Acta Astronautica 238 (2026) 332–340

Contents lists available at ScienceDirect

Acta Astronautica

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

Framing the dynamics of risk landscape amidst space economy trends

Paolo Trucco, Alessandro Paravano *, Giorgio Locatelli

Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133, Milan, Italy

ARTICLE INFO

Keywords:
Space business trends
Risk modelling
Taxonomy
Satellite technology
New space project
Earth observation

ABSTRACT

Major Space Economy (SE) trends are pushing the space industry into an era of radical transformations. New missions, infrastructures and in-space activities are envisaged under deep technological and business uncertainties, with strong implications on how space organizations identify, assess and treat risks at different levels. Space organizations should enhance their risk management models and practices to cope with an evolving risk landscape. There are two main shortcomings in the extant body of knowledge about risk management in the space domain: (1) there are no robust approaches to the modelling and analysis of risks in space projects under the SE paradigm; (2) there is still a limited understanding of how the major technological, business and regulatory trends, taking place in the SE, influence the risk profile of new space missions and services.

The aim of this study is to address these gaps by investigating how SE characteristics and trends influence the risk exposure of space organizations. The research design consists of four phases. First, leveraging a systematic literature review, a taxonomy of the 5 key trends (e.g., New organizational and operational models) characterizing the SE, divided into 25 sub-trends (e.g., platformization), and a taxonomy of 36 risks (e.g., De-orbit risk) targeting different space missions and businesses are developed. Second, rich Bow-Tie models for each risk are set, linking risk events, causes, consequences, and types of impacts. Third, interviews with space experts were run to validate the taxonomies and the Bow-Tie models. Fourth, by reviewing the extant literature and collecting experts' opinions, possible positive or negative impacts of SE trends on space missions and business risks were analyzed and summarized in a "SE Trends-Risks" matrix. Results include 40 mechanisms of influence between SE sub-trends and space mission risks, 82 % are negative (i.e., lead to risk increase), and 18 % are positive (i.e., mitigate risks). Additionally, SE sub-trends worsen the business risk exposure through 59 identified mechanisms (64 %) and contribute to mitigating it through 33 mechanisms (36 %). The results may support space organization managers in planning new space missions or in innovating their business models. Space infrastructure insurers can leverage the same results to develop appropriate risk analysis methods. Future research can take the proposed taxonomy and framework as a reference for assessing risks of new system architectures and space-based services, or for investigating the effects of new regulations and governance models on the risk landscape in the SE.

1. Introduction

According to the OECD definition [1], the Space Economy (SE) is the full range of activities that create value for human beings through exploring, researching, understanding, managing, and utilizing space. It encompasses all parties involved in creating, delivering, and utilizing space-related goods and services, including those involved in research and development, space infrastructure, applications derived from space, and the ensuing body of scientific knowledge [2]. The definition entails several concepts that have gained high relevance as the SE developed: the predominant presence of private companies, whether suppliers or customers, the democratization of the space market, and the application of new and unseen business models [3]. Because of the liberalization of space, the involvement of government agencies has become much lower, even though the public sector played a critical role in the success of the first space ventures [4]. These evolutions are boosting the development of a new business paradigm, the so-called New Space (NS), besides the more traditional and institutional-driven one.

Major trends in SE are fostering the space industry's evolution. New missions, infrastructures, and in-space activities are envisaged under

This article is part of a special issue entitled: 2024 75th IAC Milan published in Acta Astronautica.

* Corresponding author.
E-mail addresses: paolo.trucco@polimi.it (P. Trucco), alessandro.paravano@polimi.it (A. Paravano), giorgio.locatelli@polimi.it (G. Locatelli).

https://doi.org/10.1016/j.actaastro.2025.06.067
Received 19 December 2024; Received in revised form 10 March 2025; Accepted 30 June 2025
Available online 3 July 2025

deep technological and business uncertainties [5,6], with strong implications on how space organizations identify, assess and treat risks at different levels. However, the literature does not fully address the relationship between business and industrial trends and the associated risks faced by different industrial and institutional actors. Significant gaps are still present at different levels: from a theoretically grounded definition of risk and widely recognized and adopted risk taxonomies [7,8], to the systematic modelling and analysis of those risks under the influence of different technological and business trends [9,10]. More specifically, we identified two main knowledge gaps: (i) the lack of robust approaches to the modelling and analysis of the risks of space programmes under the NS paradigm; and (ii) a limited understanding of how the major technological, business, and regulatory trends influence the risk profile of space projects and programmes.

The objective of the present study is to address the abovementioned gaps by adopting a qualitative research approach when answering the following research questions.

RQ1a How to classify the mission and business risks faced by space companies under the NS paradigm?

RQ1b How to model the main risk drivers and their dependencies under the NS paradigm?

RQ2 What are the drivers of mutual influence between mission and business risks and the major trends in the SE?

In the present research context, risk is conceptualized as the "effect of uncertainty on objectives", as per ISO 31000 standard. Instead, the "risk event" is defined as the "occurrence or change of a particular set of circumstances". One or more causes can trigger the risk event and might bring several consequences, defined as the "outcome of an event affecting objectives" [11].

The rest of the paper is organized as follows: Section 2 presents the Research Methodology adopted to investigate our research questions; Section 3 describes the risk taxonomy and risk modelling resulting from our analysis. Finally, in Section 4, we discuss our results and implications.

2. Research Methodology

We leveraged three specific models and methods to answer the three research questions. We adopted a hierarchical risk taxonomy [12] to answer RQ1a. The risk tree model has been used because of its clearness and completeness, especially when risks are divided into several categories [13]. To answer RQ1b, we used the bow-tie model to link specific risk events (as reported in the risk taxonomy) with their possible associated causes and consequences [14,15]. To answer RQ2, we developed a matrix similar to the House of Quality, an instrument functional to the Quality Function Deployment (QFD) [16]. This matrix enables the mapping of both the relationships between SE trends and risks (reported in the body of the matrix) and the interdependencies among different risk categories (reported in the roof of the matrix) [17].

The adopted research approach is abductive and implemented by combining a systematic literature review with experts' interviews.

2.1. Systematic literature review

The systematic literature review was based on 147 documents; 62 % (91) were selected from scientific literature, while the remaining 38 % (56) were retrieved from technical literature.

We started by collecting data from scientific literature. We performed a systematic search [18] through the Sciverse Scopus Database, the most adopted database in social science and engineering. In May 2022, we performed the query:

TITLE-ABS-KEY ("risk" OR "risk management") AND TITLE-ABS-KEY ({space industry} OR {space project*} OR {space program*} OR {space economy} OR {new space}) AND PUBYEAR >2010 AND (LIMIT-TO (DOCTYPE, "cp") OR LIMIT TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “ch”))

We included only English articles and reviews. We limited the search to documents published after 2010 to observe the latest trends in the NS. We also included conference proceedings, articles, and book chapters to guarantee inclusivity.

