Design of a Business Roadmap methodology: Application in Materials technology for Very Low Earth Orbits (VLEO) missions

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Abstract

EN

This dissertation aims to develop a roadmap methodology incised in developing new materials in Very Low Earth Orbits (VLEO). Said orbits go from 200 to 1200 km, presenting characteristics such as extreme temperatures, radiation exposure and atomic oxygen erosion. Developing novel materials for space exploration that can withstand these conditions is crucial to future space investigation.

This roadmap offers a systematic strategy for material development, emphasizing the necessity of conducting fundamental research to comprehend how materials behave in VLEO settings and then developing and testing novel materials with improved performance and durability. Developing novel materials that enable safer and more effective operations in VLEO conditions will be made possible by following this roadmap, which researchers and companies may use to enhance space technology and exploration.

ESP

El objetivo de esta tesis es desarrollar una nueva metodología para crear un roadmap, es decir, una estrategia de planificación de alto nivel, que incisa en el desarrollo de nuevos materiales en órbitas terrestres muy bajas (VLEO). Dichas órbitas van desde los 200 hasta los 1200 km, presentando atributos característicos tales como temperaturas extremas, exposición a la radiación y oxígeno atómico erosivo. El desarrollo de materiales novedosos para la exploración espacial que puedan soportar estas condiciones se vuelve crucial para avanzar en investigación espacial.

Esta hoja de ruta ofrece una estrategia sistemática para el desarrollo de materiales, enfatizando la necesidad de realizar una investigación fundamental para comprender cómo se comportan los materiales en entornos VLEO y luego desarrollar y probar materiales novedosos con un rendimiento y una durabilidad mejorados. El desarrollo de materiales que permitan operaciones más seguras y efectivas en condiciones VLEO será posible siguiendo esta hoja de ruta, que los investigadores y las empresas van a poder utilizar para mejorar la tecnología y la exploración espacial.

CAT

L'objectiu d'aquesta tesi és desenvolupar una metodologia nova per crear un roadmap, és a dir, una estratègia de planificació d'alt nivell, que incisa en el desenvolupament de nous materials en òrbites terrestres molt baixes (VLEO). Aquestes òrbites van des dels 200 fins als 1200 km, presentant atributs característics com ara temperatures extremes, exposició a la radiació i oxigen atòmic erosiu. El desenvolupament de materials nous per a l'exploració espacial que puguin suportar aquestes condicions esdevé crucial per avançar en investigació espacial.

Aquest full de ruta ofereix una estratègia sistemàtica per al desenvolupament de materials, emfatitzant la necessitat de fer una investigació fonamental per comprendre com es comporten els materials en entorns VLEO i després desenvolupar i provar nous materials amb un rendiment i una durabilitat millorats. El desenvolupament de materials que permetin operacions més segures i efectives en condicions VLEO serà possible seguint aquest full de ruta, que els investigadors i les empreses podran utilitzar per millorar la tecnologia i l'exploració espacial.

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Chapter 1

Introduction

1.1 Aim

This thesis seeks to create a framework technique for a roadmap that will enable the development of novel materials needed for EO at VLEO. The study will gain a detailed understanding of the existing market, as well as the stakeholders and technologies that must be fulfilled, through a thorough examination.

1.2 Need identification and covering

The effectiveness of roadmapping as a technique for organised thinking to develop alternative routes to meet project needs and enable strategic planning has been demonstrated throughout numerous amount of articles and research, and the need for a clearly defined technique is expanding quickly in the sector.

The DISCOVERER project and the European Commission have been redesigning EO satellites to produce next-generation satellites that are smaller, less bulky, and less expensive to launch while maintaining the same or superior resolution that is currently available [1].

In order to help with the construction of these upgraded satellites and lower the costs associated with spacecraft manufacture, new materials for EO at VLEO must be developed as part of this project. Due to their increased resistance to atomic oxygen attacks compared to more traditional hydrocarbon polymers, this new discovery may help extend the lifespan of satellites. It is crucial to understand that polymeric materials used in spacecraft frequently deteriorate due to atomic oxygen in Low Earth Orbits, which has led to the current demand for a solution [2].

Finally, to ensure the project's success, a framework approach plan must be built to make it easier to create these new materials.

1.3 Requirements

The following is a list of the conditions that must be met to satisfy the project's needs:

- The roadmap will only cover the creation and application of materials technology
- Its application only resides in EO at VLEO

- With the aid of the completed literature research, the roadmap framework methodology will need to be created from scratch
- The developed technology is exclusively within the EU

1.4 Scope

The following subjects will be covered in this study:

1. The development of a roadmap framework methodology researching the literature of numerous papers about the development of roadmaps written by previous studies available
2. The study of the evolution of new materials in aerospace for EO missions at VLEO purposes
3. A market study, as well as a stakeholder analysis
4. The development of a situation analysis using several tools for strategy analysis, such as PEST, 5 Forces and SWOT
5. The understanding of the foresight technology methodology entails: Identifying important driving forces, linking grids, and risk analysis are all required
6. The creation of a budget estimation
7. The consideration of the many roadmap-related actions, including the layers, KPIs, and time-frame

This investigation won't delve into:

- The implementation of the roadmap
- The development of the materials technology
- The iterating process of the roadmap
- The holding of workshops

Chapter 2

Background

2.1 Orbits

Nowadays, six kinds of orbits have been identified (being able to extend it to 7, this being explained later), an orbit essentially being the curled route that a spacecraft, planet, moon, star, or other object travels while being pulled by another object's gravity [3]. Understanding orbits is crucial for positioning satellites appropriately.

- **Geostationary orbit (GEO)** GEO are those orbits at an altitude of 35786 km from the equator. Satellites that use these orbits are mainly for telecommunications since they need to be in a specific location above Earth.
- **Low Earth Orbits (LEO)**
  LEO often hovers at a lower height than 1000 km; however, it may be as low as 160 km from Earth. They are primarily used for satellite imaging.
- **Medium Earth Orbit (MEO)**
  MEO stands between LEO and GEO, mostly used for navigation and tracking.
- **Polar orbit and Sun-synchronous orbit (SSO)**
  Whereas a Sun-synchronous orbit keeps a satellite permanently in the same location concerning the Sun in the northern regions, a polar orbit compresses through the north and south of Earth. They are useful when it comes to monitoring a specific area during a period.
- **Transfer orbits and geostationary transfer orbit (GTO)**
  They are utilised to go from one orbit to a different one so that they can be placed correctly in their final scope when they are in space.
- **Lagrange points**
  Being over a million kilometres away and not immediately orbiting Earth is possible because of Lagrange points, them being certain locations in space where items are delivered and left in place [4].

Finally, the 7th orbit —which is not mentioned on the previous list —is VLEO, the one used in this project and explained in the following subsection.

2.1.1 VLEO

There are a variety of benefits to working in Very Low Earth Orbits. Recent technical advancements have significantly reduced costs, and spacecraft development has become more flexible than before [5].

Because of the speedy connections that make satellite services possible, such as television and the internet, and even environmental administration and catastrophe tracking, satellites have become a regular part of our lives [6].

As a result of the constantly evolving nature of the space industry, which creates these satellites, it can respond quickly to emerging business opportunities. Technology or methods that lower the cost of offering the services will probably be adopted relatively fast in the industry [6].

Very Low Earth Orbits travel at an altitude range where the design of satellites is significantly impacted. This results from the aerodynamics of the remnant atmosphere from these orbits [7]. The altitude range —which descends to an elevation of 450 kilometres —is defined due to the aerodynamic forces mentioned before.

Recent studies strive to identify a solution for maintaining operations at lower heights to develop novel materials and aerodynamics to achieve drag compensation [5].

Among the benefits, tolerance to radiation surroundings and the capability of launch vehicles to dispose of more payload into lower orbits for reduced currency can be established [7].

2.1.1.1 Benefits

The optical resolution, radiometric performance, transmission and Antenna Area (Radar), latency and frequency reuse, radiation environment, launch vehicle performance, end-of-life disposal, Debris Collision Resilience and Geospatial Accuracy are some of the direct benefits there can be encountered when it comes to VLEO [8]:

- **Optical Resolution**
  The altitude can be lowered due to their enhanced optical resolution. The aperture diameter may grow when the height is decreased, allowing the payload mass to fall as well [8].
- **Radiometric Performance (Optical)**
  Just as before, it can improve signal power by reducing altitude as well as increasing aperture diameter [8]. It speaks of the level of detail that an image can include [9].
- **Transmission and Antenna Area (Radar)**
  Thanks to VLEO, a reduction in the transmitted power needed and the antenna area is found [8].
- **Latency and Frequency Reuse**
  Latency is reduced when altitude is decreased as well. Also, the signal propagation time is balanced when time is switched and refined [8].
- **Radiation Environment**
  Due to sensitive electrical components, VLEO reduces radiation exposure. The performance of long-lasting materials, such as polymers, is another significant advantage [8].

- **Launch Vehicle Performance**
  Performance can be enhanced by increasing overall launch capacity, lowering cost per unit mass, and using a variety of launch vehicles with the necessary capabilities [8].

- **End-of-life disposal**
  There is no need for extra deorbit hardware [8].

- **Debris Collision Resilience**
  In essence, debris is bits of trash floating around in space. VLEO helps in terms of clearing it.

- **Geospatial Accuracy**
  Lastly, it lessens the need for ADCS (Attitude Determination and Control), albeit it must be acknowledged that detecting positional inaccuracies is more challenging when altitude is decreased [8].

2.1.1.2 Drawbacks

Amongst the drawbacks that are associated with Very Low Earth Orbits, aerodynamic drag can be found, which will be explained later on:

- *Aerodynamic drag* grows with density and velocity, both rising with decreasing altitude, such that the drag force produced by propulsion would need to be fully offset to maintain a certain orbital height [8].

- *Aerodynamic Attitude Perturbations* diminish platform stability, up the disturbing pointing torques and the need for the trajectory tracking actuator [8].

- *Atomic Oxygen Erosion:* It is crucial to know that atomic oxygen is very responsive, leading to numerous particle-surface interactions at greater densities. Orbital velocity's increased impact energy causes surface erosion and damage from oxygen atomic collisions [8].

2.1.1.3 VLEO/LEO Satellites

A satellite that orbits in Low Earth Orbits consists of an electronic circling device which surrounds the Earth at a distance of two thousand to two hundred kilometres [10].

These satellites are typically used in telecommunications and armed forces examination or espionage, resulting in different advantages. They are less expensive because they use less rocket fuel and considerably less power to travel faster. It also makes moving through a significantly denser atmosphere possible despite experiencing more aerodynamic drag [10].

2.2 Diverse developments

Due to the emerging problem, many associations have been developing solutions to the issue. Several patents have been filed to address this issue, for example:

- **Atomic Oxygen-Resistant, Low Drag Coatings and Materials**, *US20200207061A1* by *Timothy K. Minton* and *Thomas E. Schwartzentruber*. From 2020, his patent is not active yet and claims to supply an atomic oxygen-resistant material that is drag-reducing on just a portion of a spacecraft.

- **Atomic oxygen protective coating with spontaneous physical damage repairing function and preparation method thereof**, *CN108329502B*. Applied in 2018 and finally granted in 2020, this patent concerns an atomic oxygen protective coating that repairs physical damage.
- **Polymeric coating for protecting objects**, *US8053492B2* by *Garrett Poe* and *Brandon Farmer*. Being active since 2011, their invention is about creating a protective cover performed for rough environments, specifically polymeric protective coatings.

Aside from patents, there are numerous associations which have conducted research and also who are actively still doing so. Here are some organisations that can be found:

- **European Space Agency (ESA)** launched back in 2009 the *Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)*, which was the first Earth Explorer mission to study the gravity field while in orbit. On October 21st, 2013, it ended because of a fuel shortage [11].
- **Japan Aerospace Exploration Agency (JAXA)** developed the *Super Low Altitude Test Satellite (SLATS)*, a mini-satellite able to orbit the planet at the height of 180-250 km, its primary goals being the ability to ascertain whether orbit control utilising an ion engine technology (which compensates for air drag) is feasible and to comprehend the consequences of high-density atomic oxygen on the satellite [12].
- **The Air Force Research Laboratory (AFRL)**, where they will investigate how the ionosphere's ionisation processes work at VLEO.
- **DISCOVERER project** launched the *Satellite for Orbital Aerodynamics Research (SOAR)*, a 3U CubeSat mission to analyse the gas-surface interactions (GSIs) of various materials in VLEO [13], this thesis standing here.

  SOAR is enabled with [14]:

  - An Ultra-High Vacuum (UHV) that has pumping capability, allowing for the performance of FMF conditions while taking into consideration the incoming flux of AO [14]
  - An orbital flow and energy of AO provided by a hyperthermal oxygen atom generator (HOAG) [14]
  - To map the 3D particle scattering from the sample surface, a rotating sample stage and detection system with ion and neutral mass spectrometers (INMS) and residual gas analysers (RGA) are used [14]

2.2.1 DISCOVERER Project

To be able to explore new technologies for making sustainable and affordable satellites in Very Low Earth Orbits, DISCOVERER (**DIS**ruptive te**C**hn**O**logies for **VER**y low **E**arth o**R**bit platforms) was founded. It is a European project funded by Horizon 2020 with €5.7M [6].

Through the use of cutting-edge technology, like aerodynamic materials, aerodynamic attitude and orbit control techniques, this project aims to facilitate operations at these lower altitudes.

To considerably lower the cost of many European programs, they aim to revamp Earth observation satellites. In addition to giving Europe global leadership in advancing and commercialising such current innovation, these programs cover disaster monitoring, land management, maritime surveillance, intelligence and security, precision agriculture and food security, and land management [1].

The DISCOVERER project is encouraged by three challenges:

- How to improve technologies to enhance Earth Observation platforms?
- Are there any propulsion methods in which the propellant is made out of residual atmospheric gas to compensate for the drag?
- Which materials significantly reduce the drag on spacecraft surfaces?

It also contains eight work packages (WPs), each one focused on different matters:

1. **Materials and Aerodynamic Control Test Satellite**
2. **EO Aerodynamics and Control**
3. **Atomic Oxygen Wind Tunnel**
4. **Atmosphere-Breathing Electric Propulsion (ABEP)**
5. **VLEO System Design and Long-Term Business Opportunities**
6. **Project Management**
7. **Dissemination**
8. **Ethics requirements**

This thesis will mainly focus its investigation on WPs numbers 1 and 5. Its goal is to pinpoint modern and groundbreaking business models; this thesis is centred on creating a roadmap to facilitate the research of finding novel materials in VLEO.

The DISCOVERER consortium is formed by:

- The University of Manchester (UNIMAN)
- Elecnor Deimos Engineering and Systems (DEIMOS)
- Gomspace APS (GPS)
- University of Stuttgart (USTUTT)
- Universitat Politècnica de Catalunya (UPC)
- University College London (UCL)
- Euroconsult (ECONSULT)
- Concentris Research Management GMBH (CONCENTRIS)

Also —as it is said on their webpage —they have three objectives that must be fulfilled:

1. First of all, the project outcome must be discussed with different stakeholders. As mentioned, this will be done in our thesis with UNIMAN's help.
2. The research will have to have a place in the real-world context, and the benefits have to be clear
3. Finally, achieving more compact, lightweight, and affordable technologies in VLEO has to be accomplished (in this thesis, in the novel materials matter).

Chapter 3

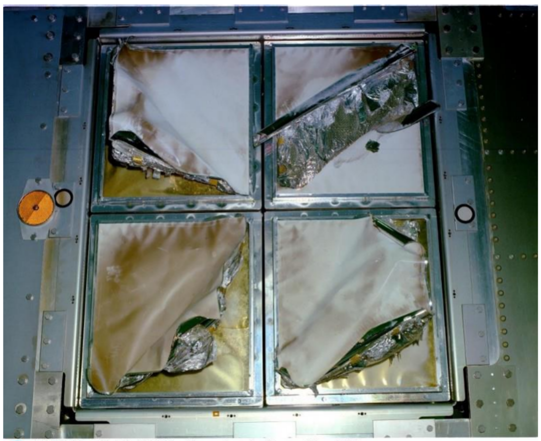
State-of-the-art

3.1 Current problem

When designing satellites operating at Very Low Earth Orbits, it is vital to consider materials resistant to atomic oxygen (AO). Since AO is the most prevalent chemical in the atmosphere in VLEO, materials with improved gas-surface interaction (GSI) performance generally concentrate on AO's characteristics [15].

Nowadays, atomic oxygen is problematic due to the degradation and damage that it creates to any spacecraft's surface. It leads to problems when it comes to performance, developing issues in terms of structure and failure [2], as well as erosive damaging spacecraft surfaces after adhering there [15].

It has to be noted that whenever there is an AO contact, it provokes a highly reactive response due to the higher density in VLEO [8]. Several factors enter a plea when operating different elements or materials, such as the residual atmosphere or the ultraviolet radiation from the Sun [16].



LDEF (Postflight), M0001 : Heavy Ions in Space, Tray H03
NASA Langley Research Center 2/6/1990 Image # EL–1994–00316

Figure 3.1: AO erosion combined with ultraviolet degradation. Extracted from NASA Langley Research Center

So, *how is atomic oxygen formed?* Photolysis of diatomic oxygen takes a toll on its creation, which consists of separating an oxygen molecule into two oxygen atoms by photons with ultraviolet radiation. It is a large component due to the small probability of ozone-forming, having high chances of survival in such altitudes [17].

These atoms are exceedingly corrosive when they come into contact with different materials. Moreover, at the high speeds that spacecraft operate, the flow of energy of 5 eV creates various chemical and physical interactions [17].

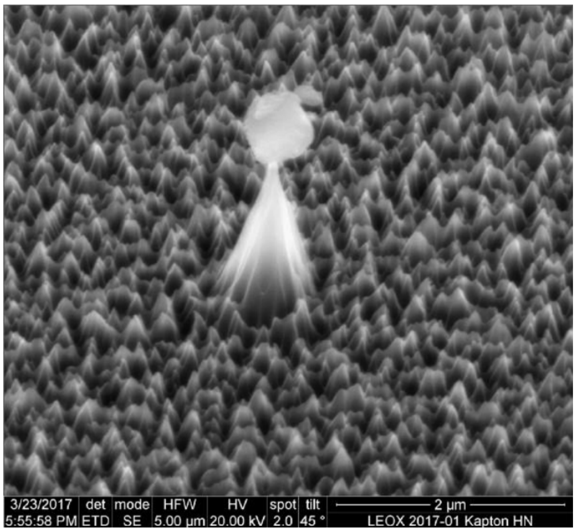


Figure 3.2: AO erosion. Extracted from ESA —CC BY-SA IGO 3.0

Atomic oxygen is significantly concerning, resulting in various consequences listed next:

- Surface degradation and structural effects: once AO has come inside regions due to the spacecraft having openings on its exterior, it can cause a direct attack on the overall space vehicle, creating several damages while degrading its optical properties and changing its morphology [18] [19]. It is pertinent to note that performance can be affected gravely. It also can cause harm to different components of the spacecraft, such as material loss and surface erosion, generating a weakened structure over time [20] [19].

- Contamination: because volatile species are condensed on the spacecraft exterior —these being a result of the reaction of polymers and carbon with AO —they get fixed on it and create surface contaminants which end up modifying optical and thermal qualities of materials [21].

- Thermal control problem: carbon-carbon composite is prone to be attacked by AO in VLEO, deteriorating its durability and disrupting its thermal regulating system [22].

Furthermore, several polymeric materials cause AO reactions with different mechanisms [19] —they usually attach to the surface, creating oxide, going straight into the material [19]. Adjacent, the attachment process is explained:

- **Abstraction:** in this process, the atomic oxygen abstracts the atom, exempli gratia, hydrogen

- **Addition:** an oxygen atom gets attached to an organic composite

- **Elimination:** the hydrogen atom is eliminated when the primary product is a vibrationally aroused molecule

- **Insertion:** AO inserts itself into an organic molecule

- **Replacement:** finally, AO replaces a part of the previous molecule, this being degraded

To conclude, novel materials are to be found, and a share of properties must be fulfiled so they are successful:

- They have to be resistant to AO effects
- Reflection that is specular or quasi-specular [8]
- They have to reduce drag
- Lift force production must be facilitated
- There has to be resilience facing thermal cycling and N_2 exposure [15]

3.2 Materials technology

3.2.1 Aerodynamic drag

Due to the exchange of molecular momentum among the atmosphere and the satellite surfaces, atmospheric drag is the primary cause of drag in a satellite in VLEO [23].

