SPACESHOT PROJECT MBSE

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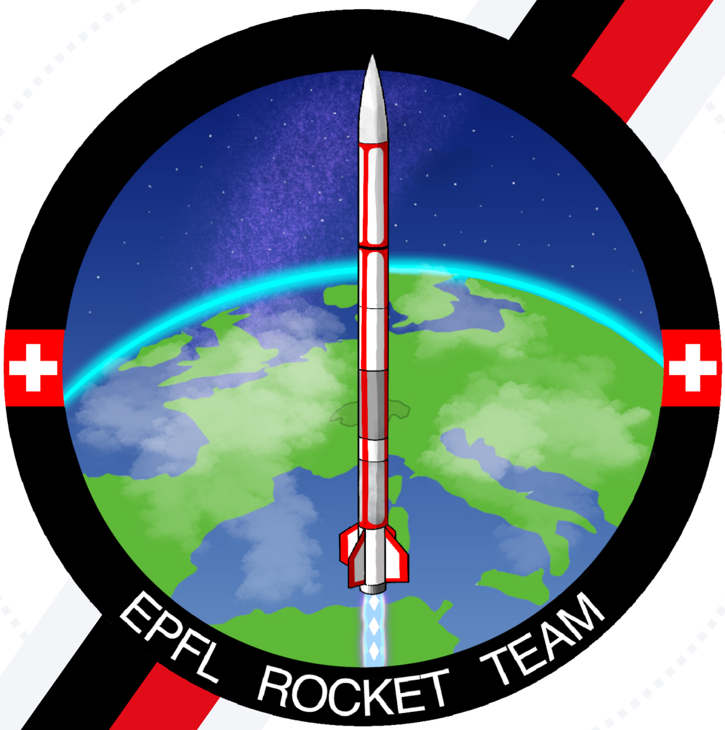

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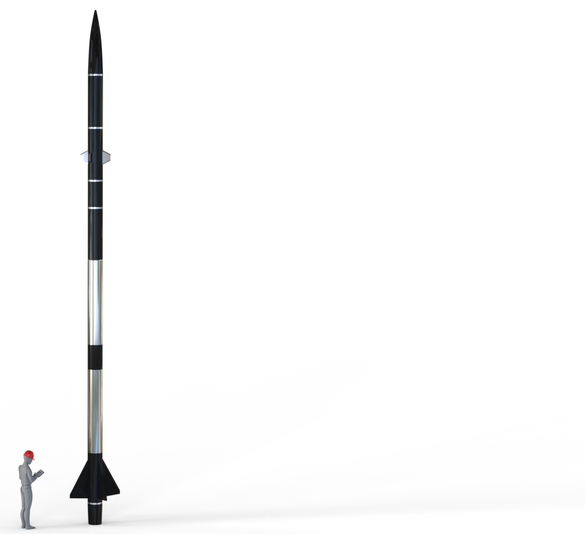
EPFL ROCKET TEAM

Contents

1 Introduction

The EPFL Rocket Team's Spaceshot project represents a bold academic and engineering challenge: to design, develop, and launch a student-built bi-liquid rocket capable of reaching space by exceeding the Kármán line (100 kilometers in altitude) before the end of the decade. This semester project, conducted in the spring of 2025, serves as a foundational step in that journey by applying Model-Based Systems Engineering (MBSE) practices to structure and guide the early phases of mission development.

As a multidisciplinary, student-led initiative supported by the École Polytechnique Fédérale de Lausanne (EPFL), the EPFL Rocket Team (ERT) is organized into specialized projects—Space Race, Icarus, Hyperion, and Competition—each contributing critical pedagogic and technical expertise. The Spaceshot project aims to synthesize these efforts into a single, large-scale mission that pushes the boundaries of what student teams can accomplish in the realm of aerospace.



In this context, the semester project was initiated to introduce and apply MBSE practices within the EPFL Rocket Team's systems engineering efforts. Its primary objective was to develop a preliminary system model of the Spaceshot launch vehicle using the SysML language, supported by a professional MBSE tool such as Cameo or MagicDraw. The approach was guided by the Object-Oriented Systems Engineering Method (OOSEM) and aligned with the early phases (0 and A) of the ECSS project framework.

Planned deliverables included a Mission Statement and Description, Stakeholder Value Network, Functional Analysis, Technical Requirements Specification, initial architectural trade studies, and a structured SysML model. The ultimate goal was to achieve Preliminary Requirements Review (PRR) readiness by the end of the semester. The project was structured over sixteen weeks, progressing through phases of planning, model setup, stakeholder and mission analysis, requirement derivation, architectural synthesis, and documentation.

Although not all planned artifacts and milestones were completed, this report documents the work carried out during the semester and serves as a reference for future team members. It offers methodological guidance, modeling practices, and systems engineering insights to support the ongoing development of the Spaceshot initiative.

2 Abbreviations

Acronyms

BDD Block Definition Diagram. 24, 26

CONOPS Concept of Operations. 19

ECSS European Cooperation for Space Standardization. 4, 7

EGSE Electrical Ground Support Equipment. 45

EPFL Ecole Polytechnique Fédérale de Lausanne. 8, 13, 48

ERT EPFL Rocket Team. 4, 12–14, 17, 18, 26, 28, 38, 39, 47, 48, 50

ESA European Space Agency. 13, 18, 38

ESC Esrange Space Center. 9, 13, 17, 18, 48

eSpace EPFL Space Center. 13, 48

EuRoC European Rocketry Challenge. 17

GCM Gravière de la Claie aux Moines SA. 12

GNC Guidance, Navigation, and Control. 45

IBD Internal Block Diagram. 26

ICD Interface Control Document. 21

LV Launch Vehicle. 27, 37, 39–42

MAKE MAKE Initiative. 13

MBSE Model Based Systems Engineering. 4, 14, 21–26, 47–50

MDR Mission Definition Review. 47

MGSE Mechanical Ground Support Equipment. 17, 45

MoE Measure of Effectiveness. 14, 15, 18, 19

MoP Measure of Performance. 14

MSC Mission Success Criteria. 9

MSD Mission Statement and Description. 8

NASA National Aeronautics and Space Administration. 38

OOSEM Object Oriented Systems Engineering Method. 4, 25

OPM Object-Process Methodology. 24

PRR Preliminary Requirements Review. 4, 45, 47

SE Systems Engineering or System(s) Engineer. 7, 21, 23, 25, 26, 39, 40, 48–50

SLRS Suborbital Launch Rail System. 7

SRAD Student Researched and Developed. 8

SRR System Requirements Review. 45

SSC Swedish Space Corporation. 17

SVN Stakeholder Value Network. 7, 11

SysML System Modeling Language. 4, 22–25, 47–49

UML Universal Modeling Language. 24

3 Systems Engineering

3.1 Overview

3.1.1 Literature and Method

To kickstart the first Systems Engineering (SE) artifacts, a set of pre-existing methods and literature was used. The main reference for this semester project was the EPFL Rocket Team's 2025 Systems Engineering Handbook [3]. It offers a structured framework for managing student-led technical projects using systems engineering methodologies, outlining roles, project phases based on the ECSS standard, and key deliverables. Its guidance supports effective planning, collaboration, and documentation in an academic context. While not all contents of the handbook were applied, the focus was placed on the preliminary project phases (0 and A), with general guidance drawn from the "Entities" and "Project Management" sections to help design a sound mission.

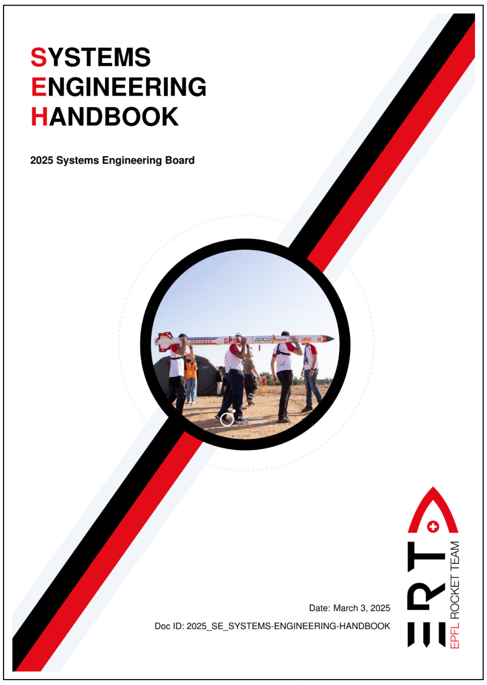


Figure 1: ERT's 2025 SE Handbook

Figure 2: SLRS Semester Project Report

Alongside the Systems Engineering Handbook, the Suborbital Launch Rail System (SLRS) Report [4] supported the development of the Stakeholder Value Network (SVN) and the Launch Site Provider Stakeholder Analysis. The SLRS is a modular launch rail designed to accommodate vehicles ranging from the EPFL Rocket Team's current launch vehicle to the future spaceshot-class rocket. The report includes a preliminary assessment of the team's stakeholder environment, as well as considerations related to the spaceshot launch site and its infrastructure, offering valuable context for understanding stakeholder interactions and site-specific constraints.