From our query, we obtained 330 papers. We included and excluded them in the final analysis according to the following criteria and steps.

- We reviewed the titles and abstracts of the selected articles to identify those that were not relevant (e.g., by excluding studies in which word risk is a keyword because the main topic concerns satellites used to manage risk); at this stage, we excluded 181 papers because out of scope.
- We retrieved the full texts of the identified relevant reports, thus excluding the ones in which the full text was not accessible through our resources; at this stage, we excluded 62 papers because the full paper was unavailable.
- We assessed whether the full texts met the eligibility criteria, marking the excluded studies as “out of scope.” We excluded 6 papers because, after reading the full texts, we understood they were out of scope.
- In the end, we included 91 papers coming from scientific literature.

Then, we searched for technical literature. We performed a query on Google searching through the query (“New space” and risks). We analyzed more than 200 reports, studies, documents, surveys, and book chapters from firms (e.g., banks) or institutions (e.g., ESA, NASA, ESPI) following the same inclusion and exclusion criteria adopted in the academic literature review. In the end, we included and analyzed 56 documents. These reports belong to the following categories: i) institutions and space agencies, 78 % (44); ii) insurance companies, 16 % (9); iii) consulting firms, 4 % (2); and iv) banks, 2 % (1).

We systematically analyzed the 147 documents included in the literature search. We built a table to collect and analyze the content of the documents. The structure of the table was the following.

- Study identifier (Authors, Title, Year of publication, Journal, Journal Quality (Quartile - SJR), Cited by (Received Citations), and source link).
- Additional information about the study (Abstract, Author Keywords, Index Keywords, Publisher).
- Risk type: i.e., the risk of the NS that is dealt with in the study. Here, we reported the labelling used by the author to identify the risk. This work contributed to elaborating the risk classification.
- Implications for insurance: this section reports comments and citations regarding insurance topics dealt with inside the studies. This was done in the initial phase of the review, to give more credit to insurance topics and examine the importance of insurance in the NS.
- Objective of the paper: the main goals of the studies have been identified to detect the most common arguments or concepts and the gaps to be tackled.
- Methodology: i.e., the method used by the author to present their study. The categories identified were case study, description, economic analysis, exploratory research, focus group, interviews, qualitative analysis (the most frequent, n = 13), quantitative analysis, report, and review.
- Conclusion: output of the study.
- Comments: our thoughts about the paper and how to include its information in the study.
- Additional notes: important citations reported that might have been relevant for the study; additionally, this section includes reference locations to effectively identify each paper's relevant parts.
- Re-reading: section used to keep track of the paper reading and re-reading status (each paper has been analyzed multiple times to discover the proper relevant information).

Table 1
Experts' profiles.

#	Profile
Expert 1	SE Senior Academic Researcher
Expert 2	SE Junior Academic Researcher
Expert 3	Space Insurance Broker Director
Expert 4	Space Insurance Broker Manager
Expert 5	Space Insurance Analyst
Expert 6	Space Senior Consultant

This information was used to build a risk taxonomy (see the Results Section for further details).

2.2. Experts' interviews

To validate and refine our results, we interviewed 6 experts [19] in the new space economy and risk management [20]. We selected experts following a purposive sampling [21,22], according to their recognized expertise in the field, qualified by apical roles in organizations dealing with NS and risk management, and scientific publications. The profiles of the involved domain experts are reported in Table 1.

We involved six domain experts in two separate stages of the research:

- First, we interviewed them in a one-to-one 1-h meeting, in which we presented the risk taxonomy resulting from the literature review to the experts. The purpose was to revise and validate the risk taxonomy and bow-tie models resulting from the literature review. This phase was very useful for revising our framework. In particular, the risk tree, namely the risk taxonomy, has been revised, by adding some risks and giving more precise names to others. Instead, the bow tie models we presented received very few corrections, therefore they were mostly validated by the experts.
- Second, at the end of the meeting, we sent them the taxonomy discussed, asking them to fill it according to their knowledge and give us written feedback. The purpose was to collect primary data from experts on the relationships between SE trends and risks and the interdependencies between risks.

The risk taxonomy and bow tie integrated with experts' comments was the final output of our research.

3. Results

3.1. Risk taxonomy

To create a comprehensive taxonomy of risks in the SE sector, we preliminarily divided the identified risks into two main categories,

<table>
<tr><th>Engineering & Development Phase</th><th>Launch Phase</th><th>Deployment & Operational Phase</th><th>Decommissioning Phase</th></tr>
<tr><td>Technology Adoption Risk</td><td></td><td></td><td></td></tr>
<tr><td>Hull Risk</td><td></td><td></td><td></td></tr>
<tr><td>Quality Assurance Risk</td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Cyber risk</td></tr>
<tr><td></td><td>Wrong Orbit Risk</td><td></td><td></td></tr>
<tr><td></td><td>Failed-to-Orbit Risk</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Space Weather Event Risk</td><td></td></tr>
<tr><td></td><td colspan="3">In-Orbit Collision Risk</td></tr>
<tr><td></td><td colspan="3">Component Failure Risk</td></tr>
<tr><td></td><td></td><td>Communication failure Risk</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">De-Orbit Risk</td></tr>
</table>

Fig. 1. Taxonomy of space mission risks.

depending on the scope of their potential effects.

- *Mission risks.* It comprises all the risks associated with the achievement of specific objectives across the different phases of a space mission (Fig. 1).
- *Business risks.* It comprises all the risks that are not directly related to mission's objectives but are associated with the overall business activities of a specific SE actor, including project management, and may influence the achievement of its business objectives (Fig. 2).

Mission risks are directly associated with one or several mission phases (Fig. 1); they were classified into the following categories.

- *Technology Adoption risk* involves the potential challenges and uncertainties linked to embracing new and innovative space technologies [7];
- *Hull risk* consists of "all risks of physical loss or damage to the [space] vehicle whilst on the ground and in transit from any cause except those specifically excluded. Standard exclusions are: wear, tear and gradual deterioration, mechanical breakdown, war, strikes, riots, civil commotions, effects of radiation or nuclear device." Hull risk includes damages to "hulls, machinery, instruments and the entire equipment of the vehicle" [23].
- *Quality assurance risk* occurs when components or modules fail to meet the required technical standards and performance specifications during the engineering phase conformance tests [12].
- *Cyber Risk* is a breach of integrity and failure of information & communication technology systems (ICT) [24].
- *Wrong orbit risk* pertains to the situation where a payload, despite successfully reaching the orbit, is positioned in an incorrect orbital location [25].
- *Failed to orbit risk*: "Launch failure in which a vehicle that left the pad did not result in a payload making it successfully into orbit. Failure modes include self-destructive, commanded destruction by Range Safety, in-flight breakup, and low launch vehicle performance, resulting in suborbital flight. […] Intentionally suborbital flights are not included." [26].
- *Space Weather Event risk* refers to adverse environmental conditions in space "which can disrupt or damage sensitive equipment that is not prepared for such an event." [27].
- *In orbit collision risk* involves the potential for two space assets to collide during their orbital lifespan [28].
- *Component Failure risk* involves the potential for a space asset, such as satellites, launch vehicles or others, to face failure between their components [29].
- *Communication risk* involves the potential for a space asset in orbit to lose, temporarily or permanently, communication with the ground system [30].
- *De-Orbit risk* encompasses the possibility of a space asset unintentionally deviating from its pre-assigned orbit during the operational phase or, without control, during the decommissioning phase. This deviation may lead to de-orbiting, possibly re-entering the Earth's atmosphere [31].