As it concerns materials, there is an uncertainty in determining how to get aerodynamic coefficients exactly [13]. Still, it is clear that when it comes to the shape of the materials, surface properties, orientation concerning the velocity vector, and velocity about the atmosphere are all elements that affect how much aerodynamic drag they produce.

Materials typically experience more drag if they have a larger surface area vulnerable to airflow. Moreover, materials with a rough surface texture will produce more drag than those with a smooth surface because the roughness will stir up the airflow and increase drag.

Generally speaking, materials with a larger surface area exposed to the airflow will experience more drag. Moreover, materials with a rough texture on their surface will generate more drag than those with a smooth texture since the irregularity will agitate the airflow and heighten drag.

As said in [13], as a result of greater aerodynamic attitude disturbances, the experimental ambiguity on the estimation of the drag coefficient normally increases with decreasing surface accommodation coefficients.

Given that drag depends on the velocity of the air, the correlation between its effect on materials can be made. The quantity of drag produced by a specific form of item depends on how inclined it is to the flow. When an item travels through the air at speeds close to the speed of sound, shock waves occur on it, adding an extra drag force known as wave drag [24]. That being said, the amount of drag is also influenced by how the materials are oriented with the velocity vector.

A reduction in drag is often accomplished for traditional materials (diffuse reemission with roughly complete energy accommodation) by decreasing the cross-sectional area. Biconical profiles, or shapes having tapered forward and rear-facing surfaces, are discovered to be ideal [15].

With cutting-edge aerodynamic materials, reducing drag is more strongly influenced by the angular position of the spacecraft surfaces in relation to the flow [15]. It may also be beneficial to generate lift forces that could be used for control [15].

Reducing the drag on materials in VLEO is key for the long-term sustainability of space activities.

3.2.2 Types of materials

Some materials are more prone to attacks from atomic oxygen than others, so this matter will be addressed in this section.

Foremost, AO is more likely to affect five kinds of spacecraft materials: *composite materials, tribomaterials, thermal control components, optical components* and finally, *space power components.*

- **Polymer matrix composite materials**

  These materials are mostly used for the spacecraft structure, payload, power and thermal control subsystem applications [19].

  When AO interacts with these materials, it deteriorates polymer matrices so that a molecular segmentation takes place, resulting in the polymer's erosion and the surface recession based on the product [19].

  Carbon fibres, Kevlar fibres, thermoplastic resin matrix and thermoset resin matrix, can be found in this group of materials.

- **Tribomaterials**

  Tribomaterials are substances that irritate and degrade when in contact with other substances. These substances, which might be solids, liquids, or gases, are frequently employed in mechanical systems, including those found in engines, pumps, and bearings.

  Solid lubricants for spacecraft can be organic or inorganic and be classified as metallic or non-metallic. They deteriorate by oxidation or erosion due to volatile oxide components evaporating [19].

  Amongst tribomaterials arise out lamellar solids (MoS_2), soft metals such as silver, lead and indium and finally *polymers*, which are widely used thanks to being lightweight and durable.

- **Thermal control components**

  When it comes to thermal control components, which are —in essence —metallized polymers and organic paints, which contain a high amount of carbon, hence these being so prone to be degraded, solar absorptivity and infrared emissivity are crucial to be taken into consideration [19].

  Amidst the effects —the ones explained before —thermo-optical assets deterioration and mass loss take place.

- **Optical components**

  For a variety of spacecraft uses, such as astronomical, atmospheric, and earth observational missions, optical systems are employed, encompassing metallic components like silver, aluminium or titanium and dielectric coatings including magnesium fluoride, thallium fluoride, zinc sulphide and calcium fluoride [19].

- **Space power components**

  At last, space power components are commonly used to transform solar energy into electrical power and gather solar radiation to drive heat engines, with elements like photovoltaic solar arrays and solar dynamic power components [19].

So that AO does not have an abrasive effect on the spacecraft's materials, protective mechanisms are used, and they must have a list of requirements (extracted from [19]):

1. First of all, it is essential they are immune to any AO attack
2. These mechanisms are to be thin, liable to adhere easily and lightweight
3. They must be perfect, not having any imperfections such as pores
4. They have to be pollution-free
5. Properties of the initial material shall not be modified, as well as the application procedure
6. They should be physically sound with the supporting substance
7. They have to be compatible with LEO/VLEO environment
8. They are to be economical

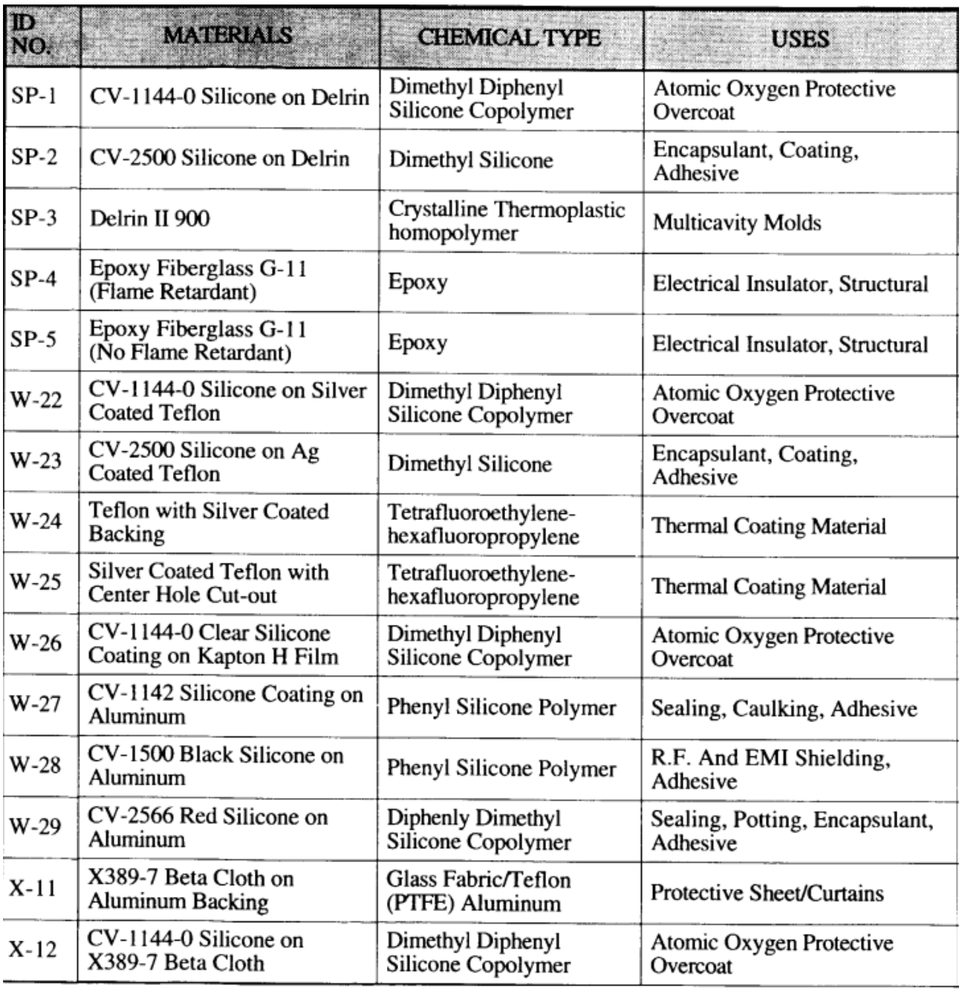
Materials resistant to AO attacks. Own elaboration								
Material	**Chemical type**	**AO attack**	**Specular/quasi-specular**	**Lightweight**	**Imperfections**	**VLEO compatible**	**Drag**	**Other comments**
CV-1144-0 Silicone on Delrin [25]	Dimethyl Diphenyl Silicone Copolymer [25]	Immune v[25]	White and shiny, when exposed there is risk of a portion of it being not as lustrous [25]	Yes	Cracks can be found close the edge of the material, as well as particle impact zones [25]	Yes	Not found	It offers resistance to radiation and thermal stress [25]
CV-1144-0 Silicone on Silver Coated Teflon [25]	Dimethyl Diphenyl Silicone Copolymer [25]	Immune [25]	Transparent and shiny, clear Coating is less reflective [25][26]	Yes	Visible cracks when exposed [25]	Yes	Not found	Low outgassing property [25]
CV-1144-0 Clear Silicone Coating on Kapton H Film [25]	Dimethyl Diphenyl Silicone Copolymer [25]	Immune [25]	Shiny and transparent [25]	Yes	Visible cracks when exposed [25]	Yes	Not found	Used for high and low temperature applications [25]
CV-1144-0 Silicone on X389-7 Beta Cloth [25]	Dimethyl Diphenyl Silicone Copolymer [25]	Immune [25]	Not found	Yes	Almost none [25]	Yes	Not found	ESD and thermal control [25]
Kapton AOR [27]	Polysiloxane and polyimide copolymers [27]	Highly resistant [27]	Not found	Yes	Likely to crack [27]	Yes	Not found	They must be subjected to both vacuum thermal cycling and VUV radiation. [27]
Siloxane coating [28]	Organosilicon chemistry (Si-O-Si) [28]	Immune [28]	Not found	Yes	No notorious peeling/cracking. There are micro-cracks [28]	Yes	Not found	Prepared by plasma polymerization deposition [28]
PECVD (plasma-enhanced chemical vapor deposition) [28]	Moisture and outgassing barrier (MOB) with AO and UV layer [28]	High effectiveness [28]	Not found	Yes	Almost none [28]	Yes	Not found	Multilayered protection barrier [28]
Al_2O_3 ALD (Atomic Layer Disposition) [29]	Aluminium oxide [29]	Immune [29]	They are smooth like the surface of the polymer they are coating [29]	Yes	The accumulation of several atomic layers on the substrate tends to smooth out flaws in the polymer surface [29]	Yes	Drag is significantly reduced [29]	May be used in extreme oxidizing and in a high-drag environment [29]
SiO_2 [27]	Silicone dioxide	Highly resistant [27]	Not found	Yes	It cracks when a flexure test is performed. It also has defects in the coating [27]	Yes	Not found	It is easy to apply, technology mature, and it has large ground and space data [27]
SiO_2 with FP [27]	Silicone dioxide with fluoropolymer	Highly resistant [27]	Not found	Yes	When it is handled it produces cracks and scratches [27]	Yes	Not found	Easy to apply and technology mature [27]
Polyphosphazenes [27]	Hybrid inorganic-organic polymers	Resistant [27]	Not found	Yes	None	Yes	Not found	There is limited data [27]

Table 3.1: AO resistant materials

The quest for innovative materials resistant to AO attacks was focused on four publications after carefully examining a collection of research papers so that the instructive grid 3.1 on the previous page was possible to make: "*Atomic Oxygen and Space Environment Effects on Aerospace Materials Flown with EOIM-3 Experiment*" [25], "*Atomic oxygen protective coatings for Kapton film: a review*" [27], "*Effect of Coating Thickness on the Atomic Oxygen Resistance of Siloxane Coatings Synthesized by Plasma Polymerization Deposition Technique*" [28] and "*On the Utility of Coated POSS-Polyimides for Vehicles in Very Low Earth Orbit (VLEO)*" [29].

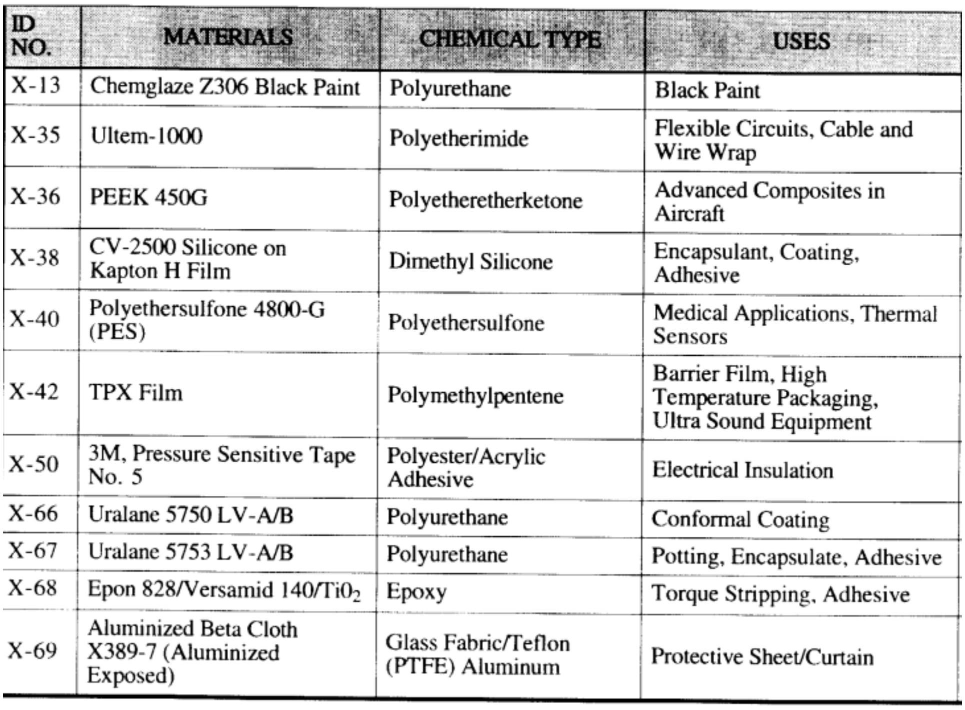
To determine which material is best multiple tests would have to be done to compare them. Only a comparative chart has been produced thus far, highlighting how much more research needs to be done in this area.

It must be noted that there are several more materials, but only those resistant have been considered to make the comparison. Subsequently, a list of materials can be observed:



ID NO.	MATERIALS	CHEMICAL TYPE	USES
SP-1	CV-1144-0 Silicone on Delrin	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat
SP-2	CV-2500 Silicone on Delrin	Dimethyl Silicone	Encapsulant, Coating, Adhesive
SP-3	Delrin II 900	Crystalline Thermoplastic homopolymer	Multicavity Molds
SP-4	Epoxy Fiberglass G-11 (Flame Retardant)	Epoxy	Electrical Insulator, Structural
SP-5	Epoxy Fiberglass G-11 (No Flame Retardant)	Epoxy	Electrical Insulator, Structural
W-22	CV-1144-0 Silicone on Silver Coated Teflon	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat
W-23	CV-2500 Silicone on Ag Coated Teflon	Dimethyl Silicone	Encapsulant, Coating, Adhesive
W-24	Teflon with Silver Coated Backing	Tetrafluoroethylene-hexafluoropropylene	Thermal Coating Material
W-25	Silver Coated Teflon with Center Hole Cut-out	Tetrafluoroethylene-hexafluoropropylene	Thermal Coating Material
W-26	CV-1144-0 Clear Silicone Coating on Kapton H Film	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat
W-27	CV-1142 Silicone Coating on Aluminum	Phenyl Silicone Polymer	Sealing, Caulking, Adhesive
W-28	CV-1500 Black Silicone on Aluminum	Phenyl Silicone Polymer	R.F. And EMI Shielding, Adhesive
W-29	CV-2566 Red Silicone on Aluminum	Diphenly Dimethyl Silicone Copolymer	Sealing, Potting, Encapsulant, Adhesive
X-11	X389-7 Beta Cloth on Aluminum Backing	Glass Fabric/Teflon (PTFE) Aluminum	Protective Sheet/Curtains
X-12	CV-1144-0 Silicone on X389-7 Beta Cloth	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat

Figure 3.3: Materials list. Extracted from [25]



ID NO.	MATERIALS	CHEMICAL TYPE	USES
X-13	Chemglaze Z306 Black Paint	Polyurethane	Black Paint
X-35	Ultem-1000	Polyetherimide	Flexible Circuits, Cable and Wire Wrap
X-36	PEEK 450G	Polyetheretherketone	Advanced Composites in Aircraft
X-38	CV-2500 Silicone on Kapton H Film	Dimethyl Silicone	Encapsulant, Coating, Adhesive
X-40	Polyethersulfone 4800-G (PES)	Polyethersulfone	Medical Applications, Thermal Sensors
X-42	TPX Film	Polymethylpentene	Barrier Film, High Temperature Packaging, Ultra Sound Equipment
X-50	3M, Pressure Sensitive Tape No. 5	Polyester/Acrylic Adhesive	Electrical Insulation
X-66	Uralane 5750 LV-A/B	Polyurethane	Conformal Coating
X-67	Uralane 5753 LV-A/B	Polyurethane	Potting, Encapsulate, Adhesive
X-68	Epon 828/Versamid 140/Ti0$_2$	Epoxy	Torque Stripping, Adhesive
X-69	Aluminized Beta Cloth X389-7 (Aluminized Exposed)	Glass Fabric/Teflon (PTFE) Aluminum	Protective Sheet/Curtain

Figure 3.4: Materials list. Extracted from [25]

3.3 Roadmap

When Stephen Baxter wrote his hard science fiction novel *Voyager*, he already knew roadmaps were the key to success: *"Since then we, and others, have worked hard to compile, umm, a road map of the future. In fact, we already have proof that our studies of the future are generally successful."* [30]

Roadmaps are becoming such an important instrument when it comes to science, technology and innovation foresight, them being a well-known approach to strategic planning. In order to meet the demands of maintaining a supply of products as well as services to the market, they tend to merge both product and business planning. Links between research projects, action mobilization, and information sharing are made simpler using visual display aids.

It is an approach that leads through organized systems thinking, visual techniques and other participatory approaches to handle organizational challenges and possibilities while encouraging communication [31].

No successful firm operates without a roadmap: it facilitates requirement alignment and keeps operations on schedule, this being able to be demonstrated dating back to Motorola's initial implementation of the entire roadmapping process in the 70s. Since then, each of their products that have entered the market has been prepared beforehand using a roadmap, allowing the process to foresee any changes and ensuring success [32].

Experts have observed that due to roadmaps being so common, they frequently aim to address three issues:

- **Where are we now?** *To know where to go, a specific goal must be set*

- **How can we get there?** *To attain one's objectives, it is important to know what they are seeking*
- **Where are we going?** *Which techniques are to be followed to fulfil the main aim*

In essence, a roadmap's graphical design and visual appeal play a significant role in how well it is viewed[33], and they serve as tools to carry out the planning and aligning processes, which are essential to roadmapping since they show potential next steps [34].

3.3.1 Different roadmap methodologies

A roadmap methodology is not a quick examination. It has been a subject of continuing research for a while, leading to a variety of frameworks created by numerous publishers and academics.

Roadmaps can be created in a variety of methods, such as by conducting research with a company that needs one in order to succeed with whatever project it is working on.

Collaborations with companies result in having to hold workshops, such as T-Plan and S-Plan, which are explained in the next section of this thesis.

A great example of this type of methodology is the one used with the LEGO Group Experience, a research carried out with Clive Kerr, Robert Phaal and Kasper Thams [34]:

1. First step would be to do pre-workshop work to make the actual workshop go like clockwork
2. Next step is the reviewing of the participants of the workshop to ensure their contributions will be useful
3. Brainstorming comes next, alongside the prioritization of them
4. The selection of the final ideas is the following stage so that the workshop can be finally closed
5. Last but not least, the post-workshop work to examine all the data and create the roadmap itself.

Another great way of roadmapping is the solution they propose from CEAS Space Journal [35]. It entails examining the launching market and its level of competition, then outlining the most promising needs and necessary functionalities. A SWOT and stakeholders analysis must be completed, after which the budget must be defined and a risk analysis executed. Ultimately, using this process, the timeline is created.

A design-driven approach can also be executed. It has four different steps [36]:

1. **Frame:** in this step, it is indeed crucial to comprehend the opportunity's specifics and the process involved. It is necessary to identify the target while also identifying the conditions that must be met.
2. **Structure:** here the layout is created while answering the key layers, *what-why-how*
3. **Relationship:** the pathways are identified, translating the layout done before into a visual arrangement
4. **Direction:** final completion of the narrative flow

The roadmap presented by Vishnevskiy et al. [37] is also interesting to be reviewed. The methodology is defined in five different steps:

1. **Pre-roadmapping:** the topic field's domain and primary priority approaches are established
2. **Desk research:** a literature review is conducted to gather basic knowledge about potential technology and goods. The technological push strategy is the key driving force behind this step
3. **Expert procedures:** expert interviews are conducted
4. **Creative analysis:** to identify the main opportunities and constraints of the subject field developments, a SWOT evaluation is performed, as well as a stakeholder study to determine the benefactors and effects of the roadmap.
5. **Interactive discussion:** workshops to lessen future uncertainty and debate potential scenarios.

University of Torino also developed a recent roadmap which is "rational, objective and traceable" [38]. It is called TRIS methodology, and it stands for Technology Roadmapping Strategy.

