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A LONG TIME FROM NOW, IN A GALAXY FAR, FAR AWAY:
Remoteness of Effects as a Factor of Sustainable Space Technologies' Market Acceptance

By Angelina Frolova

MASTER THESIS

Examining Committee:

Prof. Dr. Jean-Paul Kneib
Academic supervisor, eSpace

Dr. Davide Bavato
Academic supervisor, MTE

Sergey Gugkaev
External Expert

Executive Summary

One of the key dimensions of a sustainable transition in the space sector is ensuring the widespread adoption of sustainable technologies. This research explores the factors influencing their market acceptance, building on the Technology Acceptance Model (TAM). An introduction of a new factor ‘remoteness of effects’, with its spatial and temporal facets, is suggested. The study finds that closer, immediate benefits enhance perceived usefulness and, consequently, adoption likelihood, with temporal remoteness being more critical. The factor of "voluntariness" is analyzed through the lens of the Locus of Control Theory, concluding that space companies predominantly exhibit an external locus of control. which indicates that these companies feel compelled to adopt sustainable practices primarily due to external pressures, such as regulations and direct risks to their business operations, rather than from an internal commitment to sustainability.

Data was gathered through three rounds of semi-structured interviews: non-space industry experts provided broad insights, space industry experts added depth, and academics offered contrasting perspectives. The impact of experts' experience on perceived important factors was examined, revealing limited between-group variance.

The research includes a case study on the Open Debris Lightcurve Inventory (ODLI), demonstrating its commercialization avenues. Key recommendations for policymakers suggest putting more emphasis on strategies facilitating private adoption of sustainable space technologies with immediate, localized benefits, and governmental utilization of the technologies with more long-term and spatially diluted benefits. Internationally coordinated regulatory frameworks are crucial to promote widespread private adoption of sustainable space technologies.

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- **ADR:** Active Debris Removal
- **AI:** Artificial Intelligence
- **B2B:** Business-to-Business
- **B2C:** Business-to-Consumer
- **B2G:** Business-to-Government
- **CV:** Computer Vision
- **CXO:** Chief [...] Officer
- **ESA:** European Space Agency
- **GEO:** Geostationary Earth Orbit
- **GNSS:** Global Navigation Satellite Systems
- **HDBSCAN:** Hierarchical Density-Based Spatial Clustering of Applications with Noise
- **IADC:** Inter-Agency Space Debris Coordination Committee
- **IoT:** Internet of Things
- **ISS:** International Space Station
- **LEO:** Low Earth Orbit
- **LTS:** Long-term Sustainability
- **MDPEU:** Model of Determinants of Perceived Ease of Use
- **MEO:** Middle Earth Orbit
- **MIS:** Management Information Systems
- **NASA:** National Aeronautics and Space Administration
- **NLTK:** Natural Language Toolkit
- **NWP:** Numerical Weather Prediction
- **ODLI:** Open Debris Lightcurve Inventory
- **OECD:** Organization for Economic Co-operation and Development
- **PEU:** Perceived Ease of Use
- **PNT:** Positioning, Navigation, and Timing
- **PU:** Perceived Usefilness
- **SaaS:** Satellite as a Service
- **SDGs**: Sustainable Development Goals
- **TAM:** Technology Acceptance Model
- **TF-IDF:** Term Frequency-Inverse Document Frequency
- **TRL:** Technology Readiness Level
- **UMAP:** Uniform Manifold Approximation and Projection
- **UN:** United Nations
- **UNOOSA:** United Nations Office for Outer Space Affairs
- **XaaS:** Everything-as-a-Service

Introduction: Long Story Short

Once, it was thought impossible to reach the skies, but against this belief, rockets conquered gravity, and humans made it into space. Then, it was thought that commercial space exploration was a hoax, and whoever wanted to make a reusable launcher to make space affordable was a lunatic; but against this belief, reusable rockets started flying, and commercial space exploration began to boom. Now, it is believed that space is an environmental liability and that sustainable space utilization is impossible; but I, together with other researchers, strongly believe this assumption to be wrong. Opening the doors to space exploration was not easy, commercializing space activities was not easy, and neither will be the sustainable space transition. Yet it is possible, through cooperation, technological advances and successful adoption of the technologies and practices allowing for continuous space utilization.

Space sustainability concerns not only the future of space exploration, but also the quality of life on Earth, since many terrestrial businesses and services depend on functioning space assets: telecommunications, weather forecasts, natural disaster prediction systems, farming, navigation, etc. As ironic as it might seem, disruption in the space sector would entail an abundance of *down-to-the-ground* problems. Factor in the threat of the Kessler effect - a chain reaction of satellite destructions in orbit - and the space sustainability matter would cease to seem secondary to Earth sustainability matters. It is at least as important as any other sustainability concern. And apart from the terrestrial services, the space exploration itself, the scientific endeavors to learn more about the universe, are worthy of attention. As K. Tsiolkovsky put it: *'Earth is the cradle of humanity, but one cannot stay in a cradle forever'*. Daring exploration is in the very human nature, and we cannot afford to close the door to the final frontier simply because of our irresponsible attitude.

The danger of space becoming inaccessible is real. In recent years, the number of satellites launched into space has increased dramatically (OECD, 2023). In 2023 alone, around 3,000 satellites were launched, and this number continues to rise with projections suggesting thousands more each year due to the surge in commercial space activities (Euroconsult, 2023). This exponential growth is coupled with an alarming increase in space debris. The European Space Agency (ESA) reports that there are currently over 36,000 pieces of space debris larger than 10 cm, around 1 million pieces between 1 cm and 10 cm, and an estimated 130 million pieces smaller than 1 cm (ESA, 2024).

Despite the rapid growth of the commercial space sector and the aggravating problem of orbital pollution, private adoption of sustainable space technologies remains under-researched. This study seeks to understand the **factors influencing the adoption of sustainable space technologies by private companies**, addressing a critical gap in both academic literature and industry practice.

In order to answer the ***research question*** *'Which factors shape market acceptance of sustainable space technologies?'*, perceptions of industry experts and academics are analyzed. The theoretical framework is formed from the data collected through 35 semi-structured interviews and analyzed through ***a combination of qualitative (manual coding) and quantitative (machine text analytics, statistical tests) methods***. The research also includes a *case study* on the commercialization of ODLI - a repository containing space debris characterization, providing practical insights into real-world applications. The research does not cover technological development or technical performance aspects of these technologies.

The thesis is ***structured*** as follows: Chapter 1 reviews relevant literature on the context of the study (commercial space sector and the problem of space unsustainability), theoretical foundations (Technology Acceptance Model and its extensions), and auxiliary theories (Locus of Control Theory and XaaS model). Chapter 2 details the research setting, research design and methodology used for data collection and analysis. Chapter 3 presents the key research findings with an addition of a case study, while Chapter 4 discusses the interpretations of these results, their potential theoretical and practical contributions, limitations of the study and opportunities for future research.

The primary ***theoretical contribution*** of this research is the extension of the Technology Acceptance Model (TAM) by introducing a new factor: 'remoteness of effects'. Empirical evidence suggests that there are two facets of this factor: spatial and temporal remoteness, and the latter has more weight in the given context. This study concludes that the nearer the effects of the problem a sustainable space technology aims to address are, in terms of distance and time, the more likely private companies in the relevant domain will find it useful and adopt it. In addition to this new factor, the research also explores the role of 'voluntariness' and 'experience' with regards to sustainable space technologies' private adoption, enriching the former with insights from the Locus of Control Theory and examining the latter through between-group comparisons of interviewees and their perceptions.

The key findings ***inform practice*** allowing for actionable recommendations for private companies looking to adopt sustainable space technologies. These recommendations focus on understanding the importance of perceived immediate and localized benefits by private actors. Policymakers can use these insights to create supportive regulations and incentives, while researchers can build upon this framework to further explore the nuances of technology adoption in the space sector, or generalize these findings for sustainable technology adoption regardless of the sector.

Contrary to common perceptions, space is not too far away, and the problems arising from its unsustainable usage will deteriorate soon enough to necessitate decisive action now. Understanding the factors that drive or hinder the adoption of sustainable space technologies is crucial for ensuring the long-term viability of space activities, and this research attempts to contribute to creating a comprehensive framework that can guide future efforts in this domain.

1. Literature Review:
The Giants on Whose Shoulders I Stand

The literature review was conducted over studies from multiple domains, focusing on management science, information systems, space economy and sustainability. The priority was given to more recent publications (starting from the 2010s), yet, exceptions were made for some seminal papers that laid the foundation for generations of future researchers and have had significant impact in their respective fields.

The number of citations was taken into consideration, however, this criterion was approached with caution, as 'low' count of citations might not necessarily indicate poor quality of a publication. It was understood that the space sector, specifically, commercialization of sustainable space technologies, is a niche field, therefore, citation count for domain-specific papers is usually low compared to other areas.

In the process of searching for sources of information, apart from manual search (Science Direct, Scopus, Google Scholar, Research Gate), artificial intelligence was employed to facilitate the task. Namely, such AI tools as SciSpace, ChatGPT and Semantic Scholar were utilized. Here is a breakdown of the ways in which AI aided in the literature review:

- **SciSpace** searches for papers on a certain topic. Unlike traditional search engines, it looks not only directly at key words, but also at synonymous and semantically close formulations, which expands the range of search. Moreover, the tool provides 1-2 sentence summary next to each paper it finds.
- **ChatGPT** is a powerful tool that helped me to double-check my conclusions concerning gaps in existing literature. ChatGPT4 is capable of answering questions like "Are there any papers on […]?"; "Are there any papers using methodology […] for [….]?", etc. If the AI answered that there seems to be no research dealing with the specified problem or using the specified methodology, I could conclude with more confidence that there is a gap in existing scientific literature. Even though it does not serve as an absolute proof that there is no research in the stated direction, it increases the reliability of the results of manual search, as a human researcher is only capable of going through a handful of papers, while ChatGPT has instantaneous access to a much vaster variety of resources.
- **Semantic Scholar** works similar to movie or music recommender systems, but is tailored to find semantically similar research papers and recommend them to you based on your area of interest. Its functionality includes automatic highlighting of key insights in the texts of papers, which significantly saves time when going through a large body of literature.

Overall, the literature review at hand results from traditional literature research complemented by relevant AI tools.

1.1 Space Sector as the Context of the Study

In summer 2023, I spoke to an ESA space engineer in Portugal, and I asked him why he chose to work in the space sector. His answer made a lasting imprint in my memory, he said*: 'I chose space, because it is the most challenging, the most difficult environment to operate in'*. This answer resonated with me, because the complexity of the problem is one of the key reasons why I chose to set my research in the context of space economy.

The key aspect that differentiates space business operations from those on Earth are extremely harsh environmental conditions (vacuum, extreme temperatures, ultraviolet and ionizing radiation, micrometeoroid/orbital debris impact (NASA, 2020)), which require technological and operational excellence, setting the entry bar very high and introducing huge risks. Moreover, space requires autonomous systems, since there are no opportunities to perform maintenance (with rare exceptions, like ISS astronauts performing repairs); which leaves zero room for mistake, and, combined with the factor of harsh environment, dictates extended timeframes to reach final technology readiness level (TRL) (NASA, 2023). Technological complexity, high associated risks and long timeframes can be outlined as major obstacles for businesses that want to go beyond the Earth's boundaries. Yet, if operating in space is so difficult, costly and risky, why does the New Space Economy grow so rapidly?

The key properties of space that make it so challenging to operate there, simultaneously represent business opportunities, and many ventures are ready to take a share of that mostly untapped potential, despite the evident difficulties. In his lectures on 'New Space Economy', a founder of a space-focused venture capital fund, Raphael Roettgen gave an example of a promising business model, which would exploit such properties of space as vacuum (or microgravity, since the operations will be performed on the Earth's orbit). He expects to see in the near future companies growing human organs for transplants in orbit. Microgravity enables 3D growth, which eliminates the key problem with organ-growing on Earth - the need for scaffolding. This example demonstrates how challenges of the space environment can be counterbalanced with business opportunities; and as will be demonstrated in the next paragraph, the latter start to far outweigh the former, swaying the balance in favor of growing commercial space utilization.

To encapsulate, space is a unique environment not only due to its physical properties, but also due to its specific challenges and opportunities from a business standpoint.

New Space Economy

No specific author can be credited for coining the term 'New Space Economy', nor is there a universal agreement concerning the exact time when the said term was introduced. However, it is reasonable to say that the term gained traction in the early 2000s with the rise of SpaceX, Blue Origin and other giants, on whose shoulders the commercial innovation in the space sector stands today. In this study, I apply the definition of the 'New Space Economy' suggested by OECD:

"The space economy is the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilizing space." (OECD, 2022)

I would like to draw the reader's attention to the fact that this definition encompasses both states and enterprises active in the space domain (refer to Figure 1). Another term is used in this study to refer to exclusively private space activities: 'commercial space sector'.

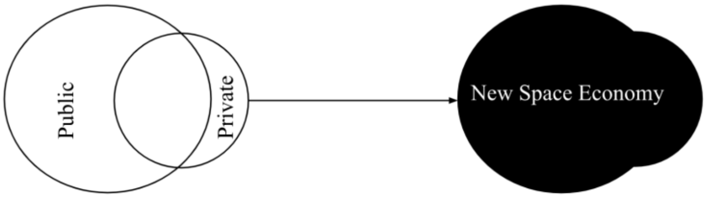

Figure 1. New Space Economy

On the left side, two overlapping circles represent the public and private sectors. The overlap between these circles indicates areas of collaboration and shared interests between public and private entities. New Space Economy encompasses both of those sectors, symbolizing the combined and expanded potential resulting from this collaboration.

Despite being an emerging field, the New Space Economy has already captured attention of both academics and industry actors, emphasizing the critical role of the shift from government-led space programs to commercialization and entrepreneurship in space exploration and utilization (Weinzierl, 2018). Yet, even the light of growing awareness about commercial opportunities in space has not effaced some common misconceptions around the field. In this section I would like to refute some of those myths hindering the development of the New Space Economy by giving an overview of existing relevant research. This overview would provide a general context for the study at hand and put it into perspective.

Misconception 1. *The space sector exists merely for two purposes: to satisfy human curiosity about the nature of the universe and to extend the arms race to the new frontier.*

Space sector does not exist in vacuum (pun intended), but is set in an intricate web of interdependencies with other sectors, which would be disrupted should the space sector stagnate or collapse. Numerous studies and commercial success stories have demonstrated the multifaceted interactions between space ventures and global economic systems. Beyond just *advancing scientific knowledge* and opening a new dimension for *national security*, the space sector provides vital resources and enhances capabilities of terrestrial sectors of the world economy. The examples of such symbioses are legion. An extensive literature review across research papers from different domain journals, market reports and other documents, has allowed me to outline 10 sectors increasingly dependent on the space industry:

- **Agriculture** utilizes Earth observation satellites for precision farming, crop monitoring, soil health assessment, and management of water resources (Fakhar, 2023).
- **Weather forecasting:** Meteorological satellites and radars gather data that is crucial for observing climate patterns, tracking hurricanes, and providing atmospheric measurements. These measurements are integrated into numerical weather prediction (NWP) models to enhance the accuracy of weather forecasts. At present, there are over 160 weather satellites in orbit, collectively producing around 80 million observations daily. (Dave, 2022)
- **Telecommunications** are largely dependent on communication satellites for broadcasting, internet services, and mobile connectivity, especially in remote areas. (Hanson, 2016; Jamalipour, 2001; Burleigh, 2022)
- **Transportation:** Logistics operations on Earth depend on the navigation services delivered from space, namely, by major navigation satellites constellations, comprising GPS, GLONASS, Galileo, BeiDu, and NavIC. Global Navigation Satellite Systems (GNSS) provide accurate positioning, navigation, and timing (PNT) services, without which modern transportation industries cannot be imagined (Grewal, 2011; Hein, 2020).
- **Climate science and environmental management** employ satellite data for monitoring deforestation, tracking wildlife, measuring pollution levels, assessing urbanization rates, mapping vegetation, analyzing the rate of ice melting at the poles, studying changes in the chemical composition of the atmosphere, and much more (Guo, 2015; Li, 2022; Ferreira, 2020).
- **Energy sector:** Satellite data aids in the exploration of oil and gas, monitoring of infrastructure, and management of renewable energy sources like wind and solar farms (Ferreira, 2020; Dubucq, 2021).
- **Insurance and finance** are a somewhat unexpected field to be found reliant on space technologies, yet it actively uses geospatial data obtained from Earth observation satellites for risk assessment in underwriting and claims, particularly in assessing damage from natural disasters (Shafapourtehrany et al., 2023; Korn, 2020).

- **Disaster Management:** Relies on real-time data from satellites to manage and mitigate the effects of natural disasters like hurricanes, earthquakes, and floods (Pandey et al., 2020; Le Cozannet et al., 2020).
- **Urban Planning and Development:** Satellite imagery supports urban planning by monitoring urban sprawl, infrastructure development, and land use changes (Ouchra et al., 2022).
- **Health and Epidemiology:** Satellite data helps track environmental factors that can affect public health, including air quality and water sources, and can even assist in predicting disease outbreaks by observing changes in environmental conditions (Acker et al., 2014; NASA Earth Observatory, 2020).

Overall, there is little doubt left around the fact that space is not a standalone endeavor, but rather an essential component of many terrestrial industries.

Misconception 2. *The expectations that the space sector will be able to generate enough profits to sustain itself are unrealistic, therefore, investing in it is akin to 'throwing the money down a rabbit hole'.*

The World Economic Forum forecasts a remarkable expansion in the space economy, projecting a surge to $1.8 trillion by 2035 from $630 billion in 2023. This prediction suggests an impressive average annual growth rate of 9%, far surpassing the global GDP growth rate. Crucial to this exponential growth are space-based and/or enabled technologies, particularly in communications, positioning, navigation, timing, and Earth observation services. (Khlystov & Markovitz, 2024). These industries not only create high-skilled jobs but also stimulate growth in ancillary sectors (SIA, 2020). The multiplier effect of space investments on national economies can be substantial, as indicated by Weinzierl (2018), who notes that every dollar spent by NASA contributes approximately $10 to the economy.

The space economy finds itself at an inflection point, and is already demonstrating its vast commercial potential. According to UBS (Berrisford, 2018): *"Key catalysts [of the space economy growth] are the deep pockets and sustained capital investment by new economy billionaires and technological advances in rocket and satellite technology."*

On top of these factors, another important trend must be added to obtain the full picture: drastic cost reduction for space venturing actors; and it is hard not to find impressive the rate at which the costs of satellite launches decrease. Adilov et al. (2024) demonstrate that launch cost reduction per satellite is complemented by reduction in average satellite mass (Figure 2).

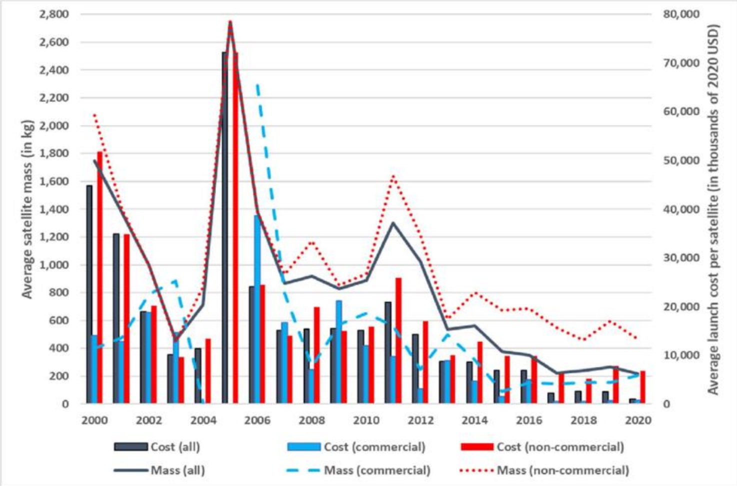

Figure 2. Trends in Satellite Mass and Launch Costs (2000-2020). Source: [Adilov et al., 2024]

In 2004, both satellite masses and launch costs peaked significantly. Post-2004, there is a notable decline in average satellite mass, particularly for commercial satellites, reflecting a shift towards more compact and efficient designs. Concurrently, launch costs have decreased, with commercial satellite launches being more cost-effective than non-commercial ones.

This reduction in launch costs, coupled with advancements in satellite miniaturization and manufacturing, underscores the increasing accessibility of space for commercial and scientific endeavors, thereby refuting the myth of commercial space unviability rooted in the assumptions dating back to the beginning of space exploration era. Nowadays, as the space sector continues to evolve, the effective shift from government-dominated strategies to commercially driven missions becomes increasingly evident.

Overall, the roots of persisting misconceptions might be insufficient body of existing research on the New Space Economy and lack of collective understanding of the space business environment. The data on space economy and space businesses is scarce (OECD, 2022); and despite the maturity and depth of research on the established 'Old Space Economy', there is a lack of extensive, diversified research focused on space innovation. Lack of comprehensive and deep research may amplify the risks, which are already high, when it comes to space ventures; therefore, this problem must be addressed in the near future. Additionally, the conducted literature review over several key scientific search engines (Google Scholar, Scopus, Science Direct, Research Gate) has demonstrated that up to this day there are but a handful of studies on sustainability aspects of commercial space exploration. Given the rapid growth of the industry, it is imperative that more research efforts are dedicated to its sustainable development.

Space (Un)sustainability

Among the 17 Sustainable Development Goals introduced by the United Nations, there are none regarding space sustainability, which gives a false impression that this dimension of human activity is irrelevant to global sustainable development (UN, 2015). The rapid expansion of the space industry has shown that this exclusion of the space sector from the UN Sustainable Development Goals is clearly an oversight, and has prompted a critical examination of current space practices through the sustainability lens. Despite the growing awareness about the problem, the existing body of scientific literature remains scarce, relevant policies remain underdeveloped and the overall effort to make the space sector more sustainable remains insufficient to yield tangible results.