Following the recommendations for the implementation of the COSO Enterprise Risk Management—Integrated Framework (2017), and the related COSO Risk Cube (2004) taxonomy, business risks in the Space Economy were divided into four main categories, as shown in Fig. 2.

- *Strategic risks* are associated with events that may impede the realization of the company's goals and hinder the achievement of its strategic objectives [32], such as socio-political, macro-economic, market, or reputation al risks.
- *Operational risks* are connected to events that may take place within and affect the performance of the company's operational processes

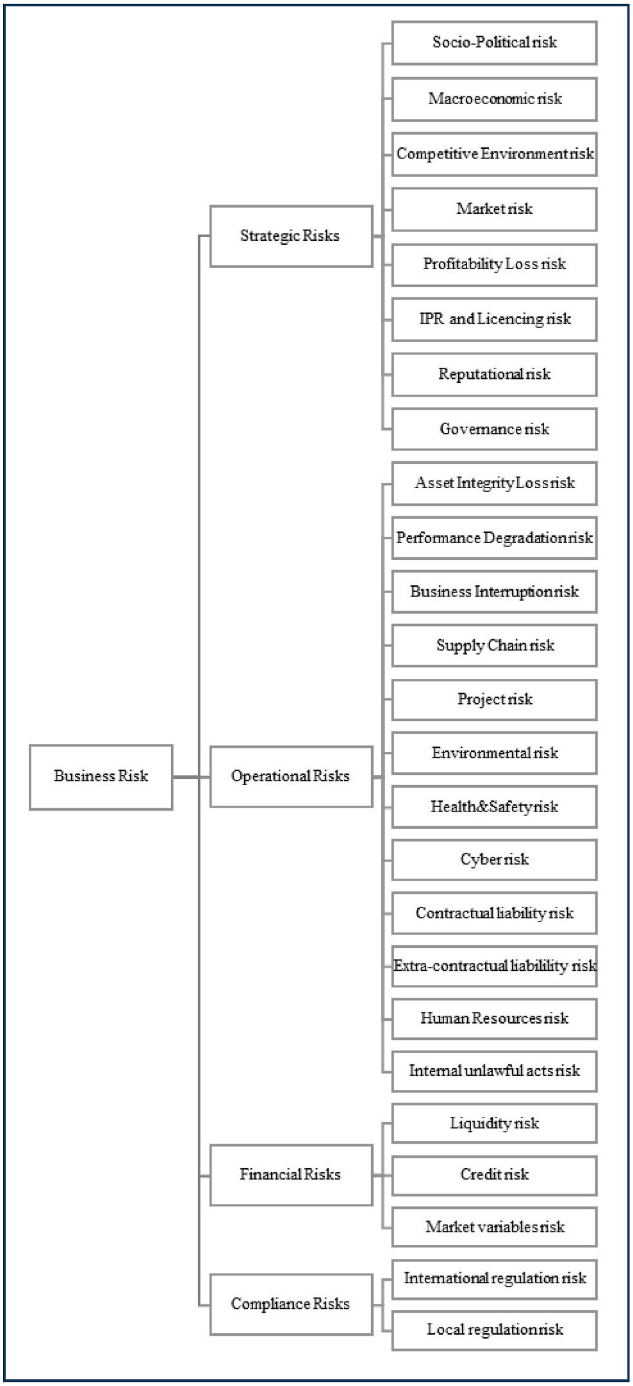


Fig. 2. Taxonomy of business risks in the SE.

[33], such as project risk, supply chain risk, cyber risk, business interruption risk, or HSE risk.

- *Financial risks* are centered on the financial management and performance of the company, such as liquidity risk and credit risk.
- *Compliance risks* encompass all risks related to the adherence to primary national and supra-national regulations and laws [34].

3.2. Risk modelling (bow-tie models)

To answer RQ1b, bow tie models for each mission risk were developed. Four risk impact categories were used to analyze the expected effects of different risk event consequences, namely.

- *Property* impact refers to the economic loss incurred in any company's asset integrity loss [35], including first party liability, even in presence of insurance coverage [38].
- *Business* impact refers to any negative effect on a company's business capabilities. In particular, it might refer to profit loss – namely the loss of current profits – or loss of profitability – namely the loss of future enterprise business and activities [33].
- *Reputation* impact refers to reputational damage, i.e., a business or entity's good name or standing [36].
- *Liability* impact pertains to any consequence, e.g., to property or people, for which the company is held liable or responsible for an action or inaction, whether or not at fault. The liability concept encompasses several instances, namely second and third-party liabilities, depending on which other parties are involved [37].

Examples of Bow-Tie models for some relevant mission risks are reported in Appendix A.

3.3. Main space economy trends

Overall, twenty-five (25) trends have been identified from the literature and further grouped into five (5) megatrends.

- *New regulations and policies*, namely the main rules and policies issued by policy-makers to govern the space industry. This megatrend includes the Liberalization of the space market, Open access, and Orbital Debris Mitigation Standard Practices [38,39].
- *New actors*, including Private space companies, Non-space companies, New space-faring nations, and New end-users [27,40,41];
- *New organizational and operational models*; this megatrend primarily refers to the emergence of Public-private partnerships, Open innovation practices, Standardization and mass production, and Platformization [6,39,42,43];
- *Commercialization of space*, including Commercial off-the-shelf, Earth observation, Global navigation satellite system, Commercial orbital transportation services, Space mining, Insurance of space systems, On-orbit servicing, and Space tourism [31,44,45];
- *New technologies*, including Spin-in, Satellite miniaturization, New manufacturing technologies and materials, Reusable rockets, and New propulsion technologies [20,46].

Domain experts validated these five megatrends and, as such, were taken as the reference for investigating the relationships between SE trends and risks, as reported in the following sub-section.