Figure 3.5: TRIS methodology. Extracted from [38]

It is based on operational capabilities, technical know-how, building blocks (substantial elements) and finally mission concepts (research work and tasks) [38].

Therefore, what qualities must a roadmap possess in order to be excellent? As said in [33], [39] and [40]:

- They must have user-friendly structures, as well as definite timelines and clear connections [33]
- Layers must be used
- A multidisciplinary team is involved [40]
- There is senior management commitment [39]

- Stakeholders are important
- Time and development costs have to be taken into account
- Explicit timelines are portrayed [33]
- There has to be colour coding as well as a one-page summary [33]
- Every roadmap has to be different based on audience [33]

3.3.2 Workshops

Agile development is what most businesses aim to achieve, so workshops are held in order to limber the process. This technique is called a *fast-start* process, allowing the commodities to arrive at enterprises. A good workshop resides in being organized, planned beforehand and having the most number of worthwhile participants.

When it comes to planning a fast-start workshop, two kinds can meet the client's expectations: *T-Plan* and *S-Plan*, each with benefits and drawbacks.

A **T-Plan process** is based on holding four workshops throughout four different days, where the focus of the first three reside on setting up the process —ergo doing an analysis of the market product and technology that will be taken into account —and the last workshop is used to combine all knowledge acquired to finally create the roadmap [41].

In counterpart, a **S-Plan process** consists of just a one-day workshop, allowing to have more flexibility when it comes to keeping the attention of the participants but having its nuisances in relation to the time used to conduct the workshop [34].

In the matter of having to choose which process is best, the next chart reflects their key characteristics next to their counterparts, allowing a better comparison:

T-Plan	S-Plan
Workshop hold in 4 different days, providing greater flexibility in terms of timing	One-day workshop, with the incovenience of having a short time frame and increased pressure
Participants may lack attention due to having extended workshops	Participants focus exclusively on the workshop, as they know the duration of it
Full understanding of the concepts	Limited understanding of the concepts
Participants' backgrounds not being as important as in S-Plan	Being more aware of the participants that are involved
Almost everything is done during the session, thus there is less post-processing.	Post-workshop process is more difficult, as the time is very limited and there's a lot of data

Table 3.2: Fast-start processes comparison chart

Each procedure has several advantages and disadvantages, as seen in table 3.2, where the colour green symbolizes the most favourable option, and red is shown as the less one. The organizer of the workshop will have the ultimate say in the final decision.

Thus, a retread: the core of a workshop is the ability to specify the vision of a product; hence its importance, and the process chosen to carry it out is crucial to the success of the final product.

Chapter 4

Roadmap framework methodology

4.1 New roadmap methodology

This section's primary goal is to create a new roadmap framework methodology for strategic planning to accomplish goals. The current atomic oxygen issue has prompted the development of upgraded satellites with new materials for EO at VLEO in an effort to reduce the costs involved with spacecraft production, which has sparked the need for this new methodology.

This methodology was developed over the span of one month by two junior engineers and a senior one while conducting a thorough evaluation of 24 articles, which allowed for the development of the presented framework.

An agile development process was used to create the final product, which involved holding weekly scrums to discuss the literature study that each engineer was reviewing, presenting their findings, and exchanging ideas.

The literature review is based on the papers in table 4.1. This literature evaluation has benefited greatly from the contributions of numerous significant authors, including Dr Robert Phaal and Dr Clive Kerr.

Phaal is the Director of Research at the Strategic Technology and Innovation Management Consortium (STIM) and the Department of Engineering (CUED) at Cambridge University. With a mechanical engineering bachelor's and a PhD in computational mechanics, he has gained experience throughout the years in industrial and technical consulting, contract research and software development [42].

Kerr is a Chartered Engineer working as a Senior Research Associate at the Centre of Technology Management at Cambridge University, with diverse publications about strategic planning and roadmapping [43].

Nº	**Article**	**Reference**
1	Scenario-driven roadmapping for technology foresight	[44]
2	Roadmapping: missed opportunities to overcome strategic challenges	[40]
3	Roadmapping and roadmaps: definition and underpining concepts	[45]
4	Science and Technology Roadmap	[39]
5	The Current State of Technology Roadmapping (TRM)	[46]
6	Twenty years of technology and strategic roadmapping research: A school of thought perspective	[47]
7	Design thinking and product roadmapping in the fourth industrial revolution	[48]
8	Characterisation of technology roadmaps: purpose and format	[41]
9	Foresight and Roadmapping Methodology: Trends and Outlook	[49]
10	Agile Roadmapping: an adaptive approach to technology foresight	[31]
11	Promising roadmap alternatives for the SpaceLiner	[50]
12	Sustaining Organizational Roadmapping implementation	[51]
13	Technology roadmapping methodology for future hypersonic transportation systems	[38]
14	Technology roadmapping - Industrial roots, forgotten history and unknown origins	[52]
15	Developing a technology roadmapping system	[53]
16	An exploration into the visual aspects of roadmaps: the views from a panel of experts	[33]
17	Integrated roadmaps for strategic management and planning	[37]
18	Scenario-driven roadmapping to cope with uncertainty: its application in the construction industry	[54]
19	Technology roadmapping and SMEs: A literature review	[55]
20	Visualizing roadmaps: A Design-Driven Approach	[36]
21	The digitalisation of roadmapping workshops	[56]
22	Technology roadmapping - developing a practical approach for linking resources to strategic goals	[57]
23	Business roadmap for the European Union in the NewSpace ecosystem: a case study for access to space	[35]
24	Customising and deploying roadmapping in an organisational setting: the LEGO Group experience	[34]

Table 4.1: Literature review articles

The following subsections show a detailed description of the roadmap methodology that has been created.

4.1.1 Phases

As stated in previous sections, a roadmap is a useful strategic planning tool that allows the user to help foresight while binding objectives.

The way towards an organised roadmap is to start defining its different steps, which will then be broken down into individual stages. In this thesis, three different phases have been defined: *Initiation*, *Development*, and finally *Integration*, while using an iterative process that will help with the final implementation.

It is not easy to enforce a structured process due to its complexity, hence the importance of defining general phases. No roadmap starts without prior thinking about how it will be created: the *Initiation* step helps introduce the problem to an association, which is crucial due to the pressure of it being acknowledged by the interested parties.

Following the first phase, the *Development* step comes in, this one being the whole creation of the roadmap, which will be defined later in this section.

The last step, *Integration*, is all about implementing the roadmap while maintaining the iterating process going back and forth through the second and final stage. Fig. 4.1 shows a simplified diagram of the phasing process.

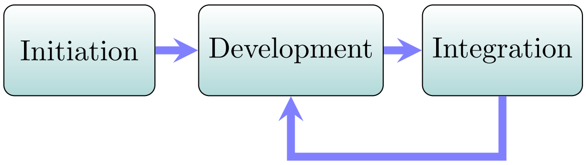


Figure 4.1: Phases of the roadmap

4.1.2 Initiation

Initiation bases itself on problem framing, meaning that the goal that has to be achieved is defined, as well as the corresponding people that must be involved. To acquire information in a methodical manner, the beginning is key [49].

The preparation of the workshops that are required to be executed is done in this stage. Given that it is vital to ensure that time is spent competently without experiencing workshop-related problems, a project team is formed to develop the roadmap. The scope, as well as the layout, are defined. Once the workshop is concluded, the analysis will be done on the further steps [44].

4.1.3 Development

The development of the roadmap is divided into three stages:

1. **Pre-processing:** State-of-the-art, the study of the market and current technology as well as a general literature review
2. **Generation and Evaluation:** scenarios generation and prioritization
3. **Action Plan:** an action plan is made, and KPIs are defined to assess the achievement

The key layers of roadmapping are addressed in this stage:

- *How?* This layer is solely based on the technologies used within the roadmap —it identifies the most propitious technologies for a given time frame, demonstrating their potential when it comes to their suitability for use and potential impact [37].
- *What?* The product itself is approached —a succinct explanation of proposed goods' commercial eagerness and potential effects on the relevant research field is given [37].

  - *Why?* Markets are analysed —negative, confident, and moderate market development scenarios are established. The key market characteristics and potential marketing approaches are also briefly portrayed [37].
  - *Alternatives* —when taking into account the kinetics of the products and their risks, all of which have already been examined, the potential creation of alternative products is proved [37].

4.1.3.1 Pre-processing

Analysing the current condition becomes essential during the pre-processing phase. A whole lot of factors are to be taken into account due to the constant changes in the market, so the driving forces are key [54].

At this stage, conducting a literature study and assessing the state of the art is the first step. Literature reviews are crucial for giving a compendium of sources of any particular topic with a determined pattern [58]. Recalling pertinent knowledge is beneficial for understanding the current issue and assessing any successful or unsuccessful judgments made in that area [59]. Thanks to literature reviews, many points can be made [58]:

- A previous planning of the problem can be performed
- The understanding is made clearer
- The research can be put in the context of the body of knowledge already available
- State of the art will be easier to demonstrate

Strategic management tools are used once the reviewing is done, which will aid in achieving the objectives. Four types of analysis will be performed in this methodology:

- **Stakeholder analysis**

  The value of a stakeholder analysis lies in the process it uses to find interested parties before the project even launches. According to their involvement, engagement, and effect in the project, all of them will be grouped in this study, and it will be used to decide how to effectively include and interact with each of them [60]. There are three steps to the analysis:

  1. Find out who the interested parties will be
  2. Organise and rank them
  3. Establish how to interact with them, making a *communication plan*

  To carry out the analysis flawlessly, another matrix must be created. When discussing the stakeholders, a Mendelow matrix will be used.

  When keeping track of all the stakeholders involved in the project, the level of power and interest is considered. If both groups are high, a stakeholder will be essential to the project, which means their involvement must be ongoing for the endeavour to be effective. It is crucial to maintain the happiness of those with greater influence but less interest so they can support the initiative at any risk. Interested parties who must be kept informed have a low level of force but a high level of interest, making them valuable from now on. The matrix will make it simpler to get rid of those who have no power or interest.

- **PESTEL Analysis**

  PESTEL stands for *Political, Economic, Social, Environmental* and *Legal.* It is a powerful technique that is primarily employed for strategic risk and that pinpoints the alterations and outcomes of the external macro-environment [61]:

  - Political: it must consider how much policymakers are expected to influence the commercial and market environment. Some examples are government policies, local legislation and funding, as well as grants [61].
  - Economic: the most visible influence on a market's or industry's profitability and general attractiveness comes from economic variables, such as local and international economy [61].
  - Social: they determine how people behave at work and how they view the world, as well as what consumers will buy and how much they will buy it; demographics, racial, ethnic and religious influences are accounted for [61].
  - Technological: it analyses new materials and any innovation done in the sector due to the quick growth of high-tech change [61].
  - Environmental: it considers every environmental matter that may affect the project.
  - Legal: it describes the legislation and regulation scenario that influences directly the organisation

- **5 Forces**

  In order to identify an industry's flaws and strengths, Porter's Five Forces analyse five competitive forces that affect every business [62]:

  1. Industry competition
  2. Possibility of new competitors
  3. Influence of suppliers
  4. Influence of customers
  5. Hazard of replacement products

- **SWOT Analysis**

  It is a tool for strategic planning that helps organisations understand how they compare to the competition and where they might expand or become susceptible and lose their competitive edge [35]. SWOT stands for *Strengths, Weaknesses, Opportunities* and *Threats.*

  To make a great SWOT analysis, the primary advantageous and disadvantageous agents have to be classified, identifying them with their respective actions aligned to the main goals of the roadmap. To facilitate the study, these actions are further divided into various groups with shared traits [35].

  A SWOT analysis entails building a matrix with opportunities and threats on the bottom left and right and strengths and weaknesses on the top left and right. The internal analysis is located at the top, and the external one is located at the bottom.

  Prioritisation must be performed in each matrix component so that the most crucial elements may be identified and used to suggest various courses of action for benefit extraction.

4.1.4 Generation and Evaluation

In this stage, foresight and scenario planning take a toll on roadmapping. A look into the future must be done, for every scenario has to be planned beforehand to explore all the possibilities. A structure has to be developed, given that the uncertainty of the future instigates previous research.

Four different key points have to be taken into account:

- Foresight
- Scenarios
- Linking grids
- Risk analysis

4.1.4.1 Foresight

The foundation of foresight is the analysis of technology, alongside consideration of the stakeholders and an eye toward the immediate future. A quantitative tool will be employed in this methodology to examine how various approaches have affected results in the past, which will be based on historical data [49].

When foresighting, it is important to consider the future implementation, as they do not have to be treated as different processes to ensure the success of it [31].

The use of foresight allows to:

- Confront the need for strategic corroboration [31]
- Reveal the inputs that require more work [31]
- Provide systematic decision issues [31]

4.1.4.2 Scenarios

At its core, a scenario is a future event that is likely to occur. It must be noted that it is not a prediction but rather a description of numerous possibilities that could occur if they were subjected to various circumstances [49].

Scenarios, alongside forecasting, help with the development of the technologies to be able to route the outcome.

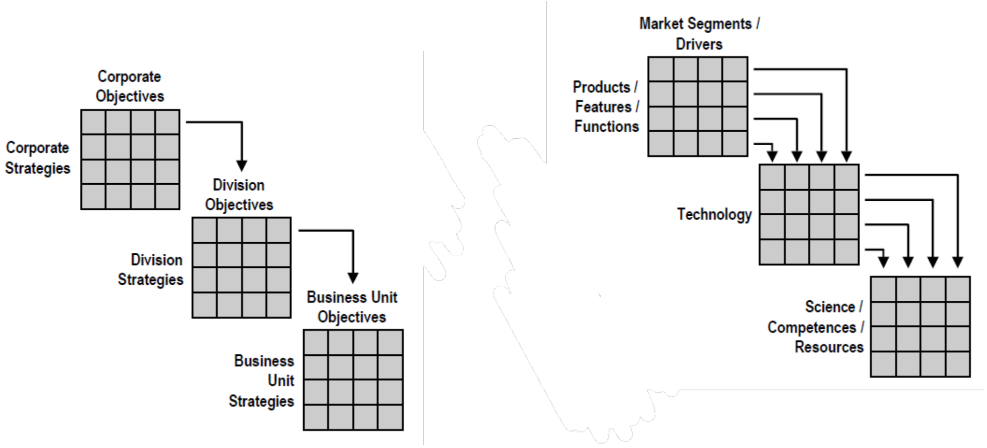
At this point, **flex points** must be addressed. So, what exactly is a flex point? They are significant events that would indicate changes along specific pathways to support efficient continuous assessment across time [44].

These points allow users to foresee any substantial environmental changes that could result in specific scenarios and plan any needed modifications. It is a fantastic approach to link hypothetical situations with possible future conditions [44].

4.1.4.3 Linking grids

This approach ties the client to technical specifications for product and process design [63].

For the understanding of this method, an example extracted from [53] will be used:



(a) (b)

Figure 4.2: Linking grids. Extracted from [53]

In figure (a), there is an ”organisational flow down/up of objectives and strategies” [53]; it facilitates businesses descending to lower levels to create class-conscious grids. In contraposition, figure (b) connects several layers and sub-layers, giving a clear picture of the order in which various technologies must be prioritised. It is a technique that enables easy management between roadmaps [53].

4.1.4.4 Risk analysis

To identify a way to prevent it, a risk analysis must be carried out to establish the likelihood of risk associated with the project.

Three factors are used to assess the threat: the maturity of the interested parties' relationship, the market's preparation, and the organisation's forwardness for the technology [35]:

- **Technology maturity [35]:** it assesses the risks associated with the R&D
- **Market maturity [35]:** risks related to the phase of product innovation
- **Value network maturity [35]:** risks affiliated to the stakeholders

4.1.4.5 Action Plan

Every plan must include a clear time-frame that depicts all progress along with the corresponding actions and the direction that must be taken to achieve it [35]. To sum up, the roadmap has to be *created*. Prioritising the market for the ensuing years will help decide which resources will be used and which items or processes will need to be created.

Also, as it has been said before, KPIs have to be calculated since they aid in defining objectives and approaches.

Layers —which have been mentioned previously —are easier to correlate thanks to flex points (also talked about in former subsections). At this juncture, actions have to be classified into different layers:

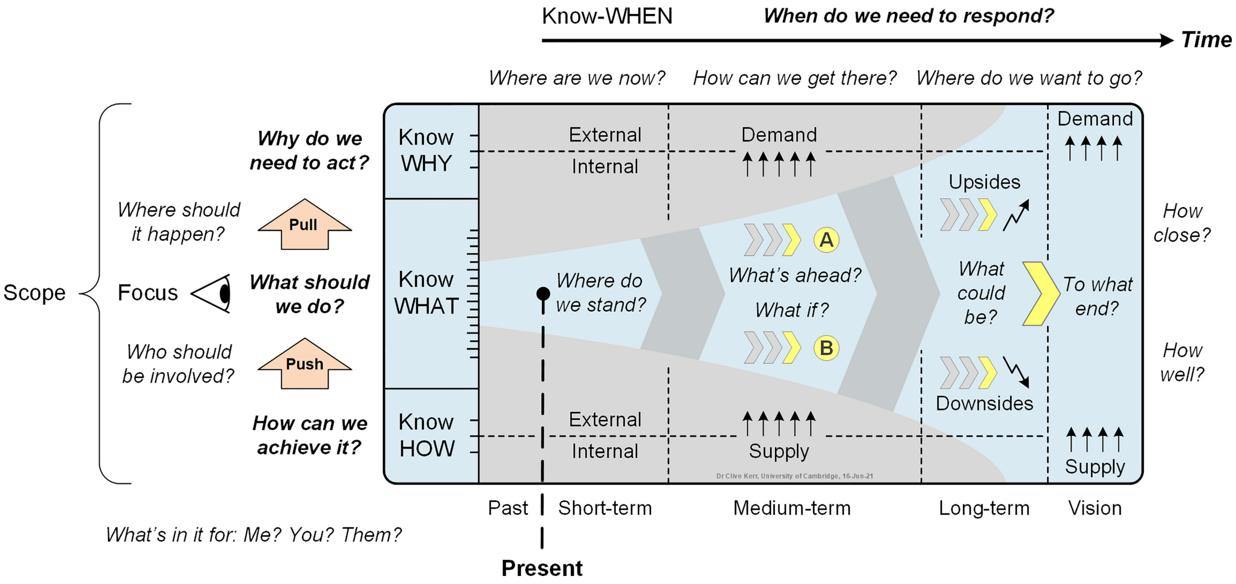


Figure 4.3: Roadmap layers. Extracted from [45]

What delivery methods are available, and how will the products change or advance? What creates value and offers benefits? *How* will the resources be acquired? *Where* correspond to the techniques used to achieve the main goal, and finally, the *why* part concerned logic and logic concerning both internal and external trends [45]. These answers will help the classification process go farther smoothly.

To finalise the development phase, it has to be acknowledged that there are four maturity levels to any roadmap ever done. The first level is *Organising* [53], where several roadmap types are employed; however, they are not usually related. Just classifying them into categories is what is done at this stage.

Level two is called *Proactive* [53], and the essence of the roadmap is designed here, achieving a robust structure. Following level two, there is the *Collaborative* [53] level, where the interconnections are made, and interactions with various individuals from various areas are conducted. Finally, the roadmap is refined in the last level, *Comprehensive* [53].

The budget estimation is also done in this phase; all projects have to estimate one to achieve success, hence the need to review these key points:

- The project's investment and running costs must be factored in, as well as the determining of the required fixed capital investment for it
- The degree of error in the cost estimation has to be taken into consideration

The starting, fixed, and circulating capital must be defined when creating a budget estimation. Management fees, a registry, studies, and research were all part of the beginning. Setting aside fixed capital, a project will need money to purchase all necessary tools for development. The funds required to cover the upfront charges is the remaining component of circulating capital [64].

4.1.5 Integration

In the final phase of this roadmap methodology, the roadmap is finally integrated, keeping in mind that an iterative process —, which will not be performed in this thesis —has to be conducted to guarantee a successful outcome. Market and expert interviews are frequently used in this iterative process to identify problems and make corrections while developing the roadmap. Additionally, the repeated holding of workshops is part of the iteration, as it helps to gain different perspectives and feedback.