While the problem of space sustainability is manifold, spanning from emissions from rocket launches to lunar soil contamination; based on the multiple reports and documents analyzed, it can be concluded that the most pressing issue is the growing number of space debris. (Undseth, Jolly & Olivari, 2020; ESA, 2023; NASA, 2024). It must be noted that in some context 'orbital debris' might mean natural space objects threatening space assets; however, in this study the term 'space debris' is used to refer exclusively to human-made 'space junk', such as defunct spacecraft and their parts, abandoned launch vehicle stages, and fragments from disintegration events.

In the past decades, the global space industry has seen unprecedented growth. The number of satellite launches skyrocketed, especially with the deployment of mega-constellations and new ambitious plans for innovative space utilization. This expansion raises significant concerns about the environmental and strategic sustainability of space as a resource (Pelton, 2020). According to Adushkin et al. (2020), the growing population of space objects aggravates the risk of collisions and space debris, which is a massive problem, specifically considering the fact that space ventures are already undertaking significant risks by operating in the hostile environment of space.

Current exponential rate of launches combined with sustainability inaction may lead to Kessler Syndrome - a scenario where few collisions cause an irreversible domino effect, destroying all space assets in orbit (Kessler & Cour-Palais, 1978). It might look like the current density of objects in orbit is far from being enough to cause such a cascade of collisions, however, without effective debris mitigation and management strategies, such catastrophic scenarios like the Kessler Syndrome may cease to seem unrealistic.

Sustainable Space Technologies: Definition

The concept of *'sustainable space technology'* is central to this study, therefore, requires elaboration and clarification.

No consensus is yet reached concerning an exact definition of 'sustainable space technology'. This leads to a broad variety of interpretations, which might be impeding consolidation of efforts towards sustainable development of the space sector, which relies on technological advancements. The literature review conducted for this study, has shown that, while the definition of 'space sustainability' is relatively well outlined (e.g., by ESA, NASA, UNOOSA), the definition of 'sustainable space technology' remains a matter of contention.

In order to unambiguously outline the object of the study, the following definition of 'sustainable space technology' was derived from the publications on space sustainability by ESA (2023), NASA (2024), UNOOSA (2019):

*"**Sustainable space technologies** are space-related technologies that ensure the long-term usability of space environments."*

Sustainable space technologies are developed and employed to mitigate the problem of space debris, enable resource optimization and reusability, shift towards environmentally-friendly approaches to space exploitation, and to perform other functions, which allow for continuous space utilization without jeopardizing the future of either space or terrestrial sectors of the economy. Examples of such technologies are: ClearSpace-1 - a mission for active space debris removal (Clearspace, n.d.); D-Orbit's D3 Decommissioning Device (D-Orbit, n.d.); Air-Breathing Electric Propulsion System for Satellites (Andreussi Ferrato, E., & Giannetti, 2022).

There are debatable cases, when 'sustainability' occurs as a side-effect rather than a core value for a technology. For instance, reusable launchers can be, on the one hand, regarded as a sustainable space technology, because they require less resources in terms of materials, finances and time; however, the purpose of their development was cost-reduction and/or interplanetary human spaceflights enablement rather than space sustainability. Moreover, such innovations can lead to a rebound effect, when cost-reduction makes launches so attractive that their number skyrockets, burning even more fuel and utilizing even more materials than before.

This study focuses on the technologies that have sustainability as their core function; however, the 'debatable cases' described above are also taken into consideration, but approached with caution.

1.2 TAM as the Theoretical Foundation of the Study

While different approaches to studying novel technology adoption have been developed in management science, one of the most influential and widely recognized theoretical frameworks remains the Technology Acceptance Model (Davis, 1989). The model suggests that there are specific factors that explain how users come to accept and use a technology. Originating in the field of information systems, TAM has become one of the most renowned models in understanding user acceptance and usage behavior in technology adoption studies.

Technological innovation is integral to the space sector (Orlova et al., 2020), within which this study is set. Therefore, understanding the factors determining acceptance of novel technologies in this industry is of paramount importance for its future development, especially so if this development needs to be channeled in a more sustainable way. This model's proven utility across diverse technological domains and its adaptability (Al-Emran & Granic, 2021; Granic, 2022) make it particularly suited to explore the unique challenges and opportunities presented by sustainable technologies in the space sector.

Original Technology Acceptance Model

The core of TAM is the proposal that two particular perceptions, perceived usefulness (PU) and perceived ease of use (PEOU), determine an individual's intention to use a system, which in turn predicts actual usage (Davis, 1989). I adapt these constructs and definitions from TAM to the sustainable space innovation adoption context. Here, ***perceived usefulness*** is defined as the company's subjective probability that using a specific technology will help the organization perform its tasks better. On the other hand, ***perceived ease of use*** is defined as the degree to which the prospective innovation adopter expects the target technology to be free of effort.

One of the revolutionary notions that the model brought was that usefulness does not equal functionality: "*Just because the system can be used does not mean it will be used. TAM asserts that perceived usefulness is the primary determinant of user acceptance, and the goals a system is capable of achieving need to be important to the user for the system to be useful.*" (Davis et al., 2024). This notion encouraged me to focus on studying perceptions of sustainable space technology adoption, rather than trying to identify a set of objective factors underlying this process.

Another powerful message of Davis's work was that usefulness can and should be assessed early in the development process. This is particularly relevant for the research at hand, because the market of sustainable space technologies is an emerging market, with an abundance of technologies at early stages of development and, hopefully, many more technologies yet to emerge.

Thus, Davis's contribution to understanding technology acceptance serves as a crucial framework for evaluating innovations in a multitude of fields, and is found particularly relevant for the emerging sustainable space technologies' market.

Current Research Edge of the Technology Acceptance Model

A landmark study by Davis (1989) suggested the model in the context of computer adoption, demonstrating that both perceived usefulness and perceived ease of use significantly predicted user acceptance and user behavior. Numerous subsequent studies have replicated these findings across different technologies and user populations, either fine-tuning the model for a certain domain, or extending it by injecting elements of other theories (Davis et al., 2024).

Analysis of various extension and review papers helped me to identify the current research edge of TAM. The model can be thought of as a tree, with precursor theories as the roots, converging at the tree trunk - TAM, and branching off as extensions with leaves as concrete application cases. Next, a question was raised: *which branch of TAM will serve as a basis for this research?* The answer depended on the object of the study and its context.

The object of the study at hand are sustainable space technologies, and there are only two types of potential adopters of such technologies: companies (B2B case) and states, including governmental agencies, organizations (B2G case). This research focuses on the technology adoption by private companies, therefore, the B2B case is relevant. The original TAM framework and the majority of its extensions deal with B2C cases. In all the literature collected and analyzed for this study, there is no paper applying TAM to a B2G case; however, several authors attempted to adapt the framework to the B2B case. As the basis of this research, I took the TAM3 iteration of the framework (Venkatesh & Bala, 2008) and combined it with the extensions applicable to B2B cases (Straub et al., 1997; Verma et al., 2018; Leso et al. 2023; Tavakoli et al., 2023).

The resulting 'branch' of the TAM serving as a theoretical foundation for this study can is visualized on Figure 3b in contrast with the TAM3 visualization on Figure 3a.

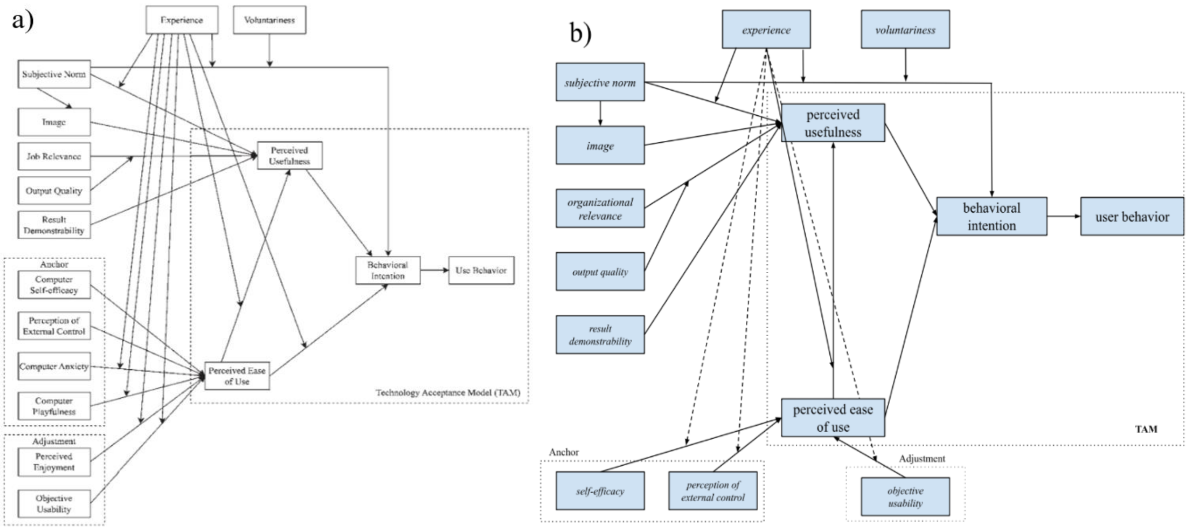

Figure 3a. TAM3. Source: Venkatesh & Bala, 2008. General case of technology acceptance: product of integration of TAM2 (Venkatesh & Davis, 2000) and MDPEU (Venkatesh, 2000).

Figure 3 b. TAM 3 adapted to a B2B case. The branch of TAM3 relevant to B2B cases, based on B2B extensions of TAM

For this study, the core of the TAM theory remains unchanged: perceived usefulness (PU) and perceived ease of use (PEU) shape behavioral intention, which in turn determines user behavior (in this case, it is technology adoption by a private company). The factors influencing perceived usefulness, perceived ease of use and overall behavioral intention, are interpreted in the following way:

- **Voluntariness** (introduced by Venkatesh & Davis (2000) as part of TAM2) refers to a degree to which potential technology adopters perceive the use of technology as being free from external pressure, for instance, legal obligations. Voluntariness is related to subjective norms (see arrow connecting the effect of 'voluntariness' to the one of 'social norm'), which involve the perceived pressure to use or not use a technology.
- **Experience** (introduced by Venkatesh & Davis (2000) as part of TAM2). While in the traditional understanding of TAM, 'experience' often refers to user's prior interaction with a certain technology; in the context of this study the understanding of this factor was broadened to incorporate experience of companies in dealing with a certain type of technology and experience of companies' managers in relevant domains (for instance, CEO's experience in the space sector or CTO's experience in research). By the number of outgoing arrows, a reader sees how many other aspects are influenced by 'experience'. This factor has an impact on all the factors shaping the 'perceived ease of use', because with increasing relevant experience users find a technology easier to handle. Experience also impacts perceived usefulness, because the more familiar a user is with the type of technology, the more functionality they can unlock and

the better they can utilize it. Finally, experience impacts behavioral intention, because prior interactions may predetermine future intentions.

- **Subjective Norm** (introduced by Venkatesh & Davis (2000) as part of TAM2) is the perceived peer pressure to perform or not perform a particular behavior, which in this case is adoption of a technology by a company. Here, 'peer pressure' is interpreted as an influence exerted by competitors and industry leaders; benchmarking and changing industry standards. Subjective norms have an impact on the image of a company, on the perceived usefulness of a technology *('if everybody else in the industry finds it useful, then it is likely to be also useful for us')* and directly on behavioral intention. The effect of subjective norm on behavioral intention may diminish over time as users gain more experience with the technology and form their own opinions about its usefulness and ease of use. (Venkatesh & Davis, 2000).
- **Image** (introduced by Venkatesh & Davis (2000) as part of TAM2) is particularly relevant in the context of sustainable technology adoption. It encompasses the reputation aspect, and sustainable technologies are oftentimes adopted by companies in order to improve their standing within their network, stakeholders, competitors (Lee, 2012).
- **Organizational Relevance** stems from the 'job relevance' factor explored by Venkatesh & Davis (2000) as part of TAM2. While job relevance refers to the degree to which an individual believes that a technology is directly applicable to their job; 'organizational; relevance' means the degree to which a certain technology is relevant to a company's core activities, to its range of primary functions, and, in a broader understanding, to its mission and vision.
- **Output Quality** (introduced by Venkatesh & Davis (2000) as part of TAM2) is a perception of how helpful a technology would be for a company; whether it can effectively and efficiently meet their needs and expectations.
- **Result Demonstrability** (introduced by Venkatesh & Davis (2000) as part of TAM2) reflects how much the results of using a technology are observable, tangible, and communicable.
- **Self-Efficacy** (introduced by Venkatesh (2000) as part of MDPEU). Originally 'computer self-efficiency' referred to an individual's belief in their capability to perform a specific task on a computer. In the case at hand, this factor is interpreted as the perception of a company's decision-makers in their ability to handle a technology and to make beneficial use of it.
- **Perception of External Control** (introduced by Venkatesh (2000) as part of MDPEU) reflects a company's perception that external organizational and technical resources are available to support the adoption of a specific technology, including developed infrastructure, legal frameworks, manuals, tutorials, etc.
- **Objective Usability** (introduced by Venkatesh (2000) as part of MDPEU) means how easily and effectively users can interact with technology, independent of their subjective perceptions.

In addition to the aforementioned factors, stemming from TAM3, the theoretical foundation of this research was enriched by insights from several TAM extensions dealing with B2B cases: Tavakoli et al. (2023) suggested two categories of factors determining AI acceptance, namely, **employee-related** and **technology-related** ones; Leso et al. (2023) looked closer into **corporate cultures** and how they influence technology acceptance; Verma et al. (2018) explore how system characteristics, such as **information quality** and **system quality**, influence managerial attitudes towards Big Data Analytics systems. A special attention was given to the study was conducted by Straub et al. (1997) and introduces the factor of **cultural differences** by applying TAM to three different corporate contexts: the USA, Switzerland and Japan. Three key components comprise the factor of cultural differences when it comes to technology acceptance: collectivism vs. individualism, uncertainty avoidance and power distance. This threefold factor is deemed as important in the B2B TAM context and included in the theoretical foundation of this study.

To conclude, this research is building on the TAM3 suggested by Venkatesh & Bala (2008) enhanced with several separate extensions relevant for the B2B case.

1.3 Auxiliary Theories

Given the scope of the research at hand, the elaboration of the resulting theoretical framework and its practical application necessitated the use of additional theories and models. In this research I used the Locus of Control Theory and the XaaS or Everything-as-a-Service model.

Locus of Control Theory

The Locus of Control Theory originates in psychology and traces back to the mid-20th century. It was formally presented to the scientific community in a seminal work by Rotter (1966), where he conceptualized the differentiation between individuals with an internal locus of control, who take responsibility for their actions and outcomes, and individuals with an external locus of control, who attribute outcomes to other people, forces and circumstances.

The existing literature acknowledged the relevance of the Locus of Control theory in the context of Management science. For instance, Steers (1977) extended Rotter's psychological concept to the field of organizational behavior and management by studying how locus of control influences job performance, job satisfaction, other work-related attitudes and, consequently, work-related behaviors. Another work that helped bridge the gap between psychological theories and practical management applications, is a study by Thatcher (2002) that examines how individual traits, including locus of control, influence computer anxiety and computer self-efficacy, which are critical factors in technology acceptance according to TAM2 and TAM3. Overall, the relevance of the Locus of Control Theory in technology adoption context has been already demonstrated (Hsu & Chiu, 2004; Mun et al., 2006), and this study is building on this body of research.

XaaS Model

The XaaS (Everything-as-a-Service) model encompasses several service models delivered over the internet. It would not be an exaggeration, if these models were called truly revolutionary because of how they transformed the very way modern information technology businesses operate, offering above all scalability, flexibility and cost-efficiency. The classical XaaS models include Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS). Nowadays, this triad of classical XaaS models is supplemented by a variety of other offerings as-a-service. A summary of key drawbacks and benefits of the XaaS model is presented in Table 1.

Benefits	Drawbacks
XaaS ***reduces expenses*** by transitioning to a pay-as-you-go model, which can lead to significant cost savings (Armbrust et al., 2010).	***Data security and privacy*** are significant concerns with XaaS models, as sensitive information is stored off-premises (Subashini & Kavitha, 2011).
Businesses can scale services up or down based on demand, providing flexibility and efficiency (Smith, 2018).	***Reliable internet connectivity*** is crucial for the seamless functioning of XaaS services, posing a risk in regions with poor connectivity (Armbrust et al., 2010).
Services can be ***accessed from anywhere*** with an internet connection, enhancing mobility and collaboration (Subashini & Kavitha, 2011).	Adhering to regulatory requirements can be complex when data is stored across multiple geographies (Marston et al., 2011).
By outsourcing IT services, businesses can ***focus on their core competencies*** rather than managing IT infrastructure (Zhang et al., 2010).	Businesses may find it ***challenging to switch providers*** due to proprietary technologies and high switching costs (Smith, 2018).

Table 1. Benefits and Drawbacks of the XaaS model.

The concept of XaaS has its roots in the early 2000s with the advent of cloud computing; and initially, the focus was on SaaS, where software applications were delivered over the internet. The success of SaaS paved the way for other service models like PaaS and IaaS (Duan et al., 2015). According to Buyya et al. (2009), the maturation of cloud computing technology has enabled the proliferation of various "as-a-service" models, for example, Database as a Service (DBaaS), Network as a Service (NaaS), and others (Marston et al., 2011). In the space sector, a good example is Satellite-as-a-Service by D-Orbit (D-Orbit, n.d.), the first space company to receive a B-corp certification and putting sustainability concerns at the forefront of its activities. The vision of D-Orbit behind introducing SaaS is that it would *"allow customers to leverage the capabilities of satellite technology without having to invest in and operate their own satellite infrastructure."*.

2. Methodology: A Toolset of Qualitative and Quantitative Methods

To answer the research question 'What factors determine market acceptance of sustainable space technologies?' a mixed-method approach was employed to best address the interdisciplinary and multifaceted nature of the inquiry. The qualitative part of the research comprises semi-structured interviews, thematic analysis, pattern recognition, commercialization approach formulation for the case study. The quantitative research tools include Kendall-Tau correlation analysis, TF-IDF for text analytics, Large Language Model (LLM), Uniform Manifold Approximation and Projection (UMAP), Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN), Kruskal-Wallis analysis of variance, and Dunn's test.

2.1 Research Setting: eSpace

To identify the factors shaping market acceptance of sustainable space technologies, I conducted an in-depth study at the EPFL Space Center (eSpace), specifically, by joining a team of researchers working on an accurate ground-based space debris characterization and 6D pose estimation tool, between March and July 2024.

The two core areas of the eSpace activities are education and research. The center supervises and conducts space-related scientific projects, teaches a minor in space technologies at EPFL, brings together students, professors, researchers, engineers, industries, and international space agencies. (eSpace, n.d.)

I chose to conduct my research at the EPFL Space Center because of its extensive collaboration both with leading academic institutions and key space industry partners; because of its focus on innovative technologies; and because sustainability is deeply integrated into every activity of the center and represents one of the pillars on which it builds its education and research.

My research was designed as an inductive study following a zigzag approach to data collection and theory formulation. The primary body of data was collected through 3 rounds of interviews with industry experts and academics. The EPFL Space Center played a crucial role in respondents' sampling, because it was mainly through its channels that space industry experts and academics were reached out to (Space Innovation Network (Space Innovation, n.d.), space-related projects' co-supervisors from other universities, and partners of the EPFL Spacecraft Team - a student-led CubeSat mission, coordinated by eSpace (EST, n.d.)). Moreover, the case study, which was included in this research, was based on the ODLI - a space debris repository created as one of the outcomes produced by the research group that I have joined. This research group closely collaborates with the Computer Vision (CV) lab at EPFL, and receives funding as a BRIDGE project designed to 'bridge' academia and industry by conducting innovative research at a university and then bringing the resulting technology to the market (Innosuisse, n.d.). This is why commercialization aspects were particularly important for the research group in question, which allowed for mutually-enriching work throughout the duration of this research.

2.2 Research Design: The Zigzag Approach

One of the starting steps defining the research design was the choice between an inductive approach and a deductive one, which are integral to social sciences, offering different paths for theory construction and testing (Bryman, 2008). I opted for the inductive approach, which implies collecting data without predefined theories, allowing insights and theories to emerge gradually from the data (Thomas, 2006). The choice was motivated by the consideration that a more open-minded initial approach would increase the chances of collecting diverse helpful insights, facilitate 'out-of-the-box' thinking, and reduce the probability of introducing a bias to the answers of interviewees by limiting their choice of options to some set of predetermined factors. Moreover, it helped to make the interview questions more accessible to non-space experts allowing to 'through a wider net' and the beginning.

Charmaz (2008) highlights that an inductive approach necessitates a *'reciprocal relationship'* between data collection, analysis and resultant theory generation; thus, this study adopted the 'zigzag' process of conducting research, described by Creswell (2007) as: *'out to the field to gather information, into the office to analyze the data, back to the field to gather more information, into the office, and so forth.'* The primary source of data gathered 'in the field' were semi-structured interviews with experts from various industries (grouped as space and non-space) and academics. After each round, the list of interview questions was revisited and updated to better inform the theory at the next step.

The zigzag trajectory of the research is visualized in Figure 4.