The space industry is becoming increasingly complex, marked by high uncertainty and rapid evolution. Identifying and understanding key megatrends in this dynamic environment is essential, as they represent critical risk factors that influence strategic decision-making, business models, and governance structures [3]. The emergence of new regulations and policies, for example, introduces compliance challenges and market opportunities, shaping the competitive landscape. Similarly, the rise of new actors, including private companies and non-traditional stakeholders, increases market volatility and competition while fostering innovation [4]. Adopting new organizational and operational models, such as public-private partnerships and standardization, drives efficiency and creates dependencies and systemic risks. The commercialization of space expands revenue streams yet introduces uncertainties regarding market stability and long-term value [43]. Finally, new technologies accelerate advancements but pose challenges in terms of integration, obsolescence, and security [24]. These megatrends collectively highlight the growing uncertainty and interconnectedness of the space industry, making their analysis crucial for risk management and long-term resilience.

Table 2
Rules for experts' judgements aggregation.

Rule	Sign
No input from the literature, and less than 2/3 of experts' agreement	<blank>
Input from the literature, and less than 2/3 in experts' agreement; OR No input from the literature, but at least 2/3 of experts' agreement	<yellow>
Input from the literature and at least 2/3 of experts' agreement	<green>

3.4. Mapping of SE trends-risk relationships

The matrix reporting the mapping of both the relationships between SE trends and risks, as well as the interdependencies between risks, is shown in Appendix B.

SE trends are listed on lines, while mission or business-related risks are listed in columns. The main body of the matrix is used to map existing relationships between SE trends and risks; the roof of the matrix is used to map existing interdependencies between risks. Table 2 provides the criteria through which we filled the matrix, combining the literature review outcomes and the expert interviews.

The cross-analysis of trends and risks derived from the matrix provides valuable insights into the most influential risk factors, allowing for a more comprehensive understanding of their potential impact. This approach helps distinguish whether each risk contributes positively, negatively, or in an ambiguous manner to the evolution of the space industry, enabling more informed strategic planning and risk mitigation efforts.

Some relevant insights can be drawn from the results summarized in the final matrix.

- The large majority of the identified relationships between SE trends and risks, 69.70 % (92), are expected to increase mission and business risks. In particular, more than 30 % of this negative impact is due to the following three SE trends: the liberalization of the space market, the predominant presence of private space companies, and space tourism. This suggests that while these trends bring significant opportunities, they also introduce complex challenges that need to be carefully managed. It is crucial to assess these risks in more detail, considering their direct effects and potential to create cascading impacts across different sectors within the space economy.
- The residual 30.30 % (40) of the identified relationships between SE trends and risks are expected to have a beneficial influence in reducing mission or business risks. In particular, more than 50 % of this positive impact is driven by the following three SE trends: the rise of public-private partnerships, the insurance of space systems, and the on-orbit servicing. They positively impact risk management as they collectively enhance collaboration, provide financial safeguards, and ensure the continued functionality of space assets, thus mitigating operational and financial uncertainties in an increasingly complex and competitive space environment. However, their effectiveness depends on properly aligning interests and establishing robust regulatory frameworks to manage potential risks associated with these mechanisms.
- Commercialization is the SE megatrend with the strongest ambiguous influence, i.e., it brings both positive and negative impacts, on mission and business risks; mission risks are predominantly negatively affected, while business risks are largely mitigated. Mission risks are predominantly negatively affected due to the increased complexity, competition, and unanticipated challenges that commercialization can bring. On the other hand, business risks are largely mitigated, suggesting that commercial opportunities in space, such as new markets and revenue streams, provide a buffer against financial uncertainties.
- Among mission risks, in-orbit collision, technology adoption, and cyber risks are the most influenced ones, receiving a predominantly negative impact; as for business risks, competitive environment, human resources shortage, and environmental risks are the most influenced ones, receiving a predominantly negative impact from the identified SE megatrends.

Finally, it is worth noting that among the 132 identified relationships, those coded in yellow are more frequent than those in green. It implies that the extant knowledge about how SE megatrends are expected to affect mission and business risks in space is still incomplete, with partial scientific evidence and a relatively limited level of agreement among experts. In particular, further investigation is needed to strengthen our understanding of the influence that new organizational and operational models and new space technologies trends may have on business risks.

4. Conclusions

The present study offers a novel framework for analyzing space mission and business risks, and their relationships with the major trends in the Space Economy (SE). The proposed risk taxonomies and models are better grounded and more comprehensive compared to prior contributions in technical and scientific literature. Both the proposed taxonomies and bow-ties might be exploited to develop more robust and reliable risk analyses for space mission planning and business model validation in the new space.

Furthermore, the SE trend-risk matrix returns a rich picture of a multifaceted relationship, entailing not only escalating (+) and mitigating (−) influences but also interdependencies between different risk items. It highlights that several SE trends are expected to have ambiguous impacts on both mission and business risks. The main implication is that under the influence of current trends, the SE risk landscape is expected to become even more complex than it was in the past. Thus, to navigate a challenging business environment, space actors will have to build stronger risk management capabilities at both project/programme and business levels.

Finally, our thorough analysis of explicit and tacit knowledge about the relationship between SE trends and risks revealed some gaps in incomplete scientific evidence and limited experts' agreement. The present study represents a first attempt to approach the problem in a systematic and comprehensive manner, and further research is needed to cover existing gaps and to offer space managers more robust insights for making risk-informed decisions and supporting the growth of the Space Economy.

CRediT authorship contribution statement

Paolo Trucco: Visualization, Investigation, Project administration, Conceptualization, Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation. **Alessandro Paravano:** Formal analysis, Writing – original draft, Data curation, Validation, Investigation, Conceptualization, Writing – review & editing, Visualization. **Giorgio Locatelli:** Writing – review & editing, Validation, Supervision, Conceptualization, Visualization, Project administration.

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.

Acknowledgements

Authors are grateful to all the domain experts for their commitment and invaluable contributions. The authors thank colleagues who provided feedback on the first version of this paper at IAC24.

Appendix A. (Examples of Bow-Tie models of Mission Risks)

Appendix A presents examples of Bow-Tie models of Mission Risks. The bow tie model is a widely used risk management framework visually representing a specific risk event's causes, consequences, and impacts.

The first Bow-Tie describes the *In-orbit collision risk*. On the left side, the model highlights the primary causes of in-orbit collision risk. The main drivers include orbital congestion, which increases the likelihood of accidental collisions due to the high density of objects in space. Whether caused by operator error or technical failures, wrong satellite maneuvers can lead to unintended trajectories and collisions. Cyber attacks pose a growing threat, as malicious actors could disrupt satellite operations or alter their courses. Loss of control, whether due to system malfunctions or external interference, can render satellites incapable of performing collision avoidance maneuvers. Additionally, human error, including miscalculations in mission planning or operational execution, can contribute to collision events.

At the center of the bow tie is the risk event itself: an in-orbit collision. This could occur between active satellites, defunct objects, or debris, potentially leading to cascading collision effects that threaten space sustainability.