4.2 Final methodology

The final roadmap framework methodology framework has been summarised in this graph:

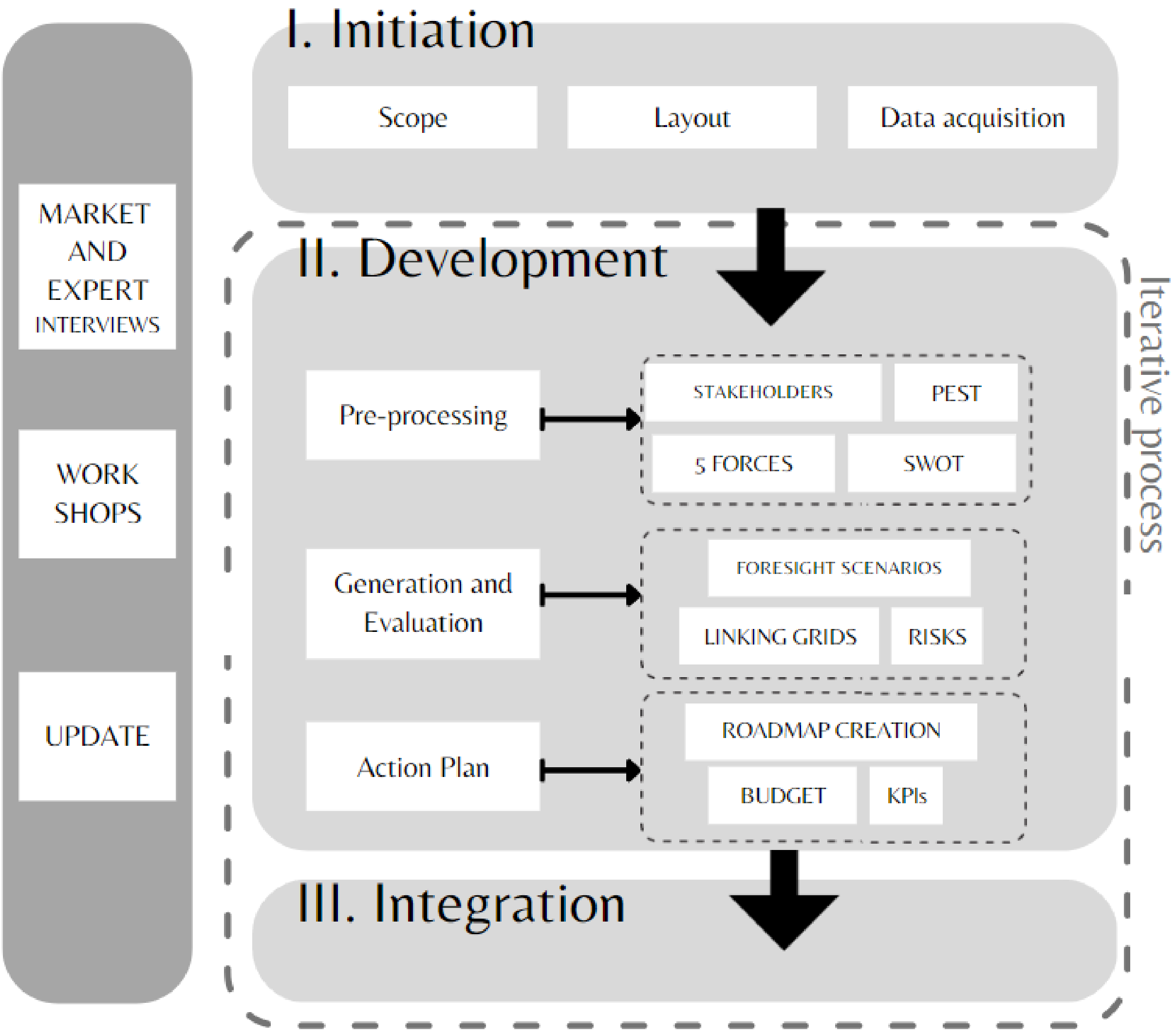


Figure 4.4: Final methodology

This roadmap methodology —, as described throughout the whole section —, consists of three phases: *initiation, development* and finally *integration.*

In the initiation phase, the scope, layout and data acquisition are done, which enables the process to be begun and structured.

This phase is followed by the development one, in which the pre-processing, generation and evaluation and finally, action plan are executed. In this phase, all analyses are done, going from a SWOT analysis to a KPIs one.

The integration phase of the roadmap follows a detailed iteration process that includes market and expert interviews to gather feedback, the holding of workshops, and the ongoing updating of the roadmap.

Chapter 5

Roadmap development

5.1 Market study

The following subsection provides an insight into the market study done to understand best where EO at VLEO for smallsats —applied to materials technology —stands. Knowing the state of the market is essential because it makes it simpler to comprehend both the needs of the consumer and the possibility of a future growth market.

This market study will have the following structure:

- Satellites' market
- Actual demand
- Future demand

5.1.1 Satellites' market

Small satellites —*smallsats* —are spacecraft which weigh less than 200 kg and have shorter processing cycles as well as cheaper costs overall —both for the creation of the satellites and their launch —when compared to standard satellites [65].

More risk-taking, experimentation and the development of novel applications not possible with larger satellites are made possible by these lower-cost satellites' expansiveness [65].

Smallsats are being used by an increasing number of people and are having an impact on practically every aspect of space technology, including communication, remote sensing, technology demonstration, and science and exploration [65].

According to the European Union Agency for the Space Programme (EUSPA) [66], the smallsats can be used in any of the 17 market sectors in the EO industry:

- **Agriculture:** in order to find solutions to optimise and promote sustainable management
- **Aviation and Drones:** one of the key objectives is to diminish their impact on the environment
- **Biodiversity, Ecosystems and Natural Capital:** to reduce biodiversity loss
- **Climate Services:** smallsats help when it comes to close monitoring

- **Consumer Solutions, Tourism and Health:** air quality and UV monitoring [66]
- **Emergency Management and Humanitarian Aid:** thanks to EO rapid responses to emergencies are being improved
- **Energy and Raw Materials:** related to the preparation and operations [66]
- **Environmental Monitoring**
- **Fisheries and Aquaculture:** smallsats give information on salinity, temperature, water characteristics, etc. [66]
- **Forestry:** carbon monitoring can be done with these tiny satellites
- **Infrastructure:** as in risk exposures and the effects of climate change in the future [66]
- **Insurance and Finance**
- **Maritime and Inland Waterways:** to calculate ship paths and optimize them
- **Rail:** smallsats will be able to identify millimetre-scale shifts in the ground [66]
- **Road and Automotive:** it will help in terms of road security [66]
- **Urban Development and Cultural Heritage:** related to health quality of the cities
- **Space**

Regarding all the applications, 5.1 shows all smallsats launched from 2013 to 2022 by application. As can be seen, the majority of launches are for remote sensing and technology development, with communications overtaking them as a result of the appearance of Starlink and OneWeb. The launch of LEO communication smallsats has also had an impact on the market growth of these satellites, which has been growing every year since 2020 with a slight decline between 2020 and 2021 due to the COVID pandemic.

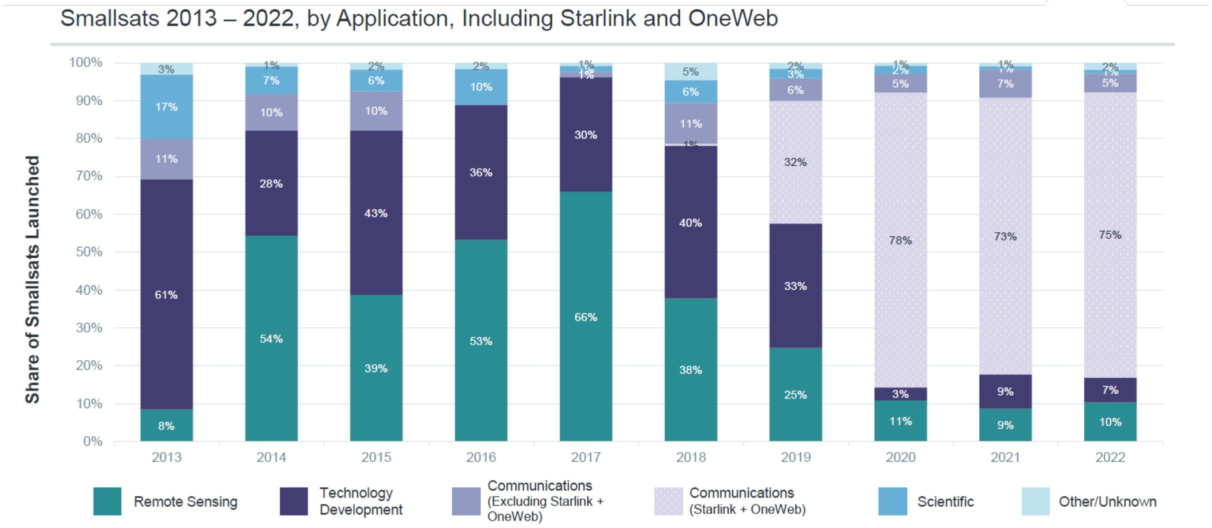


Figure 5.1: Smallsats 2013 2022, by Application, including Starlink and OneWeb. Extracted from [67]

This graph 5.1 can be classified into different mission-type trends:

1. Earth Observation: these smallsats are being utilized more frequently for Earth observation tasks like tracking natural disasters, monitoring climate change, and gathering information on agricultural and land use.
2. Communication: the creation and launching of smallsats for communications purposes, such as supplying worldwide internet connectivity, are significantly expanding the smallsat sector.
3. Remote Sensing: it includes tracking aircraft and ships, keeping an eye on oil spills, and monitoring animals.
4. Science and Exploration: the usage of small satellites in scientific research and exploration projects, such as imaging the Moon and other planets and monitoring the Earth's atmosphere, is growing.

The smallsat sector is expanding quickly, with more operators and mission types being created and put into operation. The mix of technology development, rising data and service demand, and declining launch costs are what is fueling this expansion.

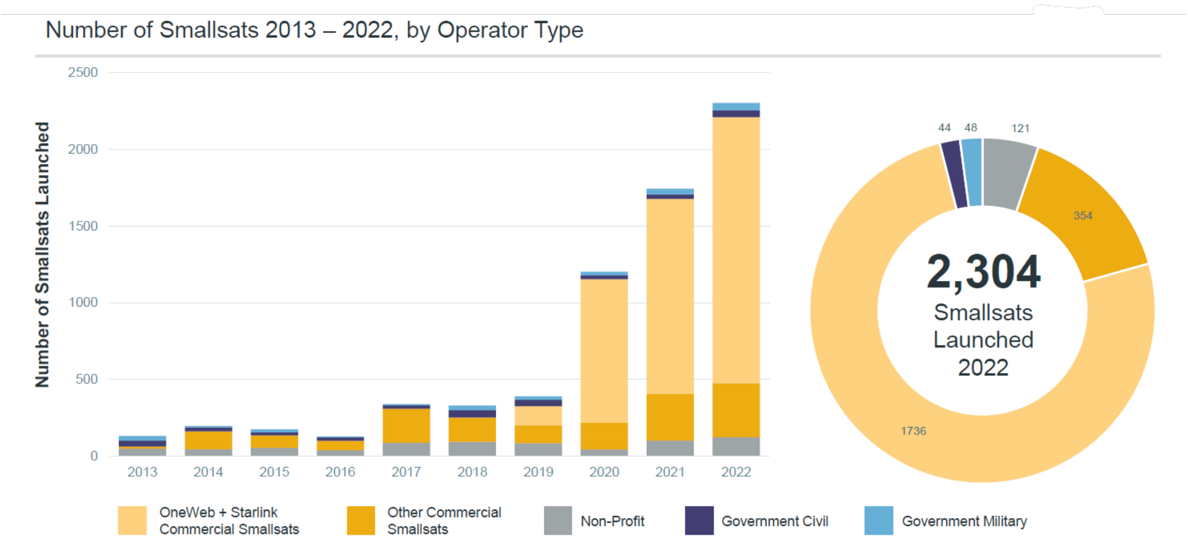


Figure 5.2: Smallsats 2013 2022, by Operator Type. Extracted from [67]

Reinforcing previous statements in 5.2, according to [67], the number of smallsat operators being created and launched has also significantly increased, from 14 in 2013 to 2090 in 2022, which makes the astonishing number of an increase of 14828%.

Operator Trends:

1. Commercial operators: they have significantly increased in number in recent years. These businesses are concentrated on offering commercial clients services including telecommunication, remote sensing, and Earth observation.
2. Government operators: governments all across the world are expanding their spending on small satellites for a number of purposes, including scientific research, weather monitoring, and intelligence gathering.
3. Research Institution and University operators: academic and research institutions can now more easily use small satellite missions for scientific research, technology advancement, and educational objectives.

Currently, out of $386B that goes to the global space economy, 72.27% ($279B) goes to the satellite industry [68], based on statistics from the year 2021. According to the report, industry revenue increased by 3% in 2021 from the previous year.

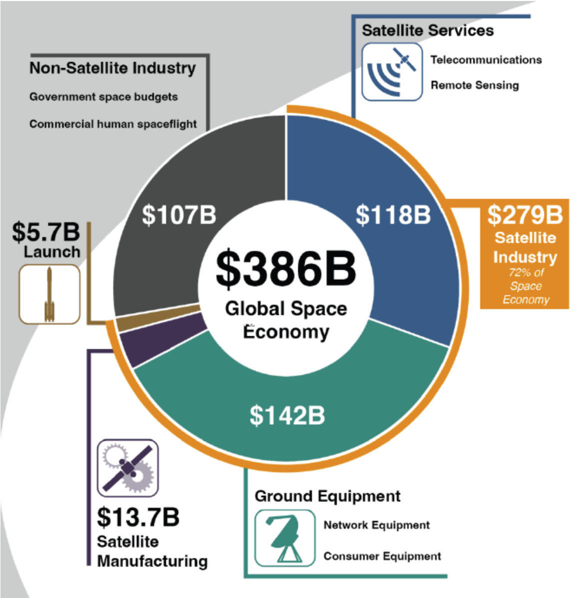


Figure 5.3: Global space economy. Extracted from [68]

The distribution of funds within the satellite sector can be seen by looking at the data from 2021.

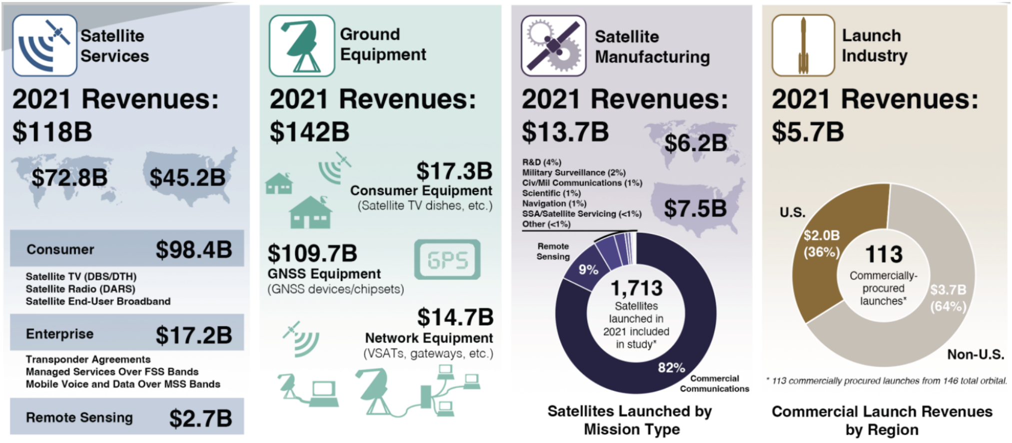


Figure 5.4: Industry revenues. Extracted from [68]

According to Bryce Space and Technology [67], in 2022 out of all spacecraft that were launched into space, 95% of them were smallsats, increasing 1% in comparison to 2021, which is estimated for a 54% of spacecraft upmass, raising the numbers again up an 11% in contrast to 2021.

It has to be said that they were carried on 108 of 186 orbital launches, a 108% more set side by side with 2021.

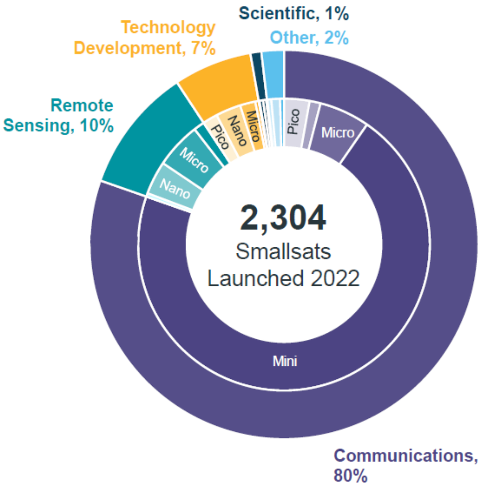


Figure 5.5: Smallsats highlights. Extracted from [67]

The emergence of NewSpace has also taken a toll on this market; it implicates sustainability when it comes to the upstream and downstream components of a space quest [69], benefiting from the economic, socioeconomic and environmental factors [69].

The design, development and processes of satellite manufacturing have been expedited; EO is providing valuable knowledge and advancing the Sustainable Development Goals (SDGs) [69].

In the following graph, different Cost Estimating Relationships (CERs) are represented, showing how CubeSats are more affordable than standard ESA satellites, reinforcing past statements and needing fewer resources to apply them:

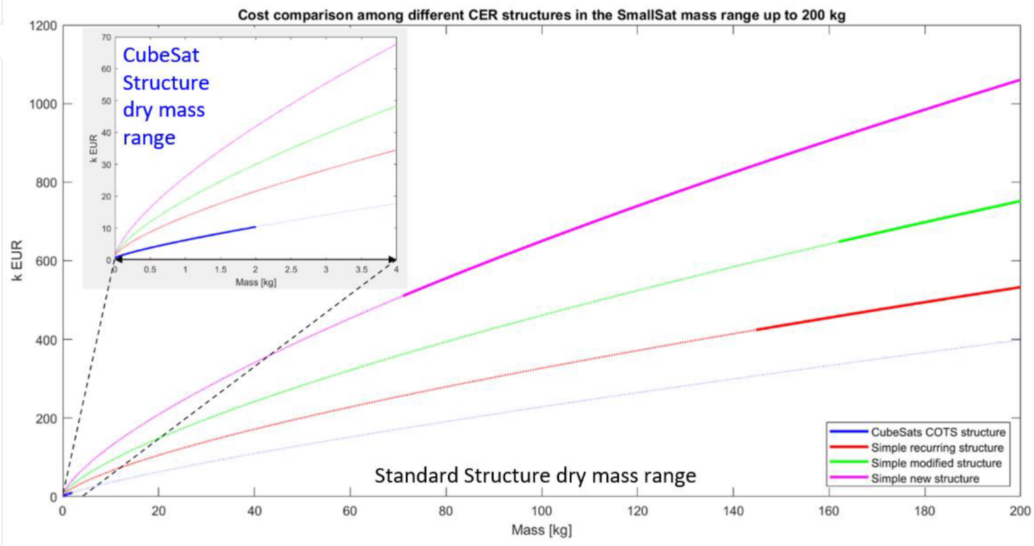


Figure 5.6: Cost comparison. Extracted from [69]

5.1.2 Actual demand

It is crucial to keep in mind the prior classification produced in the preceding part in order to understand the present demand for smallsats. As previously said, operator trends are categorized into commercial, governmental and academic and research institutions.