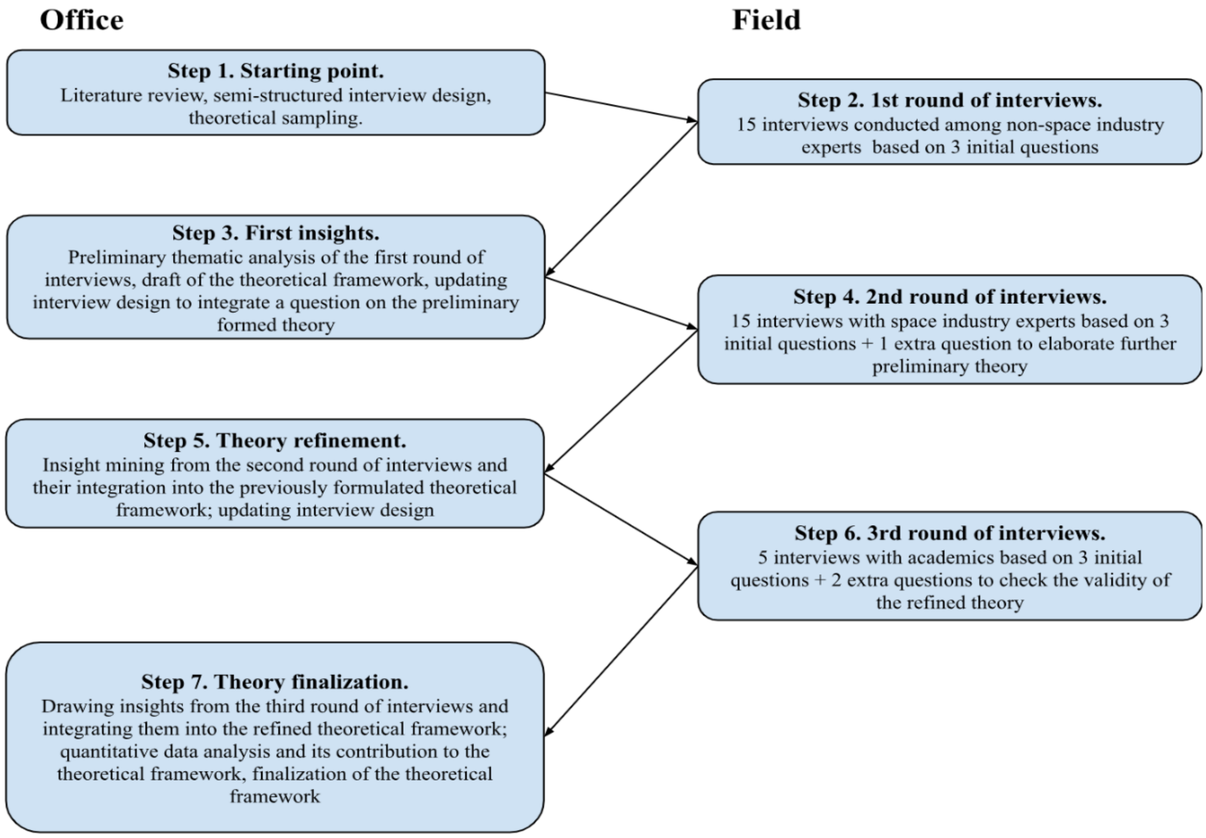

Figure 4. Research Design: The Zig-Zag Approach

The number of rounds of interviews was dictated by the theoretical sampling of 3 key categories of interviewees (non-space industry experts, space industry experts and academics) as well as the theory being elaborated in all of its complexity by the end of Round 3.

Thus, the theoretical framework resulting from this study was not predetermined with an intention to be tested by the collected data, but rather emerged gradually over different stages of data collection and analysis, following the inductive approach.

2.3 Data Collection: Semi-Structured Interviews

The choice of experts to interview was done by theoretical sampling (Creswell, 2007). First, 3 categories of interviewees were outlined with the intention to study potential variance in perceptions of sustainable space technologies' market adoption between these groups. The reasons why studying perceptions was chosen in this research over trying to extract the objective factors are the following:

1. The fact that a technology can be used, does not necessitate that it will be used; and the actual **adoption of a technology largely depends on how its usefulness and ease of use are perceived** (Davis, 1989)
2. In emerging technologies and markets, such as sustainable space technologies, there's often a high degree of uncertainty. **Objective data is scarce or unreliable, making perceptions a crucial area of study**. (Li & Li 2023)
3. In the business world, especially in sectors driven by innovation and wishful thinking, **perceptions can significantly influence reality**. How key industry players perceive a technology often dictates their willingness to invest, partner, or adopt, which in turn can affect the technology's market success. Understanding these perceptions can provide insights into potential market trends before they fully materialize.
4. By examining perceptions, researchers can identify **perceived barriers and enablers to the adoption of sustainable space technologies**. Such insights are valuable for developing strategies to enhance the adoption and success of these technologies.

To capture the perceptions of the commercial opportunity landscape for sustainable space technologies by key academic and industry players, as well as the variance between them, it was decided to conduct three rounds of interviews.

Firstly, ***non-space industry experts*** were interviewed. The choice to begin with this audience particularly was motivated by the expectation that CXOs of various technological firms could bring a fresh, diverse perspective to the matter at hand. They could project their experiences in other sectors onto the space domain, which could lead to out-of-the-box ideas. This expectation was not simply met, it was exceeded by providing a rich pool of diverse but relevant insights. Therefore, the first round of interviews provided **width** to the scope of the data.

Secondly, ***space industry experts*** were interviewed. The motivation to address this audience after having obtained the insights from non-space domain experts stemmed from the fact that the people, who work in the space sector specifically, could provide concrete, informed and domain-specific insights. They know the market from A to Z, and this nuanced perspective adds **depth** to the data collected.

Lastly, ***academics*** engaged in space-related projects were interviewed. The reason why researchers were addressed as a separate group in this study is twofold. First driver was the understanding that a significant share of space innovation is enabled by cutting-edge fundamental and applied research conducted by academia and later adopted by the industry. Since I am examining sustainable space technology adoption, it would have been an oversight not to consider one of the key nodes in the chain of this process. Second motivation stemmed from the insight collected through the first two rounds of interviews, namely, the importance of perceived temporal remoteness of the effects from adopting a technology. Since academia and industry operate under different timelines, it was deemed relevant to try to understand how the perceptions of temporal remoteness may vary between academia and industry.

The overall vision behind the design of the interviews in 3 rounds was that mining insights from the responses of different informed groups would result in fruitful cross-pollination of ideas. A total of 35 experts were interviewed, while 57 were initially invited to participate in the study, which gives an effective response rate of 61%.

Maximizing the Variance: Industry-Agnostic Experts Interviews

15 CXOs were interviewed at the Engineering Industry Day at EPFL - an event aiming at bringing together academia and industry. Given the focus of EPFL on technology, the sample of companies represented at the event consisted mostly of technological firms (robotics, software, photonics, energy, etc.) with an infusion of fintech specialists and venture capitalists.

First, interviewees were asked to fill out a printed questionnaire with the background information about their experience in academia, space industry, other industries apart from space, level of education and degree of familiarity with space technologies (refer to Questionnaire in Appendix).

The respondents were informed that all the information provided in the questionnaire would be treated as strictly confidential. The responses were aggregated and anonymized so that no individual can be identified on their basis. The participants were asked for their permission to be recorded. 11 out of 15 interviewees of the first round gave their consent to audio-recordings, and the responses of 4 remaining interviewees were written down by hand.

57% of the respondents held a PhD degree and 43% finished their education at the Master's level; none of the respondents indicated that they stopped their education at the High School or Bachelor level. Summary statistics is reported in Table 2. Their experience in academia ranged from none to 15 years, while their experience in the industry (other than space) spanned from 1 to 35 years. Some of the respondents admitted to have had some experience in the space sector, yet I still counted their responses in the 'non-space industry experts' sample, if the two following criteria were met: 1) they were not working in the space industry at the moment of the interview; 2) their experience in the space sector was no more than ⅓ of their overall experience in the industry.

	Years of experience in academia	Years of experience in the space industry	Years of experience in other industries	Familiarity with space technologies (1-10 scale)
Observations	15	15	15	15
Mean	4.13	0.73	14.47	3.80
Standard deviation	4.73	1.22	9.27	2.08
Minimum	0.00	0.00	1.00	1.00
25% (percentile)	0.00	0.00	7.50	2.00
50% (percentile)	3.00	0.00	12.00	4.00
75% (percentile)	6.000	1.500	20.000	4.500
Maximum	15.000	4.000	35.000	8.000

Table 2. Summary Statistics. Round 1

Space sector aside, the respondents had experience in the following domains: IT, chemical engineering, pharmaceuticals, food and beverage, venture capital, photonics, quantum photonics, AI, risk management, dentistry, software, solar energy, manufacturing, industrial automation. Coming from these diverse technical backgrounds, the level of confidence in one's knowledge of space technologies ranged among the respondents from 1 to 8 with a mean of 3,8 and a standard deviation of 2,08.

The CXOs of technological companies were asked to respond to 3 open-ended questions:

1. *Who do you think should pay for sustainable space technologies?*
2. *What are the main drivers of sustainable space technologies adoption by private companies?*
3. *What do you see as potential commercialization avenues for ODLI (the technology developed at eSpace)?*

The purpose of the first question *"Who do you think should pay for sustainable space technologies?"* was to initialize the conversation about sustainable space technologies, and see how much responsibility for sustainability respondents place on private actors in the space domain. The second question represents the core of the empirical study. Its aim is to identify the factors shaping the perception of sustainable space technologies' adoption on the market. The third question refers to a concrete example of a sustainable space solution - ODLI - a technology, being developed at EPFL and serving as a case study for this research. This question was accompanied by a brief explanation of what ODLI is together with some visual materials (see Figure A in Appendix)..

Since the interviews were semi-structured, the aforementioned questions served as the backbone of the conversation, but did not limit the dialogue. In the process of discussion other sub-questions often emerged and brought new insights.

Back in the office, the replies to the first round of interviews were content analyzed, key insights were extracted and systemized and a preliminary theoretical framework was formed (see Results). Among the first key insights, an emerging new factor of **remoteness of effects** particularly stood out. Based on these initial findings, the interview design was updated by introducing a 4th question:

4. *Would you agree with the following statement: "Due to space's remoteness, the indirect impact of sustainable space technologies might hinder their adoption compared to other sustainable technologies, as people are more likely to prioritize concerns with immediately perceptible effects, like deteriorating quality of food, over mitigating orbital pollution." ?*

The purpose of adding this question was to seek validation from space industry experts regarding the significance of the factor of sustainable space technologies' acceptance by the market called 'remoteness of effects', and elaborate the forming theory in more detail.

Sharpening the Focus: Space Industry Experts Interviews

Having captured a broad vision on the matter at hand by interviewing experts from various technological companies, I sought sharper focus and deeper insights from representatives of space companies and space agencies. 15 experts were interviewed in Round 2 through video conference calls following the same principle of semi-structured interviews: several backbone questions to channel the conversation allowing for spontaneous sub-questions and subtopics to emerge in the due course of the discussion. The sample was drawn through the partnership network of the Space Innovation (Space Innovation, n.d.), EPFL Spacecraft Team (EST, n.d.) and through approaching space companies' representatives at the Space Forum at the IMD Business School (IMD, n.d.).

Unlike in the first round of interviews, no questionnaires were sent out to space experts. The information on their professional experience was taken from their LinkedIn pages, and, if not available there, was asked directly during the interviews. The set of background questions remained mostly the same, except for a slight modification of question 4: "Have you ever worked in other sectors apart from space? If yes, what were those sectors?". Question 5 was removed, because the sole purpose of this question in Round 1 was to see how familiar the respondents from other sectors are with space technology; and in the case when the sample consists exclusively of space experts, there is no need for this self-assessment.

The majority of the interviewed space industry experts hold a Master's degree (60%), one third of the Round 2 respondents did a PhD, and only a small fraction (roughly 7%) stopped their education at the Bachelor level. As seen in Table 3, most of the interviewees never worked in academia. As seen in Table 3, their average experience in the space sector is 15 years with a median of 14 and a standard deviation of 8.7 years. This experience in the space sector is often complemented with experience in other sectors, such as finance, IT, energy, watchmaking, automotive, geochemical modeling, law, instrumentation, marketing; and averages 3 years with a median of 2 and a standard deviation of 3.4 years. It is important to highlight that one of the key inclusion criteria for this round of interviews was the condition that an interviewer is currently working in the space sector and holds a managerial position.

	Years of experience in academia	Years of experience in the space industry	Years of experience in other industries
Observations	15	15	15
Mean	2.10	15.00	3.00
Standard deviation	4.48	8.71	3.44
Minimum	0.00	1.00	0.00
25% (percentile)	0.00	9.50	0.00
50% (percentile)	0.00	14.00	2.00
75% (percentile)	1.00	21.00	5.00
Maximum	16.00	32.00	12.00

Table 3. Summary Statistics. Round 2

Replies to the interview questions were afterwards content analyzed, and the results of these analyses were used to update the initially constructed theoretical framework. Once again, the design of the interview was adjusted for the next round by breaking down Question 4 into two different questions:

- 4A. Would you agree with the following statement: "Due to space's remoteness, the indirect impact of sustainable space technologies might hinder their adoption compared to other sustainable technologies, as people are more likely to prioritize concerns with **spatially close effects**, like deteriorating quality of food, over mitigating orbital pollution." ?
- 4B. Positive effects from sustainable space technologies implementation have very extended timeframes, in a sense that one would not feel the benefits of investing in such technologies in the near future, but rather has to have a lot of patience. Do you think that this **temporal remoteness of the effects** negatively impacts the adoption rate of sustainable space technologies?

The reason behind splitting this question into two parts stems from the observed variance in perceptions of spatial and temporal remoteness when it comes to sustainable space technologies. (see Results)

Contrasting Insights: Academics Interviews

The sample of Round 3 interviewees were drawn from the list of various space-related research project supervisors across different universities. Only professors and postdoctoral researchers were invited to take part in the study. This sample saw the lowest response rate (27,8%), and, therefore, consisted of the least number of interviews (5 out of 18 invited).

Similar to the previous round, the background information about the participants was taken from their LinkedIn pages, and wherever not available, was asked directly during interviews. The list of background questions remained unchanged from Round 2.

All the respondents of this group hold a PhD. Some of them had prior experiences in the industry, however, a mandatory criteria for this group were that they currently work in academia on a space-related topic. Summary statistics are reported in Table 4. On average, Round 3 respondents worked 6 years in the space industry and 1,5 years in other industries, including electronics, optical glass, machine tools. By contrast, their average experience in academia was 13,2 years with a minimum of 8 years and a maximum of 21 years.

	Years of experience in academia	Years of experience in the space industry	Years of experience in other industries
Observations	5	5	5
Mean	13.20	6.00	1.50
Standard deviation	5.22	5.43	3.08
Minimum	8.00	0.00	0.00
25% (percentile)	9.00	2.00	0.00
50% (percentile)	13.00	5.00	0.00
75% (percentile)	15.00	10.00	0.50
Maximum	21.00	13.00	7.00

Table 4. Summary Statistics. Round 3

Responses of academics were preprocessed and content-analyzed using the same procedure as for the previous rounds. The theoretical framework was finalized based on the Round 3 results; and the synthesis of insights from all the interview rounds allowed to perform machine text analytics (see Content Analysis section).

2.4 Data Preprocessing: From Raw Notes to Analysis-Ready Texts

After each round of interviews, the recordings were transcribed in full. Given the fact that the interviews were oral and semi-structured, the raw notes, albeit accurate, could not have been utilized in the analysis without preprocessing, due to variety in manners of speaking, repetitions, synonyms, filler words, etc.

Chai (2023) in her work "Comparison of Text Preprocessing Methods" states that despite the fast-paced advancements in machine learning algorithms for text preprocessing, it still requires a dual machine-manual approach. In the study at hand the dual approach constituted the steps displayed in Table 5.

MANUAL	MACHINE
• Irrelevant information removal (e. g., chitchat unrelated to the interview questions was expunged); • Correction of grammatical, lexical mistakes. • Terminology standardization (e. g., *'space sector'* = *'space domain'*); • Repetition elimination (e. g., *'It is important, it is very, very important'* → *'It is very important'*).	• Stopwords removal; • Tokenization; • Lowercasing; • Lemmatization; • Contractions expanding (e. g., *'don't'* → *'do not'*); • Text normalization.

Table 5. Manual and Machine Methods of Data Preprocessing

Manual text preprocessing was conducted after each round of interviews, then coding was performed to obtain initial insights, form and refine theoretical framework following the zigzag approach described earlier. Machine text preprocessing was done over the entire corpus of texts once all interviews were done and manually preprocessed, which is explained by the fact that automated methods of data cleaning and analysis are most relevant for voluminous data. Refer to Table A in Appendix for a detailed description of data preprocessing tools utilized, and to Figure B in Appendix for a detailed visualization of data handling processes in the given research.

2.5 Content Analysis: Human and Artificial Intelligence

In this thesis, the content analysis of the interviews with experts was conducted through a multi-stage process that employed both qualitative and quantitative tools to ensure a comprehensive examination of the data.

Initially, at the end of each interview round, the qualitative approach involved detailed coding of the transcripts and the identification of emerging themes and topics, mining of potentially useful insights, and understanding of the underlying narratives and patterns within the interview data. Subsequently, when all interview rounds were finished and all the data was accumulated, quantitative tools were employed to further analyze the narratives outlined earlier.

By integrating these qualitative and quantitative approaches, the analysis benefitted from the depth of manual coding and the scalability and objectivity of automated methods, providing a robust foundation for the interpretation of the data.

Factor Analysis: Manual Coding

Following Williams & Moser (2019), I went through 3 stages of coding: open, axial and selective.

In the first level of coding, distinct concepts and themes were identified for categorization. This is an iterative process, where the indicators of emerging themes and concepts are constantly compared to those outlined earlier (Saldana, 2021), and in this thesis the process spanned 3 iterations corresponding to 3 Rounds of interviews. It must be noted that concepts are not equal to factors: they represent an intermediary result and are more specific than factors.

Answers to all the questions were scanned for potential insights, and not only to Question 2, which directly asks about the factors determining market adoption of sustainable space technologies. This is explained by the assumption that interviewees might indirectly mention relevant concepts, while answering the question about who should pay for sustainable space solutions, or what could be the potential commercialization avenues for the technology developed at eSpace, or any other subquestions emerging in the due course of semi-structured interviews. The only question that was excluded from this stage of content analysis was the one on the remoteness of effects, which was introduced in Round 2 and split into two subquestions about the spatial and temporal aspects of remoteness in Round 3. This part of the interview was excluded from open coding, because it is specific to one particular factor, and could have otherwise introduced a bias.

Once the bank of open codes was formed, the second stage of coding, namely 'axial' was performed. Williams & Moser (2019) write: *"In contrast to open coding, which focuses on identifying emergent themes, axial coding further refines, aligns, and categorizes the themes."* In other words, the second stage focuses on connections and relationships between the concepts and themes identified previously, and attempts to systematize them. Thanks to these identified relationships between concepts, they can be grouped into categories, which in the case of the research at hand, are factors shaping market acceptance of sustainable space technologies.

Finally, selective coding was conducted to achieve a higher level of abstraction and theory creation. This stage implies identifying the core category, relating all other categories to the core category, and building a theory around it (Williams & Moser, 2019). Since this study does not represent an attempt to create a new theoretical framework 'from scratch', but rather to extend an existing model; this final stage of coding is adjusted to the case. Instead of trying to build a narrative around the core category identified through iterative coding; categories and concepts were compared against the factors of the existing extended TAM. The baseline model was TAM3 adjusted to the B2B case; however, if no corresponding factor was identified among the factors of TAM3, a broader pool of extensions, TAM++, was consulted (refer to Table E in the Appendix).

Machine Text Analytics

The manually extracted insights were complemented with the results obtained through machine text analytics. For this task, I tried several machine learning algorithms capable of grasping context and nuanced meanings, including Neural Variational Document Model (NVDM), BERTopic and several models of OpenAI Large Language Model (LLM). The outputs were compared, and the Large Language Model (LLM) offered by OpenAI, GPT-4 model, proved to be the most coherent when performing the task of extracting key concepts from the interview notes (refer to the Code Repository in Appendix). Despite its outstanding ability to take context into account, this model has its limitations. In this particular case, it produced 83 concepts, some of which were repetitive, which necessitated dimensionality reduction.

Dimensionality reduction was performed in several steps. First, the extracted factors underwent preprocessing, including tokenization, stopword removal, and lemmatization, using NLTK (Bird et al., 2009) in order to ensure that the text was clean and standardized for a more accurate analysis. Then, TF-IDF (Term Frequency-Inverse Document Frequency) vectorization was applied to convert the preprocessed text into a numerical format that reflects the relevant importance of terms within the documents (Rajaraman & Ullman, 2011). TF-IDF was chosen because it helps in emphasizing significant words while reducing the weight of commonly used words across documents, therefore, is more suitable in this case, when identification of specific concepts is required rather than identification of one or several overarching themes.

Following TF-IDF vectorization, UMAP (Uniform Manifold Approximation and Projection) was employed for dimensionality reduction (McInnes, Healy, & Melville, 2018), which preserves the global structure of data while maintaining local relationships.

Next step was clustering, which was done using HDBSCAN (Hierarchical Density-Based Spatial Clustering of Applications with Noise) (Campello, Moulavi, & Sander, 2013). This algorithm was chosen because of its ability to effectively identify clusters of varying shapes and sizes: this makes it particularly useful for identifying meaningful clusters in noisy data, which is typical in natural language processing tasks. Refer to Code Repository in Appendix.

3. Results: Factors Shaping Market Acceptance of Sustainable Space Technologies

Based on the collected data, 37 concepts related to sustainable space technologies' private adoption were identified through manual coding: *distance, minimum effort/maximum results, pain-point, uncertainty, tradeoff, user-friendliness, industry standards, cost reduction, legal obligation, tipping point, urgency, timeframes, technological complexity, technological capabilities, reputation, security, policies, connection to other sectors, necessity, risk mitigation, affordability, reliability, relevance, proactive approach, international coordination, understanding of the problem, terrestrial precedent, investment risks, access to funding, scale, additional benefits, availability, cultural differences, technological compatibility, TRL, knowledge*. Refer to Table B of the Appendix for the matrix, where lines correspond to IDs of interviewees and columns correspond to the identified concepts; and to Table C in the Appendix for a detailed table with all the concepts, explanations, their indicators and references from interview texts.

Overall, 16 factors were formed out of 37 initially identified concepts (refer to Table D in the Appendix). Some of the concepts became independent factors (*cultural differences, reputation, proactive approach, knowledge, tipping point, connection to other sectors, industry standards*), others were merged to create new categories (*regulatory landscape, remoteness of effects, market dynamics, added value, financial considerations, opportunity costs, awareness, financial considerations, technological characteristics, organizational relevance*).