3.2 Artifacts

3.2.1 Mission Statement and Description (MSD)

The Mission Statement and Description (MSD) is placed at the beginning of this document to clearly establish the strategic direction and high-level intent of the Spaceshot project from the outset. Although presented early for clarity, this section is the result of the extensive systems engineering analysis and modeling efforts detailed throughout the report. The MSD serves as both a guiding vision and a reference point for the subsequent steps described in later sections.

Context

The EPFL Rocket Team is a student association based in Lausanne, Switzerland, with the ambitious goal of reaching space by the end of the decade using their own bi-liquid rockets. Backed by the École Polytechnique Fédérale de Lausanne (EPFL), the team advances its mission through four distinct projects. Space Race focuses on educating and onboarding new members, while Icarus is dedicated to developing advanced active control systems to limit the launch vehicle's flight envelopes. Hyperion centers on the innovation of bi-liquid engines and associated technologies, and the final project, Competition, is dedicated to designing and building rockets for international competitions. This final initiative is poised to develop into the Spaceshot, an ambitious project aimed at overcoming the challenge of reaching space within an academic framework, while collecting all the technical data generated by the three other projects.

Mission Statement

"To achieve, before 2030, an apogee exceeding 100 km using a SRAD liquid propulsion system; to provide controlled exposure of the payload to space conditions during the ballistic coast phase; and to ensure the safe and complete recovery of at least the payload, and if possible, the launch vehicle as well."

Mission Objectives and Constraints

Apogee Achieving an apogee beyond the Kármán line requires the integration of advanced technologies into the launch vehicle, along with intricate and costly logistical preparations to facilitate launches at such altitudes.

Payload Operation While reaching the target apogee is a significant challenge on its own, the EPFL Rocket Team aims to maximize this launch opportunity by carrying a payload. Although the specific type of payload has yet to be determined, the near-space conditions present during the coast phase offer a valuable opportunity for internal or external stakeholders to leverage this flight for research or technological experimentation.

Recovery Although sustainability is not the main priority, the recovery of both the payload and the launch vehicle is encouraged by the launch site and presents clear advantages, especially in terms of retrieving flight data. This information is valuable not only for the EPFL Rocket Team's development efforts but also for advancing knowledge within the amateur rocketry field.

Mission Success Criteria

Mission Success Criteria (MSC)

Mission Success Criteria are high-level outcome-based measures used to assess whether the mission objectives have been met. They provide a clear definition of what constitutes minimum and full mission success from both technical and stakeholder perspectives, guiding system validation and anchoring the project's performance expectations.

The Mission Success Criteria (MSC) are categorized into Minimum and Full success levels. Minimum MSCs define the essential conditions required to declare a partial mission success, while Maximum MSCs set the targets for achieving full success. Each criterion is numbered accordingly, some MSCs apply only to minimum success, whereas others include both minimum and maximum thresholds to reflect a graduated evaluation of mission performance.

- **Minimum Success**
  - **MSC 1min – Apogee**
    - *Criteria:* The launch vehicle shall reach an altitude of at least 80 km.
    - *Rationale:* This threshold marks exposure to near-space conditions, where atmospheric pressure and temperature are sufficiently low to validate space-relevant payload performance. However media exposure is reduced as most countries consider 100 km as the space limit[18].
  - **MSC 2min – Flight Data Recovery**
    - *Criteria:* The flight data shall be successfully recorded and recovered.
    - *Rationale:* Ensures mission telemetry and critical system performance metrics are available for analysis, even in the event of hardware loss. Exact data type is yet to be defined.
  - **MSC 3min – Payload Data Recovery**
    - *Criteria:* The payload data shall be able to be recovered.
    - *Rationale:* Allows mission goals to be met even without nominal physical payload recovery.
  - **MSC 4min – Payload Environmental Protection**
    - *Criteria:* The payload shall be protected from landing and recovery loads as well as environmental stressors (e.g., temperature, vibration).
    - *Rationale:* Confirms that mission hardware can withstand spaceflight and recovery conditions, preserving its scientific or technical value.
  - **MSC 5min – Launch Site Compliance**
    - *Criteria:* The mission shall comply with Esrange Space Center's (ESC) interface, safety, and operational requirements.
    - *Rationale:* Regulatory and operational compatibility is required to obtain launch clearance and conduct the mission within the launch site.
- **Full Success**

- **MSC 1max – Apogee**
  - *Criteria:* The launch vehicle shall reach an altitude of at least 100 km.
  - *Rationale:* This altitude is internationally recognized as the boundary of space (Kármán line), offering exposure to true space conditions for payload validation as well as proper media exposure in case of mission success.
- **MSC 2max – Complete Vehicle Recovery**
  - *Criteria:* The launch vehicle shall be recovered in a condition suitable for post-flight exhibition and extended flight data analysis.
  - *Rationale:* Demonstrates structural resilience and supports reuse or display for outreach and analysis.
- **MSC 3max – Payload Location and Recovery**
  - *Criteria:* The payload shall be successfully located and recovered after landing.
  - *Rationale:* Enables inspection, reuse, or extended experimentation with the payload post-flight.
- **MSC 6max – Flight Media Recording**
  - *Criteria:* Onboard video streams of the flight shall be recorded and successfully recovered.
  - *Rationale:* Provides visual documentation for analysis, public outreach, and sponsor deliverables.
- **MSC 7max – Sponsor Visibility**
  - *Criteria:* The mission shall include a livestream of key events and pre-flight milestones to invite sponsors.
  - *Rationale:* Demonstrates value to sponsors through visibility, transparency, and event participation.
- **MSC 8max – Timely Execution**
  - *Criteria:* The mission shall be completed within two years of project designation and before the end of the decade.
  - *Rationale:* Confirms the project's feasibility within organizational timelines and strategic planning.

Description of Approach

Apogee The Competition project will evolve yearly, gradually increasing engine performance, structural capabilities, and avionics sophistication. This iterative approach ensures that each generation of launch vehicles builds upon previous successes and failures. Critical milestones include static fire tests, subscale demonstrators, and incremental altitude increases, ultimately leading to a full-scale single-stage launch vehicle capable of exceeding 100 km.

Payload Operation Given the evolving nature of the project, payload integration will remain flexible to accommodate various stakeholders. A standardized payload bay and environmental shielding will allow for a range of research applications.

Recovery Recovery solutions will be developed through extensive testing and simulation, incorporating both active and passive descent mechanisms. Strategies may include drogue and main parachute deployment, autonomous flight termination systems, and real-time tracking to ensure precision landing. Data from previous competition launches will inform system design, with a focus on re-usability and reliability.

3.2.2 Stakeholder Value Network (SVN)

This document provides a summary of the stakeholder environment in which the Spaceshot project will evolve throughout its entire lifecycle. Extensive analysis are done for the Payload Provider in section 3.2.3 and Launch Site Provider in section 3.2.4.