The right side of the Bow-Tie outlines the consequences of an in-orbit collision. These include asset integrity loss, where a satellite or space system sustains irreversible damage. Reduced lifetime of operational assets can result from minor collisions or debris impacts. Unintended de-orbiting can occur if a collision disrupts a satellite's orbit, causing it to re-enter the atmosphere prematurely. Orbit loss can render an asset non-functional, eliminating its ability to provide intended services. Business interruption may arise due to service outages, affecting industries that rely on space infrastructure. Furthermore, collisions can cause first, second, and third-party damage, impacting other operators and stakeholders in the space-operators and stakeholders in the industry.

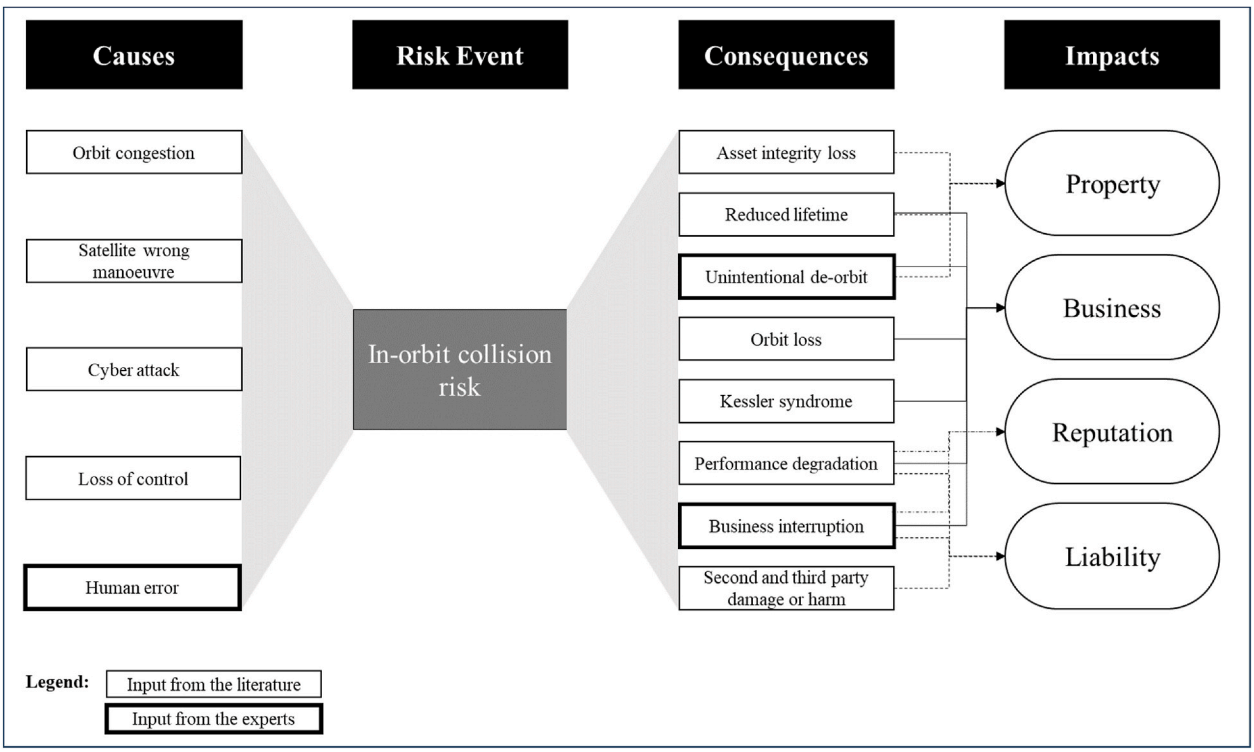


Fig. 3. Appendix A – Bow-Tie In orbit collision risk

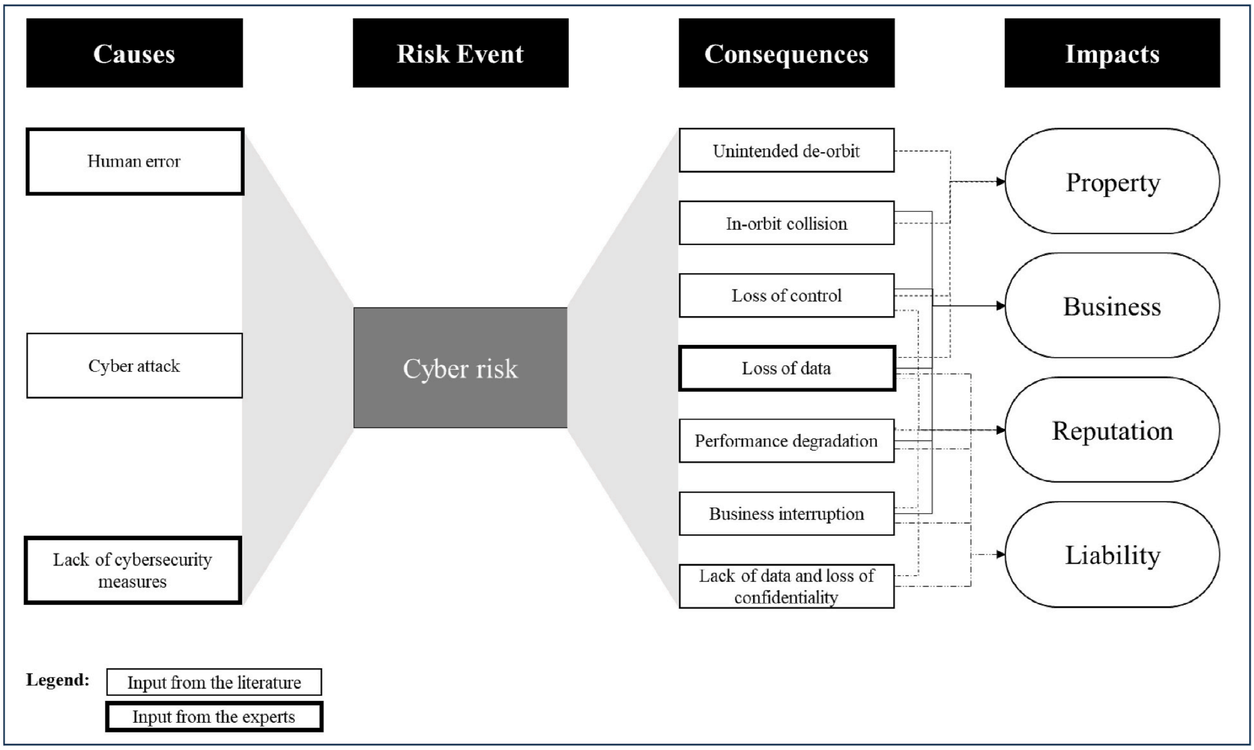


Fig. 4. Appendix A – Bow-Tie Cyber risk

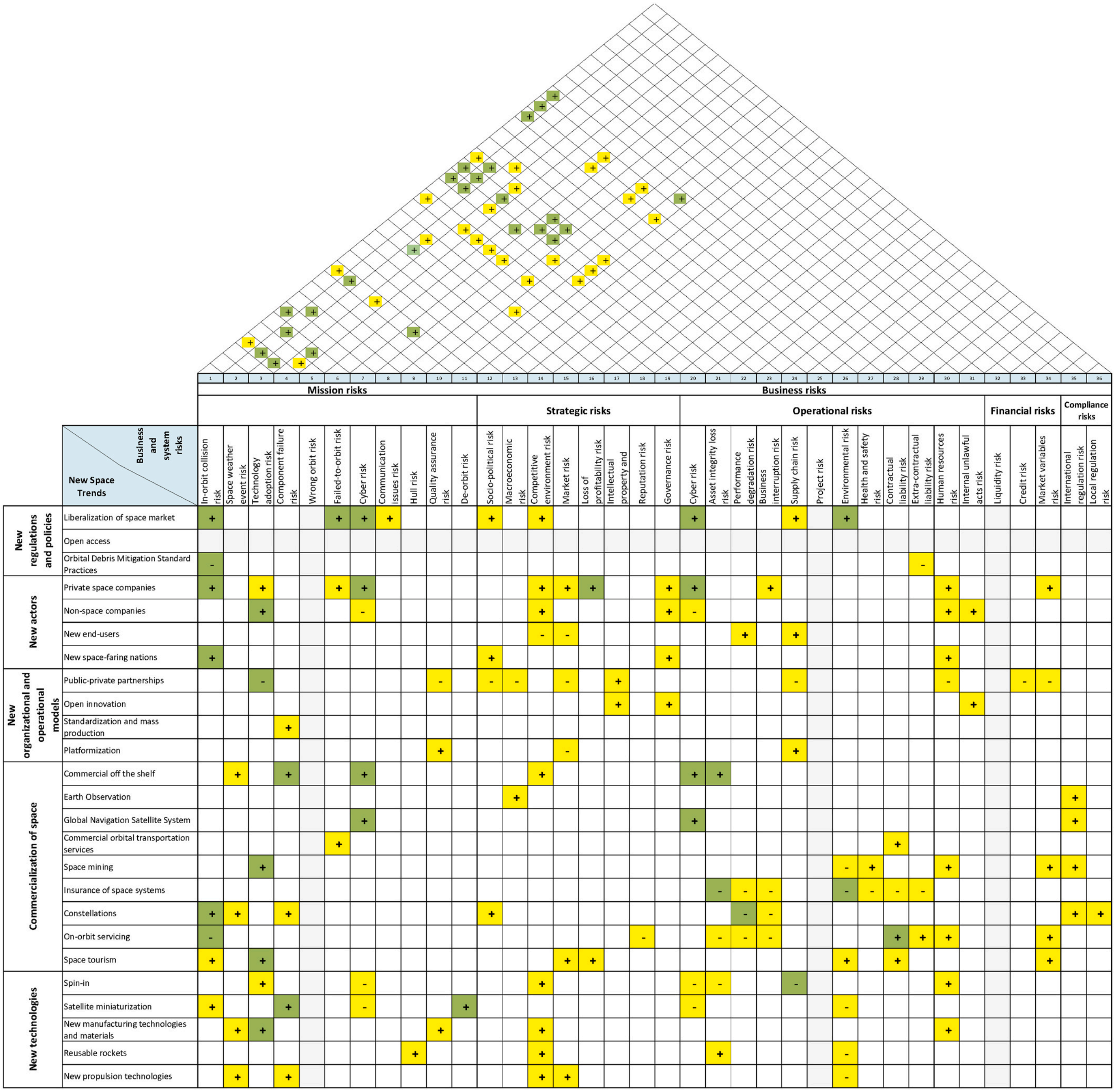
The second Bow-Tie models the *Cyber risk* of a space mission. The left side of the Bow-Tie highlights the primary causes of cyber risk in space operations. The main drivers include human error, where mistakes in coding, system configuration, or operational procedures can create vulnerabilities that cyber threats may exploit. Cyber attacks pose a significant risk, as malicious actors can target satellites, ground stations, or communication links to disrupt operations, steal data, or take control of assets. Additionally, a lack of cybersecurity measures, such as insufficient encryption, outdated software, or weak access controls, increases the likelihood of cyber incidents affecting space systems.

At the center of the Bow-Tie is the risk event itself: a cyber incident. This event could range from unauthorized access to critical satellite functions to full-scale attacks that disrupt or turn off space-based operations.

The right side of the Bow-Tieoutlines the consequences of a cyber risk event. These include unintended de-orbiting, where a compromised satellite may be forced out of its designated orbit, leading to mission failure. In-orbit collisions can result if a hacked satellite is moved unpredictably, increasing the likelihood of space debris generation. Loss of control is another critical consequence, where operators may be unable to command or retrieve data from their spacecraft. Loss of data can occur if cyber attackers erase or corrupt mission-critical information. Performance degradation may arise as malicious code slows down or alters system operations, affecting the reliability of services. Business interruption is a major risk, as satellite-dependent industries may face downtime due to compromised infrastructure. Furthermore, a lack of data availability and loss of confidentiality can have severe implications, including breaches of sensitive information and strategic disadvantages for space operators.

The broader impacts of cyber incidents extend to property loss, business disruptions, reputational damage for space agencies and private operators, and increased liability due to regulatory and financial consequences.

Appendix B. (Mapping of the SE trend-risk relationships)