The literature review showed that two of the factors do not have direct analogues or are not substantially studied either in TAM3 or TAM++: 'remoteness of effects' and 'connection to other sectors'. Using the Concepts Matrix (refer to Table B in Appendix), for both of these factors I calculated the number of mentions, and the factor of 'remoteness of effects' scored the highest in the first round, when the initial theoretical framework was formed. It is worth mentioning that when all the interview rounds were concluded, the chosen factor remained the most frequently mentioned one between the two under-researched factors ('remoteness of effects': 19, 'connection to other sectors': 3). Thus, the decision to explore further **'remoteness of effects'** as a factor of technology acceptance, is motivated by the fact that prevalence of this factor in empirical observation is not matched by the attention given to it by the existing body of research.

The results of the machine text analytics (26 general factors) were cleaned from irrelevant topics (mostly, those that are specific to the case study) and empty entries, and then compared to the manually extracted factors. This resulted in 22 outputs, which overlapped with 10 of the factors identified through manual coding, namely: *'regulatory landscape', 'remoteness of effects', 'organizational relevance', 'technological characteristics', 'awareness', 'financial considerations', 'added value', 'industry standards', 'proactive approach', 'reputation'*. It is important to note that the machine-introduced factor linked to *'remoteness of effects'* was comprised of components, which referred exclusively to the temporal aspect of remoteness; while the only component on the spatial aspect was attributed by the algorithm to the group with the components referring to *'organizational relevance'*. This observation was taken into consideration, allowing to suggest the relations of the two facets of the newly introduced factor with other factors.

The 6 factors, which do not seem to have direct analogues among the categories identified by the machine learning algorithms, are *'tipping point', 'opportunity costs', 'connection to other sectors', 'market dynamics', 'knowledge', 'cultural differences'*. This does not necessarily mean that these factors are not valid, but rather can signify that these factors are too specific for an artificial intelligence to grasp. The main results of this research are presented in Figure 5.

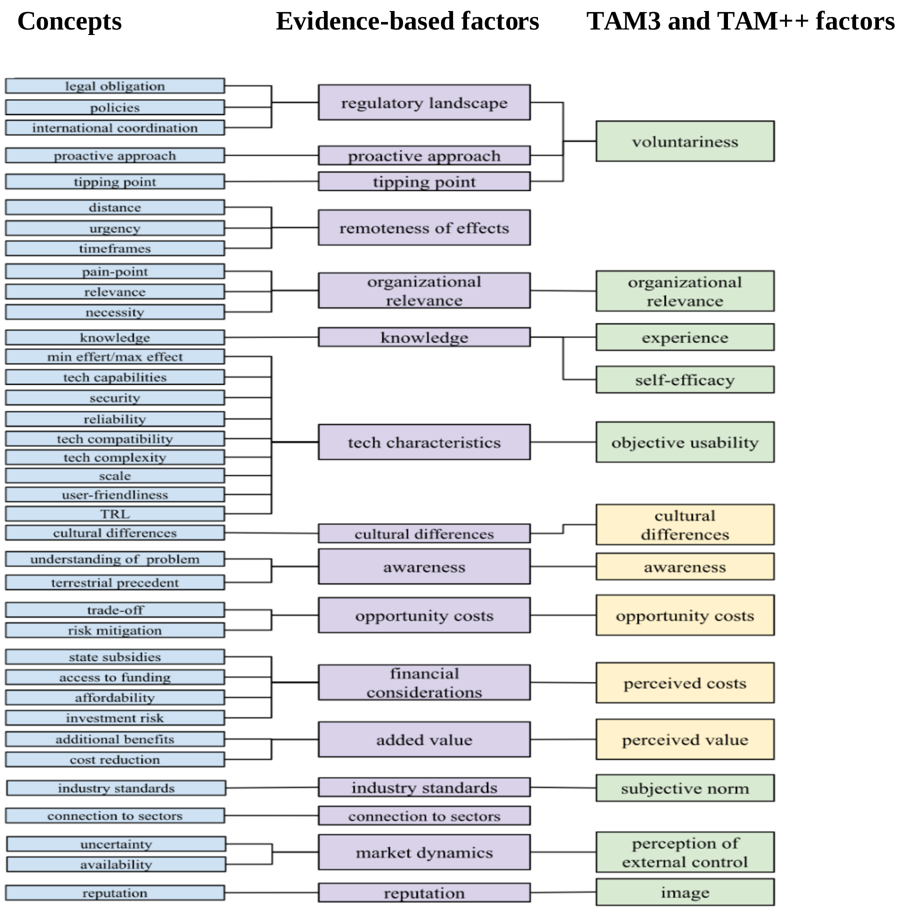

Figure 5. Main Results

Each level of the 'tree' corresponds to a stage in manual coding: first, in blue, are presented individual concepts; then, they are grouped into evidence-based factors in purple; finally, these factors are associated with a factor either from TAM3 (green) or TAM++ (yellow).

In order to trace the magnitudes and directions of relationships between the identified factors, I have conducted correlation analysis using the Kendall Tau method, which was chosen because it does not assume a normal distribution; is less sensitive to outliers compared to Spearman and Pearson, and is suitable for smaller datasets. The results are reported in the heatmap of Figure 6. Additionally, p-values were calculated to determine statistical significance. The standard thresholds of 5%, 1% and 0,1% were used. A table of coefficients with significance levels is reported in Table F of Appendix.

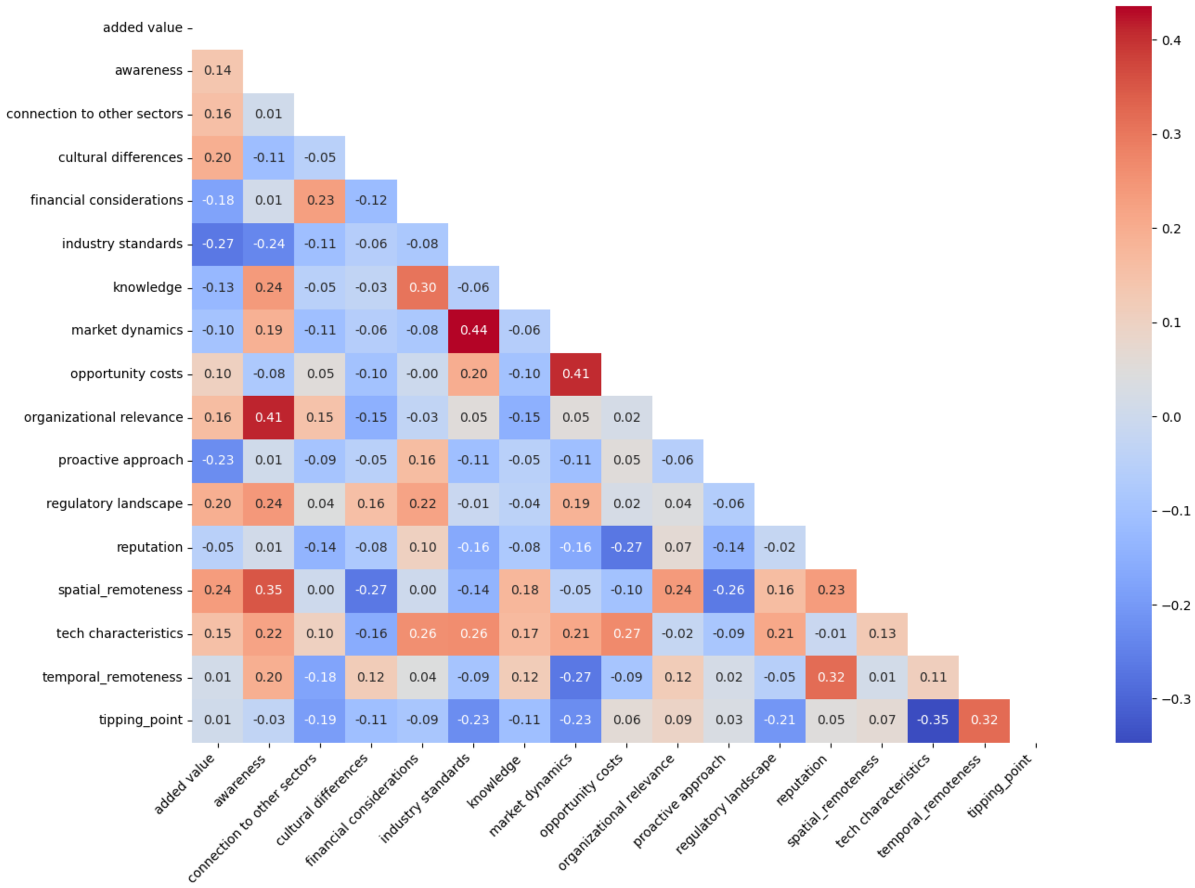

Figure 6. Factors Correlations Heatmap.

The figure reports Kendall Tau correlation coefficients of factors, where darker blue hues correspond to larger negative values and brighter orange hues correspond to larger positive values. Small values around 0 are colored in gray hues. The 'remoteness of effects' factor was decomposed into its spatial and temporal aspects.

There are several important insights that can be drawn from the correlation coefficients:

- 'Spatial remoteness' is positively correlated with 'awareness', and this correlation is statistically significant at the 5% level. This might indicate that the closer the effects of a problem are, the more likely the companies are to be aware of it; and the more the companies are aware of the problem, the closer they might perceive it. It is important to underscore that these factors are not equal, albeit correlated. As one of the interviewees (ID: 213) put it: *'People* *might be very well aware of what is happening somewhere far away, and still not care at the slightest [...] Awareness helps, but [...] you would rather care about a small problem close to you than a big problem somewhere far away'*.

- The factor of 'tipping point' is negatively correlated with the factor 'technological characteristics' (5% significance level), which may reflect the following relation: if the situation is grave enough to demand adoption of sustainable technologies, their exact technological capabilities would matter less as perceived by potential adopters.
- 'Organizational relevance' is positively correlated with 'awareness' (5% significance level), and the magnitude of this correlation is one of the highest (0,41), which means that perceived relevance of a technology for core business activities goes hand in hand with the level of awareness about the said technology.
- The positive correlation between 'opportunity costs' and 'market dynamics' (5% significance level) suggests that as the consideration of 'market dynamics' increases, the importance placed on 'opportunity costs' also tends to increase, which is understandable, because market dynamics, such as, availability of a technology and market uncertainty, influence the perception of the opportunity set (Miozzo, 2020). Moreover, 'market dynamics' is positively correlated with 'industry standards' which might indicate that as firms pay more attention to the changes and forces within the market, they also tend to adjust more to industry standards. To take it one step further, firms that are sensitive to market conditions may prioritize aligning with industry standards as a way to mitigate risks associated with market volatility and to capitalize on emerging opportunities effectively.

Out of the 16 factors derived from the empirical data, 3 were chosen to be studied in more detail: 'remoteness of effects' (refer to New Factor 'Remoteness of Effects'), 'voluntariness' (refer to 'Voluntariness' Factor and the Locus of Control Theory) and 'experience' (refer to 'Experience' Factor: Between-Group Variance).

3.1 New Factor: 'Remoteness of Effects'

The analysis of the empirical results provided an extension to TAM through an introduction of a new factor, namely, 'remoteness of effects'. **Remoteness of effects** refers to the perception of how distant the impacts of the problem that the technology aims to address are from the actor considering the adoption of the technology. This factor holds potential importance because of the observed imbalance in the existing research addressing it in the context of technology adoption and the collected evidence (refer to Table B in Appendix).

It was observed that interviewees mentioned two different aspects of 'remoteness of effects': spatial (the concept of 'distance') and temporal (the concepts of 'urgency' and 'timeframes'). Question 3 in Round 2 and Questions 3A and 3B in Round 3 allowed me to explore this factor with its two facets deeper. The answers of interviewees to the questions related to the new factor were coded as a matrix (Table 6), where different weights were assigned to replies depending on agreement or disagreement of experts with the notion of importance of the factor in question.

ID	Remoteness of effects		
	spatial	temporal	
201	-1	1	
202	1	1	
203	0,1	0,1	*indirect
204	0,1	0,1	*insignificant
205	-1	1	
206	1	1	
207	1	1	
208	1	1	
209	1	1	
210	0,1	0,1	*indirect
211	0,1	1	*insignificant
212	1	1	
213	1	1	
214	1	-1	
215	-1	1	
301	-1	0,1	*insignificant
302	-1	1	
303	1	1	
304	1	-1	
305	1	1	
	6,4	11,4	

Color codes

(red)	disagree
(green)	agree
(yellow)	neither agree, nor disagree

Table 6. Assessment of relevance and importance of the new factor 'remoteness of effects'

The table displays quantification of space experts' opinions on whether spatial and temporal remoteness matter in the context of sustainable space technologies' acceptance. If an expert disagrees, '-1' value is assigned, if they agree, '1' is assigned, if they consider the impact of the factor in question indirect or insignificant, then '0,10' is assigned.

As seen in the matrix above, space industry experts and academics supervising space projects, in the majority of cases, showed agreement with the significance of such a factor as remoteness of effects. A higher score of the temporal aspect compared to the score of the spatial aspect (11,4 against 6,4) suggests that actors knowledgeable in the space domain assign greater importance to the temporal remoteness of effects from sustainable space technologies as a potential hindrance to their market adoption.

3.2 'Voluntariness' Factor and the Locus of Control Theory

The majority of interviewed experts (89%) underscored the importance of legislative obligation in the context of sustainable space technology adoption, more than a third of respondents (37%) mentioned the likelihood of such technologies' adoption in the case when a tipping point is closing in, leaving companies little to no choice; while very few spoke about the proactive approach of company leaders driven by internal motivations (7%). This striking imbalance coupled with the importance of such a factor as 'voluntariness' highlighted by previous studies (Venkatesh & Davis, 2000; Venkatesh & Bala, 2008; Wu & Lederer, 2009; Abbasi et al., 2011), and the relation to it of the 'remoteness of effects' factor suggested by the interviewed experts, explain the decision to study perceived voluntariness of sustainable space technologies' adoption in more detail.

Perceived 'voluntariness' signifies the extent to which individuals or groups perceive adoption of a technology to be free from external pressure or mandatory requirements. Studies have shown that voluntariness can moderate the impact of perceived ease of use and perceived usefulness on behavioral intention, meaning that these relationships are stronger when technology use is voluntary compared to when it is mandatory (Wu & Lederer, 2009).

In the context of this study, the Locus of Control Theory was deemed relevant to explore deeper the factor of 'voluntariness' in the adapted TAM framework, because it can be categorized into two types: internal locus of control and external locus of control, which correspond to the 'proactive approach' and 'regulatory landscape' plus 'tipping point' concepts. 'Proactive approach' means that a company is willing to adopt a sustainable space technology, because it understands the importance of such measures, is willing to set an example to other players in the sector, or motivated by other internal drivers; while 'regulatory landscape' refers to the pressure of law, regulations, formal standards on companies; and 'tipping point' refers to a catastrophic threshold upon surpassing which the situation deteriorates so drastically, that the problem can no longer be ignored, forcing companies to take action.

The evidence suggests that 'Remoteness of effects', or, in this case better to say 'proximity of effects', can exert external pressure on the companies active in the space domain: *'Unfortunately, companies tend to be short-sighted when it comes to sustainability. Is there a grave problem right now or a grave problem looming right over me? No? Then I will continue doing business as usual.'* (ID: 2); *'The market will only be ready to adopt something when there is an absolutely pressing need, and this is not the case with sustainable space tech'* (ID: 25), '*Unfortunately, companies will not act unless they perceive a real danger. If there is so much space debris that the risk of collision is catastrophic, it would make economic sense to pay for sustainable solutions.*' (ID: 7). In other words, the closer in space and time the effects of the problem which a technology is designed to address are, the more companies would perceive that they have to adopt such a technology, consequently, the less they would perceive adoption as voluntary, which, in turn, would weaken the impact of perceived usefulness and perceived ease of use on the behavioral intention.

The integration of the Locus of Control Theory with the 'Voluntariness' factor of TAM with the links to the factors identified in this research, is depicted on Figure 7.

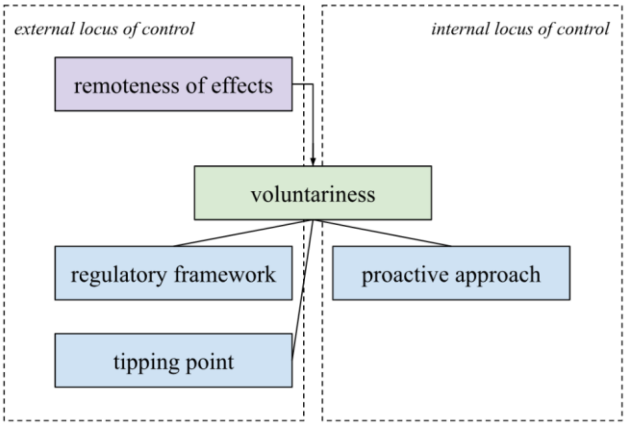

Figure 7. Two sides of 'Voluntariness'

The factors 'regulatory framework' and 'tipping point' identified through evidence analysis are attributed to the external locus of control; while 'proactive approach' is attributed to the internal locus of control. Perceived 'remoteness of effects' might decrease perception of voluntariness in the context of sustainable space technologies' private adoption.

The main conclusion, based on the conducted interviews, is that as of now, the companies active in the space domain predominantly have an external locus of control. This means that regulations, the threat of a tipping point (such as the Kessler effect) and, indirectly, spatial and temporal proximity of a problem, are likely to be much stronger drivers of sustainable space technologies' adoption by private companies than their proactive approach stemming from their internal values.

3.3 'Experience' Factor and the Between-group Variance

Having taken into consideration the theoretical sampling of interviewees in 3 groups, and the profound moderating role of such factor as 'experience' in the extended TAM model (Venkatesh & Davis, 2000; Abbasi et al., 2011), I asked myself a question: does experience influence the perception of factors shaping market acceptance of sustainable space technologies? And if yes, to what extent?

Summary statistics of the experts' background information is reported in Table 7.

	Years of experience in academia	**Years of experience in the space industry**	**Years of experience in other industries**
Observations	35	35	35
Mean	4.56	7.60	7.70
Standard deviation	5.87	8.98	8.78
Minimum	0.00	0.00	0.00
25% (percentile)	0.00	0.00	0.25
50% (percentile)	1.00	2.00	5.00
75% (percentile)	7.50	13.5	11.5
Maximum	21.00	32.00	35.00

Table 7. Three Samples of Interviewees: Summary Statistics

In order to answer this question, I first studied Kendall Tau correlation coefficients between background variables and factors (refer to Table 8). To determine statistical significance, p-values were calculated and thresholds of 5%, 1% and 0,1% were considered.

	academia	space	non-space	education
regulatory landscape	-0.10	0.44**	-0.29*	-0.14
knowledge	0.15	-0.03	-0.19	0.16
tipping point	-0.15	-0.22	0.33*	-0.12
proactive approach	0.14	-0.02	0.11	0.10
organizational relevance	-0.08	0.12	-0.15	-0.05
technical characteristics	-0.07	0.22	-0.13	-0.04
cultural differences	-0.16	0.21	-0.19	-0.16
awareness	0.07	0.13	-0.23	0.04
opportunity costs	-0.03	-0.07	0.26	-0.06
financial considerations	-0.07	0.19	0.06	-0.12
added value	0.01	0.16	-0.15	-0.16
industry standards	-0.10	0.27	-0.18	0.00
market dynamics	0.06	0.01	0.05	0.17
reputation	-0.07	0.03	-0.10	0.00
connection to other sectors	-0.22	0.08	0.10	-0.29
spatial remoteness	-0.06	0.04	-0.10	0.03
temporal remoteness	-0.14	-0.00	0.06	-0.25

Table 8. Background Variables and Factors Correlation Coefficients.

*The table reports Kendall Tau correlation coefficients; statistically significant values are denoted with *** at 0,1% level, ** at 1% level and * at 5% level.*

From these correlation coefficients, the following can be inferred:

- 'Regulatory landscape' is positively correlated with experience in the space sector (1% significance level), and negatively correlated with experience in other sectors (5% significance level), which implies that experts closely familiar with the space domain are more likely to highlight imposed regulations as an important factor of sustainable space technology adoption. This, in turn, supports the key conclusion of the previous paragraph that space companies predominantly have an external locus of control when it comes to sustainability measures, and would adopt sustainable technologies when sufficient pressure is exerted by governments, international organizations, and stakeholders in general. This assumption is supported by the negative correlation of experience in the space sector and the factor of 'proactive approach', however, this correlation is not statistically significant, therefore, its interpretation should be approached with caution.
- Years of experience in other sectors are positively correlated with the factor of 'tipping point' at the 5% significance level, which indicates that exposure to other domains than space might help experts recognize the influence of a looming catastrophic threshold on sustainable space technology market acceptance.

It is noteworthy that both ‘regulatory landscape’ and ‘tipping point’ are considered in this study as the ‘external locus of control’ side of the ‘voluntariness’ coin; and ‘proactive approach’ is attributed to the ‘internal locus of control’. Therefore, correlation of these factors with experts’ experience in industry suggests that, in the context of sustainable space technology adoption, there is a link between ‘experience’ and ‘voluntariness’.

Next, the data was grouped according to the interview round, in order to check whether there are significant differences in how experts from different backgrounds identify important factors of sustainable space technologies’ adoption. Key assumptions were checked before choosing an appropriate method: Shapiro-Wilk test for normality and Levene's test for homogeneity of variance showed (see Code Repository in Appendix). Given the results of these assumptions checks, Kruskal-Wallis test was chosen and applied to determine whether there are significant differences between the medians of the groups (interview rounds) for each factor. The results are reported in Table 9.