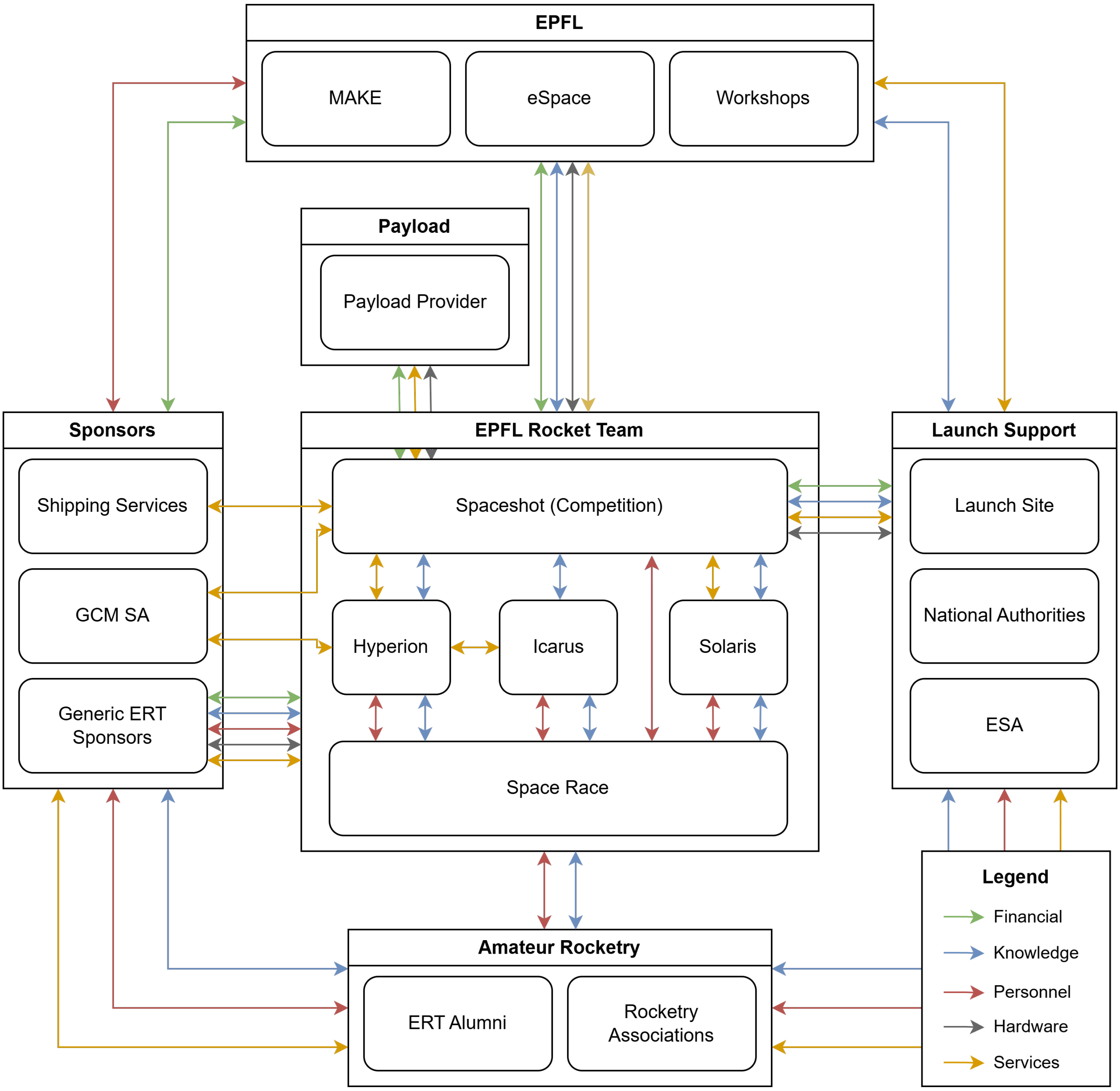


Figure 3: Stakeholder Value Network

EPFL Rocket Team

The EPFL Rocket Team oversees multiple interconnected projects that collaborate to support the main Spaceshot initiative.

- **Spaceshot (Competition):** The Spaceshot project is the last iteration of the competition project, with the goal to reach space by the end of the decade.
- **Hyperion:** The Hyperion project aims to develop SRAD bi-liquid propulsion solutions for the Icarus and Spaceshot projects.
- **Icarus:** The Icarus project focuses on developing SRAD active control solutions for reusable bi-liquid propelled vehicles. These technologies are transferred to the Spaceshot project to enhance its GNC capabilities.
- **Solaris:** The Solaris project is dedicated to manufacturing and operating a large-scale launch rail and rocket testing platform, which will serve as the MGSE for the Spaceshot launch vehicle's lift-off.
- **Space Race:** The Space Race project is an annual educational initiative designed to introduce new members to the fundamentals of rocketry, preparing them to transition into more advanced ERT projects.

Payload

The payload cluster is composed of the payload provider only.

- **Payload Provider:** The payload provider is the primary stakeholder of the Spaceshot project, responsible for designing the payload to be carried aboard the launch vehicle. Its identity has not yet been finalized and could range from an external laboratory or company to an internal entity within the EPFL Rocket Team. As a contingency, the Hyperion P-Class subsystem is developing a backup payload in the event that no external provider is secured.

Sponsors

The sponsors of the EPFL Rocket Team serve as the financial and service backbone.

- **Generic ERT Sponsors:** Most of the EPFL Rocket Team sponsors are dedicated to provide services and support to the overall association, they often do not interact directly with a specific project.
- **GCM:** Gravière de la Claie aux Moines SA provides the Rocket Team with a testing site, where an engine testing facility has been built. The site is also suitable for vehicle testing in the final stages of launch vehicle development.
- **Shipping Services:** Given the complexity and weight of the Spaceshot launch vehicle and its ground segment, a dedicated shipping service provider will be secured as a stakeholder.

EPFL

The École Polytechnique Fédérale de Lausanne (EPFL) provides academic, financial, and service support to the Rocket Team. Comprising multiple entities, it represents one of the largest stakeholder clusters with which the EPFL Rocket Team interacts.

- **MAKE:** The MAKE initiative oversees the EPFL prototyping associations and provides financial support each year.
- **eSpace:** The eSpace laboratory oversees some activities of the Rocket Team while providing logistical support and advice.
- **Workshops:** The EPFL workshops provide support during the manufacturing activities at the Rocket Team, often with reduced pricing and sped-up manufacturing delays.

Launch Support

The launch support stakeholder cluster includes all public entities that the EPFL Rocket Team must engage with to secure a Spaceshot launch opportunity.

- **Launch Site:** The Launch Site provides the launch pad where the Solaris rail will be assembled to launch the Spaceshot rocket. They should also offer feedback to the engineering team during the Spaceshot design phase.
- **National Authorities:** The Launch Site is overseen by national authorities such as aviation agencies that can enforce strict flight safety rules.
- **European Space Agency (ESA):** The European Space Agency interacts with the rocket team through the Esrange Space Center (ESC. They encourage the development of aerospace activity throughout Europe.

Amateur Rocketry

The Amateur Rocketry stakeholder cluster gathers all the associations and old team members that work on sounding rockets.

- **Alumnis:** Over the years, the ERT has established a strong alumni network, providing current Rocket Team members with valuable advice and experience to build upon.
- **Rocketry Associations:** By participating in multiple rocketry competitions, the EPFL Rocket Team has built a strong network with competitors, facilitating the exchange of knowledge and personnel.

The stakeholder value network analysis highlights the diverse ecosystem of actors that contribute to the success of the Spaceshot project. From internal technical branches within the EPFL Rocket Team to institutional bodies such as EPFL and Esrange Space Center, each stakeholder provides specific value, whether through technical expertise, infrastructure, regulatory support, or funding. The central role of the payload provider, combined with the critical support of sponsors and academic partners, reinforces the multidisciplinary and collaborative nature of the mission.

3.2.3 Payload Provider Stakeholder Analysis

After the different project stakeholders had been mapped, it was decided to perform a more in-depth analysis of certain specific stakeholders. This is because the MBSE tool wasn't available at this time of the project, and because some of these stakeholders needed to be better analyzed to continue the project.

The first analysis was performed on the payload provider. Contrary to previous ERT launches at the time of writing this report, it was identified that the spaceshot payload could potentially be supplied by an external stakeholder instead of being developed internally. While launches at traditional student rocket altitudes (<9[km]) offer limited value for potential scientific payloads, it is undeniable that there could significant interest for scientific payloads to use the spaceshot. To perform this analysis, NASA's Expanded Guidance for NASA Systems Engineering was followed[21]. An important point to note is that, because the specific payload provider hasn't yet been identified as of writing this report, this analysis is left intentionally vague. In case a provider is identified later, it shall be performed again.

The detailed analysis is documented on ERT's wiki[13], and for the sake of brevity, only the most important results are presented here.