To generalize, these were the operators that deployed for the first time smallsats against the ones who had already done it through the years 2013 to 2022, seeing how the numbers become more equal over time:

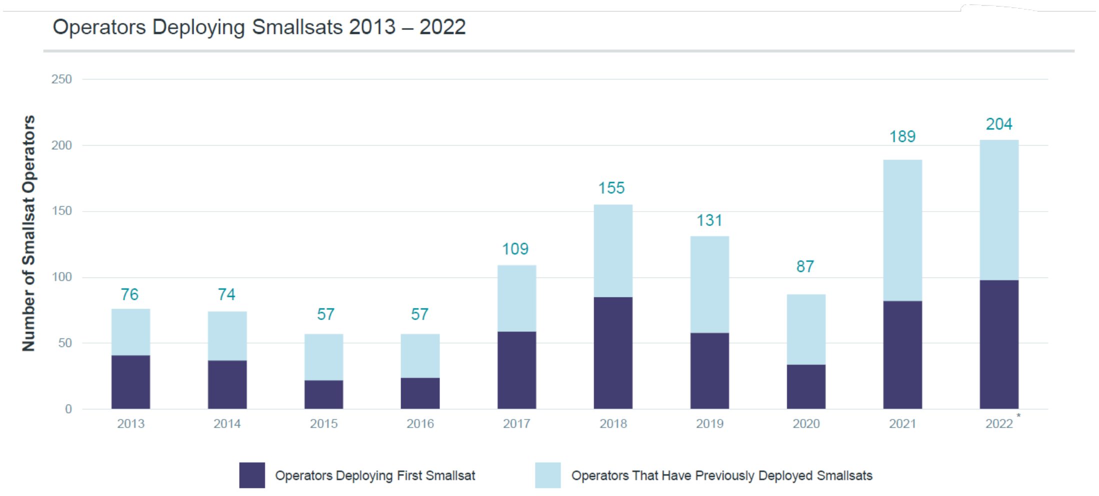
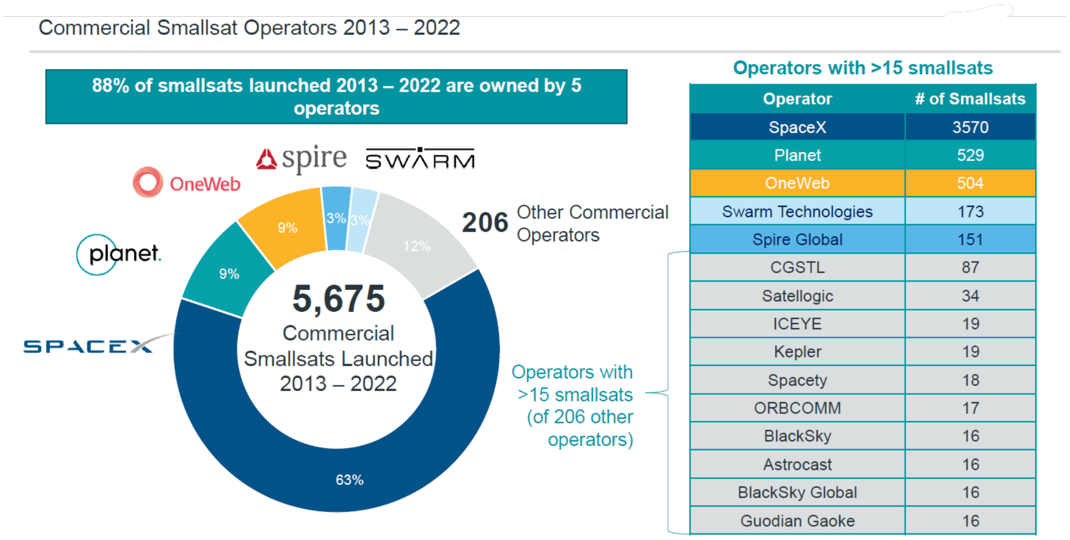


Figure 5.7: Operators Deploying Smallsats 2013 2022 [* Some 2022 operator information not available]. Extracted from [67]

- **Commercial operators**



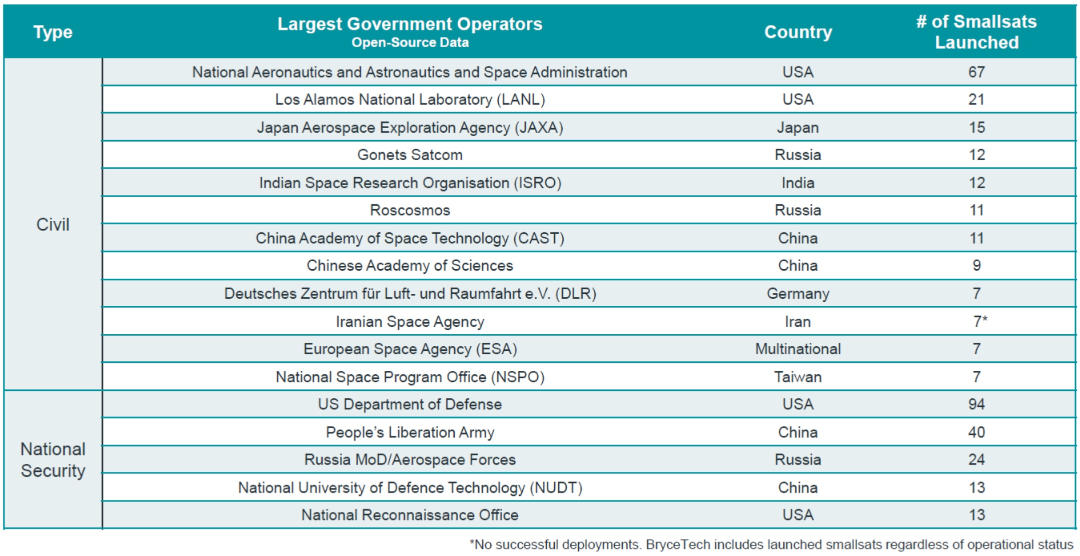
Operators with >15 smallsats

Operator	# of Smallsats
SpaceX	3570
Planet	529
OneWeb	504
Swarm Technologies	173
Spire Global	151
CGSTL	87
Satellogic	34
ICEYE	19
Kepler	19
Spacety	18
ORBCOMM	17
BlackSky	16
Astrocast	16
BlackSky Global	16
Guodian Gaoke	16

Figure 5.8: Commercial Smallsats Operators 2013 2022. Extracted from [67]

As illustrated in 5.8, the operators that launched the most smallsats were SpaceX, Planet, OneWeb, Swarm Technologies and Spire Global, SpaceX from the USA standing out from the rest having the most launches till date.

- **Governmental operators**



Type	Largest Government Operators Open-Source Data	Country	# of Smallsats Launched
Civil	National Aeronautics and Astronautics and Space Administration	USA	67
	Los Alamos National Laboratory (LANL)	USA	21
	Japan Aerospace Exploration Agency (JAXA)	Japan	15
	Gonets Satcom	Russia	12
	Indian Space Research Organisation (ISRO)	India	12
	Roscosmos	Russia	11
	China Academy of Space Technology (CAST)	China	11
	Chinese Academy of Sciences	China	9
	Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)	Germany	7
	Iranian Space Agency	Iran	7*
	European Space Agency (ESA)	Multinational	7
	National Space Program Office (NSPO)	Taiwan	7
National Security	US Department of Defense	USA	94
	People's Liberation Army	China	40
	Russia MoD/Aerospace Forces	Russia	24
	National University of Defence Technology (NUDT)	China	13
	National Reconnaissance Office	USA	13

*No successful deployments. BryceTech includes launched smallsats regardless of operational status

Figure 5.9: Governmental Smallsats Operators 2013 2022. Extracted from [67]

Again, the USA takes the podium when it comes to the operator that launches the most smallsats, this time with NASA being first.

- **Academic and research institutions operators**

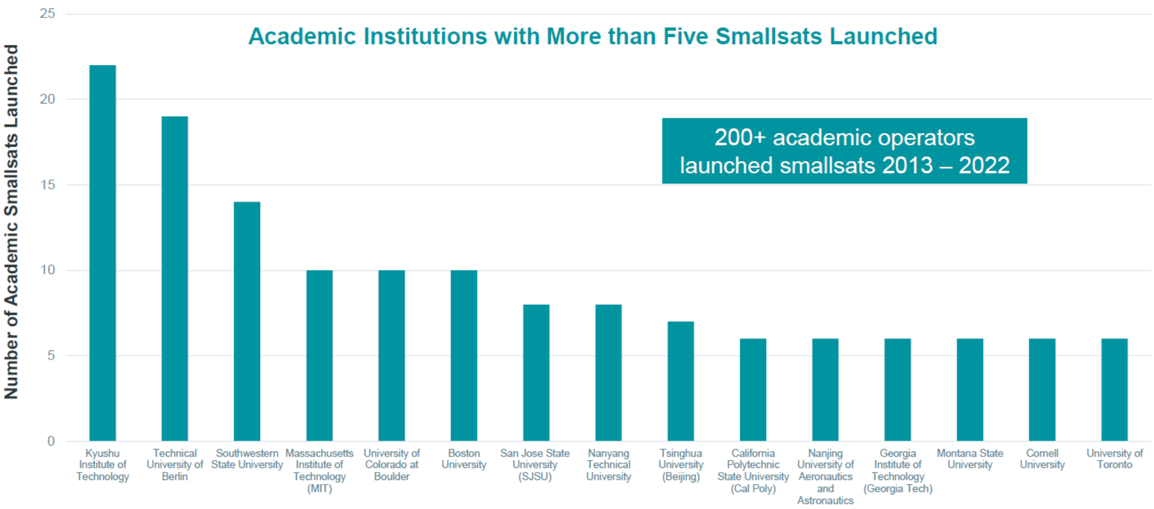


Figure 5.10: Academic and research institutions Smallsats Operators 2013 2022. Extracted from [67]

Finally, when talking about academic operators, Kyushu Institute of Technology from Japan is the one that has thrown the most smallsats yet, followed by the Technical University of Berlin, Southwestern State University and Massachusetts Institute of Technology (MIT).

5.1.3 Future demand

Back in 2017, a group of researchers from STPI (Science and Technology Policy Institute) chose four scenarios that were likely to happen in the period of time from 2027 to 2032 in the satellites market:

1. "Two or more large smallsat constellations in low Earth orbit (LEO)" [65]. This scenario will likely happen due to the growing demand for these technologies. In essence, this instance offers low-latency, worldwide broadband internet [65].

2. "Smallsats near-parity with larger satellites in remote sensing" [65]. This case exposes the increase in technology access due to the commercial availability of remote sensing capabilities outside of the United States in a variety of nations [65]. It is likely to be attainable.

3. "Unsafe for satellite operation in LEO" [65]. In this scenario, because there is a risk of collision and they are not practical for commercial usage in this situation, operating these types of satellites is dangerous [65]. It is unlikely to happen.

4. "On-orbit servicing, assembly, and manufacturing of spacecraft a reality" [65]. It is the most unrealistic out of them all, with multiple persistent platforms in LEO and GEO being utilized by governments and private sectors [65].

These scenarios lead to various drivers:

- **Market demand:**
  - An increase in the demand for LEO-based services [65] due to the growing affordability and development of novel technologies
  - Infrastructure drivers come into demand due to their encompassing of technology and systems that allow the improvement of Space Situational Awareness (SSA) [65]

- **Access to space:** related to the launching of the smallsats

- **Competing alternatives:** such as terrestrial and airborne platforms that can either support or refute the argument against smallsats [65]

- **Government policies:** which can affect either negatively or positively regarding the private sector interest [65]

To conclude, according to both these previous assertions and Bryce [67], some final declarations can be made when talking about future demands:

- **Business Outcomes:** there will be an increase when it comes to smallsats ventures, macroeconomic considerations having an influence on how they are affected [67]

- **Communications Megaconstellations:** these operators controlled smallsat action in 2022, growing even more in 2023 [67]

- **Smallsat Launch Options:** it is a sector that is on constant rise, with several companies consistently developing new small launch vehicles

- **Government Use of Smallsats:** the first U.S. national security-related architectural deployments are most probable in 2023. To enhance current capabilities, governments have started considering utilizing small satellites or adding them to architecture projects [67].

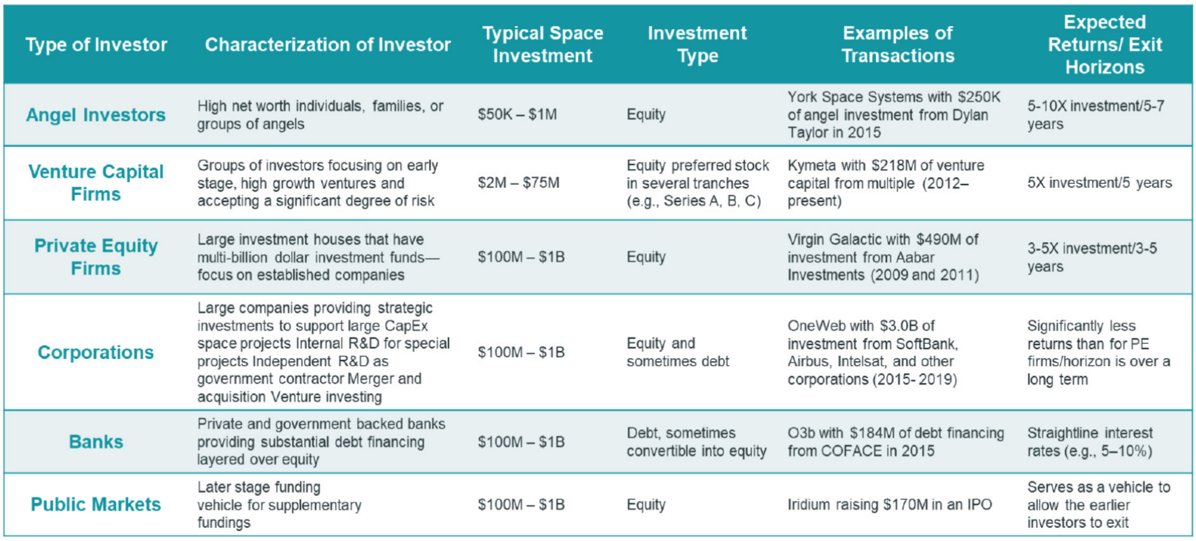
- **Smallsat Driven GEO/NGSO Integration:** organizations will be expanding steadily as regards to this area

5.2 Stakeholders

Thanks to the previous market study, a list of stakeholders has been identified. They will be classified first into investors, manufacturers, launch service providers, and government agencies finalizing with academic and research institutions.

Investors

There are five different kinds of investors according to Bryce [72]: angel investors, venture capital firms, private equity firms, corporations, banks and public markets.



Type of Investor	Characterization of Investor	Typical Space Investment	Investment Type	Examples of Transactions	Expected Returns/ Exit Horizons
Angel Investors	High net worth individuals, families, or groups of angels	\$50K – \$1M	Equity	York Space Systems with \$250K of angel investment from Dylan Taylor in 2015	5-10X investment/5-7 years
Venture Capital Firms	Groups of investors focusing on early stage, high growth ventures and accepting a significant degree of risk	\$2M – \$75M	Equity preferred stock in several tranches (e.g., Series A, B, C)	Kymeta with \$218M of venture capital from multiple (2012–present)	5X investment/5 years
Private Equity Firms	Large investment houses that have multi-billion dollar investment funds—focus on established companies	\$100M – \$1B	Equity	Virgin Galactic with \$490M of investment from Aabar Investments (2009 and 2011)	3-5X investment/3-5 years
Corporations	Large companies providing strategic investments to support large CapEx space projects Internal R&D for special projects Independent R&D as government contractor Merger and acquisition Venture investing	\$100M – \$1B	Equity and sometimes debt	OneWeb with \$3.0B of investment from SoftBank, Airbus, Intelsat, and other corporations (2015- 2019)	Significantly less returns than for PE firms/horizon is over a long term
Banks	Private and government backed banks providing substantial debt financing layered over equity	\$100M – \$1B	Debt, sometimes convertible into equity	O3b with \$184M of debt financing from COFACE in 2015	Straightline interest rates (e.g., 5–10%)
Public Markets	Later stage funding vehicle for supplementary fundings	\$100M – \$1B	Equity	Iridium raising \$170M in an IPO	Serves as a vehicle to allow the earlier investors to exit

Figure 5.11: Types of investors. Extracted from [72]

Most angel investors are billionaires like Jeff Bezos, Richard Branson and Elon Musk, who have either founded a space company or have invested in one of them. The activity of angel investors is growing by the year, with the USA having the biggest impact. These investments are not usually public, so the number of investors is expected to be much higher than it already is, and the investment is foreseen to be returned in 5 to 7 years from it.

Regarding Venture Capital Firms, invest in companies in their early stages, most of them being start-ups [72]. VCs expect a high return due to the risk of investing in them.

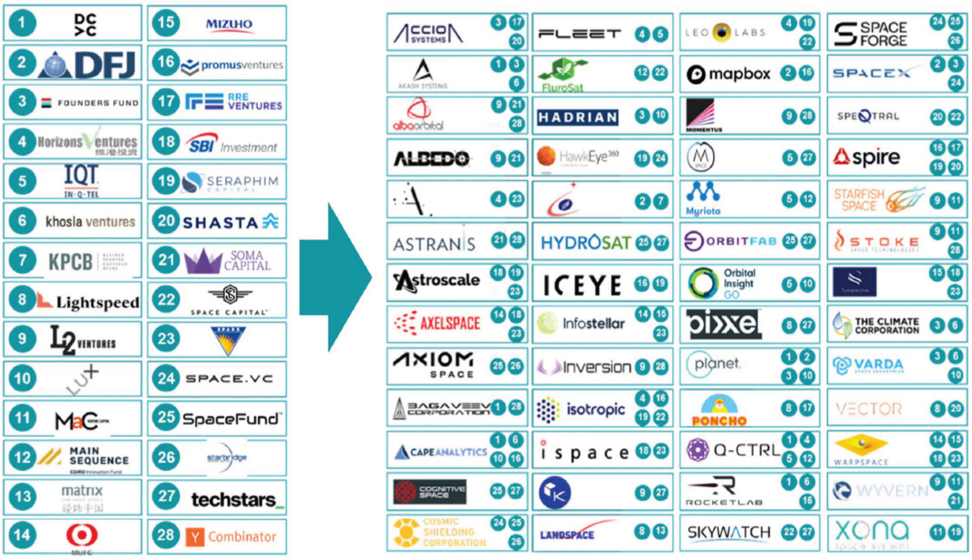


Figure 5.12: VC that invested in space start-ups since 2000. On left, the investors can be seen, with their investments on the right. Extracted from [72]

Figure 5.13: Number of investments each VC has done. Extracted from [72]

After carefully reviewing each company the ventures have invested in, as well as the investors, the list of possible venture capitalists for this project has been reduced to 5, enumerated by interest (1 being the most and 5 the less):

1. Promus Ventures
2. Founders Fund
3. Khosla Ventures
4. Space VC
5. DC >C (Data Collective)

Private investors —though being the ones that usually have the most power —tend to have poor interest; they limit their investments in companies that already have stable cash flows.

The corporations that invest the most in the space ecosystem are Airbus, Boeing, Google, Lockheed Martin, Softbank and Tencent [72]. Banks are the ones who have the least interest of them all, though important as they have the most power. Nevertheless, the major investments in this project may come from the European Union, thanks to their research-focused grants.

Manufacturers

On the subject of manufacturers, seven different companies have been identified, all of which design, build and launch smallsats:

- Airbus
- Boeing
- Planet Labs
- Spire Global
- Blue Canyon Technologies
- NanoRacks
- AAC Clyde Space
- GomSpace
- Tyvak Nano-Satellite Systems

Launch service providers

SpaceX provides the *Smallsat Rideshare Program*, where they offer launch services for missions whose budgets are as low as $275K. With their Electro program, which only launches small satellites and has launched 159 to date, Rocket Lab follows SpaceX in offering launch services. Both Arianespace and Virgin Orbit also offer launch services, as well as Firefly Aerospace and United Launch Alliance (ULA).

Government agencies

Several government agencies use smallsats:

- **National Aeronautics and Space Administration (NASA):** smallsats have been used by NASA for a number of missions, including space exploration, technology development, and Earth observation.
- **National Oceanic and Atmospheric Administration (NOAA):** smallsats are used by NOAA to collect information on weather trends, climate change, and oceanography.
- **United States Department of Defense (DoD):** reconnaissance, monitoring, and communication are just a few of the military uses for smallsats that the DoD employs.
- **United States Geological Survey (USGS):** USGS mainly uses smallsats to gather information on land use, natural resources and environmental risks.

- **European Space Agency (ESA):** used for multiple missions such as EO, scientific research and technology development
- **Japan Aerospace Exploration Agency (JAXA):** used for multiple missions such as EO, scientific research and technology development
- **Indian Space Research Organisation (ISRO):** used for multiple missions such as EO, scientific research, technology development and navigation

Academic and research institutions

As said before in the market study, several academic institutions take part in the smallsats environment, though by means of this project, institutions that were not mentioned before will be added to the list:

- The University of Manchester (UNIMAN)
- Hebei University of Technology
- Polytechnic University of Catalonia (UPC)
- Georgia Tech Research Institute
- Technische Universität Braunschweig
- Massachusetts Institute of Technology (MIT)
- University of California, Berkeley (UC Berkeley)
- Stanford University
- University of Cambridge

5.2.1 Mendelow matrix

After assembling all information and revising it —as a means to map the stakeholder analysis —a Mendelow matrix has been done, selecting those interested parties that are the most necessary to the project.