	H-statistic
regulatory landscape	7.78*
knowledge	6.00*
tipping point	4.17
proactive approach	2.60
organizational relevance	4.38
technical characteristics	4.70
cultural differences	1.33
awareness	8.63**
opportunity costs	3.48
financial considerations	1.89
added value	1.72
industry standards	2.01
market dynamics	0.73
reputation	2.08
connection to other sectors	0.94
spatial remoteness	0.34
temporal remoteness	0.59

Table 9. Kruskal-Wallis Test Results

*In addition to H-statistics, p-values were calculated for each of the factors, and statistically significant values were denoted with * at 5% significance level, ** at 1% significance level, and *** at 0,1% significance level.*

Higher H-statistic values indicate greater differences between the groups. Based on the p-values, it can be drawn that the majority of observed differences are likely due to chance, and only three factors’ medians vary significantly depending on the round: ‘regulatory landscape’, ‘knowledge’, ‘awareness’. To take it one step further, I conducted Dunn’s test, which provides pairwise comparisons between the interview rounds for each significant factor. The results are reported in Table 10.

		Round 1	Round 2	Round 3
regulatory landscape	**1**	1.00	0.02*	0.40
	2	0.02*	1.00	1.00
	3	0.40	1.00	1.00
knowledge	**1**	1.00	1.00	0.07
	2	1.00	1.00	0.07
	3	0.07	0.07	1.00
awareness	**1**	1.00	0.24	0.01*
	2	0.24	1.00	0.34
	3	0.01*	0.34	1.00

Table 10. Dunn's Test Results

*Statistically significant values according to p-values, are marked with * at 5% significance level, ** at 1% significance level, and *** at 0,1% significance level.*

As seen in Table 10, there is a significant difference in the 'regulatory landscape' scores between interview rounds 1 and 2, which suggests that there is a considerable gap in the perceptions of this factor by space and non-space industry experts.

The perception of knowledge does not seem to vary significantly from round to round, however, p-values for pairwise comparisons between Round 1 and Round 3, Round 2 and Round 3, are close to the threshold of 0.05, indicating a marginal difference. This might mean that the perceptions of 'knowledge' as a factor of sustainable space technology adoption of academics differs from the one of industry experts, regardless, whether the latter are from a space or non-space sector.

There is a significant difference in how academics knowledgeable in the space domain and industry experts working in the sectors other than space perceive awareness. Such a difference is not observed when non-space industry experts are compared to space industry experts, or when space industry experts are compared to academics.

Overall, experience seems to have limited impact on the set of factors that experts identify. Still, an important finding is that experience in the space sector and other domains seems to influence respondents' perception of voluntariness ('regulatory landscape', 'tipping point' and 'proactive approach').

3.4 Case Study: Commercialization Avenues for ODLI

In order to see how the updated theoretical framework can inform practice, I conducted a case study on a sustainable space technology, developed jointly by the EPFL Space Center (eSpace) and Computer Vision (CV) lab. A diverse team of EPFL researches works on a project titled 'Accurate Ground-Based and In-Orbit Tracking for Space Debris Capture', which includes:

- Improving the accuracy and comprehensiveness of databases that record orbital parameters and other characteristics of space debris using astronomical imaging and radar data.
- Developing advanced deep learning algorithms for estimating the 6D pose (position and orientation) of space debris, which is crucial for successful rendezvous and capture missions, such as ClearSpace-1 mission.
- Creating domain generalization techniques to ensure that algorithms trained on Earth can reliably function in space, accounting for different conditions without the need for extensive re-training.
- Designing and training compact neural networks that can run efficiently on the limited computational resources available on capture satellites, ensuring real-time processing capabilities.

This project was chosen for a case study for several reasons:

- It addresses one of the most pressing problems in the area of space sustainability - orbital pollution, more specifically, in LEO - the most crowded orbit as of now (Osoro et al., 2024).
- It is a 'BRIDGE' project designed to conduct applied research in the academic domain with a vision of commercializing the results and enriching the market with a novel technology, therefore, it is not only a matter of curiosity to explore the technology's potential market acceptance, but also one of the primary goals of the project.
- The project supports a collaborative effort between academia (EPFL), industry (ClearSpace), and government agencies (ESA), making it an excellent example of multi-stakeholder engagement and cooperation.
- The technology at hand is a novel technology, which involves state-of-the-art machine learning techniques and their innovative usage for pose estimation and tracking, along with the development of compact neural networks.
- The technology is currently at an early stage of development, which is the perfect time to assess how it is perceived by potential adopters (Davis, 1989).

Given the broad scope of the project, one specific previewed outcome of the researchers' work was chosen as the focus the case study - ODLI, which stands for 'Open Debris Lightcurve Inventory' and refers to a repository of space object observations extracted from raw observatory images using cutting-edge computer vision algorithms. The methodology behind ODLI is also included in the scope of the case study.

Every interview contained a question about potential commercialization avenues for ODLI, however, not every respondent offered his or her opinion on the matter, oftentimes referring to their lack of experience with this particular type of technologies (40% of non-space experts abstained from offering their opinion, 13% of space experts did not give any suggestions and none of the academics skipped this question). The answers to the question related to ODLI's commercialization avenues were coded using the same methodology as the answers to other questions (refer to 'Qualitative Analysis: Manual Coding'). The results are reported in Table G in Appendix.

Just as with the main theoretical framework, when preliminary insights were extracted from the interviews during Round 1 content analysis, an initial commercialization scenario was formed and tested in later rounds by introducing a more specific subquestion. This initial option was XaaS, or Everything-as-a-Service, suggesting that EPFL retains the ownership of the technology and provides temporary access to the repository for a certain fee. In this scenario, the technology is commercialized only partially, which is likely the most realistic option, because many experts underscored that full commercialization of such a repository would be from somewhat improbable to outright impossible: *'It would be very hard to find customers'* (ID: 8), *'Operating profitably in such a niche market is tough'* (ID: 30), *'I do not see why companies would voluntarily pay for it'* (ID: 28), *'It's a very specific use case: there's only a handful of companies that perhaps would want to pay for that information and they would just look at a handful of objects'* (ID: 214), etc.

To explore XaaS as a potential commercialization avenue further, I introduced a subquestion to the interviews of Rounds 2 and 3, asking respondents' take on this model for ODLI. 45% of experts knowledgeable in the space domain suggested to modify the strategy by adopting a hybrid approach (refer to Table H in the Appendix). One expert elaborated: *'Consider a hybrid approach with an open-source raw database, allowing contributions from other entities to enhance its value. Sell value-added services on top and include future projections of space debris movement and evolution.'* (ID: 205). Another expert suggested the following: *'Offer subscriptions (commercial side) in a time-sensitive manner, meaning that any update within X hours will be accessible. But then this update will be delayed by several days before it is open-sourced and reaches the general public. You basically have a premium access and premium knowledge on what is happening, and for that you would pay a premium price.'*

(ID: 206). Given the high support from several experts for this approach, it was decided to retain it as a primary recommendation for commercialization of ODLI. Next, the chosen scenario was elaborated in more detail.

Open-Source Repository

Objectives:

- Provide researchers with high quality photometry of space debris for further analysis, allow them to contribute to the repository with their own data, and enhance the general understanding of the orbital debris situation.
- Conduct initial validation by collecting and implementing the feedback.

Implementation:

- ➢ Limited Duration Access: open-source the basic dataset for six months to a year.
- ➢ Data Scope: Include data on well-known objects, with information on orbital parameters, size, CAD models, and reflectivity.
- ➢ Community Engagement: raise awareness about this tool among various academic institutions, research groups, and startups to use, test, and contribute to the dataset. Impose obligatory quality checks, which every contribution needs to pass, to ensure uniformity of methods and data.
- ➢ Feedback Loop: establish a system for users to provide feedback, report errors, and suggest improvements. Implement this feedback, where necessary to improve the repository and prepare it for commercial use.

Commercial Repository

Objectives:

- To provide detailed, high-value data and services for commercial and government clients.
- To partially commercialize ODLI and receive additional cash to enable further work on the tool, methodology and repository.

Implementation:

- ➢ Enhanced data: offer a more comprehensive dataset with detailed information on additional objects.

- ➢ Supplementary materials: provide manuals both as detailed documents and video tutorials on how to navigate and use the repository.
- ➢ Value-added services: advanced analytics, training sessions, processing of customer's data using the developed methodology.

Monetization:

- ★ A low-cost subscription model for continued access to the enhanced dataset, with tiered pricing based on the level of detail and services required.
- ★ Consulting services to help companies, space agencies and governments interpret the data in the repository, process their own data, develop risk mitigation strategies, etc.
- ★ Training sessions and support to help users effectively utilize the dataset and tools.

Target Customers:

- ➔ ADR companies - to identify possible targets for removal from the orbit (further observations would still be required, but ODLI can provide a good starting point).
- ➔ Satellite operators - to improve their knowledge on space debris density clouds, and potentially to integrate the methodology of space debris characterization and positioning on board of their satellites.
- ➔ Insurance companies - to provide risk quantification data that helps to assess the risk of satellite operations.
- ➔ Governtal space agencies - to better estimate the risks of their missions and to develop more informed strategies for dealing with increasing orbital pollution.

By implementing this hybrid approach, ODLI can serve both academic and commercial purposes, while providing an additional source of income for the research team behind it. The open-source component fosters collaboration and community validation, while the commercial component provides advanced services and generates revenue for the research team.

The set of recommendation on ODLI's commercialization strategy would have been incomplete without incorporation of several other insights offered by the interviewed experts:

- **Technical advice** included suggestion to use synthetic data for training the model and real data for its validation (ID:2); ensuring compatibility with other systems, which might use the methodology and data as a basis for further development (e.g., dynamic map of skies) or operations (ID: 304); and providing transparency (ID: 209).

- **User-friendliness** was highlighted by several experts, who pointed out that commercial actors would favor highly processed data (31), ready solutions and detailed answers to their questions (209). They would offer to pay for interpretable results and would require an intuitive interface (2).
- When formulating **value proposition**, the following features and capabilities should be highlighted:
    - capability to detect relatively small debris: ~10 cm in LEO, ~5 cm in GEO (ID: 203);
    - potential to enhance knowledge or predict the viability and operational duration of systems (ID: 207);
    - potential for integration of the developed algorithms in satellites, which would allow for better autonomousness in collision avoidance (ID: 31);
    - information on density clouds (ID: 215).
- **Affordability** was mentioned, and the experts underscoring these aspects, said that a commercialization strategy should not be an attempt to pay off all the costs (ID: 215), but rather set a reasonable low price to partially offset the costs, but not discourage commercial actors from adopting sustainable solutions (IDs: 208, 204).
- **Scale** appeared as one of the key considerations, as experts highlighted the need for a comprehensive and systematic cover of skies for the repository to have sufficient value on the market.
- Scale must not be confused with the next recommendation **- scalability**, which implies the potential of the repository to serve as a basis for other tools, such as a dynamic map of skies for space traffic management (ID: 208); or the potential of the methodology to be applied in other contexts (ID: 210).
- **Marketing strategies**, according to Interviewee 303, should be centered upon direct communication with target companies.

Some experts raised ethical concerns highlighting the need for universal accessibility to such data. According to them, necessity to pay creates barriers on the way to achieving sustainability of Earth's orbit utilization, and such repositories, methodology and services must be open-source for everyone: governmental and commercial actors alike (IDs: 205, 211, 301). Another expert raised concerns about security aspects, arguing that such a repository has little value if it is not comprehensive, while it cannot be comprehensive in practice, due to state security, military objects in space and different jurisdictions in spacefaring nations, prioritizing their national interests (ID: 7). Last but not least, limited demand was mentioned among key concerts by several experts, meaning that the use-cases for such a technology are very few, the market is niche and there is but a handful of potential customers on the market, which would hinder technology's commercialization (IDs: 8, 30, 214).

Overall, it has been acknowledged by numerous experts within and outside of the space domain, in academia and industry, that there is a limited commercial potential for ODLI.

3.5 Validation with Key Stakeholders

When the research took shape and the results were finalized, a discussion with key stakeholders was organized. Key stakeholders chosen for the results validation were the researchers working at eSpace on the accurate ground-based and in-orbit space debris characterization and positioning tool. The choice was motivated by the fact that the study was set at eSpace to begin with, and the research team in question provided the case study for it. Moreover, they will be the first ones to try to put the findings of this thesis to practice through the ODLI case.

In this focus group discussion, the first step from my side was to ensure that stakeholders understand the conceptual domain of the research, the methods and the outcomes. The team had access to the text of the research, and the key points were covered in the beginning of the meeting. This was followed by a session of questions and answers to resolve all doubts and clear all uncertainties.

In the spirit of this research, which followed an inductive approach to theory formulation and semi-structured format of interviews for data collection; the focus group discussion revolved around 4 *open questions* with a possibility of sharing insights without the confines of multiple-choice questions. I asked the stakeholders to provide the following inputs:

1. *Would you agree with the introduction of the 'remoteness of effects' factor to the TAM model, with its spatial and temporal facets?*
2. *Would you agree that space companies have predominantly external locus of control when it comes to sustainable practices?*
3. *Would you agree that a decision-maker's experience has a very limited impact on the factors they perceive as important?*
4. *Do you consider the hybrid approach a viable solution for ODLI?*

Overall, the stakeholders expressed strong support for the introduction of the 'remoteness of effects' factor to TAM. They were convinced at how I came to identify it and that it could enrich our understanding of sustainable space technologies' market acceptance. One participant emphasized that the 'remoteness of effect' is indeed a crucial factor, not only for space sustainability but for many other kinds of 'sustainabilities.'

Doubts were raised about the suggested relations of the newly introduced factor to other factors. The participants of the focus group discussion recognized the significance of machine learning factorization and categorization, however, they advised to exercise caution when speaking about the direction of the suggested impacts.

As for the ‘voluntariness’ factor, it was unanimously agreed that the external locus of control prevails in space companies when it comes to sustainable behaviors. It was highlighted that a critical point (Kessler syndrome) and efficient policies are likely to move the industry in the direction of sustainability, and little hope can be placed on reliance on companies’ internal motivation. However, it was noted that this might slowly be changing towards a more proactive approach by space actors.

The ‘experience’ factor was characterized by the stakeholders as distinct from the other factors, for it is based on quantitative survey responses, while the analysis of other factors was built on a qualitative foundation. The focus group discussion participants found the statistical analysis convincing, and agreed that the ‘experience’ factor did indeed seem to have a low correlation to many of the factors. Yet, they considered this finding counterintuitive as they would have expected the opposite.

The case study spurred an active discussion. An important validation came from the team’s experience at ‘Venturelab’, where Dr. Andrew Price presented a full startup case for ODLI to the jury of investors and collected their feedback. The investors were not convinced that such a venture could sustain itself, therefore, the path of a spinoff startup was deemed a dead-end. Academics engaged in the project agree that the niche market of ODLI makes it difficult to compete with large companies in Space Situational Awareness (SSA), suggesting that the true potential of ODLI lies mostly in supporting academic research and only partially in supporting commercial endeavors. Later, Dr. Price presented a hybrid business model to the BRIDGE committee, and the project was cleared to continue, which signals that this is the commercialization avenue worth exploring. Overall, the team thinks that the model identified in this research is the most logical and feasible one.

To conclude, the focus group discussion with eSpace stakeholders validated key aspects of the research.

4. Discussion: What Does This Research Bring and Who Cares About It?

Against a background of sparse prior research, this thesis has resulted in several interesting findings, which hold potential both for management science and practical implications. In a nutshell, this study suggests that sustainable technologies offering immediate and localized benefits are more likely to be perceived as useful by private space companies, and, therefore, to gain a widespread commercial adoption. The temporal closeness has more weight than the spatial one, as perceived by key actors in the space industry. Additionally, it was concluded that space companies tend to have external locus of control, meaning that they are likely to adopt sustainable technologies out of necessity rather than on their own initiative driven by responsible approach.

4.1 Interpretation and Contributions

In *Chapter 1 Literature Review*, after systemizing the relevant accumulated knowledge on the commercial space sector and space sustainability, I introduced a definition of 'sustainable space technologies' to clarify this key concept for this research and to contribute to the broader discourse on space sustainability by reducing ambiguity in the understanding of this term. In the same chapter, I described the B2B branch of TAM and provided a schema for better visual representation.

Next Chapter, *Methodology*, explained how qualitative and quantitative approaches to research were combined in an iterative process. Theoretical sampling is of particular interest here: I implemented an approach, where I first seek to capture the width of insights through industry-agnostic interviews, then complement it with the depth of industry-specific experts' knowledge, and finally, contrast it with perceptions of academics. It must be recognized that I belong to one of the first generations of researchers to have AI tools at their disposal; therefore, the way an LLM text analytics approach was integrated into the research, this approach can be seen as both innovative and transformative. This method allowed me to uncover patterns and themes that might have been overlooked through traditional means. By leveraging these advanced AI capabilities, the research not only gained precision and depth but also set a precedent for future studies in the field.

Chapter 3 'Results' elaborated on the key findings of the research. The main ***theoretical contribution*** of this study is an extension of the TAM through introduction of a new factor: 'remoteness of effects' with its two facets - spatial and temporal remoteness. This study suggests that the closer the effects of the problem that a sustainable space technology is designed to address are, in terms of distance and time, the more private companies in the corresponding domain will perceive it as useful, and the more likely they will be to adopt it. In the given context, the two sides of the 'remoteness' coin do not appear to be equal, which suggests that the existing management science literature needs to better reflect the difference between temporal and spatial myopia of key industry players in the context of technology acceptance.

Empirical evidence suggests that the perception of how far away the effects are, influences perceived usefulness of a sustainable space technology directly, and machine analysis revealed a potential link of spatial remoteness with 'organization relevance', which represents an indirect impact (refer to the paragraph 'Machine Text Analytics'). It must be noted that the direction of the influence was not inferred directly through machine analysis, and is presented here as the author's interpretation. Additionally, this research proposes a link between the perception of remoteness of effects and perception of voluntariness, suggesting that the closer (in terms of time or distance) the effects of the problem are, the more a company would feel like it *has* to adopt a technology for tackling the problem.

In addition to the introduction of the new factor, this research takes a closer look at the factor of 'voluntariness'. This integration of the Locus of Control Theory with evidence-based findings suggests that companies managed by people with a high internal locus of control or having autonomy as one of their key corporate values, are likely to view voluntary adoption of technology more positively. They may feel more responsible for learning and using new technology, leading to higher intrinsic motivation to adopt it. In the context of space sustainability, it would mean that these companies are more likely to perceive sustainable space technologies as useful and easy to use because they feel confident in their ability to influence outcomes through their actions, and therefore, could be more eagerly participating in sustainable transition of the sector.

Conversely, those with a high external locus of control may feel that their technology usage is influenced by external pressures, even in voluntary contexts. Such companies and their management might perceive the adoption of sustainable space technologies merely as compliance with legal norms, perceived organizational expectations and perceived urgency, closeness of the problem. Moreover, they might not invest as much effort into understanding and using the technology, leading to lower perceived ease of use and usefulness, and ultimately, suboptimal performance of the technology.

A closer look at 'voluntariness' and 'experience' revealed that space companies seem to have a predominantly external locus of control, which means that the companies active in the space domain are unlikely to exhibit proactive approach when it comes to sustainable transitions, and would rather adopt relevant technologies out of necessity, brought either my regulations or a threat of an irreversible large-scale problem. This finding has important implications for policy-makers, suggesting that a stricter and more elaborate regulatory framework needs to be introduced on a global level, and the dangers of space unsustainability need to be quantified and communicated better.

Figure 3b from the literature review was updated to represent the suggested contributions of this study to TAM as depicted on Figure 8.

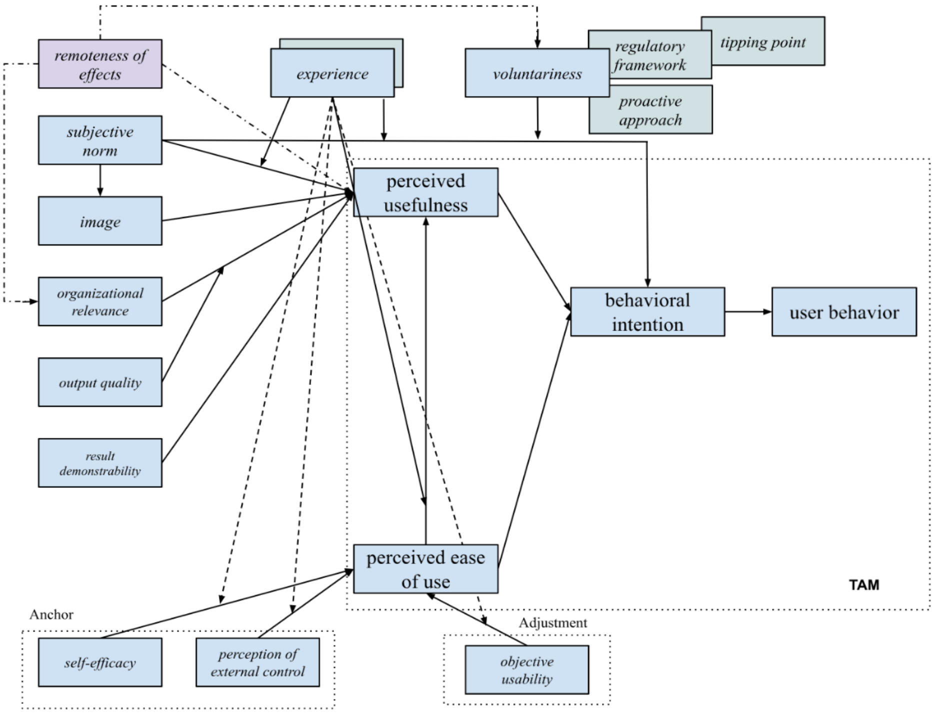

Figure 8. Extended TAM

The Figure presents the focus and main theoretical contributions of this study in terms of TAM factors. In purple rectangle is depicted a suggested extension to TAM: a new factor 'remoteness of effects'. Outgoing arrows represent suggested links that this factor might have with other factors of the model. Green rectangles behind 'experience' and 'voluntariness' show that these two factors, albeit not new, were studied more in depth in this thesis.

This study's theoretical contribution might extend to the opportunity recognition theories, for example, shedding the light on CXOs' myopia, when it comes to recognizing the effects from grasping a certain business opportunity, which are far away in terms of space and/or time, might enrich the studies on the opportunity landscape perceptions by entrepreneurs (Gruber et al., 2008; Gaglio et al., 2001).