Measures of Effectiveness

Measures of Effectiveness (MoEs)

Measures of Effectiveness (MoEs) are the measures of success that are designed to correspond to the accomplishment of the system objectives as defined by the stakeholder's expectations. They are stated from the stakeholder's point of view and represent criteria that must be met for the stakeholder to consider the project successful.

They can be synonymous with mission/project success criteria.

Typically, multiple MoPs, which are quantitative and measurable, are needed to satisfy a MoE, which can be qualitative.[21]

- **MoE 1 – Flight Achieves Near-Space Conditions**
  - A suborbital flight is conducted that places the payload in near-vacuum conditions at or above 80 km altitude, enabling the intended exposure to space-like environments.
- **MoE 2 – Vehicle Maintains Acceptable Flight Corridor**
  - The rocket remains within an acceptable lateral and angular deviation corridor from liftoff through apogee, ensuring the payload experiences the planned environment.
- **MoE 3 – Payload Data Collection**
  - The payload data are successfully transmitted from liftoff through apogee (and descent, if applicable), regardless of whether hardware is physically recovered.
- **MoE 4 – Payload Is Recovered in Operational State**

  - The payload is located and retrieved post-flight with minimal damage, allowing it to be powered on or inspected in a working condition.

- **MoE 5 – Launch Environment Stays Within Payload Tolerances**
  - The in-flight loads (acceleration, vibration, shock, thermal) remain within the payload's specified tolerance envelope, preserving payload functionality.

- **MoE 6 – Payload Can Be Integrated Rapidly and Safely**
  - The payload is integrated into the launch vehicle with minimal rework and without compromising payload integrity.

Concept of Operations

Concept of Operations (ConOps)

After the initial stakeholder expectations have been established, the development of a Concept of Operations (ConOps) will further ensure that the technical team fully understands the expectations and how they may be satisfied by the product, and that this understanding has been agreed to by the stakeholders.[21]

The second main artifact that was derived is a Concept of Operations (ConOps) that applies specifically to the payload provider's expectations.

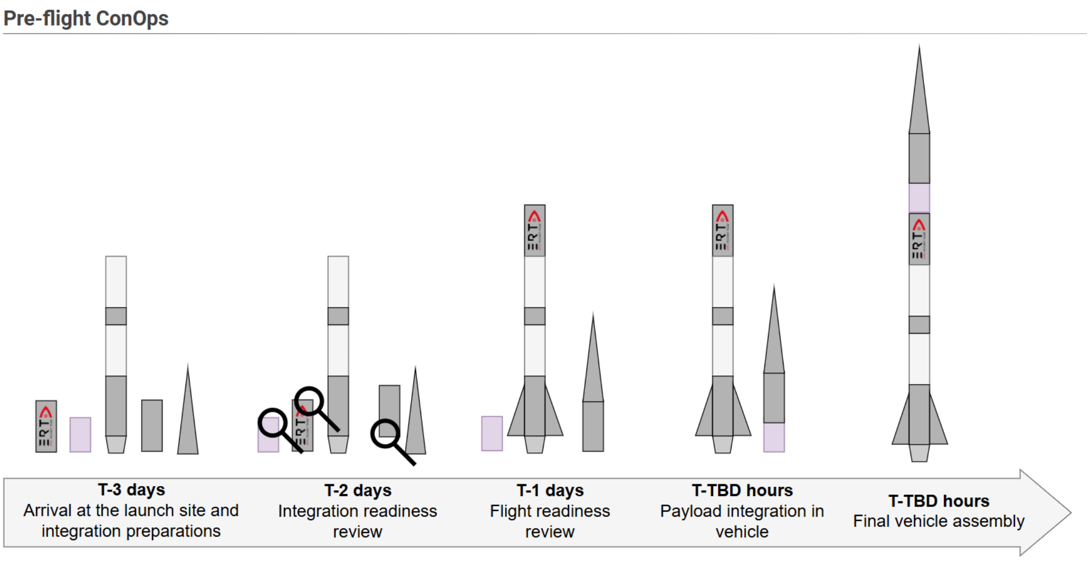


Figure 4: Pre-flight ConOps specific to the payload provider stakeholder.

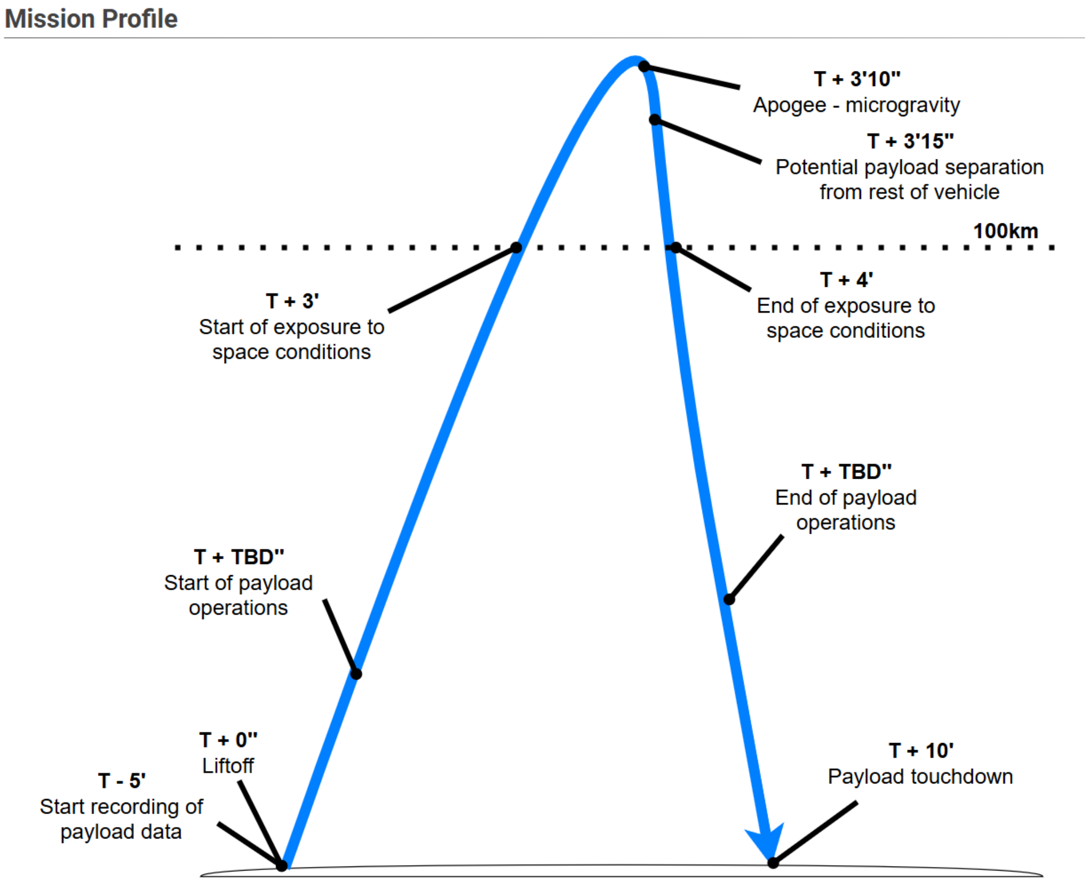


Figure 5: Mission profile specific to the payload provider stakeholder.

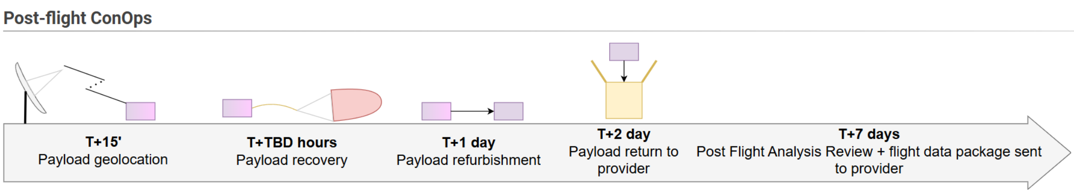


Figure 6: Post-flight ConOps specific to the payload provider stakeholder.

The key takeaways here are:

- **Payload Assembly:** The Payload is assembled on site with the rest of the launch vehicle.
- **Payload Operations:** It is expected that payload operations (such as experimental data gathering) do not affect the flight itself.
- **Trajectory and Timings:** The ConOps is obviously purely indicative and doesn't reflect the final timings of flight events.
- **Data Package:** It is expected from the team to send back the full flight data package to the payload provider after the flight has been analyzed.

