cluster 3 (Blue)	Space Debris Monitoring and Satellite Maintenance Systems
	Japan	Cluster 4 (Yellow)	Space Debris Detection and Monitoring Systems
	Japan	Cluster 5 (Purple)	Space Debris Detection, Motion Measurement, and Vibration Monitoring Systems
	France	Cluster 1 (Red)	Optical Monitoring Systems for Space Debris Surveillance
	France	Cluster 5 (Purple)	Passive Optical Detection of Space Debris
	France	Cluster 4 (Yellow)	Debris Detection and Monitoring Using Microsatellites
Spacecraft Protection and Shielding Systems	EU	Cluster 4 (Yellow)	Hypervelocity Shielding and Debris Elimination Devices
	USA	Cluster 1 (Red)	Spacecraft Protection and Debris Mitigation Systems
	Japan	Cluster 1 (Red)	Space Debris Shielding, Removal, and Protection Technologies
	UK	Cluster 1 (Red)	Spacecraft Impact Shielding and Debris Protection Systems
	UK	Cluster 2 (Green)	Deployable Heat Shield Systems for Spacecraft

	Russia	Cluster 3 (Blue):	Debris Protection and Removal Systems
Removal			
Debris Removal via Harpoon, Tether, or Similar Capture Systems	EU	Cluster 2 (Green)	Harpoon and Tether-Based Debris Removal Systems
	EU	Cluster 6 (Cyan)	Chemical Propulsion and Harpoon-Based Debris Removal
	USA	Cluster 6 (Cyan)	Debris Interception and Tether Systems
	China	Cluster 1 (Red)	Space Debris Removal and Capture Technologies
	China	Cluster 2 (Green)	Space Debris Removal Systems and Active Debris Management
	Japan	Cluster 2 (Green)	Space Debris Removal and Satellite Deployment Technologies
	Russia	Cluster 1 (Red)	Magnetic and Mechanical Systems for Space Debris Collection and Removal
Debris Capture, Collection, and Stabilisation Systems	EU	Cluster 7 (Orange)	Debris Collection and High-Speed Particle Capture
	EU	Cluster 8 (Pink)	Adhesion and Harpoon-Based Debris Deceleration Systems
	USA	Cluster 3 (Blue)	Debris Capture, Deorbit, and Stabilisation Systems
	USA	Cluster 4 (Yellow)	Debris Capture and Deorbiting Systems
	Japan	Cluster 3 (Blue)	Debris Capture, Deorbit, and Stabilisation Systems
Electromagnetic, Atmospheric, and Passive Debris Removal Systems	EU	Cluster 10 (Gold)	Artificial Atmosphere and Veil Systems for Debris Removal
	USA	Cluster 5 (Purple)	Electromagnetic and Atmospheric Debris Removal Systems
	Russia	Cluster 2 (Green)	Electromagnetic and Mechanical Collection Systems for Space Debris Disposal
	China	Cluster 4 (Yellow)	Passive Debris Deorbiting Systems
	France	Cluster 2 (Green)	Capture and Removal of Space Debris Using Flexible System
Prevention			
	France	Cluster 3 (Blue)	Fluid Propulsion and Discharge Systems for

			Spacecraft End-of-Life and Debris Deviation
	EU	Cluster 9 (Teal)	Satellite Disposal and Orbital Path Adjustment Systems
Unique Clusters			
	Germany	Cluster 1 (Red)	Particle-Based Space Debris Deceleration
	Germany	Cluster 2 (Green)	Asteroid-Derived Construction and Docking Systems
	France	Cluster 6 (Cyan)	Laser-Based Space Debris Removal System
	Russia	Cluster 4 (Yellow)	Destruction and Protection Systems for Space Debris and Natural Objects

Table 9-4: Summarises mitigation and spacecraft protection technologies identified in the patent analysis, grouped by country or region and mapped to corresponding DBSCAN clusters. Descriptions reflect the dominant technological focus of each cluster within the broader space debris management framework.

9.2 Publications

9.2.1 Chapter 2 (Paper 1)

The following paper has been published as part of this research and is included in full below:

Martin-Lawson, D., Paladini, S., Saha, K., et al. (2024) The cost of (Un)regulation: Shrinking Earth's orbits and the need for sustainable space governance. *Journal of Environmental Management*, 349: 119382. doi:10.1016/J.JENVMAN.2023.119382, <https://www.sciencedirect.com/science/article/pii/S0301479723021709>

9.2.2 Chapter 3 (Paper 2)

The following paper has been published as part of this research and is included in full below:

Martin-Lawson, D., Paladini, S., Saha, K., et al. (2026) Charting the course of space tourism toward a sustainable future. A cross-cluster thematic analysis. *Journal of Transport Policy*, 183: 104107. doi.org/10.1016/j.tranpol.2026.104107, <https://www.sciencedirect.com/science/article/pii/S0967070X26001174?dgcid=coauthor>