A revised Technology Acceptance Model, tailored for the sustainable space technologies case, offers a meaningful contribution to the academic discourse around space sustainability and its legal, business and management implications (Iliopoulos & Esteban, 2020).

Apart from theoretical contribution, this research holds yet untapped potential for practical implementations. I see the main ***potential contribution to practice*** in aiding policy-makers in developing more efficient policies to incentivize sustainable technologies adoption in the commercial space sector through better understanding of the factors that shape market acceptance of such technologies as perceived by key industry and academic players. Most generally, my findings indicate that policy-makers should act on several key areas:

1. Statistically significant positive correlation between such factors as 'awareness' and the spatial dimension of 'remoteness of effects' suggests that the negative effect of spatial myopia of companies with regards to sustainable space technologies might be, at least to a certain extent, offset by enhancing market awareness and understanding of sustainable space technologies. This can be done by promoting educational initiatives and disseminating information about their long-term benefits. More specifically, this can be achieved through targeted campaigns and collaboration with industry leaders and academic institutions to create a more informed stakeholder base.
2. The implementation of supportive regulatory frameworks is crucial. The importance of the 'voluntariness' factor, specifically, its 'regulatory landscape' ingredient, has been highlighted by the majority of interviewed experts, which is a strong call for policies to be designed in a manner that encourages voluntary adoption while also including mandatory regulations where necessary. For instance, introducing clear international standards and guidelines can ensure consistent compliance and incentivize companies to adopt sustainable practices to avoid penalties.
3. Additionally, the findings of this research would be relevant for those developing sustainable space technologies. Given that 'remoteness of effects' impacts perceived usefulness of a technology in the eyes of private companies, technology developers should consider addressing commercial actors if the effects from their technology are more locally concentrated and immediate, while governmental actors can be their potential customers if the effects are global and more long-term. This strategy has the potential to improve the chances of successful technology adoption.

The results of this research are applicable to cases, like ODLI. The team working on the project needed to identify commercialization avenues for their technology, its potential adopters. As the famous saying goes: 'a well formulated question contains half of the answer'. My key recommendation to the team, based on the research at hand, is to ask themselves the following questions:

1. *Are the effects from implementation of this technology spatially diluted/spatially remote or locally concentrated?*
2. *Are the effects from implementation of this technology (almost) immediate or long-term?*

Higher importance should be placed on the second question. If the answer is that the effects of the technology are locally concentrated and almost immediately perceptible, then the technology has higher chances to be seen as useful and to be adopted by private companies. Otherwise, developers of the technology might consider focusing on governments and governmental agencies, as well as research institutes as potential customers, and follow the path of partial commercialization (e.g., XaaS model, subscriptions model, free demo version and added-value paid services on top).

To sum up, this study advances theoretical understanding and offers practical guidelines to boost the adoption of sustainable space technologies, contributing to the broader discourse on space sustainability.

4.2. Limitations and Opportunities for Future Research

Before concluding, some limitations of the research at hand should be carefully noted.

First, the reliance on qualitative interviews as the primary data source introduces potential biases and subjectivity in the findings. The sample of interviewees is relatively small (35), and all of the interviewed industry experts had at least some connection to EPFL, therefore their opinions and perceptions might not be representative of the entire industry. In future research, expanding the sample size and including a more diverse range of industry players and academics from various geographical regions could enhance the generalizability of the findings.

Second, even though I tried to minimize subjectivity of the results by combining manual and machine methods of text analytics, both have their own limitations. Anonymization of the responses reduces replicability and robustness of the study, yet, is justified by the intention to protect interviewees' identities. Manual coding is influenced by the researcher's personal interpretation and perspective. Different researchers may code the same data differently, leading to variability in results. Machine text analytics, although considered to be less subjective, also has limitations. The GPT-4 model, although advanced, produced repetitive concepts necessitating significant dimensionality reduction. This process, involving tokenization, stopword removal, lemmatization, TF-IDF vectorization, and UMAP for dimensionality reduction, while thorough, may still result in the loss of nuanced data. Moreover, the clustering using HDBSCAN, despite its effectiveness, might not capture all subtle interconnections between themes.

Third, all the data collected are hypothetical in nature, meaning that the experts talked about the factors that they consider as important when it comes to technology adoption, and I did not compare it to actual cases of sustainable space technology adoption, due to the lack of open and detailed information on such cases and strict timeframes for a master thesis completion. Therefore, the introduction of the new factor 'remoteness of effects' to TAM, as well as my findings regarding the links between this and other factors, are only suggestions. For 'remoteness of effects' to be fully and rightfully integrated into the model, a longitudinal study needs to be conducted to accompany concrete cases of sustainable space technologies' adoption from the early stages of their development to their full-scale market adoption. Such a study could also assign weights to spatial and temporal dimensions of the said factor. This constitutes an important avenue for future research; however, I recognize that at the moment there might not be enough cases of successful sustainable space technologies commercialization to constitute a pool of examples that is big enough to yield robust results.

Another limitation of the research at hand concerns the impact of the 'experience' factor. The background questions about experts' experience concerned their years of work in the space sector, other sectors (without a breakdown of a specific number of years worked in each non-space domain), years of work in academia, their level of education. Undoubtedly, there are many more parameters in 'experience' that might impact experts' perceptions, which were not accounted for, for example, their country of origin and the countries where they worked, their major in a degree, their age, their stance on sustainable transition in general, and many others. The findings that 'experience has a limited impact on the perception of sustainable space technologies' market acceptance' is therefore restricted to the specific parameters asked for in the questionnaire. In further studies building on this research, conducting a more detailed questionnaire could reveal more detailed insights on how experience may change perception of sustainable space technologies' market acceptance.

As for the 'voluntariness' factor, the analysis lacks assessment of the loci of control of respondents, which could be compared to which factors they assign most importance to, and, therefore, shed some light on how exactly decision-makers' locus of control influences their perceptions when it comes to sustainable space technology adoption.

Then, I did not differentiate by a type of sustainable space technology, such as software or hardware, technology related to ground segment, launch segment or space segment, etc. This lack of differentiation could oversimplify the factors influencing adoption. By not distinguishing categories of technologies, the study potentially overlooks specific barriers and facilitators relevant to each type of technology, impacting the applicability of the findings. If future researchers decide to address this limitation, understanding how perceptions and adoption factors vary across these categories can provide more nuanced insights and targeted recommendations.

I believe the findings of this research could be relevant not only to the specific case of sustainable space technologies, but to the adoption of sustainable technologies in general. Spatial and temporal remoteness might impact adoption of any sustainable technology: to please its stakeholders, a company might opt for adopting a technology that has a more locally concentrated and immediate effect. For instance, water filters that prevent polluting a river in the region where the main plant of a company is located might be preferred over a technology that cleans up the oceans from rubbish, even if this company's waste does end up in the ocean too. Another example to consider is a food producer, which, to check the 'sustainability' box, might opt for energy-saving lighting in its retail stores rather than soil regeneration through agroforestry, which might take decades to show tangible results, Voluntariness, too, is worth studying deeper in the general context of sustainable technologies, because 'regulatory landscape', 'tipping point' and 'proactive approach' might be highly relevant for all sectors undergoing (or needing) sustainable transition.

Another interesting angle for future research might be studying how the newly outlined factor impacts investment propensity. Some researchers have already explored the impact of extended timeframes on Venture Capital investments in Cleantech startups (Cumming, Henriques & Sadorsky, 2016), however, the studies on how spatially remote or spatially diluted positive effects impact investment propensity in sustainable technologies, specifically, sustainable space technologies, remain scant.

Future research could also explore the impact of specific regulatory frameworks and policies on the adoption of sustainable space technologies, and sustainable technologies in general, by examining how different legal environments influence industry behavior, and how the weights of other factors change depending on the regulatory landscape.

Investigating the role of public-private partnerships, such as university-company collaborations, are of potential interest in the context of sustainable space technologies. Examples such as ODLI can be investigated, and lessons learnt from such collaborations could provide valuable insights to policy-makers.

By addressing these areas, the findings of the research at hand can be used as seeds to grow new helpful insights from, and facilitate sustainable transition in the space sector and beyond.

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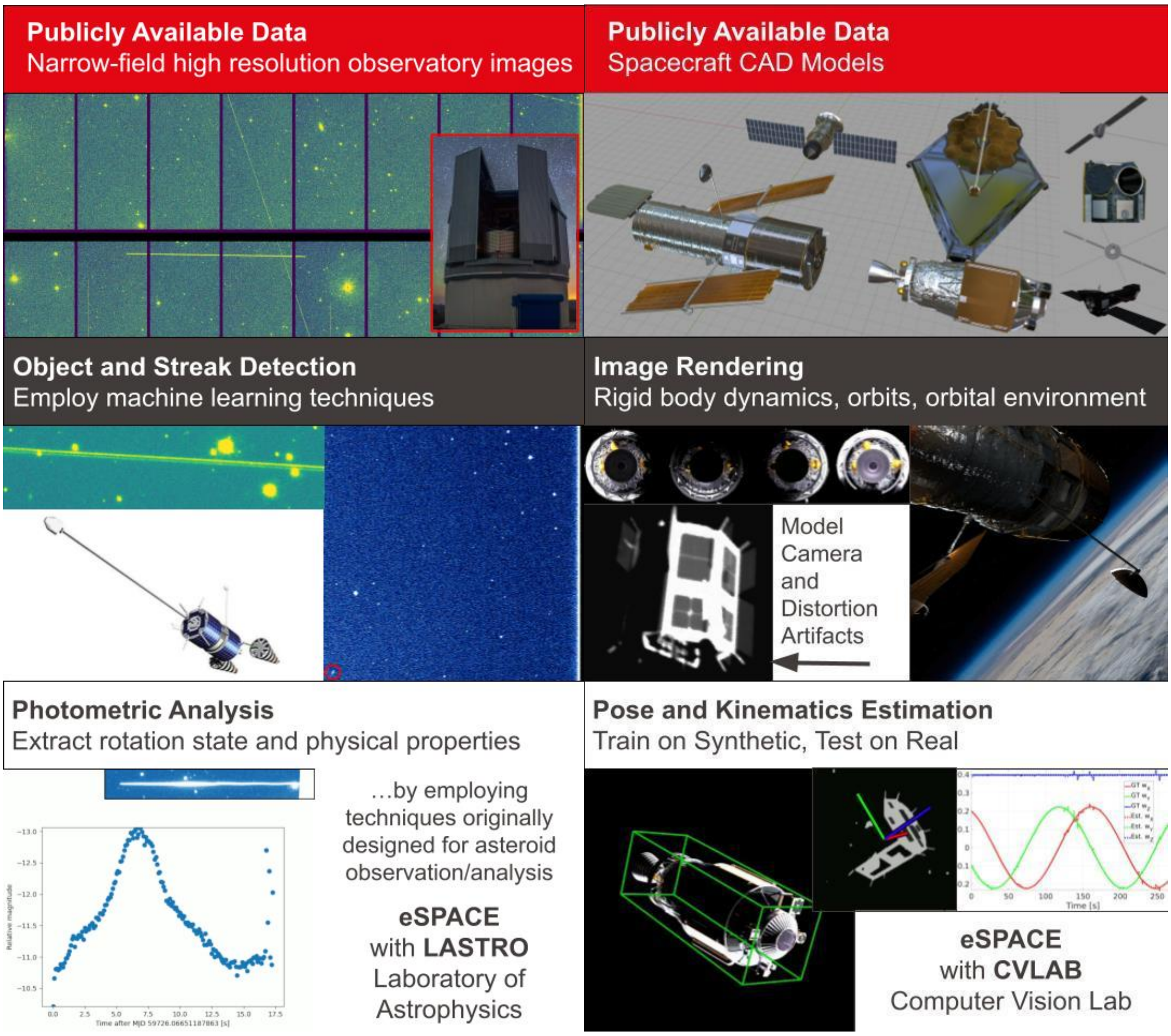
Appendix

Figure A. ODLI Presentation



Credit: the visual materials were prepared by Dr. Andrew Price

Questionnaire.

The questionnaire was printed and handed out to the first-round interviewees during the EPFL Engineering Industry Day.

Number: ____________________ Date: ____________________

Questionnaire

Please be assured that all information provided in this questionnaire will be handled anonymously. Your responses will be aggregated with those of other participants, and no individual will be identified or quoted in any reports or publications resulting from this research.

Your privacy and confidentiality are of utmost importance. If you have any concerns or questions about the handling of your data, please do not hesitate to contact me at angelina.frolova@epfl.ch.

1. Years of experience in academia:

2. Years of experience in industry, space sector:

3. Years of experience in industry, other sectors:

4. Field of work (e. g., IT, pharmaceuticals, architecture, etc.)

5. Level of education:

   a) High school diploma; b) Bachelor; c) Master; d) PhD

6. How familiar are you with space technologies?

   0 - completely unaware — 10 - expert

Table A. Detailed Data Preprocessing Techniques

MANUAL DATA PREPROCESSING TECHNIQUES	
Irrelevant information removal	Chitchat unrelated to the topic of the interview was expunged.
Correction of grammatical, lexical mistakes	Merriam-Webster Dictionary of American English (2022) was used as a standard.
Terminology standardization	In their speech, people might use synonyms while referring to the same concept of phenomenon. Therefore, synonymical structures were standardized (e. g., *'space sector'* = *'space domain'*).
Repetition elimination	In oral speech, repetition is common, however, it can introduce a bias in text analytics, therefore all cases of unnecessary repetitions were removed from interview transcripts (e. g., *'It is important, it is very, very important'* -> *'It is very important'*).
MACHINE DATA PREPROCESSING TECHNIQUES	
Stopwords removal	Stopwords are filling words, auxiliary verbs and other parts of speech, which occur in texts quite often, but do not bear any semantic significance. Examples of such words in English are 'the', 'is', 'but'.
Tokenization	Tokenization is the process of breaking down text into individual units called tokens, such as words or phrases. In this study the texts were split text into words, using spaces and punctuation as delimiters.
Lowercasing	In order for an algorithm not to consider the same words written with a capital letter and a lower case letter as two different tokens, all texts were lowercased.
Lemmatization	Lemmatization reduces words to their base or dictionary form, considering the context (e.g., *'better'* -> *'good'*, *'doing'* -> *'do'*). Lemmatization was chosen over stemming, because, unlike the latter, it allows to obtain the root of irregular words as well as the regular ones.
Contractions expanding	Contracted words were turned back into their full forms (e.g., *'don't'* - *'do not'*).
Text Normalization	The process involves standardizing date formats and normalizing whitespace.

Figure B. Schema of the Data Handling Process

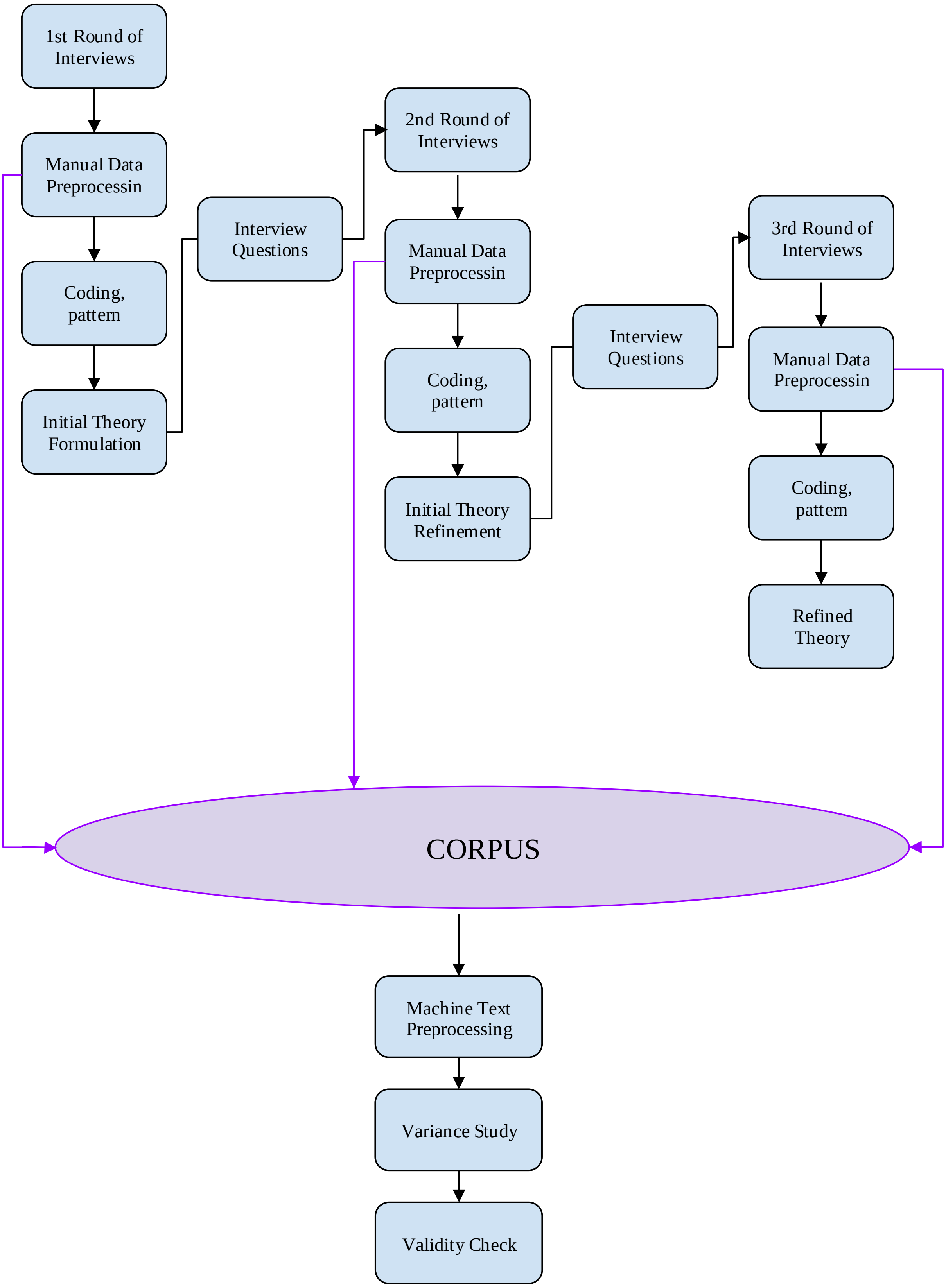


Table Ba. Concepts Matrix (Round 1, Part 1)

Concepts	Expert ID														
	1	2	3	6	7	8	23	24	25	26	27	28	29	30	31
distance															
min effort/ max results															
pain-point															
uncertainty															
trade-off															
user-friendliness															
industry standards															
cost reduction															
legal obligation															
tipping point															
urgency															
timeframes															
technological complexity															
technological capabilities															
reputation															
security															
policies															
connection to other sectors															
necessity															
risk mitigation															

Table Bb. Concepts Matrix (Round 1, Part 2)

Concepts	Expert ID														
	1	2	3	6	7	8	23	24	25	26	27	28	29	30	31
affordability															
reliability															
relevance															
proactive approach															
international coordination															
understanding of the problem															
terrestrial precedent															
investment risks															
access to funding															
scale															
additional benefits															
availability															
cultural differences															
technological compatibility															
TRL															
Knowledge															

Table Bc. Concepts Matrix (Round 2, Part 1)

Concepts	Expert ID														
	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215
distance		■										■			
min effort/ max results							■					■			
pain-point															
uncertainty										■					
trade-off							■			■					
user-friendliness							■		■			■			■
industry standards		■								■					■
cost reduction							■					■		■	
legal obligation	■	■	■	■	■		■	■		■	■		■	■	
tipping point											■	■			
urgency													■		
timeframes	■						■					■			
technological complexity	■						■								■
technological capabilities			■	■		■		■	■						
reputation						■		■			■		■		
security			■				■			■					
policies	■	■		■		■									
connection to other sectors			■						■						
necessity												■	■		
risk mitigation			■												

Table Bd. Concepts Matrix (Round 2, Part 2)

Concepts	Expert ID														
	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215
affordability															
reliability															
relevance															
proactive approach															
international coordination															
understanding of the problem															
terrestrial precedent															
investment risks															
access to funding															
scale															
additional benefits															
availability															
cultural differences															
technological compatibility															
TRL															
Knowledge															

Table Be. Concepts Matrix (Round 3)

Concepts	Expert ID				
	301	302	303	304	305
distance					
min effort/ max results					
pain-point					
uncertainty					
trade-off					
user-friendliness					
industry standards					
cost reduction					
legal obligation	■			■	■
tipping point					■
urgency					
timeframes					■
technological complexity					
technological capabilities					
reputation					
security			■		
policies		■	■		
connection to other sectors					
necessity	■	■			■
risk mitigation					
affordability			■		
reliability					
relevance				■	
proactive approach		■			
international coordination				■	■
understanding of the problem			■	■	■
terrestrial precedent		■			
investment risks					
access to funding			■		
scale					
additional benefits	■				■
availability					
cultural differences					
technological compatibility				■	
TRL			■		
Knowledge			■		

Table C. Concepts, factors and explanations

Category - Factor	Concepts	Explanation
regulatory landscape	legal obligation	A system of national and international laws, policies and agreements that need to be observed by the companies active in the space domain.
	policies	
	international coordination	
remoteness of effects	distance	A perception of how distant the impacts of the problem that the technology aims to address are from the actor considering the adoption of the technology.
	urgency	
	timeframes	
organizational relevance	pain-point	A perception of how much the technology corresponds to the core activities of the company, solves the problems specific to it and addresses its pain-points.
	relevance	
	necessity	
tipping point	tipping point	A critical threshold upon surpassing which it is no longer possible to ignore the problem, because it disrupts normal activities to an intolerable extent.
technological characteristics	minimum effort/ maximum results	Refer to the specific attributes and features of a technology that influence how easily and effectively it can be integrated and utilized within a given context.
	technological capabilities	
	reliability	
	technological compatibility	
	TRL	
	scale	
	user-friendliness	
	technological complexity	
	security	
awareness	understanding of the problem	The extent to which potential adopters are informed about the existence, benefits, and functionalities of a technology.
	terrestrial precedent	
opportunity costs	trade-off	Represent the perception of the benefits a company could have received by choosing the alternative option.
	risk mitigation	
financial considerations	access to funding	Perception of potential expenses, obtainable financial support, possible losses, and other considerations associated with the cost of a technology.
	affordability	
	investment risk	
added value	additional benefits	Value, apart from sustainability, that a

	cost reduction	technology brings; such as improved performance, cost reduction, extended lifetime, process optimization, etc.
industry standards	industry standards	Generally adopted rules of the industry, which are, even though not legally binding, respected by industry players, because they are generally accepted by companies active in the industry in question.
connection to other sectors	connection to other sectors	The degree of mutual dependency and interconnectedness with other sectors of the economy, apart from space.
market dynamics	uncertainty	Perception of the forces that shape market trends, that shape the context around technology adoption.
	availability	
knowledge	knowledge	Does the accumulated knowledge and expertise in the company allow it to understand the opportunities of a novel technology, to successfully adopt it, and to efficiently use it?
proactive approach	proactive approach	A mentality of companies that pushes them to pioneer in the field of sustainability, even if they are not forced to do so.
reputation	reputation	Image of a company perceived by the general public, competitors, partners, investors, other industries, etc.
cultural differences	cultural differences	Culture-specific mentality traits; specifically, the differences in attitudes towards space sustainability between the Western world and the emerging spacefaring nations.