3.2.4 Launch Site Provider Stakeholder Analysis

The second deep-dive analysis focused on the Launch Site Provider. While the final provider has not yet been confirmed, the Esrange Space Center in Kiruna, Sweden, was selected as the reference case to narrow the scope of the analysis.

Unlike previous ERT missions, the Spaceshot project presents a significant logistical challenge, approaching the complexity of professional or scientific suborbital campaigns. Ensuring the feasibility of the mission requires identifying a launch site provider capable of supporting complex logistics, enforcing robust safety protocols, and offering a well-defined operational framework.

The analysis was conducted using the same methodology applied to the payload provider. Full details are available on the ERT internal wiki[12]; for conciseness, only the most relevant findings are summarized below.

Esrange Space Center (ESC)

During the semester project, several meetings were held with the Esrange Space Center (ESC) in preparation for the Firehorn II launch, the EPFL Rocket Team's first out-of-competition flight of a large-scale launcher. These discussions also informed the Spaceshot project by providing valuable insights into ESC's capabilities, operational requirements, and strategic objectives as well as potential collaboration points on on-site competitions (similar to EuRoC) and MGSE sharing. These findings are reflected in the Measures of Effectiveness and Concept of Operations sections. While many precise technical and logistical metrics were identified during these exchanges, this section focuses on providing a broader overview of the Esrange Space Center.

Figure 7: Esrange Space Center, Kiruna, Sweden

The Esrange Space Center (ESC), located near Kiruna in northern Sweden, is one of Europe's leading facilities for launching sounding rockets and high-altitude balloons. Operated by the Swedish Space Corporation (SSC), ESC has supported atmospheric, microgravity, and reentry research missions for over 50 years. Its remote Arctic location offers a vast uninhabited recovery area, making it ideal for suborbital trajectories and safe reentry operations.

ESC features a comprehensive ground infrastructure, including integration halls, storage facilities, launch pads, and control centers. It also provides logistical services such as transport of launch vehicles between facilities, cryogenic propellant handling, and environmental support systems. The site operates under strict regulatory and safety frameworks, coordinated with national authorities and aligned with international best practices.

Beyond its operational capacity, Esrange plays a strategic role in Europe's space ecosystem. It regularly hosts institutional missions, supports ESA campaigns, and is undergoing expansion to accommodate orbital launches in the near future. Its blend of robust infrastructure, regulatory compliance, and expanding capabilities positions ESC as a cornerstone of European suborbital and space access.

Measures of Effectiveness

The following Measures of Effectiveness (MoE) criteria were derived.

- **MoE 1 – Mission Execution Without Incident**
  - The mission is completed with no safety incidents or disruptions to ESC's ongoing operations or those of its other stakeholders.
- **MoE 2 – Successful Bi-Liquid Demonstration**
  - The bi-liquid launch vehicle achieves liftoff and apogee without anomalies, and ESC infrastructure supports the operation effectively.
- **MoE 3 – Positive Financial Transaction**
  - ESC receives the agreed-upon financial compensation from ERT prior to launch, with no budget overruns during operations.
- **MoE 4 – Effective Communication and Outreach**
  - The mission receives media coverage through ERT's social channels and a livestream is successfully broadcast via ESC platforms.
- **MoE 5 – Full Mission Lifecycle Completion**
  - The vehicle is launched, reaches apogee, is recovered successfully, and the ERT demobilizes efficiently post-mission.
- **MoE 6 – Infrastructure Compatibility**
  - The launch vehicle integrates successfully with ESC facilities and ground support systems, from preparation through launch.
- **MoE 7 – Regulatory Compliance**
  - The mission adheres to all applicable safety and procedural regulations established by ESC and national authorities.

- **MoE 8 – Environmental Tolerance and Launch Window Adherence**
  - The launch vehicle functions within expected environmental conditions and conducts flight operations within the allocated time slot.

Concept of Operations

The second main artifact that was derived is a Concept of Operations (CONOPS) that applies specifically to the launch site provider's expectations.

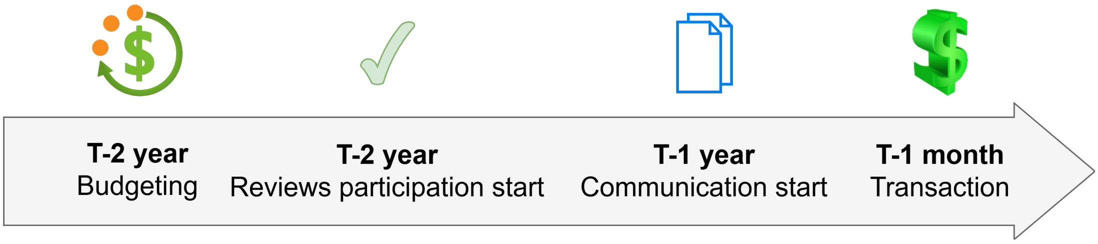


Figure 8: Pre-arrival ConOps specific to the launch site provider stakeholder.

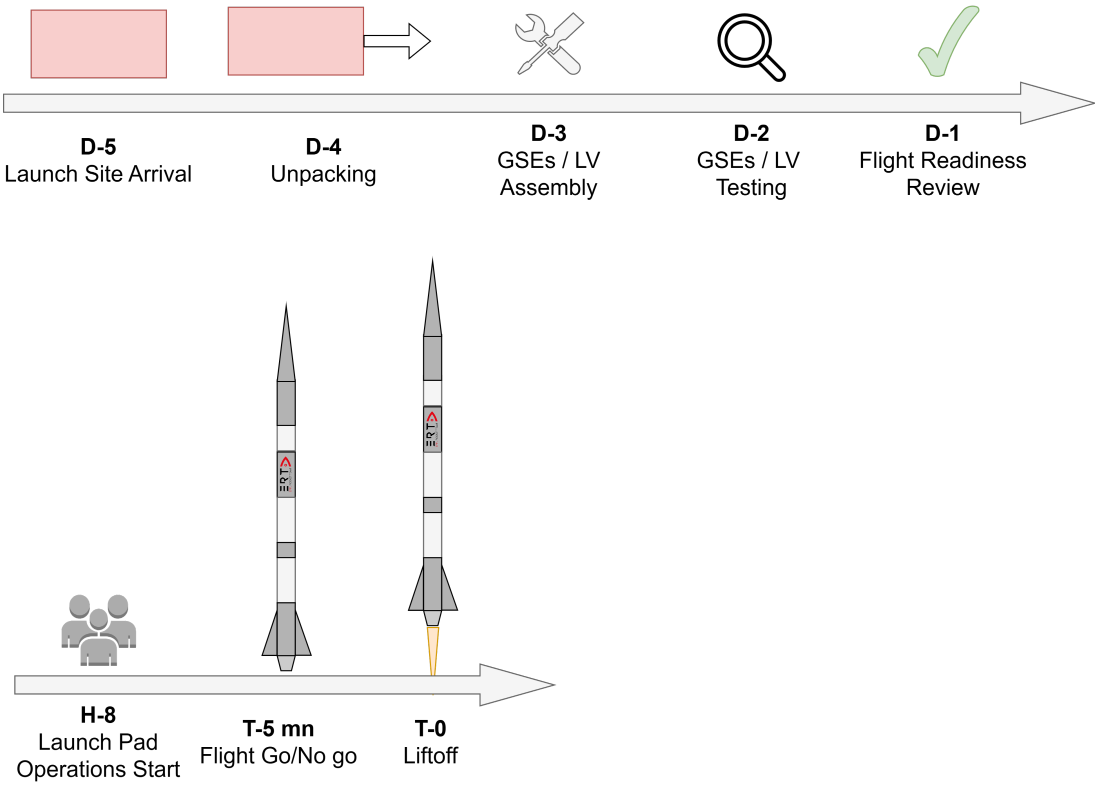


Figure 9: Pre-flight ConOps specific to the launch site provider stakeholder.