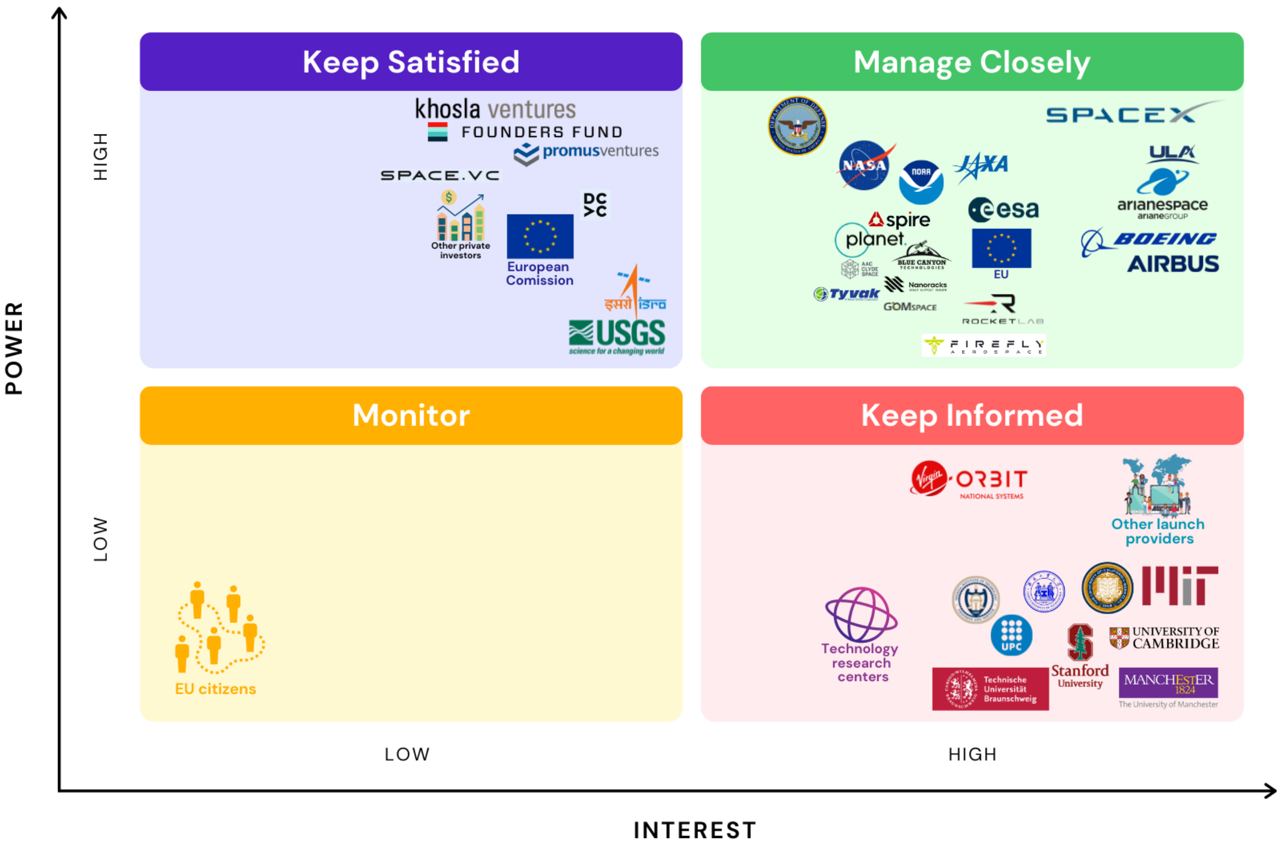


Figure 5.14: Mendelow Matrix. Done with previous information and with data extracted from [35]

5.3 PESTEL analysis

A PESTEL analysis will help analyze the macro-environmental factors of the industry.

- **Political:**
  - Without government assistance, no commercial small-satellite service has demonstrated its viability [73]
  - A comprehensive strategy for space, security, and defence is missing in the EU [35]
  - There is an international cooperation between many space agencies [35]
  - The European Defense Agency (ESA-EDA) is one of the new partnerships that the ESA is launching, and it will help the organization be better prepared to use emerging technologies to support Earth observation [74].
  - The US Government will encourage initiatives for marginalized populations and more diversified research [75]
  - The U.S. Government will establish collaborations and disseminate research results from space-based R&D to both government and non-government research communities [75].
  - The Engineering and Physical Sciences Research Council avoids supporting space technology development, and the UK Space Agency prioritize industrial development, so space technology development for university-developed technologies is not well supported by UK Research and Innovation [76].

- **Economical:**
  - SpaceX is working on diminishing satellite launch costs around \$5 million, in comparison to the current \$60 million [73]
  - Bank of America and Merril Lynch scheme that by 2050, the global space business will be worth at least \$2.7 trillion [73].
  - More private businesses are entering the market to offer space-related goods and services, and venture capitalists and private firms are investing more in the space industry. By the end of 2022, 1791 different companies had received private investments totalling around \$272 billion since 2013 [77].
- **Social:**
  - The smallsat industry is not in the peek of interest of the majority of investors [73]
  - Within the next ten years, China is projected to surpass the United States in space [73]
  - Growth in terms of rivalry [73]
  - EU involves many stakeholders that usually take no risks, always looking for benefits, in contrast to the USA [35]
  - It will promote data sharing, to expand fast, free, and fair access to publicly sponsored research [75]
  - Small satellite proliferation has resulted in a significant increase in sensors, which have improved as a result of the development of novel materials. This growth is encouraging the emergence of new businesses that use remote sensors in space [78].
  - In order to address the demand for in-space manufacturing —which requires raw materials and rare elements among others —the space mining of these novel components could emerge as the next competitive sector [78].
- **Technological:**
  - Smallsats are said to be a disruptive technology [73]
  - Little satellites are substantially less expensive to produce and launch per unit than bigger spacecraft, allowing for the replacement of on-orbit systems when more cutting-edge technologies become readily accessible [73]
  - The targeting dynamics for US and foreign counter-space weapons are altered by constellations of hundreds of satellites [73]
  - There is an increased resolution, an increase in the sensor capacity and a reduced power consumption [79].
  - Thanks to developing novel materials, the AO interactions can be diminished, as well as reducing aerodynamic drag presence [8].
  - The space industry has benefited greatly from the developments in materials science and 3D printing, such as the use of advanced composites and carbon fibre, which have drastically reduced launch costs [78].
- **Environmental:**
  - Development of green hydrogen as a fuel [35]
  - Reduction of carbon emissions due to developing new materials in VLEO [1].

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[1] From previous information recollected

  - The reduction of the effects of atomic oxygen diminishes the production of non-volatile silica deposits due to the reduction of the oxidation of silicones and silicone contamination [80].
  - Because fewer short-lived excited state species are present, radiation near the spacecraft's surfaces is decreased [80].
  - The development of new materials that can help with debris densification within the space community, which has turned into a very serious environmental problem [81].
  - VLEO has the ability to support corporate innovation while limiting long-term effects. It offers a resilient and sustainable option for higher orbits. However, space policy must acknowledge the advantages of using VLEO and require its use [76].

- **Legal:**
  - The use of small commercial satellites will be subject to national security considerations by the US government because they constitute sizable targets for cyber exploitation [73]
  - Security restrictions for launch and orbital operations must be considered when designing smallsats [82]
  - Law of Space operations is defined in France [82] Germany, Sweden, Norway, and Spain are funding small launcher projects in Europe, but they have not yet put a legal framework in place [82]
  - A policy is required to promote the creation of technologies that will make VLEO satellites possible [76].
  - Even though the Civil Aviation Authority rates launches into VLEO as low risk because of the little likelihood of other space assets being damaged and, consequently, the low risk to the space operator and the government, an international agreement would be needed to limit communications and remote sensing to VLEO [76].

5.4 Porter's 5 Forces Analysis

As said before, when carrying out this kind of analysis, five competitive forces must be considered, which will be evaluated in the following subsections. Five Forces Analysis is important for understanding the industry that must be faced.

5.4.1 Industry competition or competitive rivalry

The industry competition is growing daily, becoming extremely competitive in the smallsats sector. According to Allied Market Research [83], the key market players in the sector are the following:

Airbus	Gomspace	L3Harris Technologies
Planet Labs	Sierra Nevada Corporation	Thales Group
Lockheed Martin Corporation	Northrop Grumman Corporation	Boeing Company
The Aerospace Corporation	SpaceX	OneWeb

Table 5.1: Key Market Competitors

Due to the high level of power, these companies hold —such as Airbus, Lockheed Martin, Thales, Boeing or SpaceX among all the others —and the constant growth of the market, the rivalry in the sector is **very high**.

- Airbus is one of the leading aerospace companies, having Bartolomeo and OneWeb platforms to ease access to the VLEO/LEO environments. Airbus has also developed a space coating to protect satellites against atomic oxygen in these orbits
- GomSpace has a signed contract with ESA to improve smallsats, and they specialise in the sector
- L3Harris offers multiple solutions to commercial and government organisations
- PlanetLabs has launched over 400 smallsats to date, a company specialising in these small satellites as well as in Earth Observation
- SierraNevada has a bunch of programs related to smallsats
- Thales Group also puts itself in the market with them, having signed a contract with Arianespace
- Lockheed Martin, Northrop and Boeing offer launch services as well as smallsats services
- Aerospace Corporation offers the space sector technical and scientific expertise
- SpaceX designs and launches smallsats. They offer launch services too.
- OneWeb —just like PlaneLabs —has launched a significant number of small satellites, and they have more to come in the near future

These businesses do not provide pricing information publicly since it is confidential and requires direct communication with the business.

When talking about companies that do research on novel materials in VLEO (apart from the ones that have already been mentioned), **NanoRacks, Rocket Lab, Iceye, Akash** and **Leo Labs** have to be taken into account.

5.4.2 Possibility of new competitors or threat of new entrants

Since the technology needed to create and produce smallsats is becoming more widely available and reasonably priced, the smallsats market has little competition. The chance of new rivals entering the market and competing with established companies could enhance competition and pressure prices.

Due to the high level of appeal of the tiny satellite market, new entrants may strive to do so. The creation of novel materials for VLEO has made it simpler for smaller businesses to enter the market due to the reduced entry costs associated with the launch and manufacturing processes, resulting in a **high** possibility of new competitors.

5.4.3 Influence of suppliers or supplier power

Manufacturers of satellite parts and launch service providers make up most of the small satellite market's vendors. Due to their ability to set pricing, regulate component quality, and introduce new services, suppliers have a reasonable amount of bargaining leverage. Over time, this bargaining leverage has diminished due to the advent of multiple launch providers. The number of component suppliers available to manufacturers also lessens the bargaining strength of any one supplier.

The connection between COTS structures, 3D printing, and smallsats has reduced the cost of manufacturing, giving established businesses a chance to hold onto their market share while enabling new suppliers.

Suppliers have little negotiating power since creating new materials for VLEO needs specialised knowledge and capabilities that are hard to come by.

Therefore, the power is **high**.

5.4.4 Influence of customers or buyer power

The disposable income of buyers and their credit accessibility are important economic factors to consider, as they can have a substantial effect on the demand for new materials in VLEO.

Universities, private businesses, and government organisations are the customers in the small satellite market. Because few businesses provide tiny satellite services, these purchasers have a lot of negotiating leverage. If customers are unhappy with the quality of the goods or services they are receiving, they can easily transfer vendors. To keep clients, providers must continuously innovate and offer top-notch services.

The influence is **very high**.

5.4.5 Hazard of replacement products or threat of substitution

Due to smallsats being quite specialised in what they perform, very few ideas come to mind when considering alternatives that could eventually replace them.

There is a choice of stratollites and High Altitude Pseudo-Satellites (HAPS); thus they must be reviewed:

- **Stratollites:** it is a lower-altitude balloon with cameras that can monitor explicit areas of the Earth and serves as a less expensive alternative to tiny satellites. The disadvantage is that they cannot orbit the earth and can only be in flight for a short period of time, thus, it is not thought that they pose a significant threat to small satellites.
- **High Altitude Pseudo-Satellites (HAPS):** according to Amprius [84], they are unmanned aircraft capable of maintaining a fixed location that operates in the stratosphere.

  HAPS could be thought of as the gap between satellites and aircraft [84], yet given that they need constantly developing batteries and solar cells to run and support a tiny payload with poor electric power [84], they could not replace smallsats. They discovered that putting them into location was challenging as well.

Unmanned aerial vehicles (UAVs), often known as drones, have drawn much interest in both military and commercial uses, according to recent research [85]. For a variety of commercial purposes, drones and airships have been proposed as smallsat alternatives in Very Low Earth Orbit (VLEO) [86]. New materials for VLEO could boost the space industry's economy, reducing costs and boosting the demand for smallsats. The threat of alternatives is **low**; therefore, it might not be possible to replace smallsats with drones or airships.

This Porter's Five Forces analysis can be summarised in the following graph:

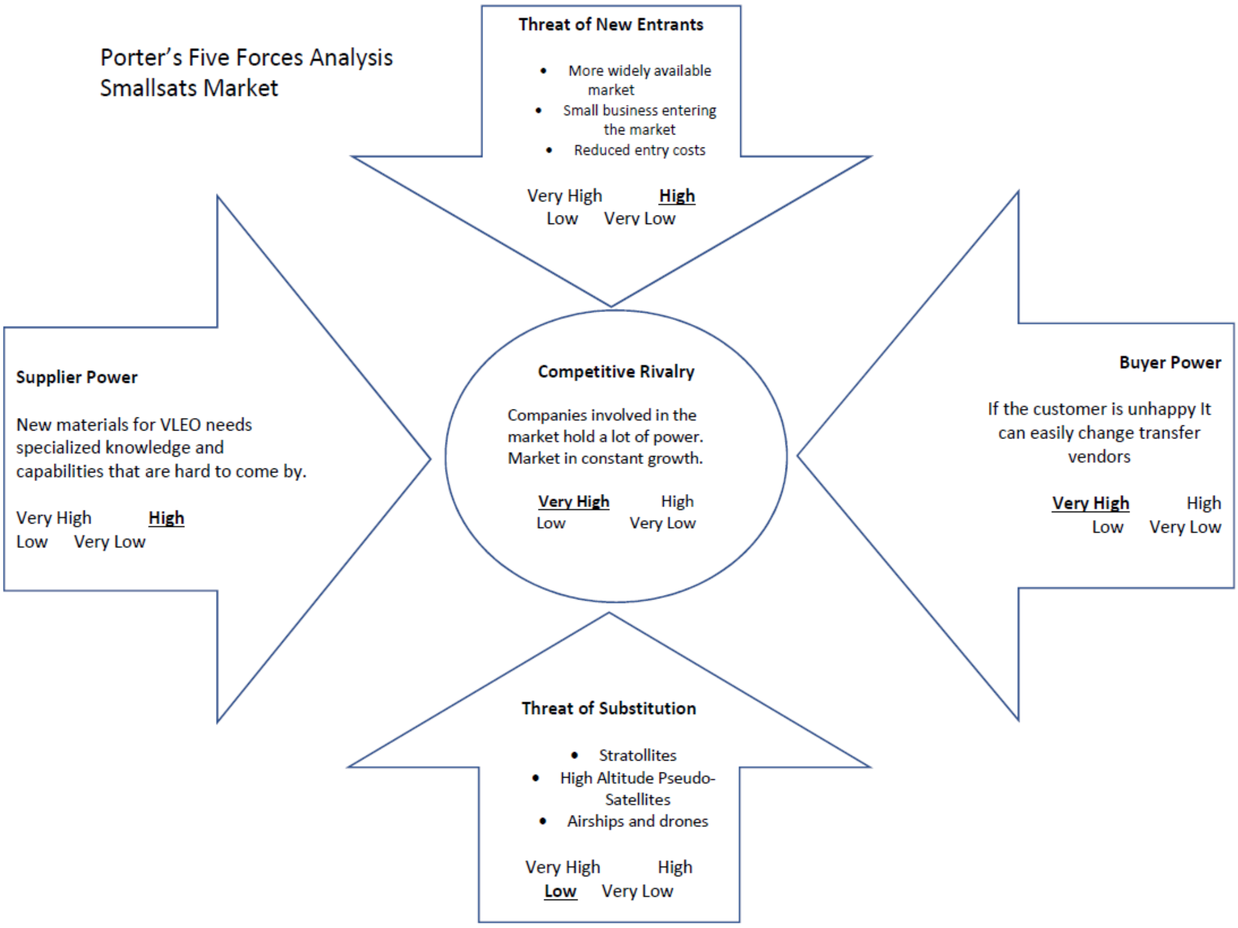


Figure 5.15: Five Forces Analysis. Done with previous information. Template extracted from [87]

5.5 SWOT analysis

SWOT analyses are mostly done to see where a company stands in the industry, in this case, where the development of new materials in VLEO stands, alongside their actions. This SWOT analysis has been generated with all information gathered previously, which can be seen in the first chapter of the Annex.

5.6 Generation and evaluation

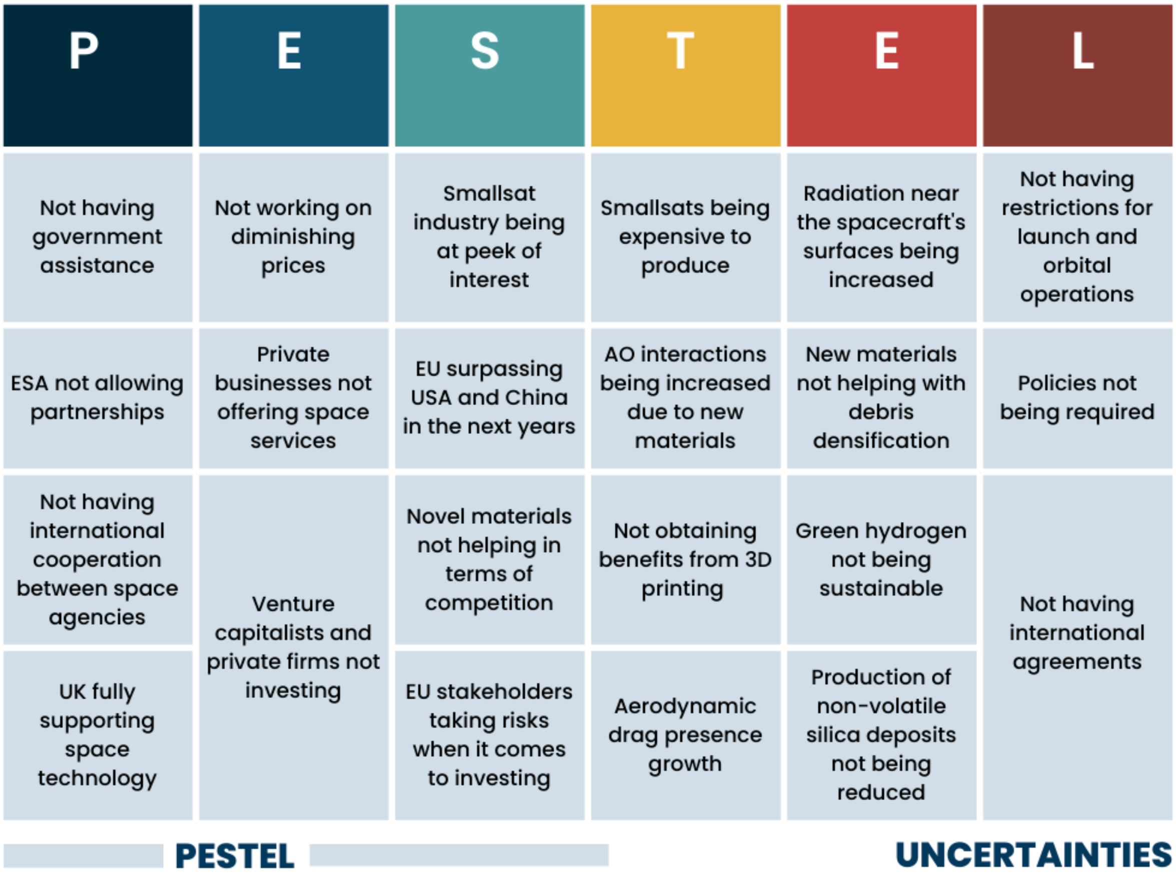
5.6.1 Foresight scenarios and risks

Following the pre-processing development, the plausible scenarios most likely to occur throughout the process will be assessed.

To create scenarios, various steps are to be followed:

1. Identify the uncertainties of the project within the PESTEL analysis done previously
2. Identify the drivers of the field so that they can be matched up to the next challenges that must be determined
3. Identify the challenges
4. Create an uncertainty/impact matrix to classify the various challenges to make the final choosing process smoother
5. Choose the most plausible challenges/uncertainties
6. Finally, generate the scenarios by making 2x2 matrices

A share of uncertainties must be pinpointed so that they can be prioritized. Taking note of the previous PESTEL analysis, this matrix has been created so that the factors can be looked into more thoroughly:



P	E	S	T	E	L
Not having government assistance	Not working on diminishing prices	Smallsat industry being at peek of interest	Smallsats being expensive to produce	Radiation near the spacecraft's surfaces being increased	Not having restrictions for launch and orbital operations
ESA not allowing partnerships	Private businesses not offering space services	EU surpassing USA and China in the next years	AO interactions being increased due to new materials	New materials not helping with debris densification	Policies not being required
Not having international cooperation between space agencies	Venture capitalists and private firms not investing	Novel materials not helping in terms of competition	Not obtaining benefits from 3D printing	Green hydrogen not being sustainable	Not having international agreements
UK fully supporting space technology		EU stakeholders taking risks when it comes to investing	Aerodynamic drag presence growth	Production of non-volatile silica deposits not being reduced	

PESTEL **UNCERTAINTIES**

Figure 5.16: PESTEL's uncertainties

The major drivers of change in the sector must be recognized while creating a scenario plan to understand potential future effects on the project. A share of drivers has been selected, recompiling information throughout the whole roadmap:

1. **New commercial opportunities;** as seen in 5.7, the market is growing by the year, making it an important driver.