Table D. Concepts and indicators

Round 1. Non-Space Industry Experts		
concept	***indicators***	***explanation***
distance	'far away' (ID:1), 'we cannot directly see what is happening there [in space], we cannot feel how the situation is deteriorating or improving'' (ID: 3), 'space is so distant, so there would not be much public attention, it is not as visible as the effects on earth' (ID: 27), 'sustainability is oftentimes pushed for by the public, and the public is more preoccupied with what is happening on Earth, in their countries, in their regions; and they would push their government to take local measures' (ID: 31), 'same thing with investors: if they are environmentally conscious, they would rather invest in something that would have a tangible effect on the society where they live' (ID: 31), 'relevance for people and their quality of life' (ID: 212), 'because it would impact the Earth ecology directly' (ID: 212), 'in order to be commercially successful, a sustainable space technology must target a need that is tangible and noticeable directly on Earth and has an almost immediate effect on the quality of people's lives' (ID: 212),	Space is perceived as being physically far away, therefore the problems of the space sector and any positive effect arising from adopting sustainable space technologies, are overlooked.
autonomous systems	'no control over them [space assets]' (ID:1), 'once your asset is in space, it is stuck' (ID: 2), 'operating in space is a difficult task, leaving no room for error, since it is a fully autonomous environment' (ID: 31), 'in space you cannot go and change something on a satellite that has been launched' (ID: 205),	Space necessitates autonomous systems, which have to operate without human intervention.
diluted responsibility	'nobody owns it [space]' (ID: 1), 'it is a tragedy of commons' (ID: 2), 'space is owned by everyone and no one, like the oceans, so the issue is that a private company would be the sole bearer of costs, but the benefits would be distributed among all actors, including its competitors' (ID: 29), 'the orbits are controlled by nobody' (ID: 213), 'space does not belong to anyone, but also space belongs to everyone' (ID: 302),	Space does not belong to anyone, therefore, there is a tendency to exploit it without taking the responsibility for maintaining it.
minimum effort/ maximum result	'leverage that yields the most results' (ID: 1), 'maximum results for minimum effort' (ID: 1), 'companies want a solution that would not cost them a lot money, time and efforts, and that would be efficient' (ID: 30), 'companies wouldn't want to waste too much time figuring out how to use your technology, they want quick solutions' (ID: 207), 'a sustainable space technology requires capital and resources, so it must maximize the effect to be commercially interesting; so minimum investment, maximum effect' (212)	A combination of very low effort and tangible, concentrated positive effect is very attractive for private actors.

pain-point	'an example of a pain point is when you want to launch a space asset, you need to avoid the zones of high space debris concentration' (ID: 2), 'space energy sources could be an incredible investment, as they will become profitable in future, but you cannot use that energy if space isn't clean' (ID: 31)	A company is most likely to adopt a sustainable technology, if it addresses one of its pain-points; for example, when you are launching a satellite, you would be ready to pay to know where the zones of high debris concentration are in order to avoid them.
uncertainty	'the market is suffering from not knowing' (ID: 2), 'unknown, rapidly changing set of regulations' (ID: 31), 'it is uncertain if you will find sufficient data to compliment your database' (ID: 210),	Lack of reliable and comprehensive information about the market, sustainability issues; unpredictability of the market.
trade-off	'how much does the pain cost?' (ID:2), 'if there is so much space debris that the risk of collision is catastrophic, it would make economic sense to pay for sustainable solutions' (ID: 6), 'cost effectiveness: to implement a sustainable technology must be cheaper than to deal with the problems that arise if you do not implement it' (ID: 29), 'it is easier to incentivize the prevention of orbital pollution that to clean it up afterwards' (ID: 30), 'it is cheaper for them to use than not to use it [sustainable space technology]' (ID: 207), 'considerable risk that your business could be disrupted to a certain extent' (ID: 210),	The trade-off between paying for a sustainable technology and having to face the consequences of not acting sustainably.
user-friendliness	'the technology needs to be clear and intuitive' (ID: 2), 'translated into meaningful values for those not involved in the technical details' (ID: 2), 'an interface that makes the data comprehensible to a general audience or a business developer' (ID: 2), 'intuitive, ready to be used, does not require special education to operate' (ID: 31), 'you need to teach people, you need to provide them with solutions that will help them to process the data and use it for their own needs' (ID: 207), 'if companies want to pay, they expect a ready product, [...], ready solutions, ready answers to their questions' (ID: 209), 'manuals to help companies figure out' (ID: 212), 'streamline it for the industry' (ID: 215),	Intuitiveness, simplicity, straightforwardness and other characteristics of a technology, which make it easy for a user to handle.
state subsidies	'governments either subsidize companies…' (ID: 3), 'governments can subsidize companies' (ID: 7), 'needs to be subsidized by the governments' (ID: 8), 'sustainable space technologies will never be fully commercially viable, therefore, there will always be the need for governmental subsidies' (ID: 26), 'will likely be introduced with governmental aid' (ID: 28), 'there is a lot of public money flowing in' (ID: 30), 'subsidies, tax benefits' (ID: 30), 'the government should fund startups to accelerate new trials and attempts' (ID: 303),	financial assistance provided by a government to a business to promote certain economic and social policies, in this case, sustainable space policies.
taxes	'... or [governments] make them [companies] pay taxes' (ID: 3), 'some form of tax on all the	Taxes levied from companies in order to finance development and

	companies that build satellites' (ID: 29), 'laws and taxes' (ID: 31), 'at least, there should be a tax' (ID: 207), 'a certain tax that a company pays to the government' (ID: 305),	implementation of sustainable space solutions by governments.
industry standards	'SpaceX is the benchmark of the market' (ID: 2), 'all companies will look up at what big players do' (ID: 2), 'it should become normal to care' (ID: 202), 'they [companies] are motivated to work together on a system where they can ensure reduced collision risks and debris formation' (ID: 210), 'winner-takes-it-all mentality' (ID: 215),	Generally adopted rules of the industry, which are, even though not legally binding, respected by industry players, because they are generally accepted by companies active in the industry in question.
state and big corporations orders	'funding would come from governments or companies like SpaceX' (ID: 2), 'governmental order, B2G' (ID: 7), 'when orbital pollution becomes a major threat, [...] private companies will have the incentive to develop sustainable space technologies with the aim to sell them to the military' (ID: 31), 'specific companies appointed by the states [...], and it's funded by taxpayers' (ID: 201), 'they [governments] are the biggest customers' (ID: 209), 'I do not see how it [sustainable space technology] can be profitable, unless government is your customer' (ID: 213),	States and big space corporations are the ones to feel the consequences of space unsustainability the most, therefore, the demand for sustainable technological solutions from their side would be one of the key drivers for other companies to supply such technologies to them. States and big corporations have enough reasons and enough financial resources to place such orders.
cost reduction	'sustainability is often just a side effect while companies chase cost reduction'' (ID: 3), 'reducing costs by reducing fuel consumption' (ID: 7), 'cost effectiveness: to implement a sustainable technology must be cheaper than to deal with the problems that arise if you do not implement it' (ID: 29), 'reduces their risk of losses' (ID: 31), 'they say it [reusable launchers] is to prevent pollution (and, it is the case), but it is in fact because it is less expensive' (ID: 207), 'sustainability as a side-effect: we optimize production, supply chain, fuel consumption during launch in order, first of all, to reduce costs, but it also has sustainability benefits' (ID: 212), 'reducing costs' (ID: 214),	While the core value and motive behind adoption of a technology may be different, sustainability might come as a 'side-effect'. For example, reusable launchers are designed to make space flights less expensive, but they also allow economization on material and waste. Rebound effect to be taken into consideration.
legal obligation	'legislation is the most powerful tool to ensure sustainability' (ID: 3), 'national jurisdiction to ensure compliance' (ID: 6), 'clear international regulations and criteria for companies to follow' (ID: 7), 'needs to be enforced by governments' (ID: 8), 'international agreements' (ID: 8), 'clear and effective framework for industry practices' (ID: 8), 'laws must change' (ID: 25), 'law - the main driver' (ID: 27), 'there needs to be a legal framework' (ID: 30), 'governments can force or incentivize companies to participate in sustainable transition' (ID: 31), 'the more you pollute, the more you pay' (ID: 201), 'the launching state should establish rules on how to remove and mitigate these activities' (ID: 201), 'the solution could be the UN: whoever is responsible for the launch should have an obligation	A system of laws and regulations, which are mandatory to abide by.

	to pay for any measures that need to be taken to maintain space 'clean', available for future launches and sustainable' (ID: 202), 'If it [sustainable technology] does not concern a company's core business, a private company wouldn't bother, unless it is forced by law' (ID: 202), 'it depends on regulations, because the private sector has no interest in investing in sustainable technology if they are not forced to do so' (ID: 203), 'incentives by law, both national and international, are necessary' (ID: 204), 'governments should mandate it' (ID: 205), 'it is either you force companies to use sustainable components and solutions…' (ID: 207), 'private companies will only adopt sustainability practices if mandated by law' (ID: 208), 'if it is not regulated, companies will not pay for it' (ID: 210), 'if there are regulations, then the entities that want to exploit space will have to comply' (ID: 211), 'someone should take control and enforce it' (ID: 213), 'require governments to mandate that operators remove their spacecraft at the end of life' (ID: 214), 'the regulatory side, would involve national regulators setting clear rules for what satellite operators can do and the consequences for non-compliance, such as, fines' (ID: 214), 'they [private companies] need to pay penalties if they don't use them [sustainable space technologies]' (ID: 301), 'law is necessary' (ID: 304), 'you need a legal base' (ID: 305),	
tipping point	'we, as people, will only start caring about space sustainability when the situation is truly catastrophic; before that, we will focus only on our own, earthly problems' (ID: 3), 'companies will not act until they perceive a real danger' (ID: 6), 'there is now no need and no urgency' (ID: 23), 'the market will only be ready to adopt something when there is an absolutely pressing need, and this is not the case with sustainable space tech' (ID: 24), 'will depend on the severity of the pollution problem' (ID: 27), 'the threshold for a problematic level of pollution' (ID: 27), 'the problem needs to become extremely grave for people and the media to start noticing it' (ID: 27), 'that's not going to be in a while, because, the situation is not yet catastrophic in space' (ID: 29), 'there's a tipping point looming' (ID: 30), 'it's unfortunate that we often reach a crisis point before taking action' (ID: 30), 'if we don't perceive a threat, it doesn't seem important' (ID: 211), 'there are not enough satellites and debris now in orbit for private companies to get truly concerned, and therefore to start investing in cleaning up the path for themselves' (ID: 212), 'once the risk increases related to collision with debris' (ID: 305),	A critical threshold upon surpassing which it is no longer possible to ignore the problem, because it disrupts normal activities to an intolerable extent.
urgency	'companies and governments will first act to solve the most pressing and immediately threatening	A pressing need to act as soon as possible; level of delay tolerance.

	problem' (ID: 6), 'there is now no need and no urgency' (ID: 23), 'not anytime soon, because it is not the most urgent matter' (ID: 24), 'urgent and important need' (ID: 26), 'people would likely invest in something more urgent and tangible' (ID: 27), 'pressing need' (ID: 29), 'space debris now is not an urgent problem' (ID: 213),	
research and development	'cutting-edge research backed by public funding' (ID: 7), 'technological advances' (ID: 8), 'governments definitely should support and fund researchers' (ID: 206), 'technological breakthroughs that help develop more commercial opportunities' (ID: 210), 'offer your know-how' (ID: 210), 'collaboration between academia and industry is essential for fresh ideas and competitiveness' (ID: 304), 'you have to do this research and implement sustainability' (ID: 305),	Fundamental and applied research dedicated to sustainable space solutions, development of sustainable space technologies.
timeframes	'technology developed over a long period of time' (ID: 7), 'companies want a quick solution' (ID: 30), 'it takes a long time to get a return on your investment' (ID: 31), 'it's a long path' (ID: 201), 'space is quite [...] lengthy' (ID: 201), 'sustainability programs are longer' (ID: 201), 'companies are operating under short timeframes' (ID: 207), 'it must be visible now and here' (ID: 212), 'they [private companies] have to show good results every trimester' (ID: 305),	Temporal misalignment between long-term space sustainability and short-term business objectives.
technological complexity	'complicated technology' (ID: 7), 'technological barriers' (ID: 31), 'level of technological complexity' (ID: 201), 'space is a complex field' (ID: 207), 'no solution' (ID: 215),	Sustainable space technologies require excellence, and are generally very technologically complex, which might create barriers.
technological capabilities	'a technology needs to be efficient and solve several problems at once' (ID: 7), 'efficient solution' (ID: 30), 'if you improve that, that could be interesting for sure' (ID: 203), 'the most accurate data possible' (ID: 204), 'information is key, and accuracy and timeliness of information make it even more valuable' (ID: 206), 'purely technical rationale' (ID: 208), 'you need to show people that your data is solid' (ID: 209),	Functionality range of a technology, the quality of its performance. What does the technology do and how well does it do it?
reputation	'positively contributes to a company's image' (ID: 7), 'public opinion' (ID: 27), 'predominantly because of social pressure and social norms' (ID: 206), 'this value might even be a form of greenwashing allowing companies to claim that they invest a portion of their profits or emissions into sustainable research and monitoring' (ID: 208), 'the value could be reputation or ethical' (ID: 208), 'increased public concern can pressure companies to act responsibly, because they wouldn't want to be seen in a bad light' (211), 'to maintain a good image, a good reputation' (ID: 213),	Image of a company perceived by the general public, competitors, partners, investors, other industries, etc.

security	'concerns about security and jurisdiction arise when observing objects in space, particularly military satellites' (ID: 7), 'there is always the willingness to have your own information' (ID: 203), 'most of the companies would prefer embedding your solution in their solution' (ID: 207), 'they [military] might be interested in your methodology, but not your archives, as they would have their own trusted sources of data' (ID: 210), 'they [private companies] often use internally developed tools' (ID: 303),	Concerns around the safety of data and operations.
policies	'institutional-level discussions' (ID: 8), 'space sustainability has to be recognized as a domain of strategic interest' (ID: 8), 'space sustainability should be organized much like the sustainability ecosystem on Earth' (ID: 201), 'policies of the big spacefaring nations: they have the most space assets, so they would be most interested in sustainability in space' (ID: 202), 'sharing arrangement between the private and public sectors, according to the number of spacecraft in orbit' (ID: 204), 'we should put this on top of the agenda, as a priority, with the support of governments' (ID: 206), 'balance economic and geopolitical interests' (ID: 215), 'incentives from the government or policymakers' (ID: 302), 'need to establish an economic ecosystem to facilitate the money flow' (ID: 303),	The concept encompasses both 'soft law' and formal guidelines, channeling behaviors of actors in the space domain
connection to other sectors	'downstream companies, like telecom, data science centers, farmers' (ID: 8), 'if it's for commercial end-users, like telecom or commercial exploration, then it means that it has to be, as a minimum, co-funded by the private sector' (ID: 203), 'lack of understanding that the risk is for entire industry, including downstream application, and not just for space companies' (ID: 209),	The degree of mutual dependency and interconnectedness with other sectors of the economy, apart from space.
necessity	'space exploration is not a necessity' (ID: 24), 'if the effect is negligible, then why bother?' (ID: 212), 'it's not profitable per se, but it's essential' (ID: 213), 'to avoid Kessler syndrome, where this part of space is not useful or usable anymore' (ID: 301), 'if you want something to continue, it should be sustainable enough to keep working for a few decades or more' (ID: 302), 'depends on the levels of actual risk' (ID: 305)	The interplay between how essential space exploration is perceived to be, its immediate profitability, and the critical need to ensure long-term sustainability and usability of space.
risk mitigation	'there is a market for them [sustainable space technologies], because sustainability also means fewer risks' (ID: 25), 'reduces their risk of losses' (ID: 31), 'how much risk it represents for space assets in general?' (ID: 203),	Sustainable space solutions as a means to reduce one's own risks, primarily, collision risks.
affordability	'must be affordable' (ID: 25), 'all space solutions are very costly' (ID: 27), 'these technologies would be quite resource-intensive in terms of money and	Financial considerations in the development, implementation, and adoption of space technologies.

	personnel' (ID: 28), 'companies want a solution that would not cost them a lot of money' (ID: 30), 'space is quite capital-intensive' (ID: 201), 'space sector is capital-intensive' (ID: 202), 'costs will stay high; sustainability is a burden, and companies don't want a financial burden' (ID: 202), 'there should be a financially feasible scheme so that everyone can afford this access' (ID: 204), 'added costs are reasonable' (ID: 208), 'but not at an extra cost' (ID: 209), 'companies tend to go for the lowest cost and easiest path by default' (211), 'fail due to the high costs involved' (ID: 303),	
reliability	'must be reliable, safe' (ID: 25),	How reliable is the technology?
relevance	'how useful are these technologies?' (ID: 27), 'it [private company] would adopt a technology is it concerns its core business' (ID: 202), 'the final use case for the technologies' (ID: 203), 'it depends on the type of the mission' (ID: 207), 'have a technology that is inherently sustainable and is so good that companies want to apply it, because of its utility' (ID: 209), 'allow companies to decide whether the basic open-sourced version meets their needs or if a commercial version with additional features and support is worth investing in' (211), 'enhance their usefulness' (304),	Relevance of the technology to a company's core activities; its usefulness for the company's operations.
proactive approach	'companies might recognize the problem and take initiative' (ID: 28), 'private companies are lazy' (ID: 30), 'private companies shouldn't only focus on profits and business; rather, they should adopt a more sustainable approach' (ID: 302),	A mentality of companies that pushes them to pioneer in the field of sustainability, even if they are not forced to do so.
international coordination	'ensuring compliance and enforcement across various jurisdictions is no small feat' (ID: 30), 'investment propensity and adoption rate largely depend on stability, geopolitical environment, and currently it is a far cry from perfect' (ID: 31), 'needs to be very well coordinated on the international level' (ID: 201), 'through UN treaties or ITU that regulates telecommunication' (ID: 202), 'the main launching states have much more responsibility, and should pay more for the debris currently in space' (ID: 204), 'everything should be regulated by international agreements' (ID: 205), 'it should be managed by the UN or a kind of consortium of all the space agencies' (ID: 207), 'the only feasible solution might be an international treaty enforced by user demand' (ID: 208), 'legislation limited to one country, one government will have no effect' (ID: 208), 'if there are restrictions in one country, a company can avoid them by moving abroad' (ID: 209), 'key nations that control access to space need to have common standards and guidelines' (ID: 209), 'hopefully, coordination will be conducted on a global scale' (210), 'there needs to be international	Global cooperation, alignment of goals, rules and policies between different nations.

	collaboration between key spacefaring nations to coordinate legislation' (ID: 212), 'there has to be a consistent agreement among a critical mass of national regulators' (ID: 214), 'this should be aglobal rule, not just a national one' (ID: 304), ' it's extremely difficult to implement, because there is no agreement between countries' (ID: 305),	
understanding of the problem	'governments raising awareness' (ID: 31), 'wee need to communicate better to the general public the importance of space activities' (ID: 204), 'the problem of orbital pollution and so on are really not yet clearly understood by the population' (ID: 206), 'most of the public doesn't know anything about the effect of space debris' (ID: 207), 'we need to quantify the risks and communicate them better' (ID: 209), 'we need to think about the future now, and not when it is already happening' (ID: 209), 'they [people] do not realize that they use space-based services everyday and that these services could become unusable [...], it's crucial to make more noise, raise awareness' (211), 'we need to have some more precise estimations of the environmental effect of the space activities to motivate states to unite and impose those conditions [to use sustainable technologies]' (ID: 212), 'it's challenging to make this clear' (ID: 214), 'educating people' (ID: 214), 'the mass media plays a critical role' (ID: 303), 'direct communication with relevant companies is crucial' (ID: 303), 'we need to incentivize the population to understand how space technologies impact their daily lives' (ID: 304), 'space is still something quite far from the understanding of people' (ID: 305),	The necessity for better communication, education, awareness-raising efforts with the aim to help the general public and relevant stakeholders understand the importance of space activities, the risks of space debris, and the need for sustainable space technologies' adoption.
terrestrial precedent	'to prevent what is happening on Earth from happening in space too, and to help mitigate climate change on Earth' (ID: 31), 'learn from what we have done on Earth' (ID: 302),	The example of environmental problem on Earth can motivate space actors to take action in order to prevent similar problems in space; to learn from the mistakes made on Earth.
investment risks	'space is quite [...] risky, and offers interns on investment that are quite different from other industries like retail or IT' (ID: 201), 'considering there is a return on investment' (ID: 203),	The specific risks associated with space activities and the distinct nature of returns on investment compared to other industries.
access to funding	'access to funding is a crucial barrier to advancing these initiatives sooner rather than later' (ID: 201), 'it can be public or private funding' (ID: 203), 'due to limited funding' (ID: 303),	The existence of funding schemes, availability of funding for sustainable space technologies' development and deployment.
rise of the private space	'space is becoming more privatized' (ID: 201),	Shift from predominantly governmental space activities to increasingly private space businesses.

scale	'scale: only governments can be expected to maintain clean the entire space infrastructure' (ID: 201), 'a company should be big enough' (ID: 202), 'how systematically do you cover the sky with your observations?' (ID: 210), 'as complete a picture of the sky as possible' (ID: 210), 'there is little value in archived data from a handful of observations' (ID: 215), 'make it more comprehensive' (ID: 215),	The importance of scale, comprehensiveness, of the solution.
additional benefits	'need to either improve the performance [...]. or with an extended lifetime, or with equivalent performance but cheaper' (ID: 203), 'if the technology makes it cheaper, better, faster, one of the three, two of the three or ideally three of the three, then they [private companies] would adopt it' (ID: 205), 'if there is an added value that you can deliver to a company' (ID: 205), 'you need to teach people, you need to provide them with solutions that will help them to process the data and use it for their own needs' (ID: 207), 'the tools provided should enhance knowledge or predict the viability and operational duration of systems' (ID: 208), 'operators need to perceive a tangible value against the costs' (ID: 208), 'if the technology allows us to do things better, but not at an extra cost' (ID: 209), 'cost reduction or generating new revenue' (ID: 214), 'enables new business models' (ID: 214), 'creates a new market and financial incentives for using sustainable approaches' (ID: 214), 'make money from sustainable technologies' (ID: 301), 'the problem with sustainability is that there is no added value, purely financially speaking' (ID: 305),	Other benefits, apart from sustainability, that a technology brings; such as improved performance, extended lifetime, process optimization, etc.
availability	'if the system is only available for a significant fee that smaller actors cannot afford, it could be problematic and cause more damage' (ID: 204),	If a private company is motivated to adopt a sustainable space technology, how easily can it get it?
cultural differences	'this is a very Western way of seeing this concept' (ID: 206),	Country-specific mentality traits; specifically the differences in attitudes towards space sustainability between the Western world and the emerging spacefaring nations.
niche market	'space is a niche market, so the pressure of the public is very minor; it's a large usage, but a niche market' (ID: 207),	A specialized market.
technological compatibility	'most of the companies would prefer embedding your solution in their solution' (ID: 207), 'providing a starting point for further integration and development' (ID: 208), 'so that others can apply your methodology on their data, otherwise there will be no uniformity' (ID: 215), 'it is important to establish a common language for these datasets to ensure compatibility' (ID: 304),	The need for solutions that can be easily embedded within existing systems and infrastructures, combined with existing technologies and business models.
Technology	'once such technology is established, the private	Maturity level of a technology.