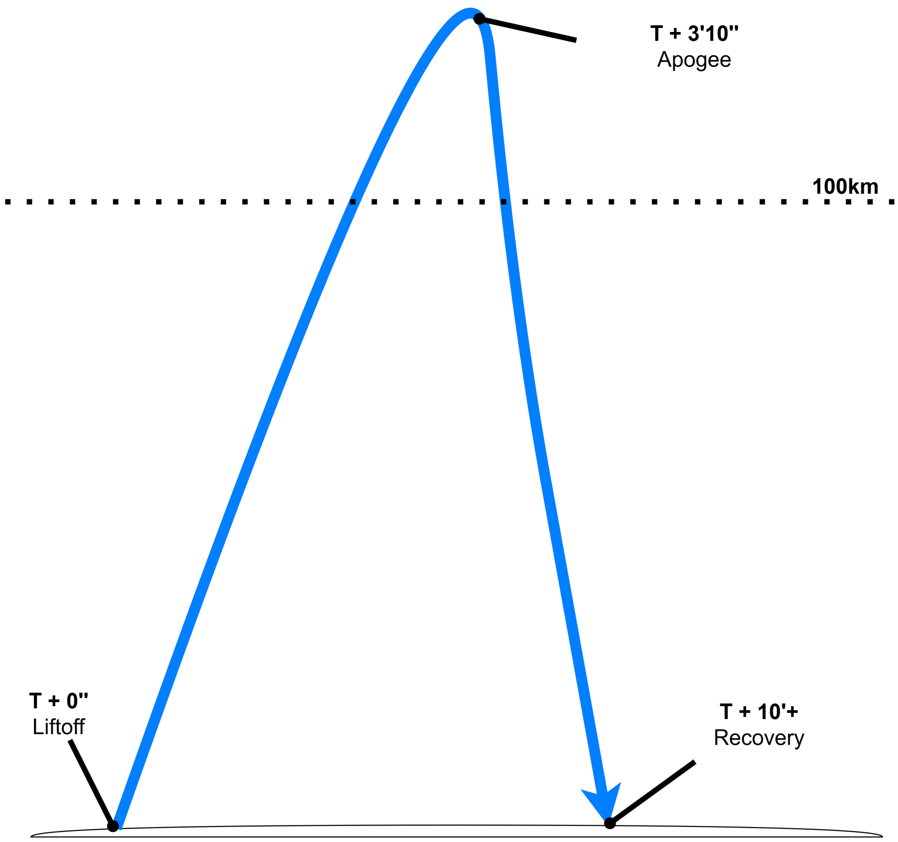


Figure 10: Mission profile specific to the launch site provider stakeholder.

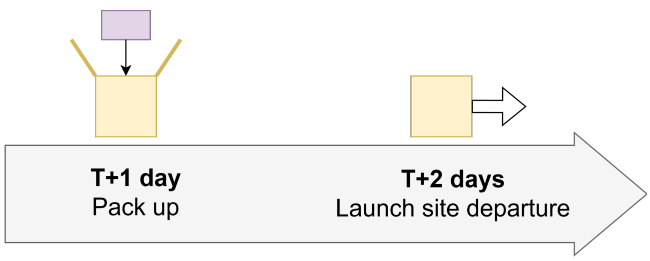


Figure 11: Post-flight ConOps specific to the launch site provider stakeholder.

The key takeaways here are:

- **Early Collaboration** Measures of effectiveness begin to apply early in the project lifecycle, particularly during budgeting and the initial exchange of requirements. Establishing a collaborative relationship from the outset is critical.
- **Operational Window** The timeframe between arrival at and departure from the launch site is limited and influenced by budget constraints. Precise logistical coordination is essential to maximize the likelihood of a successful launch within this narrow window.
- **Flight Profile** The launch site provider has relatively few measures of effectiveness directly tied to the flight profile itself. Most relevant effectiveness criteria are met prior to launch, focusing on safety, readiness, and regulatory compliance.

4 Model Based Systems Engineering

4.1 Overview

The idea of this part of the report is to provide a brief overview of MBSE with our own words. MBSE is not being taught at EPFL, which means that the only way for us to learn it was to look at literary resources. Any student wishing to learn it should to de same, and we hope to provide here enough guidance to allow future students to know where to look.

The core idea behind Model Based Systems Engineering (MBSE) is that the *single source of truth* that holds authority on the system is a model and not a series of documents. MBSE is often opposed to the traditional/document-based systems engineering practices.

For document based engineering, if an engineer for example wants to know something about an interface between subsystems, he has to read one or multiple Interface Control Documents (ICD). If he wants to update a requirement, he has to update it in the list of all requirements, as well as in all other documents that mention/refer to the modified requirement, such as Design Justification or Definition Files, ICDs, Operations and Test Procedures, etc. This is time consuming and error-prone.

For MBSE, since we are not working with a series of documents but with a *model*, updating the requirement propagates the change to all other aspects of the model that refer to it. Understanding what the *model* is requires a bit of reading, but the basic idea is that it is an abstract object that represents all aspects of the system. In order to view or edit the contents of the model, *diagrams* are used. But the diagrams are not the model itself, just a 'window' to look at specific parts of it.

In order to perform MBSE, three different *pillars* are needed: a *language*, a *tool*, and a *method*. Each of these pillars will be briefly explained, and the specific solution used for this project will be given.

4.1.1 Literature

This part of the report aims to provide both an overview of the literature that was used during the project, and a small guide to help future students approach MBSE. Since we had to start learning MBSE from scratch, the first thing we did was ask experienced Systems Engineers for advice on the SE subreddit[24]. It was extremely helpful, and based on their advice and feedback, we could proceed with the literature review.

Handbook of Model-Based Systems Engineering[16], *A Practical Guide to SysML*[9] and *SysML for Systems Engineering*[14] are all resources that were recommended to us but that we haven't used much for the project.

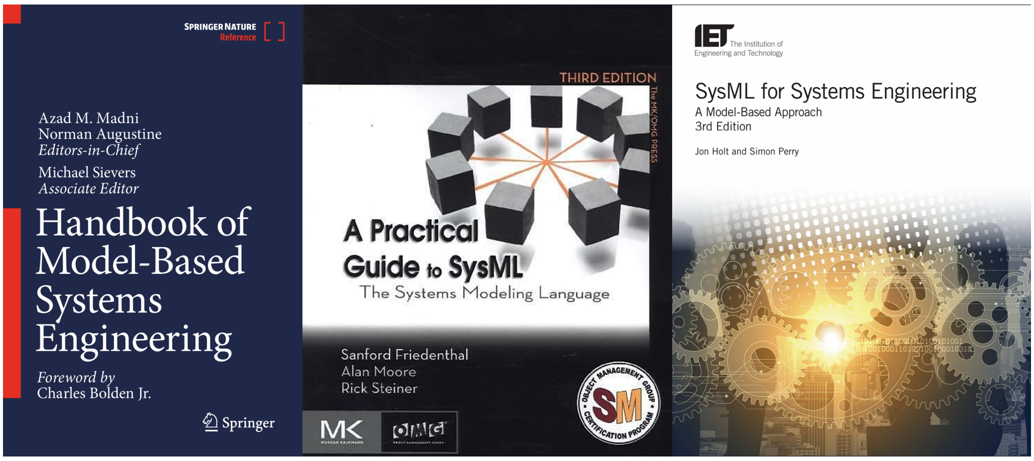


Figure 12: References that were obtained at the beginning of the project but not used.

We instead worked extensively with *SysML Distilled*[7] at first in order to understand the basics of MBSE and SysML. After getting this introductory knowledge, we then transitioned to *Architecting Spacecraft with SysML*[10] which we used as a *cookbook* to know what to do when during the project.

SysML Distilled[7] is an excellent resource to get introduced to both MBSE and SysML. It can be used at any stage of a project to get deeper understanding of specific SysML diagrams and rules, but it isn't a methodology book by any means. This means that it is of great help to better understand certain diagram elements, but it is in no way a resource that explains what to do when during a MBSE project.

Contrary to this, *Architecting Spacecraft with SysML*[10] is a methodology book. This means that it contains information regarding what to do a which stage of a MBSE project and why, but it doesn't explain the SysML aspects in too much detail. While this is undeniably a great resource, we found that in order to best follow it, a student would require either previous experience in MBSE work, or the direct supervision of a mentor with extensive MBSE experience. This is because although it explains what to do, it rarely explains *how* to do it, that is *on what button to click*, so to speak. Therefore, we often found ourselves quite lost when working with it, especially when working on artifacts that we had never derived before. Note that this book isn't available online and must be purchased, although it is rather cheap.