2. **Capability of funding;** as discussed in previous analysis in this thesis, funding is a crucial point to strengthen the development of novel materials.
3. **Technological advancements;** as it makes the competitiveness go higher
4. **Environmental troubles;** space debris densification has become a problem, as said in the PESTEL analysis, and developing new materials could help.
5. **Government policies;** government support is crucial for the project.
6. **Cost reduction;** reducing high costs is also essential, as it is an actual risk.

Every industry faces a particular set of problems that must be solved. Businesses must traverse a complex terrain to remain competitive and succeed in today's fast-paced economy, from shifting customer preferences to regulatory unpredictability.

Depending on the particular industry and market circumstances, a given sector's difficulties and problems can differ. These are the ones that come up when developing novel materials in VLEO, related to previous drivers found:

- Driver 1 - New commercial opportunities

  Challenge 1

  Challenge 1 suggests that those materials suitable for space are also suitable on Earth, developing new commercial applications to expand the business. It creates new commercial and industrial opportunities in space. According to this, new firms will form due to the discovery of novel materials, enabling expansion in the sector and across Europe while establishing themselves as market leaders.

  Challenge 2

  Challenge 2 hints at the possibility of competitors taking over; them having lower prices and more economical options, withdrawing the project.

- Driver 2 - Capability of funding

  Challenge 3

  Challenge 3 implies not being given any support from grants or alliances, making the EU weaker than before.

- Driver 3 - Technological advancements

  Challenge 4

  Challenge 4 suggests an ideal circumstance where materials that exactly suit the requirements needed in VLEO are provided, together with the necessary funding and partnerships.

  The created materials enable long-lasting missions, ongoing research into the subject, and a steady and linear rise in technological advancement.

  Challenge 5

  Challenge 5 proposes that those materials that were considered suitable turn out to be unfit in VLEO.

  Challenge 6

  Challenge 6 implies communication failure due to the components of said material, resulting in data loss, among others.

- Driver 4 - Environmental troubles

  Challenge 7

  Challenge 7 insinuates that the materials found have a negative environmental impact, resulting in serious pollution back on Earth. It also leads to negative outcomes regarding the market: partnerships and alliances are broken due to the damage done, and grants are not given due to the events.

- Driver 5 - Government policies

  Challenge 8

  Challenge 8 indicates that regulatory and legal policies do not allow for new materials to be developed, resulting in the total failure of the project.

  Challenge 9

  Challenge 9 suggests that the development of new materials is found to be beneficial to VLEO, but they lack support from the government and other organizations, being difficult to sustain.

- Driver 6 - Cost reduction

  Challenge 10

  Challenge 10 implies that due to high costs and the difficulty of simulating real-life conditions with long development cycles, the project fails and is not feasible. Also, having economies of scale —which are cost challenges driven by businesses once the manufacturing is competent —, can help when it comes to increasing demand and making the product more competitive; that way mass production can be used to reduce manufacturing costs.

Once the challenges are put on the table, an ”uncertainty/impact” matrix is generated to see their potential and to prioritize them, with the aid of previous information in this thesis.

The first quadrant, ”low uncertainty/high impact”, shows those that are very likely to happen, as the data that is possessed is pretty clear on what the future will most probably be. The second quadrant, ”high uncertainty/high impact,” indicates the ones that will have a strong impact on the project but the information in them is very little to know the likelihood of it. The next quadrant, ”low uncertainty/low impact,” shows those that one is sure but does not know if there is a possibility of happening. Finally, ”high uncertainty/low impact” are less likely.

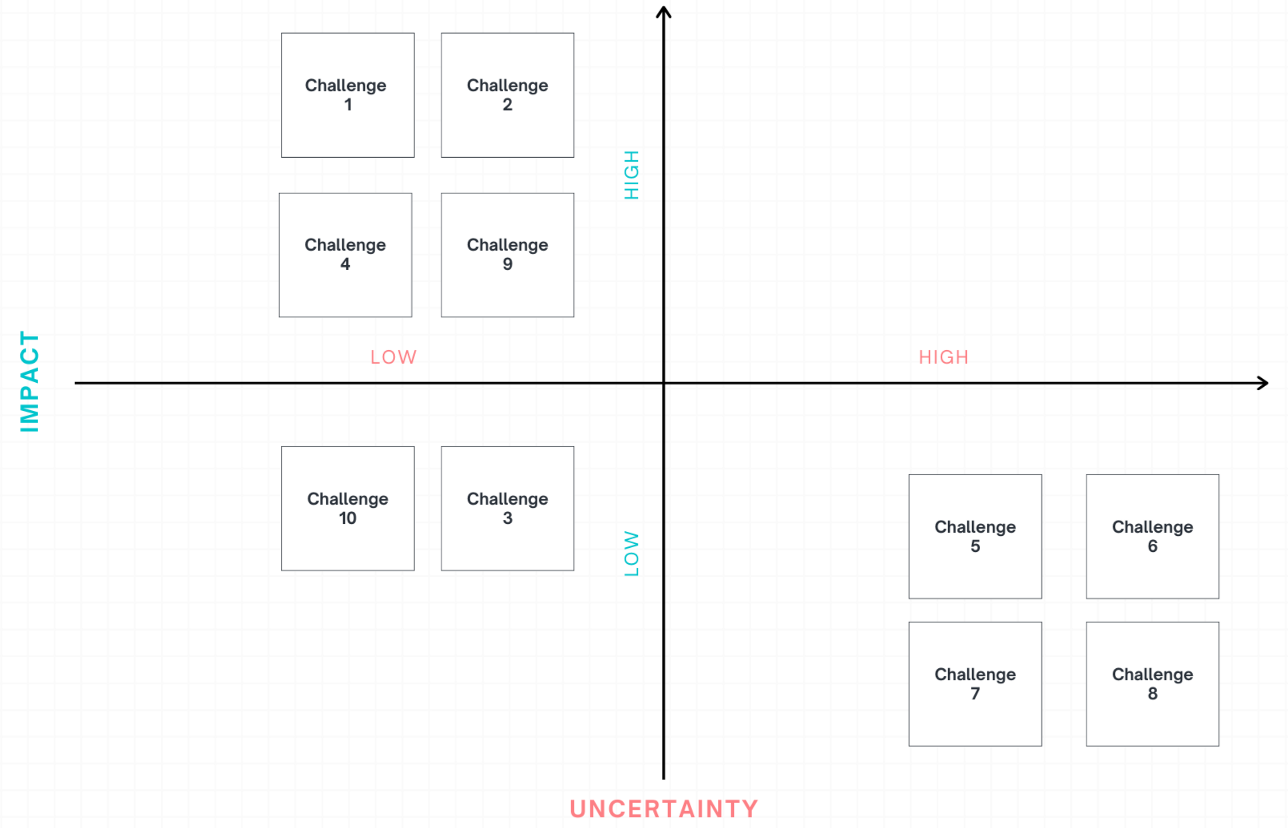


Figure 5.17: Uncertainty/impact matrix

To sum up all challenges/uncertainties in creating the final scenarios, the most plausible challenges have been put together:

1. Not having support from the government and other organizations. As a result, the project slows down, and the costs are increased.
2. Stakeholders and investors being reluctant to take risks is a major social challenge.
3. The cost is one of the significant economic obstacles in developing novel materials for VLEO.
4. Finally, creating materials that can resist the harsh atmosphere of VLEO is another difficulty. High amounts of ionizing radiation, humid temperatures, and atomic oxygen erosion are all hazards for satellites in VLEO. As a result, durable materials that can endure these circumstances are needed.

Finally, the scenarios can be generated by using different matrices:

Not having government support / Stakeholders-investors being reluctant to take risks	
LOW/HIGH	**HIGH/HIGH**
-Even though funding would be received, thanks to government support, there still would be a lack of financial resources due to not having stakeholders/investors -Investors and stakeholders frequently bring viewpoints and factors based on the market. Without them, the government might have a less comprehensive understanding of consumer needs and business prospects. A less market-oriented approach to the material development could come from this. -Fewer partnerships could be made -There would be a full dependence on the government	-This scenario would result in a lack of funding, hampering the project -Lack of interest in the field would be spread, reinforcing the shortage of goods -Benefits that come along with VLEO would diminish, losing opportunities, as in this scenario the development of novel materials would not be feasible
LOW/LOW	**HIGH/LOW**
-An increase in the number of funding would be seen, as the collaboration of all parties would result in a boost in acquisitions -More researchers and experts could be gathered -Thanks to the diverse network's stakeholders /investors have, the development of tests could be carried -Support from the government could help to balance society and business objectives	-Government assistance is essential to keep in mind since it may foster collaboration, enable long-term research, and provide the basic infrastructure and funding for large-scale initiatives like VLEO. -The scope, coordination, and pace of advancement in the material development for VLEO may be constrained by the need for more government assistance, even though stakeholders can make a considerable contribution. -Not having government support means not receiving funding -Possibility to stand out from the competition, as having investments would mean having more resources in terms of investigation and R&D

Table 5.2: Scenario Matrix 1

Not having government support / High costs	
LOW/HIGH	**HIGH/HIGH**
-There would probable be a budget constraint, as the high costs would carry limitations -Due to high costs, partnerships would be limited -The project would be lengthened	-High costs and no government support would result in insufficient funding and limited financial resources -The scope of the project would have to be limited -Partnerships would be almost impossible to find -Start-ups and research groups would have it difficult to enter the market
LOW/LOW	**HIGH/LOW**
-Enough funding would be granted -There would be a lot of partnerships and collaborations available -Research institutions could offer scholarships and workshops as well as training initiatives, reinforcing the EU's background due to educating professionals	-With no government support, a reliance on private funding would have to be made -There would be a lack of interest in the field - Private funding without high costs could allow for flexibility when it comes to research

Table 5.3: Scenario Matrix 2

Not having government support / Not having suitable materials	
LOW/HIGH	**HIGH/HIGH**
-The government can encourage collaboration between academic institutions, business professionals, and industry researchers to share information, skills, and resources, enriching the EU -The government can create a long-term plan for material development in VLEO, defining precise objectives -The government can promote partnerships and collaborations	-The private sector would need to take the initiative -Research becomes more difficult due to a lack of resources -Small entities may encounter problems when entering the sector -Private sector would become reluctant as a result of not seeing outcomes
LOW/LOW	**HIGH/LOW**
-Research becomes more feasible -Missions become safer thanks to having support from the government and finding suitable materials -Long-term strategic plans can be established with government assistance.	-Again, the private sector would have to take the lead -There would be some resource limitations due to the government not being supportive -Partnerships would be an option thanks to finding suitable materials

Table 5.4: Scenario Matrix 3

Stakeholders-investors being reluctant to take risks / High costs	
LOW/HIGH	**HIGH/HIGH**
-Lack of funding due to the shortage of stakeholders/investors -Without enough investments, the full potential of new materials could not be exploited -Lack of resources	-Research would not be possible, and progress would become difficult due to high costs and no investments -Lack of competition -Lack of interest
LOW/LOW	**HIGH/LOW**
-Increase in partnership opportunities due to the high interest -Accessibility for start-ups -Potential for disruptive technologies and increase in innovation	-Without stakeholders/investors there are limited resources and total dependency on funding -Limited partnership/collaboration opportunities -Difficulties for start-ups

Table 5.5: Scenario Matrix 4

Stakeholders-investors being reluctant to take risks / Not having suitable materials	
LOW/HIGH	**HIGH/HIGH**
-Stakeholders and investors can facilitate collaboration, as well as research and initiatives -Stakeholders can find alternatives to deal with the difficulties of finding suitable materials	-Lack of investment and funding -Lack of access to the resources needed would become a major obstacle. -Not finding suitable materials would lead to a lack of innovations, as well as to an increase in costs and delays in VLEO missions
LOW/LOW	**HIGH/LOW**
-There would be a huge support for the development and commercialization of new materials -Various applications can be researched -Partnerships and collaborations are encouraged -It generates market growth and innovations	-Limited resources for development -Reliance on funding -Lack of collaboration and partnerships -Missing opportunities due to the lack of stakeholders/investors

Table 5.6: Scenario Matrix 5

High costs / Not having suitable materials	
LOW/HIGH	**HIGH/HIGH**
-The initial cost of materials may be low, but adopting unsuitable materials could result in higher long-term costs since they require frequent upkeep, repairs, and replacements. -Cost overruns may arise, and the potential for long-term cost savings may be constrained.	-Lack of funding -Lack of partnerships and collaborations -Relying on funding -Missing opportunities -Dependency on the government -Restrained budget
LOW/LOW	**HIGH/LOW**
-Acceleration on the development of new materials -Increase in partnerships and collaborations, as well as in investments -Engagement of stakeholders -Market growth and innovation	-Using appropriate materials could lead to long-term cost savings thanks to lower maintenance, repair, and replacement expenses. -It may lower the cost of VLEO missions and promote investment in the field, but it may also impair their viability, impede advancement, cause cost overruns, weaken competition, and suppress chances for innovation.

Table 5.7: Scenario Matrix 6

To narrow down the options, it is necessary to choose the top three most feasible scenarios out of the 24 generated. This requires evaluating which ones are most intriguing, challenging, and merit further investigation:

- Having government support - stakeholders/investors being reluctant to take risks
- High costs - Having suitable materials
- Having government support - Not having suitable materials

Once the final scenarios are generated, the flex points have to be identified:

- If funding is not granted and partnerships are not accepted.
- If costs are considerably high
- If there is no support from the government
- If suitable materials are not found
- If stakeholders and investors are not interested

Finally, a new SWOT analysis is to be done, bearing in mind everything that has been identified:

Strengths	
SWOT analysis	**Action**
S1: Funding would be granted, and collaborations and partnerships are strengthened	AS1: a way to improve this strength is to increase funding, collaborate with private companies and invest more in education so that the EU has a strong background.
S2: Performing with new materials in VLEO enhances the capability to endure challenging spatial environments	AS2: invest in R&D, the continuous development and improvement of new materials, as well as the carrying out of different tests. Different applications are being found, and 3D printing is used to reduce costs Also, the EU can make investments in cutting-edge technology research and development. Additionally, by funding educational and training initiatives, the EU can concentrate on cultivating talent and subject-matter knowledge.
S3: VLEO missions may become cheaper	AS3: Conducting tests for the integration of these materials onto the spaceship, as using appropriate materials could lead to long-term cost savings

Table 5.8: Strengths with their actions

Weaknesses	
SWOT analysis	**Action**
W1: Small entities may encounter problems when entering the sector	AW1: Small businesses may benefit from establishing alliances or joint ventures with major industry players, as well as encouraging access to funding and assistance programs.Government grants, angel investors, and venture capital investment are examples of this.
W2: Lack of innovations and delayed progress	AW2: identifying strategic partners, as well as developing a thorough strategy. Assisting to industry events and networking opportunities can be a great way to enhance the opportunity
W3: Limited resources	AW3: Request more grants and collaborations and applying for grants can be a great investment boost

Table 5.9: Weaknesses with their actions

Opportunities	
SWOT analysis	**Action**
O1: The government can encourage collaboration between academic institutions, business professionals, and industry researchers to share information, skills, and resources, enriching the EU	AO1: the EU can work with other spacefaring countries and promote the private sector involvement.
O2: A long-term plan for material development in VLEO, defining precise objectives can be made	AO2: Creating a roadmap that explains the procedures and checkpoints necessary to accomplish the stated goals.
O3: Increase in partnerships and collaborations, as well as in investments	AO3: actively look for possible partners by going to conferences, taking part in online forums and debates, and networking with industry

Table 5.10: Opportunities with their actions

Threats	
SWOT analysis	**Action**
T1: There could be regulatory obstacles	AT1: working closely with regulatory organizations is crucial to making sure that the relevant safety standards and procedures are in place. Creating alliances with other businesses in the sector can also help when it comes to regulatory issues.
T2: There may be full dependence on the government and they might have a less comprehensive understanding of consumer needs and business prospects	AT2: invest in the implementation of safety regulations, providing training and certification as well as monitoring safety compliance are great ways of minimizing the threat, as stakeholders, investors and private entities may look at the chance to form collaborations
T3: The difficulty to obtain appropriate resources could lead to technological stagnation.	AT3: Promoting the space industry becomes crucial when it comes to drawing attention and interest. Also, collaborations with organizations may help the research gain validity and reputation, which may improve its chances of receiving additional money or support.

Table 5.11: Threats with their actions

5.6.2 Linking grids

The roadmap classifies into three different layers: *market (who)*, *technology (what)* and *resources, capabilities and investments (how).*

To create linking grids is important to keep this classification in mind, as it will be created following the different layers the roadmap possesses.

5.6.2.1 1st linking grid: market (who)

The first step in this linking grid is to identify the markets that need novel materials in VLEO, which have been detected before in this thesis when doing the market study:

- Satellites
- Rockets
- Hypersonic flights
- Propulsion systems
- Space tourism

These identified markets have to be prioritized in order to select those of more importance, following criteria based on the growth forecast, the social impact, the environmental impact and the material dependence. The scoring table 5.13, assigns punctuation from 1 to 3, 1 being the smallest impact and 3 being the highest.

5.6.2.2 2nd linking grid: Tech

The second linking grid is used to determine what technology is required to develop the markets with the highest growth and dependence on materials:

Market	**Satellites/Smallsats**	**Rockets**
Technology	Thanks to the development of new materials, smallsats could endure high temperatures and they could be more light. Also, their exposure to AO would be significantly reduced	New materials could lead to more efficient and powerful engines, allowing a better rocket performance, lower fuel consumption and even better maneuverability
Synergies	The performance of the smallsats is improved due to the lightness that is gained (mass reduction). The lifespan of said smallsats is also lengthened, and the costs are greatly reduced	The performance and effectiveness of satellite propulsion systems can be improved, as new materials allow for a weight reduction, helping rockets deliver bigger payloads. The cost is also reduced and a sheltering against radiation is provided. Also, it can help to reduce the environmental impact that rockets have.
Products/ Services	-Smallsats constellations -3D printing -COTS components	-Propulsion systems (materials that fight against AO improve them) -Reusable rockets (materials that are able to stand high temperatures enhance these rockets)
Flexpoints	-The use of lightweight materials -Materials resistant to AO attacks -Advanced materials with improved performance when it comes to high frequencies -The elongation of the lifespan of the smallsats due to the materials -Collaborations with researchers, developers, manufacturers	-The use of lightweight materials -The development of materials resistant to radiation -The development of materials that improve propulsion systems, specially resistant to AO attacks -The creation of materials that are resistant to high temperatures to help with the development of reusable rockets

Table 5.12: 2nd linking grid

Market	*Insight*	**Growth Forecast**	*Insight*	**Social Impact**	*Insight*	**Environmental impact**	*Insight*	**Material Dependence**	**Total**
Satellites	According to [88], the CAGR (Compound Annual Growth Rate) of the satellites market lingers around a 14% in the next years. It has to be noted that a CAGR greater than 12% in an industry of this scale is considered to be great [89].	3	According to [90], satellites have a big positive impact on humanity. Related SDGs: quality education, good jobs and economic growth, innovation and infrastructure and partnerships for the goals	3	Earth Observation is used to monitor many of the 17 SDGs [91], hence the impact of satellites being pretty high. Related SDGs: clean water and sanitation, renewable energy, sustainable cities and communities, climate action, life on land	3	As seen in this thesis, the dependence is high	3	**12**
Rockets	According to [88], the rocket market has a CAGR of 8.5% in the following years, resulting in a medium growth forecast	2	According to [92], rocketry leads to many advances that benefit Earth. Related SDGs: quality education, good jobs and economic growth, innovation and infrastructure and partnerships for the goals.	3	Rockets are not environmentally friendly, though since launches are not so frequent the impact is relatively low [93].	2	As seen in this thesis, the dependence is high	3	**10**
Hypersonic flights	According to [94], the CAGR is of 2.73%, having a poor growth	1	The SDGs related would be quality education and innovation and infrastructure	2	According to [95] the environmental impact is pretty high	2	Not much dependence	1	**6**
Propulsion systems	According to [96], it has a CAGR of 8.5% in the following years, resulting in a medium-growth forecast	2	Related SDGs: quality education, good jobs and economic growth, innovation and infrastructure and partnerships for the goals	2	Related SDGs: renewable energy, sustainable cities and communities, climate action	2	Relatively high, due to the effects of atomic oxygen [97]	2	**8**
Space tourism	According to [98], the space tourism market has a CAGR of 38.6% in the following years, resulting in a very high growth forecast	3	The impact is still being discussed, according to [99]	2	The potential environmental damage from space travel is substantial. Due to the emissions of black carbon, increased rocket fuel combustion during space tourism could affect the planet's ozone layer and accelerate global warming [100]	3	Space tourism is not done in VLEO	1	**9**

Table 5.13: Market's prioritization

5.6.2.3 3rd linking grid

The last linking grid allows to take a look at the resources, capacities and investment needed by these markets to develop the technologies identified as most in demand:

Market	Satellites/Smallsats	Rockets
Industrial capabilities development	Manufacturing and integration, specialized laboratories equiped to develop and test new materials, 3D printing facilities, environmental testing facilities, specialized softwares	Manufacturing, facilities to assembly, propulsion system development, specialized laboratories, testing facilities, specialized softwares
Technological capabilities development	Miniaturized components, communication systems, sensor technologies, data processing algorithms	Advanced propulsion systems as ABEP (Atmosphere-Breathing Electric Propulsion), rocket engine technology, materials science, aerodynamics, ability to research high-temperature materials
Human Resources (HHRR)	Engineers, data analysts, chemists, material scientists, scientists	Engineers (specially in the field of aerospace), rocket scientists, technicians, chemists, material scientists, scientists
Public Investment	Government funding for Earth observation programs, satellite launches	Government funding for space exploration programs, launch infrastructure development
Private Investment	Start-ups, satellite operators, commercial space companies	Venture capital investments, partnerships and alliances
Alliances or Collaborations (Private or Governmental)	Partnerships with manufacturers, research institutions and government agencies	Collaboration between space agencies, government contracts
Strategic Capabilities	Satellite constellation management, satellite network planning and optimization, orbital slot management	Rocket launch and recovery capabilities, reusable rocket technology, spaceport infrastructure
Patents	Patents for satellite systems, satellite communication technologies, Earth observation data processing algorithms. Also, patents for developed materials in VLEO	Intellectual property protection, patents for rocket technologies and for developed materials in VLEO
Physical Infrastructures	Ground stations, satellite control centers, satellite deployment systems, tracking and telemetry equipment, 3D printers, testing facilities	Rocket launch facilities, launch pads, ground support equipment, 3D printers, testing facilities

Table 5.14: 3rd linking grid

5.6.3 Risk analysis

As said before, to carry out a risk analysis, three factors must be taken into consideration: *technology maturity*, *market maturity* and *value network maturity*.