Readiness Level	sector should play and important role in sustaining these activities' (ID: 303),	
Knowledge	'allowing them [private companies] to gain knowledge and know-how' (ID: 303),	Does the accumulated knowledge and expertise in the company allow it to understand the opportunities of a novel technology, to successfully adopt it, and to efficiently use it?
Investment propensity	'they [investors] are not willing to invest in sustainability' (ID: 305)	The likelihood or willingness of individuals, companies, or institutions to invest in sustainable space technologies.

Table E. Identified factors and corresponding TAM3 or TAM++ factors

Identified Factor	TAM3	TAM++ factor
regulatory landscape	voluntariness	
remoteness of effects	-	
organizational relevance	organizational relevance	
tipping point	voluntariness	
technological characteristics	objective usability	
awareness		awareness (Mutahar et al., 2018)
opportunity costs		opportunity costs (Brock et al., 2017)
financial considerations		perceived cost (Ozbek et al., 2015; Tiwari & Tiwari, 2020)
added value		perceived value (Hajiha et al., 2015)
industry standards	subjective norm	
connection to other sectors	-	
market dynamics	perception of external control	
knowledge	experience, self-efficacy	
proactive approach	voluntariness	
reputation	image	
cultural differences		cultural differences (Straub et al., 1997)

Table F. Factors Correlation Table with Significance Levels

Correlation between factors

	added value	awareness	connection to other sectors	cultural differences	financial considerations	industry standards	knowledge	market dynamics	opportunity costs	organizational relevance	proactive approach	regulatory landscape	reputation	spatial_remoteness	tech characteristics	temporal_remoteness	tipping_point
added value	1.00	0.14	0.16	0.20	-0.18	-0.27	-0.13	-0.10	0.10	0.16	-0.23	0.20	-0.05	0.24	0.15	0.01	0.01
awareness	0.14	1.00	0.01	-0.11	0.01	-0.24	0.24	0.19	-0.08	0.41*	0.01	0.24	0.01	0.35*	0.22	0.20	-0.03
connection to other sectors	0.16	0.01	1.00	-0.05	0.23	-0.11	-0.05	-0.11	0.05	0.15	-0.09	0.04	-0.14	0.00	0.10	-0.18	-0.19
cultural differences	0.20	-0.11	-0.05	1.00	-0.12	-0.06	-0.03	-0.06	-0.10	-0.15	-0.05	0.16	-0.08	-0.27	-0.16	0.12	-0.11
financial considerations	-0.18	0.01	0.23	-0.12	1.00	-0.08	0.30*	-0.08	-0.00	-0.03	0.16	0.22	0.10	0.00	0.26	0.04	-0.09
industry standards	-0.27	-0.24	-0.11	-0.06	-0.08	1.00	-0.06	0.44**	0.20	0.05	-0.11	-0.01	-0.16	-0.14	0.26	-0.09	-0.23
knowledge	-0.13	0.24	-0.05	-0.03	0.30*	-0.06	1.00	-0.06	-0.10	-0.15	-0.05	-0.04	-0.08	0.18	0.17	0.12	-0.11
market dynamics	-0.10	0.19	-0.11	-0.06	-0.08	0.44**	-0.06	1.00	0.41*	0.05	-0.11	0.19	-0.16	-0.05	0.21	-0.27	-0.23
opportunity costs	0.10	-0.08	0.05	-0.10	-0.00	0.20	-0.10	0.41*	1.00	0.02	0.05	0.02	-0.27	-0.10	0.27	-0.09	0.06
organizational relevance	0.16	0.41*	0.15	-0.15	-0.03	0.05	-0.15	0.05	0.02	1.00	-0.06	0.04	0.07	0.24	-0.02	0.12	0.09
proactive approach	-0.23	0.01	-0.09	-0.05	0.16	-0.11	-0.05	-0.11	0.05	-0.06	1.00	-0.06	-0.14	-0.26	-0.09	0.02	0.03
regulatory landscape	0.20	0.24	0.04	0.16	0.22	-0.01	-0.04	0.19	0.02	0.04	-0.06	1.00	-0.02	0.16	0.21	-0.05	-0.21
reputation	-0.05	0.01	-0.14	-0.08	0.10	-0.16	-0.08	-0.16	-0.27	0.07	-0.14	-0.02	1.00	0.23	-0.01	0.32	0.05
spatial_remoteness	0.24	0.35*	0.00	-0.27	0.00	-0.14	0.18	-0.05	-0.10	0.24	-0.26	0.16	0.23	1.00	0.13	0.01	0.07
tech characteristics	0.15	0.22	0.10	-0.16	0.26	0.26	0.17	0.21	0.27	-0.02	-0.09	0.21	-0.01	0.13	1.00	0.11	-0.35*
temporal_remoteness	0.01	0.20	-0.18	0.12	0.04	-0.09	0.12	-0.27	-0.09	0.12	0.02	-0.05	0.32	0.01	0.11	1.00	0.32
tipping_point	0.01	-0.03	-0.19	-0.11	-0.09	-0.23	-0.11	-0.23	0.06	0.09	0.03	-0.21	0.05	0.07	-0.35*	0.32	1.00

Table G. Recommendations on ODLI Commercialization

Category	Concept	Suggestion	ID
Technical recommendations	Synthetic data validation	Training your model with synthetic images that closely resemble reality can work. Use synthetic data for initial training and then validate the model with real data to ensure accuracy.	2
	Compatibility	Integrating machine learning with optical systems on CubeSats, Starlinks, or Kuipers to analyze live data could be beneficial. It's important to establish a common language for these datasets to ensure compatibility.	304
	MVP	A proof of concept shows feasibility but needs to be validated with real data to reach the minimum viable product (MVP) stage.	2
	transparency	They [companies] want transparency, so they would also want to see the raw data to be able to compare it to other raw data and ensure consistency.	209
User-friendliness	Interpretability	Ensure the data makes sense and is interpretable. While curves and graphs are good, they need to be translated into meaningful values for those not involved in the technical details. Add an interface that makes the data comprehensible to a general audience or a business developer.	2
	The most processed data is the best one	The easier it is to make predictions - the better. Hence, the most processed data is the most useful one for private actors, who would not want to waste time and other resources on processing the half-ready data themselves. They want software that is intuitive, ready to be used, does not require special education to operate, and reduces their risk of losses (collision risks).	31
	Quick solutions	Space is a complex field, and companies are operating under short timeframes. They would not want to waste too much time figuring out how to use your technology, they want quick solutions.	207
	Ready answers	If companies want to pay, they expect a ready product. it is hard to sell raw data, they need ready solutions, ready answers to their questions. For example: "Is it safe to deploy our constellations in this orbit?". This you can sell.	209
Market awareness	Understanding the market	For commercializing space debris removal, understanding the market and incentives is crucial.	2
open-source	Collective effort	I believe such a repository should be open-source. The ultimate goal is to contribute to space sustainability by improving debris tracking and potentially aiding in debris removal, and there is no use in it unless it is a collective effort. The only way to ensure that as many actors as possible are on board is to provide unrestricted access to the technology and persuade them that it is necessary.	6
	Companies would not pay voluntarily	I do not see why companies would voluntarily pay for it. I believe the only way to get your technology recognized is to open-source it.	28
	Free access	I've often heard that space traffic and accessibility should be free, as it's fashionable to think everything	204

		should be free. However, there is work involved, and it's normal to pay for that.	
	Global problem	If it is a global problem, it should be open-sourced.	205
	Contributions from the community	Ideally, it should be open-source, similar to how Google Maps started. This approach allows the community to contribute, enhancing its functionalities, such as possibly predicting dynamic collisions in the future.	211
		What you could do is to keep it open-source so that other teams like yourselves can add more information to it.	215
	Ethical concern	Ethically, using public money to generate revenue for private companies is questionable. Initially, public money was not meant to generate revenue for the private sector.	301
	Academics' demand for opne-source databases	Academic researchers often rely on open source resources due to limited funding. However, industrial sectors may not pay much attention to open source software, as they often use internally developed tools.	302
		Open source it for everyone, so that academics, who have more time and patience, can learn how to use your technology by themselves. And, maybe, they would also contribute with their data. And then you sell training sessions to companies.	27
security	Security and jurisdiction concerns	I have doubts that companies would be able to use such a technology, even if they were willing to pay for it. Concerns about security and jurisdiction arise when observing objects in space, particularly military satellites.	7
	Self-reliance	There is always the willingness to have your own information. If you are able to develop a system that permits to track and which is located at a certain place, then it means that you are able to consolidate some analysis yourself, some observation yourself, not only based on information you will receive from outside.	203
customers	Whoever launches a new satellite	Your potential customer is whoever launches a new satellite - governments or companies, so that they know they won't get in the way of space debris.	29
	Entities that would like to clean or to launch new satellites	Who could be interested - entities that would like to clean or to launch new satellites, to avoid collisions; actors that would like to control and to enhance databases with objects, and more data on the object.	30
	army, national agencies or international agencies, operators.	Who is interested in knowing what the debris is, where they are located, how much risk it represents for space assets in general? It is the army, national agencies or international agencies, it is the operators that are intending to fly in specific orbits that can be already pretty messy with such debris.	203
	Insurance companies	If you could really quantify the risks, that would be especially valuable. Particularly to insurance companies, because when a satellite operator wants to insure their satellite, an insurance company would want to have the most accurate and objective image of potential dangers.	209
		Maybe the insurances could be your customers.	305

	The SSO and Swiss army	The Swiss Space Office and the army might be interested.	210
	Sates	If we ever have state-organized space traffic management, then state-owned sensors will also be used. They might be interested in your methodology, but not your archives, as they would have their own trusted sources of data.	210
	Companies doing active debris removal or end of life services	I think if the repository has specific information about large debris objects, if you could provide information on the rotation rate and its configuration; then that has value to companies that would be looking to do active debris removal or end of life services or something like that.	213
	Small companies	Focusing on smaller companies that can benefit from your solution might be more effective. Engage with companies working on debris assessment and data collection to understand how they quantify existing debris. This collaboration can help validate and improve your model. Smaller companies are often more open to discussions and can provide valuable insights and data.	2
	Defence	From my perspective, what you are doing relates to security and defense, so this might be your starting point.	8
	ESA	Once you have pinpointed your value proposition to the market, you can address ESA, because they are actively identifying future technological needs.	8
	Satellite operator	In a commercial context, ODLI data would be very useful for any satellite operator or company planning to send anything to space. They can plan their missions based on this data, including their orbits and astrodynamics.	302
	Dynamic map of skies creation	Or it could be for someone who is actually creating a dynamic map of skies. They need the initial data, and the methodology on how to identify space debris.	305
	NGOs	There will not be so many NGOs interested in space. An NGO cannot live from space because they need to have people paying for what they are doing with animals, with poverty. With space, it's much more difficult. The distance, the remoteness is clearly an element. It's really not easy.	305
Limited demand	Specific use-case	It's a very specific use case: there's only a handful of companies that perhaps would want to pay for that information and they would just look at a handful of objects.	214
	Niche market	Operating profitably in such a niche market is tough.	30
	Lack of potential customers	It would be very hard to find customers.	8
XaaS	XaaS	A potentially interesting and viable model is XaaS. When the government/space agencies bear the costs of the development of a sustainable space technology, and then rent it out to companies, other states on demand. For example, in the case of the BRIDGE project, EPFL will remain the owner of the tech/software/repository, and	26

		organizations/companies/agencies could rent it when they need it.	
tipping point	Crisis point	As space gets more congested, launching satellites becomes increasingly tricky. There's a tipping point looming. It's unfortunate that we often reach a crisis point before taking action, like a messy teenager's room - it won't be cleaned until it is impossible to cross it.	30
	Risk threshold	Maybe once the risk will increase related to the collision of debris, these insurances could be the leverage.	305
value proposition	Minimum size of detected debris	The question revolves around the minimum size of the debris we are able to track. If you improve that, it will be interesting for sure.	203
	Enanced predicablity	The tools provided should enhance knowledge or predict the viability and operational duration of systems.	207
	Autonomous systems' need for collision avoidance	Autonomous systems are necessary in space, therefore there appears a market necessity to predict & avoid collisions - this is the commercial value for private companies and governmental agencies operating in space.	31
	More accurate predictions	There is always value in the data that allows us to predict things more accurately, that is why I see commercial value in your project.	31
	Density clouds	You can streamline it for the industry and let them pay for your information on density clouds.	215
	Collision avoidance	Collision avoidance would be an interesting service to provide. Commercial entities would be extremely interested in it. If you can provide data for smaller particles, because even a 1-cm object can have a devastating impact on the ISS or a satellite.	205
	improved satellite longevity and reliability	The value might be more direct and technical, quantifiable through improved satellite longevity or reliability.	208
affordability	universal avalibality	It's in the interest of all space actors to access the most accurate data on space debris possible. If the system is only available for a significant fee that smaller actors cannot afford, it could be problematic and cause more damage. There should be a financially feasible scheme so that everyone can afford this access, as equal access to space is crucial.	204
	high initial costs	I do not think that it will ever pay off in full, in the end, the initial costs were enormous.	215
	reasonable added cost	You could propose integrating a function in their system that enhances sustainability, potentially increasing system costs by about 5%. This added cost is reasonable and could attract private companies to contribute.	208
opportunity costs	Trade-off	We [a space debris removal company] would pay a reasonable amount of money to get that information so that we knew that when we built the spacecraft to go up there and remove it we knew exactly what it was doing before we got there. Without that information it's quite risky.	213
hybrid approach	Open-source raw database + paid	Consider a hybrid approach with an open-source raw database, allowing contributions from other entities to	205

	value-added services	enhance its value. Sell value-added services on top and include future projections of space debris movement and evolution, with relevant statistics (e.g., orbit safety duration). Ensure quality checks on contributions.	
	Open-sourced database + training sessions, API and ergonomic solutions	If you want to broadcast and if you want to have an impact on the industry, then open-source it, combine with training sessions, performing API, and ergonomic solutions. And you will be paid for the training sessions, for the expertise and not for your data.	207
	Open-sources database + paid know-how	Making it open source would allow other observatories to contribute. If you still want to pursue commercial avenues, you might offer your know-how.	210
	Trial period	This could allow companies to decide whether the basic open-source version meets their needs or if a commercial version with additional features and support is worth investing in.	211
	Repository as demonstration + paid manuals, work	Simply giving access is not enough. You might consider producing some manuals to help private adopters figure out how to navigate your repository. Or you can offer companies to process their data using your methodology, and they would pay for your work. then, you would use your repository as a demonstration of what you can do.	212
	Limited open-source repository + more detailed one as a paid service	You could do both: have a limited open-source repository with data on well-known objects for academic collaboration or studying space debris dynamics. Additionally, offer a more detailed, potentially sensitive repository as a paid service.	214
	Trial and Transition Licensing	Open source the dataset for six months to a year, gather feedback, and then decide whether to move to a licensing model. A low-cost licensing model could allow continued access while supporting further development. Offering free access for research purposes to those enhancing the dataset could also be an effective approach. This combined model allows for the intake of user feedback to improve the dataset or tool.	304
	Time-sensitive subscriptions	Offer subscriptions (commercial side) in a time-sensitive manner, meaning that any update within X hours will be accessible. But then this update will be delayed by several days before it is open-sourced and reaches the general public. You basically have a premium access and premium knowledge on what is happening, and for that you would pay a premium price. And doing this can be very useful for key actors, for example, insurance companies, because they would want to know what orbits are polluted or are expected to become polluted, meaning, the risk of collisions is increased, meaning that the premium they would have to pay for insurance will also be increased. But also for coordination of activities, orbital transfer, large-scale maneuvers that will happen in different orbits that is also the prime information that you would want to know ahead of everyone else, because	206

		then you would want to take preliminary action and not just consult an open-source environment.	
	Free academic acces + different subscription modes for commercial customers	You could provide free access to academics while private companies pay a fee, or offer a demo version with limited access to the general public and different subscription modes.	302
image	Greenwashing	Operators need to perceive a tangible value against the costs. This value might even be a form of greenwashing, allowing them to claim they invest a portion of their profits or emissions into sustainable research and monitoring. [...]	208
	Reputation	Furthermore, the value could be reputational or ethical, enhancing a company's image by demonstrating a commitment to addressing space debris.	208
consulting service	consulting service	I see it as a consulting service. Since you are the ones creating the dataset, you know it the best, so you could sell knowledge to companies and governments. [...] You really need to show people that your data is solid, but complex, so you can help companies figure out how to use your insights to help their businesses.	209
scale	Systematical cover of the skies	The question is: how systematically do you cover the sky with your observations? In the context of space traffic management with large constellations in orbit, we need structure.	210
	Comprehensive cover of the skies	There is little value in archived data from a handful of observatories. You first need to make it more comprehensive. Once you have acquired enough data to make a map of skies (not necessarily dynamic even), you can try to partially commercialize it.	215
urgency	future need in smart systems for collision avoidance	Currently, there is no problem with managing orbital traffic, but soon we will need smart systems that allow satellites to avoid collisions.	210
	data for space traffic management system	Space traffic management is very data-driven. Having data to measure different objects is valuable and can contribute to developing a more comprehensive space traffic management system, which we will soon urgently need	210
scalability	applicability is other cases	While it is limited in scope, you can demonstrate its applicability to other cases.	210
	ground for other tools development	This could also form a foundation for developing other tools, such as dynamic maps of space debris, providing a starting point for further integration and development.	208
marketing strategies	direct communication with companies	Direct communication with relevant companies is crucial to demonstrate the advantages of open-source tools.	303

Table H. XaaS Validation

XaaS validation	**ID**
The problem with the XaaS model is: are you sure there is a market for that? And whether there is a market or not, you will discover only having some business development activities, but if you do not have the pressure of the return on investment you have made, it means you have time, you have no investor to make happy. It's a low-risk initiative, so no reason not to try.	203
XaaS is a feasible approach to maintain public funding for basic research while transitioning to private sector exploitation when ready. If efficient, larger actors might significantly contribute to this system, enhancing global security in outer space.	204
Consider a hybrid approach with an open-source raw database, allowing contributions from other entities to enhance its value. Sell value-added services on top and include future projections of space debris movement and evolution, with relevant statistics (e.g., orbit safety duration). Ensure quality checks on contributions. Note that space debris databases already exist, such as those from NASA and ESA.	205
It is an intermediate solution. With this solution you would address part of the market, but most of the companies would probably prefer embedding your solution in their solution. So, some of the companies accept external IPs in their solutions, but most of them want to export, they don't want to negotiate with third parties if they are allowed or not allowed to use the IPs. I think you constrain your market.	207
XaaS is a good model, but simply giving access is not enough. You might consider producing some manuals to help private adopters figure out how to navigate your repository. Or you can offer companies to process their data using your methodology, and they would pay for your work. then, you would use your repository as a demonstration of what you can do.	212
If you ask me, this is not quite what I associate with academia.	301

Github Repository

Pre-processed data and python code used for machine text analytics can be found in the following GitHub repository: AngelinaFrolova/Master_Thesis_E4S_2024

The repository is private, therefore, to get access to it, please, send me a request by email: angelina_frolova@epfl.ch