Figure 13: References that were obtained at the beginning of the project and were used throughout the project.

Finally, late into the project, we also discovered the official *MagicGrid Book of Knowledge*[23] from Dassault Systèmes. This resource is also a methodology book just like *Architecting Spacecraft with SysML*[10], but it goes into much more detail on the *what button do I need to click on*. Therefore, although we have never worked with it ourselves, we believe that it could be a better alternative for unexperienced students.

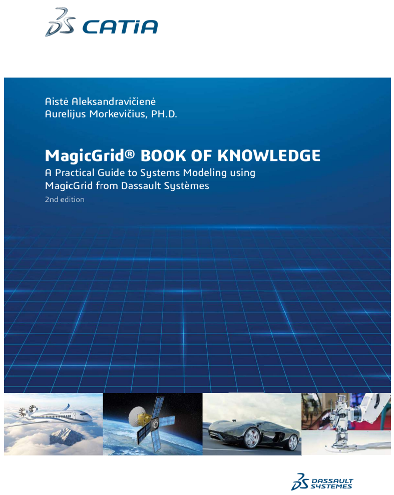


Figure 14: Reference that was obtained too late to be used in the project.

Guide for Future Students

For future students willing to get into MBSE, we would recommend the following steps. This is what we would do if we were to do the project again:

1. Read chapter 1 and 2 of *SysML Distilled*[7] to get an introductory understanding of MBSE
2. Follow *MagicGrid Book of Knowledge*[23] as your methodology cookbook in order to know what to do and how to do it
3. Purchase a copy of *Architecting Spacecraft with SysML*[10] and follow it along with [23] in order to compare both methodologies and to follow an example directly related to aerospace systems
4. In order to deepen your understanding of MBSE and SysML, during your project:
   (a) Read some of the examples of *Handbook of Model-Based Systems Engineering*[16] and *A Practical Guide to SysML*[9]
   (b) Watch some YouTube tutorials on MBSE and on Cameo

Note that we believe that MBSE is definitely doable for students, but only if they have a very strong basis in systems engineering. Therefore, if you do not have practical SE experience, we do not recommend that you attempt a MBSE project. Not only would you have to learn a completely new discipline and methodology, but you would also have to learn a modeling language and a modeling tool on top of it. We strongly believe that this is likely to be overwhelming.

4.1.2 Language

A *language* gives MBSE its vocabulary and grammar: it defines the formal elements (blocks, ports, requirements, behaviors, . . .) and the relationships that may exist between them. To keep it as simple as possible, the language defines 'which shape or arrow to use in a diagram in order to convey which type of information'. The language ensures that engineers interpret a diagram exactly the same way and that the model can be analyzed by a machine.

SysML (Systems Modeling Language) is the de-facto standard for this purpose, but other exist, such as for example Object-Process Methodology (OPM). For this project, it was decided to use SysML as it is the industry standard, which we wanted to learn. SysML is a graphical language that is itself an extension of UML.

To keep the report short, we will not define here what each type of diagram is and what it does. We strongly recommend to read *SysML Distilled*[7] to better understand these points. Both Figure 15 and Figure 16 are taken directly from this reference.

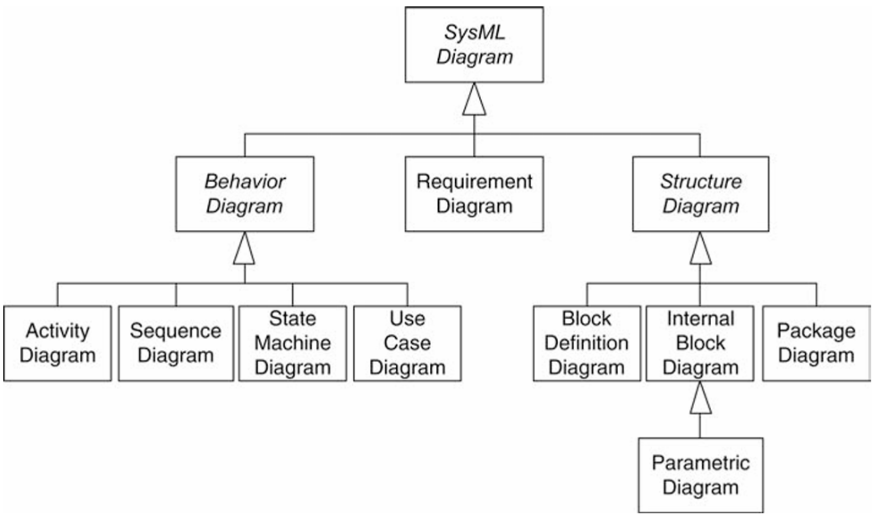


Figure 15: 9 different types of SysML diagrams and their relations to eachother[7].

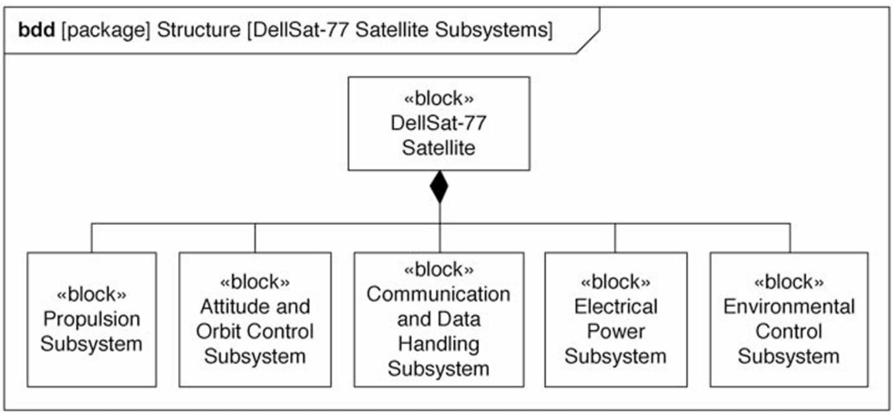


Figure 16: Example of a typical SysML diagram, in this case a BDD[7].

4.1.3 Tool

A *tool* is the software environment that instantiates the language and puts it to work: it stores the model in a database or repository, provides diagram editors and validation engines, and connects to external simulators, requirement managers or code generators. To keep it simple, it is the actual software that enables you to do MBSE work. Examples range from commercial suites such as Cameo Systems Modeler, Capella or Rhapsody to open-source options like Modelio or Gaphor. One important distinction to make is that there are two types of tools: *modeling* tools and *diagramming* tools. While diagramming tools allow you to draw specific model diagrams that respect SysML grammar, only modeling tools will ensure that all these diagrams stay interconnected, or enable you to run simulations for example. In our case, again to learn industry standard, it was decided to use Cameo Magic System of Systems Architect[5].

4.1.4 Method

It is also important to note that performing MBSE is still doing SE work, just in a slightly different way. MBSE System Engineers therefore need to follow a method to design their system, but adapt their work to MBSE practices. While the language says *what* can be expressed and the tool provides a way to do it, a *method* prescribes *how* and *when* to use both throughout the life-cycle: which kinds of diagrams to create at each phase, how to structure the model, how to trace requirements to logical and physical solutions, and how to review or verify the results. Well-known methods include INCOSE's MBSE Roadmap, the Harmony SE process and OOSEM (Object-Oriented Systems Engineering Method). For this project, while it was first decided to try to follow the OOSEM framework, we ended up just following [10] as a cookbook.

4.2 Artifacts

Due to the various difficulties encountered during the project, less MBSE artifacts were generated than originally planned. While the initial objectives were to perform MBSE up to the white-box modeling at the system level, only the problem domain could be modeled. The following subsections will present and explain the different artifacts that have been generated. An important note is that while the following artifacts are presented in the same order that they were chronologically derived, the very first step of any MBSE workflow is not to generate diagrams but to define and organize the modeling effort. This is well documented in the cookbook[10] and will not be explained here, but this must be kept in mind for any future student wishing to do MBSE.

The model is available on the EPFL Drive at this link, and can be opened using the Magic Systems of Systems Architect. Installation files and license access for the software are available here. Full-page screenshots of the MBSE Artifacts can be accessed in the appendix.