It is impossible to determine the technological maturity level of newly developed materials for VLEO since there is a lack of available data on the subject.

As per the findings of [15], certain developmental milestones are yet to be accomplished, which suggests that the TRL level in this regard may currently be at TRL 4 or 5. In other words, the validation of components still needs to be demonstrated in both laboratory and relevant environments.

According to [35], to develop a risk analysis —done for each action encountered in the SWOT analysis —, the following tables are to be assessed, where 1 is the minimum risk and 3 the maximum:

Stage	**TRL**	**Technological risk**
Basic R+D	1-4	3
Innovation	5-7	2
Proven technologies	8-9	1

Table 5.15: Risk values of the technology maturity. Extracted from [35]

Stage	**Risk**
Introduction	3
Growth	2
Maturity	1

Table 5.16: Risk values of the market maturity. Extracted from [35]

Stage	**Risk**
Prepare	3
Accept	2
Commit	1

Table 5.17: Risk values of the value network maturity. Extracted from [35]

Each action carries its own set of risks, and to determine the overall risk, the number of risks associated with each area must be multiplied. This calculation provides a ranking for the final risk, based on the following criteria:

- Low risk: if a score amongst 1 and 9 is obtained
- Medium risk: if a score amongst 10 and 18 is obtained
- High risk: if a score amongst 19 and 27 is obtained

Action	**Technology risk**	**Market risk**	**Value network risk**	**Final score**	**Final risk**
AS1	1	3	3	**9**	LOW
AS2	3	3	3	**27**	HIGH
AS3	3	3	3	**8**	HIGH
AW1	3	3	3	**27**	HIGH
AW2	3	3	3	**27**	HIGH
AW3	3	3	3	**27**	HIGH
AO1	1	2	2	**4**	LOW
AO2	2	2	2	**8**	LOW
AO3	2	3	3	**18**	MEDIUM
AT1	1	3	3	**9**	LOW
AT2	1	3	3	**9**	LOW
AT3	3	3	3	**27**	HIGH

Table 5.18: Risk analysis

5.7 Action Plan

5.7.1 Timeline and Budget

A timeline is needed to know its path to success. The first point to be done is the **classification** of the actions. The actions will be grouped into market, tech and resources and capabilities.

The final table can be seen in 5.18.

The periods of time result in the following, extracted from [35]:

Stage	**Period (years)**
Short-term	0-5
Medium-term	5-10
Long-term	10-15

Table 5.19: Periods of time. Extracted from [35]

Keeping in mind all procedures done, the timeline can be created:

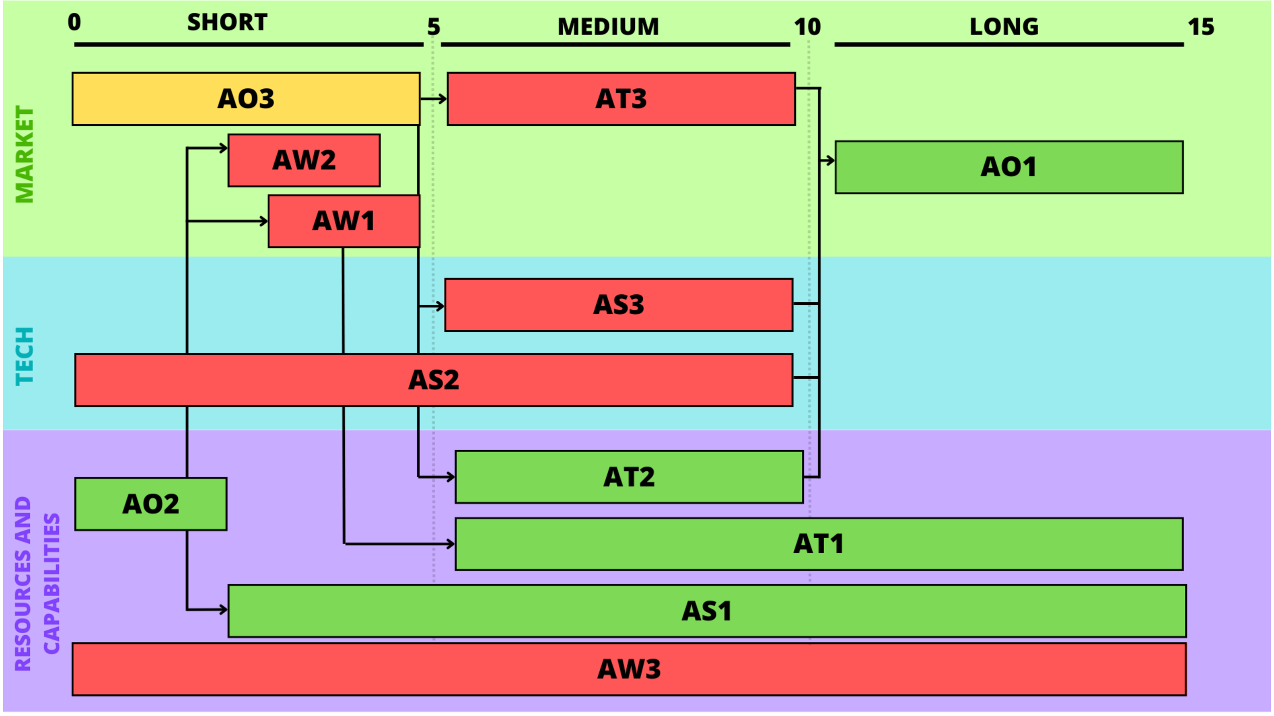


Figure 5.18: Roadmap's timeline

In the following table, a summary of the roadmap can be seen:

ID	Term	Actions	Budget (M€)	Risk	Stakeholders	Leverage factor
AO3	Short	Assist to networking events	36	Medium	All stakeholders	3
AO2	Short	Creation of a roadmap	6	Low	GA-ARI-CORP-MAN-LSP	0
AW2	Short	Identify strategic partners and developing a strategy	20	High	GA-ARI-ALA-MAN-LSP-EC-EU	6
AW1	Short	Small business creating alliances to enter the sector	20	High	ALA-GA-LSP-MAN-EC-EU	4
AT3	Medium	Promoting the space industry	24	High	All stakeholders	5
AO1	Medium	The EU working with other countries	3	Low	EC-EU-GA	0
AS2	Medium	The continuous development and improvement of new materials, alongside the EU investing in cutting-edge technology research and development	55	High	All stakeholders	8
AW3	Long	Requesting of grants and collaborations	2	High	EC-EU-ARI-ALA	0.5
AS1	Long	Investing in education so that the EU has a strong background	43	Low	EC-EU-ARI-ALA	6
AS3	Long	Conducting tests for the integration of new materials in VLEO	55	High	GA-ARI-MAN-LSP	8
AT2	Long	Investing in the implementation of safety regulations and providing training and certification	23	Low	MAN-LSP-GA-ARI-EC-EU	6
AT1	Long	Working closely with regulatory certifications	17	Low	GA-MAN-CORP-LSP-EC-EU	4

Table 5.20: Summary of the roadmap

Stakeholder	Acronym
Angel Investors	AI
Venture Capital Firms	VCF
Private Equity Firms	PEF
Corporations	CORP
Banks	BAN
Public Markets	PM
All investors above	AIA
Manufacturers	MAN
Launch service providers	LSP
Government agencies	GA
Academic and research institutions	ARI
Citizens	CIT
European Union	EU
European Commission	EC

Table 5.21: Acronyms used for the stakeholders

It has to be noted that the budget has been calculated using the references [[101], [102], [103]], of which a percentage of 6% has gone to the roadmap, as it involves just a portion of the VLEO environment. The budgets that have been designated are international for the space sector, so out of the €375 million, €73 million are for public investment.

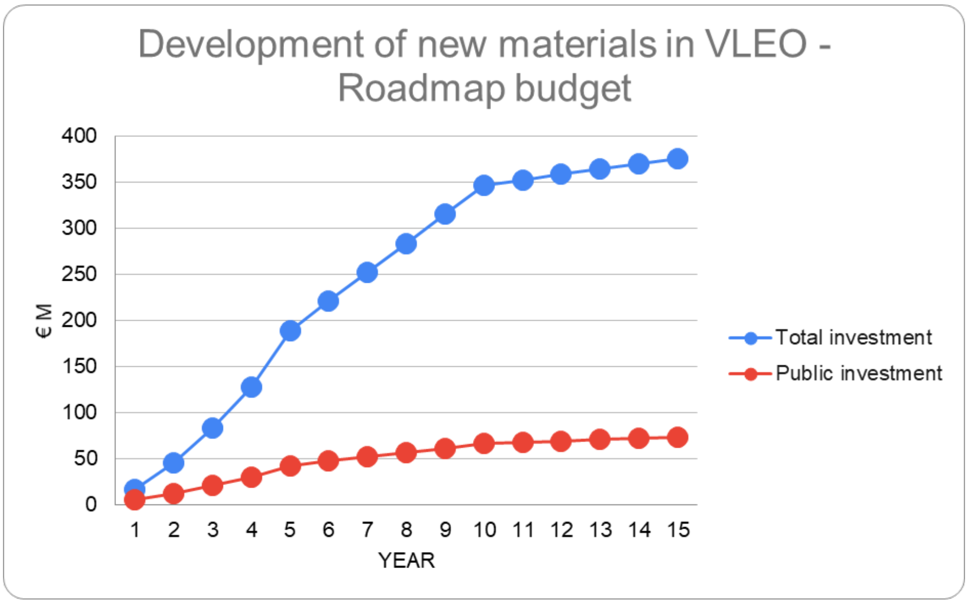


Figure 5.19: Evolution of the budget needed to implement the roadmap. Own source, done with [101], [102], [103]

In the first place, from Fig. 5.19, the periods of the roadmap that are reflected on the timeline can be seen clearly, observing an increase the first years and a stabilization on the latter ones.

The leverage factor (LF) has also been calculated, which is the proportion between private and public investments, being related to the level of technological maturity when the action is being conducted [35], getting an average LF of 4 of the roadmap.

In the short term, the private investment is €147 million, increasing notably in the medium term, being up to €281 million. Regarding the public investment in these two terms, the increase is not very notable, the short term being €42 million and the medium being €66 million. At last, when it arrives to the long-term period, the numbers balance more, rising just to €302 million when it comes to private investment and €73 million in public investment in the last year.

Moreover, in order to calculate the necessary estimations to obtain the final budget, the actions have been classified into different objectives:

Classification	Actions
Market (companies collaboration)	AO3, AW2, AW1, AT3, AO1
Economical - Private and Public Investing	AO3, AO2, AW1, AS2, AS3 AT3, AW3, AS1
Technological - Technology advances development	AO3, AO2, AS1, AS2, AS3
Space Regulation	AT1, AT2

Table 5.22: Classification of the actions

5.7.2 KPIs

KPIs (Key Performance Indicators) provide a ranking of a company's effectiveness. To make the potential future calculations easier, various indications will be proposed in this thesis:

1. **CRL (Commercialization Readiness Level):** its calculation can provide some insights into the technology and its progress in time. It considers elements including consumer demand, business model readiness, legal compliance, production capabilities, and the competitive environment.

   It can be used, for instance, to check the project's development, if the milestones are being achieved and assess the melding and suitability of various technologies. It could even be used to determine if the project can be applied to a particular grant.

2. **Market share:** market share is a good indicator as it provides insights regarding competitiveness, ergo how well the project/company is doing compared to their competitors. It also gives information on growth and industry trends, allowing a broad perception of the business and leading to strategic decision-making.

3. **Average Operational Lifetime:** this KPI will give insights on the reliability and sustainability of VLEO missions, bringing perception on the effectiveness of it.

4. **Earned value:** with this KPI, the progress and performance of the project can be estimated when it comes to planning a timeline and the budget. It uses the cost variance (CV), schedule variance (SV), cost performance index (CPI) and schedule performance index (SPI) to make the approximation by comparing the actual values to the planned ones made in the beginning. It can help in terms of providing efficient resource management for projects, the detection of deviations from the plan, and the implementation of necessary remedial measures.

5. **Financial KPIs**

   - EBIT (Earnings Before Interest and Taxes): serves as a measurement of the profitability and performance of a company, providing insights on how to generate earnings. It is useful to evaluate cost management strategies, make investment decisions, and track goals.
   - Expenses: used to track financial performance and efficiency, it helps control the costs and budgets and helps with decision-making.

- IRR (Internal Rate of Return): it estimates the potential return on investment along with helping prioritize tasks and assess the risk of the project.
- Cash-flow: it is related to the influx and efflux of money from a company over a predetermined time frame. It provides insights into financial stability, liquidity, and the ability to meet short-term obligations. By monitoring their cash flow, businesses can assess their cash management practices, determine profitability, make informed investment choices, and forecast future cash needs.
- Lastly, fundraising success can be assessed as a KPI by looking into the amount of funding raised.

Chapter 6

Environmental impact

This thesis chapter aims to portray the environmental impacts of implementing a roadmap in developing new materials in VLEO.

Throughout the whole dissertation, various points have been shown, resulting in the following summary:

- By utilizing VLEO orbits, the amount of radiation exposure can be decreased. This is due to a reduction in the number of short-lived excited state species present, leading to a decrease in radiation near the surface of the spacecraft.
- New materials in VLEO are to be pollution-free
- The use of smallsats in VLEO allows for environmental monitoring
- As mentioned in the earlier PESTEL analysis, decreasing the impact of atomic oxygen leads to a decrease in the formation of non-volatile silica build-up by decreasing the oxidation of silicones and silicone contamination.
- The space community is facing a significant environmental problem with debris densification. Therefore, the development of new materials helps to tackle this issue.

Moreover, various Sustainable Development Goals of the United Nations can be related to this thesis:

- SDG 4 Quality Education
- SDG 9 Industry, Innovation and Infrastructure entails the research of the different new materials and the manufacturing and various technologies
- SDG 11 Sustainable Cities and Communities. New materials enhance the creation of sustainable satellite systems, improving communication, and Earth Observation, amongst others. Additionally, it facilitates disaster management and environmental monitoring, as said before.
- SDG 13 Climate Action, due to the actions described before, fitting accordingly to climate policies.
- SDG 17 Partnerships for the Goals. Working together is crucial in developing new materials for VLEO. Involving stakeholders from academia, businesses, governments, and international organizations enhances information exchange, transfer technology, and building capacity.

Chapter 7

Budget summary

A previous section of this project outlines the economic strategy for developing new materials in VLEO listed in the roadmap. In this chapter, a brief summary of the feasibility assessment of the thesis is defined.

Therefore, the budget of the thesis is attached in another document to satisfy the university's criteria. The total budget is 10,832 €.

Chapter 8

Conclusions

To thoroughly review the work, the most important findings, contributions, and implications will be gathered in this final part. This thesis has looked into implementing a roadmap for developing new materials in Very Low Earth Orbits (VLEO).

The key conclusions from the study will be summarized, and the overall significance of the field research will be reviewed as the thesis is concluded. The study's limitations will be delved into, and this section will offer potential directions for further investigation and real-world applications.

Following a brief first look at the project, exploring VLEO gives excellent potential for developing novel materials. Thanks to its distinguished environment, which involves the proximity to Earth and space-related challenges, it offers a powerful testing ground for developing said materials. Researchers learn much about materials' performance, resilience, and durability by exposing them to harsh VLEO conditions, such as strong radiation, vacuum, temperature changes and atomic oxygen. This information, therefore, makes it easier to create materials with improved qualities, including increased strength, radiation resistance, and thermal stability. Furthermore, the absence of Earth's gravity in the microgravity environment of VLEO makes it possible to experiment with novel production methods and observe material behaviour, opening the way to developing novel materials with distinctive structures and features. Research into VLEO-based materials has the potential to transform several industries, including aerospace, communications, and energy, by enabling the development of more sophisticated and effective technologies.

With them being a well-known method of strategic planning, roadmaps are increasingly becoming a crucial tool in science, technology, and innovation foresight. To complete this thesis, an innovative methodology was developed through an agile development process after reviewing multiple papers, enabling an innovative way to reach the initial goal. The new methodology consists of three phases: initiation, development and integration. The scope, layout, and data gathering are completed in the initiation phase, allowing the process to be started and structured. The development phase comes after this one, during which the pre-processing, generation, evaluation, and execution of the action plan are carried out. All analyses are completed in this phase, ranging from a SWOT analysis to KPIs proposals. The plan's integration phase comes after a thorough iteration process that includes workshops, market and expert interviews to obtain feedback, and regular updating of the roadmap.

A market and stakeholder study was conducted, resulting in a forceful tool to carry out the PESTEL analysis on the latter and Porter's 5 Forces and SWOT Analysis. Those resulted in a very intense competitive rivalry which new entrants threatened. Later on, the scenarios were put on the table, which helped generate a final SWOT analysis that helped generate the final roadmap and budget.

Various conclusions can be extracted from this roadmap; implementing a roadmap for developing new materials in VLEO can enhance collaboration among different stakeholders, encouraging partnerships that could lead to accelerated progress in material development. Also, it serves as a guiding tool to organize research activities; the roadmap promotes a focused and coordinated approach to innovation by specifying important milestones, priorities, and dates. As a result, materials with better radiation and atomic oxygen resistance, thermal stability, and mechanical strength may evolve more quickly.

Nevertheless, it is vital to note that for the goal to be achieved in 15 years, its development should receive more significant funding and research, as well as more promotion of the space industry and the EU working with other countries. Having government support becomes crucial in this field.
As for further research, a meeting with KREIOS Space was carried out, where they pointed out how the next steps on the development of new materials in VLEO applied in ABEP (Air-Breathing Electric Propulsion) systems were headed into the motor intake and materials that protect anodes.

Moreover, it should be noted that numerous grants are currently available due to the COVID pandemic. However, these grants are predicted to be phased out within the next five years. Therefore, it is crucial to establish collaborations, partnerships, and meaningful alliances.

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