	Business and system risks / New Space Trends	Mission risks											Business risks – Strategic risks								Business risks – Operational risks												Business risks – Financial risks			Business risks – Compliance risks	
		1 In-orbit collision risk	2 Space weather event risk	3 Technology adoption risk	4 Component failure risk	5 Wrong orbit risk	6 Failed-to-orbit risk	7 Cyber risk	8 Communication issues risk	9 Hull risk	10 Quality assurance risk	11 De-orbit risk	12 Socio-political risk	13 Macroeconomic risk	14 Competitive environment risk	15 Market risk	16 Loss of profitability risk	17 Intellectual property and	18 Reputation risk	19 Governance risk	20 Cyber risk	21 Asset integrity loss risk	22 Performance degradation risk	23 Business interruption risk	24 Supply chain risk	25 Project risk	26 Environmental risk	27 Health and safety risk	28 Contractual liability risk	29 Extra-contractual liability risk	30 Human resources risk	31 Internal unlawful acts risk	32 Liquidity risk	33 Credit risk	34 Market variables risk	35 International regulation risk	36 Local regulation risk
New regulations and policies	Liberalization of space market	+					+	+	+				+		+						+				+		+										
	Open access																																				
	Orbital Debris Mitigation Standard Practices	-																												-							
New actors	Private space companies	+		+			+	+							+	+	+			+	+			+							+				+		
	Non-space companies			+				-							+					+	-										+	+					
	New end-users														-	-							+		+												
	New space-faring nations	+											+							+											+						
New organizational and operational models	Public-private partnerships			-							-		-	-		-		+							-						-			-	-		
	Open innovation																	+		+												+					
	Standardization and mass production				+																																
	Platformization										+					-									+												
Commercialization of space	Commercial off the shelf		+		+			+							+						+	+															
	Earth Observation													+																						+	
	Global Navigation Satellite System							+													+															+	
	Commercial orbital transportation services						+																						+								
	Space mining			+																							-	+			+				+	+	
	Insurance of space systems																					-	-	-			-	-	-	-							
	Constellations	+	+		+								+										-	-												+	+
	On-orbit servicing	-																	-			-	-	-					+	+	+				+		
	Space tourism	+		+												+	+										+		+						+		
New technologies	Spin-in			+				-							+						-	-			-						+						
	Satellite miniaturization	+			+			-				+									-						-										
	New manufacturing technologies and materials		+	+							+				+																+						
	Reusable rockets									+					+							+					-										
	New propulsion technologies		+		+										+	+											-										

Fig. 5. Appendix B – SE trends and risks framework

Appendix B presents the SE trends and risks framework developed in this study. The framework is structured around the House of Quality model, illustrating the relationships between risks and trends. It is divided into two main sections: the "roof" and the "body." The roof displays the relationships between different risks, showing how they are interlinked. The body focuses on the interdependence between trends and risks, depicting how trends influence risk levels. Specifically, a "plus" sign ("+") indicates that a trend escalates a risk, increasing its likelihood or severity, while a "minus" sign ("-") shows that a trend reduces the risk, mitigating its impact (See the legend). This structure helps to map out both the positive and negative influences of trends on risks, providing a clear visual representation of their effects. For example, let's look at the first cell on the right of the matrix. The liberalization of the market increases the number of actors and objects in space, thereby having a positive impact on the risk of in-orbit collisions. We filled in the framework based on literature input and expert agreement. A blank cell indicates no input from the literature, and less than two-thirds of experts agree on the relationship. This signifies a low level of consensus and support for the identified connection. A yellow cell represents situations where there is either input from literature, but expert agreement is still below two-thirds, or there is no input from literature, but at least two-thirds of experts agree. This suggests a moderate level of support, with either literature backing the relationship or expert consensus, but not both. Green cell signifies a strong relationship, where literature supports the connection, and at least two-thirds of experts agree. This indicates a well-established and widely accepted relationship between the trend and risk.

References

[1] OECD, in: OECD Handbook on Measuring the Space Economy, second ed., OECD, 2022 https://doi.org/10.1787/8bfef437-en.

[2] A. Paravano, B. Rosseau, G. Locatelli, M. Weinzierl, P. Trucco, Toward the LEO economy: what is the value of new commercial space stations? Acta Astronaut. (2025) https://doi.org/10.1016/j.actaastro.2024.11.060.

[3] A. Paravano, G. Locatelli, P. Trucco, Evolution of space programs governance, in: Research Handbook on the Governance of Projects, Edward Elgar Publishing, 2023, pp. 411–428.

[4] K. Davidian, What makes space activities commercial? Acta Astronaut. 182 (2021) 547–558, https://doi.org/10.1016/j.actaastro.2021.02.031.

[5] A. Paravano, G. Locatelli, P. Trucco, Creating and claiming social value by joining the governance of science-driven capital projects: an investigation in the new space economy, IEEE Eng. Manag. Rev. (2024) 1–44, https://doi.org/10.1109/EMR.2024.3428327.

[6] A. Ansar, B. Flyvbjerg, A platform approach to space exploration, Harv, Bus. Rev. (2022). https://hbr.org/2022/11/a-platform-approach-to-space-exploration (Accessed 20 October 2023).

[7] M.L. Cummings, Factors that influence acceptance of new aerospace risk assessment techniques, in: AIAA Scitech 2020 Forum, vol. 1, 2020, https://doi.org/10.2514/6.2020-0707. PartF.

[8] G.P. Moynihan, D.J. Fonseca, P.S. Ray, A hybrid system approach for space station risk analysis, Int. J. Risk Assess. Manag. 3 (2002) 292–309, https://doi.org/10.1504/ijram.2002.002559.

[9] M.P. Daniels, M.-E. Pate-Cornell, Risk-based comparison of consolidated and distributed satellite systems, IEEE Trans. Eng. Manag. 64 (2017) 301–315, https://doi.org/10.1109/TEM.2017.2665558.

[10] P. Boateng, Z. Chen, S.O. Ogunlana, An analytical network process model for risks prioritisation in megaprojects, Int. J. Proj. Manag. 33 (2015) 1795–1811, https://doi.org/10.1016/j.ijproman.2015.08.007.

[11] ISO, ISO 31000:2018 - risk management — guidelines. https://www.iso.org/obp/ui/#iso:std:iso:31000:ed-2:v1:en, 2018. (Accessed 10 September 2024).

[12] S. Başar, A. Kucuk Yilmaz, M. Karaca, H.T. Lapçın, S.İ. Başar, Fleet modelling in strategic multi-criteria decision-making of approved training organization from capacity building and resource dependency theory perspective: risk taxonomy methodology, Aircraft Eng. Aero. Technol. 92 (2020) 917–923, https://doi.org/10.1108/AEAT-03-2020-0051.

[13] W.G. Johnson, MORT: the management oversight and risk tree, J. Saf. Res. 7 (1975) 4–15.

[14] N. Khakzad, F. Khan, P. Amyotte, Dynamic risk analysis using bow-tie approach, Reliab. Eng. Syst. Saf. 104 (2012) 36–44, https://doi.org/10.1016/j.ress.2012.04.003.

[15] R. Ferdous, F. Khan, R. Sadiq, P. Amyotte, B. Veitch, Analyzing system safety and risks under uncertainty using a bow-tie diagram: an innovative approach, Process Saf. Environ. Prot. 91 (2013) 1–18, https://doi.org/10.1016/j.psep.2011.08.010.

[16] L.P. Sullivan, Quality function deployment, Qual. Prog. 19 (1986) 39–50.

[17] Y.-P. Fang, C. Fang, E. Zio, M. Xie, Resilient critical infrastructure planning under disruptions considering recovery scheduling, IEEE Trans. Eng. Manag. 68 (2021) 452–466, https://doi.org/10.1109/TEM.2019.2902916.

[18] J.P.T. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M.J. Page, V.A. Welch, Cochrane Handbook for Systematic Reviews of Interventions, John Wiley & Sons, 2019.

[19] H. Aguinis, A.M. Solarino, Transparency and replicability in qualitative research: the case of interviews with elite informants, Strateg. Manag. J. 40 (2019) 1291–1315.

[20] A. Golkar, A. Salado, Definition of new space—expert survey results and key technology trends, IEEE J. Miniaturization Air Space Syst. 2 (2021) 2–9, https://doi.org/10.1109/JMASS.2020.3045851.

[21] I.T. Coyne, Sampling in qualitative research. Purposeful and theoretical sampling; merging or clear boundaries? J. Adv. Nurs. 26 (1997) 623–630, https://doi.org/10.1046/j.1365-2648.1997.t01-25-00999.x.

[22] L.A. Palinkas, Qualitative and mixed methods in mental health services and implementation research, Journal of Clinical Child \& Adolescent Psychology 43 (2014) 851–861.

[23] D. Bensoussan, Space tourism risks: a space insurance perspective, Acta Astronautica 66 (2010) 1633–1638, https://doi.org/10.1016/j.actaastro.2010.01.009.

[24] G. Falco, Cybersecurity principles for space systems, Journal of Aerospace Information Systems 16 (2019) 61–70, https://doi.org/10.2514/1.I010693.

[25] K. Malinowska, Risk management and the insurance of On-Orbit servicing, The Insurance Industry as a Driver of Risky Space Innovation (2020). in: International Astronautical Federation, IAF, Online, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85100943840&partnerID=40&md5=5c7bfe6014901894a62c311180331806.

[26] B.R. Sullivan, Technical and Economic Feasibility of Telerobotic On-Orbit Satellite Servicing, 2005.

[27] A. Anderegg, B. Blakney, J.K. Lee, S.D. O'neil, M.R. Ross, Preserving space through collaborative decision making by space operators, in: Accelerating Space Commerce, Exploration, and New Discovery Conference, ASCEND 2021, 2021, https://doi.org/10.2514/6.2021-4086.

[28] D. Casanova, C. Tardioli, A. Lemaître, New methods for space debris collision assessment, Proceedings of the International Astronomical Union 9 (2014) 150–153, https://doi.org/10.1017/S1743921314008084.

[29] Y. Demchenko, C. De Laat, P. Membrey, Defining architecture components of the big data ecosystem, in: 2014 International Conference on Collaboration Technologies and Systems, CTS 2014, IEEE Computer Society, 2014, pp. 104–112, https://doi.org/10.1109/CTS.2014.6867550.

[30] J.C. Denton, D.D. Hodson, R.G. Cobb, L.O. Mailloux, M.R. Grimaila, G. Baumgartner, A model to estimate performance of space-based quantum communication protocols including quantum key distribution systems, Journal of Defense Modeling and Simulation: Applications, Methodology 16 (2019) 2017, https://doi.org/10.1177/1548512916684562.

[31] S.K. Borowski, S.W. Ryan, D.R. McCurdy, B.G. Sauls, Key technologies, systems, and infrastructure enabling the commercialization and human settlement of low Earth orbit, the moon, and cislunar space, New Space 9 (2021) 104–122, https://doi.org/10.1089/space.2020.0029.

[32] R. Casadesus-Masanell, J.E. Ricart, From strategy to business models and onto tactics, Long Range Planning 43 (2010) 195–215, https://doi.org/10.1016/j.lrp.2010.01.004.

[33] S.E. Galaitsi, E. Pinigina, J.M. Keisler, G. Pescaroli, J.M. Keenan, I. Linkov, Business continuity management, operational resilience, and organizational resilience: commonalities, distinctions, and synthesis, Int J Disaster Risk Sci 14 (2023) 713–721, https://doi.org/10.1007/s13753-023-00494-x.

[34] C.I.S. Mandatory, Procedural NASA Systems Engineering Processes and Requirements Responsible Office : Office of the Chief Engineer Table of Contents Change Log Chapter 4, 2013, pp. 1–202. NASA Oversight Activities on Contracted Projects Appendix A . Definitions Appendix B . Acronyms Appen.

[35] H.X. Bao, J.P. Larsson, V. Wong, Light at the end of the tunnel: the impacts of expected major transport improvements on residential property prices. https://doi.org/10.1177/0042098020967308, 2021.

[36] P.W. Roberts, G.R. Dowling, Corporate reputation and sustained superior financial performance, Strategic Management Journal 23 (2002) 1077–1093, https://doi.org/10.1002/smj.274.

[37] T. Aven, The risk concept—historical and recent development trends, Reliability Engineering & System Safety 99 (2012) 33–44, https://doi.org/10.1016/j.ress.2011.11.006.

[38] M. Borowitz, Strategic implications of the proliferation of space situational awareness technology and information: lessons learned from the remote sensing sector, Space Policy (2019), https://doi.org/10.1016/j.spacepol.2018.05.002.

[39] D. Martin-Lawson, S. Paladini, K. Saha, E. Yerushalmi, The cost of (Un)regulation: shrinking Earth's orbits and the need for sustainable space governance, Journal of Environmental Management 349 (2024), https://doi.org/10.1016/j.jenvman.2023.119382.

[40] A. Paravano, G. Locatelli, P. Trucco, What is value in the new space economy? The end-users' perspective on satellite data and solutions, Acta Astronautica 210 (2023) 554–563, https://doi.org/10.1016/j.actaastro.2023.05.001.

[41] B. Adams, Cooperation in space: an international comparison for the benefit of emerging space agencies, Acta Astronautica 162 (2019) 409–416, https://doi.org/10.1016/j.actaastro.2019.06.011.

[42] B. Detsis, E. Detsis, The benefits brought by space - general public versus space agencies perspectives, Acta Astronautica 88 (2013) 129–137, https://doi.org/10.1016/j.actaastro.2013.03.021.

[43] A. Paravano, G. Locatelli, P. Trucco, Projects benefit realisation through sustainable innovation: drivers and challenges, Management Decision (2025), https://doi.org/10.1108/MD-08-2024-1751.

[44] A. Paravano, G. Locatelli, P. Trucco, End-users engagement for enacting value of complex projects: an ecological perspective, Journal of Management Engineering 40 (2024), https://doi.org/10.1061/JMENEA.MEENG-5724.

[45] M. Andraschko, J. Antol, S. Horan, D. Neil, Commercially hosted government payloads: lessons from recent programs, in: IEEE Aerospace Conference Proceedings, 2011, https://doi.org/10.1109/AERO.2011.5747491.

[46] L. Bach, P. Cohendet, E. Schenk, Technological transfers from the European space programs: a dynamic view and comparison with other R&D projects, Journal of Technology Transfer 27 (2002) 321–338, https://doi.org/10.1023/A:1020259522902.