4.2.1 Viewpoints

Like for document based SE, the first MBSE activity described in the cookbook[10] is to define the different stakeholders and their expectations. To do this, a *viewpoints* diagram is generated (by creating a *package* diagram). This diagram connects *view* objects to *viewpoint* objects. View objects can be linked to external documents that explain the stakeholder concerns, such as pdf contracts, excel requirements lists, etc. This is a way to keep a trace of these formal documents in the model. The view is linked to the viewpoint object, which can itself be connected to other model elements to ensure traceability. While the view object is connected to elements external to the model, the viewpoint is connected to internal elements to the model, such as requirements, IBD or BDD. In this project, the 4 main stakeholder clusters are represented:

1. Payload Provider
2. ERT
3. Launch Site Provider
4. Sponsors

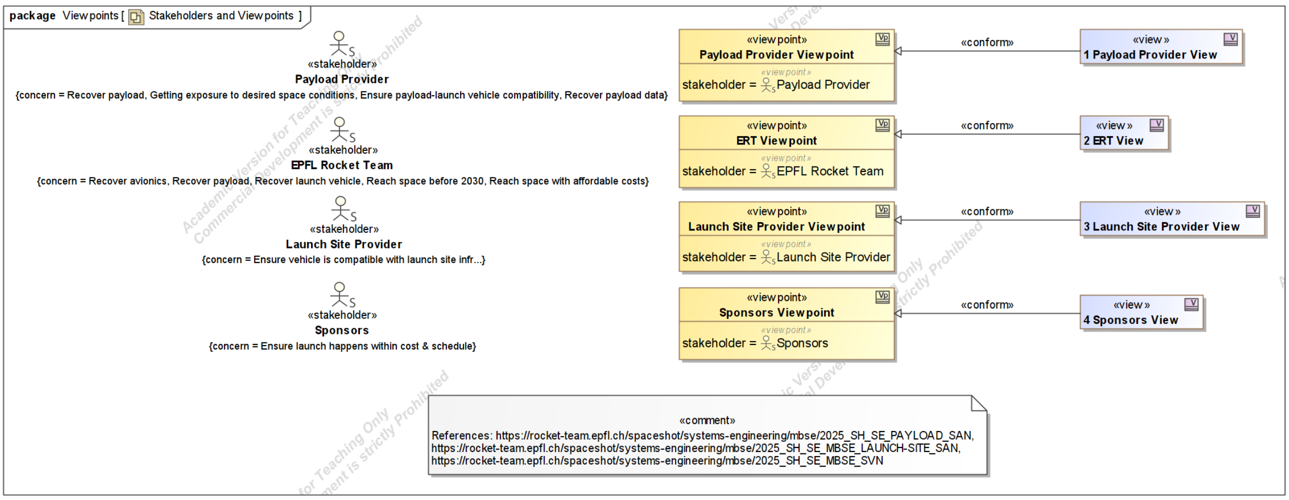


Figure 17: Viewpoints Diagram.

4.2.2 Mission Objectives

After the viewpoint diagram as been created to link external documents to the model, the next step in the cookbook[10] is to define the mission itself. To do this, a *Mission Use cases* or *Mission Objectives* diagram is created. This diagram is used to formally define in the model what each stakeholder expects from the mission, before the system is defined accordingly.

In this case, the key takeaways are that according to our analysis, it is also of interest for Esrange to demonstrate the use of a biliquid vehicle. Moreover, we consider that it is most beneficial for sponsors if both the LV and the payload can correctly operate in a space environment, as it could allow them to use the mission as a demonstration for some of their parts. This is of course not the only way to model the expectations of each stakeholder, and can be updated later on in the project based on new analyses.

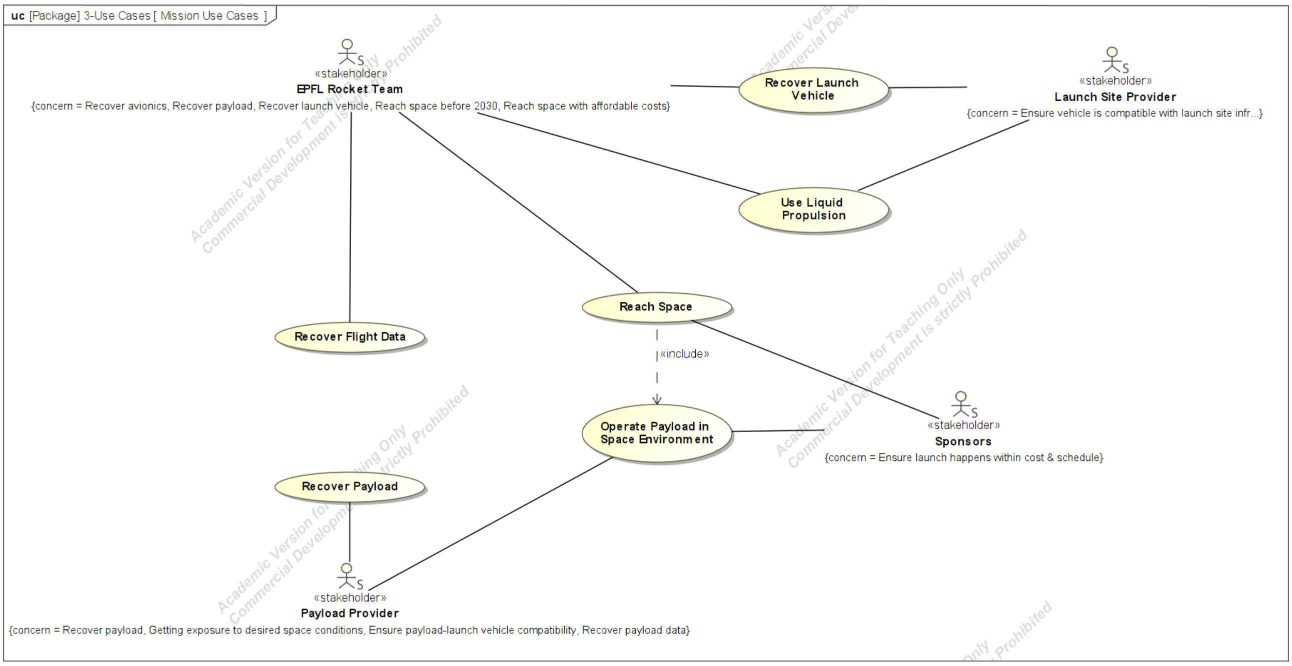


Figure 18: Mission Use Cases/Objectives Diagram.

4.2.3 Mission Requirements

Based on the stakeholder analyses and defined mission objectives, a preliminary set of mission requirements was established and organized by major stakeholder group. These requirements serve as high-level directives that reflect the contractual expectations of each stakeholder. Although not explicitly technical, they will significantly influence the overall mission design and decision-making process.

Two artifacts were developed to represent the mission requirements: a structured table and a hierarchical requirement tree. These tools facilitate traceability between stakeholders and their corresponding requirements.

#	Name	Text
1	1.1 ERT Initial Requirements	
2	1.1.1 Apogee	Launch Vehicle and Payload shall reach an apogee over 100km AGL
3	1.1.2 Mission	The spaceshot project shall comply with the EPFL Rocket Team mission : "Engage Students in Space Technology Projects in Collaboration with Academia and Industry Partners"
4	1.2 Payload Provider Initial Requirements	
5	1.2.1 Launch Vehicle Interface	Payload shall be able to integrate into Launch Vehicle
6	1.2.2 Data Recovery	Payload data shall be recovered
7	1.2.3 Payload Recovery	Payload should be recovered
8	1.2.4 Payload Environment	Payload shall be submitted to acceptable environment
9	1.3 Launch Site Provider Initial Requirements	
10	1.3.1 Location	The launch shall occur at Esrange Space Center
11	1.3.2 Safety	The launch vehicle shall be operated in a safe manner.
12	1.3.3 Propulsion Type	The launch vehicle propulsion type shall be liquid to serve as a demonstrator for ESC.
13	1.3.4 Disturbance	The launch activities shall not impede any ESC stakeholders onsite.
14	1.4 Sponsors Initial Requirements	
15	1.4.1 Exposure	The spaceshot shall provide adequate exposure to sponsors.
16	1.4.2 Timeframe	Project should be done before end of decade.

Figure 19: Mission Requirements Table

We can observe that the EPFL Rocket Team aims to design a project aligned with its broader pedagogical mission, emphasizing learning, technical challenge, and internal capability development. In contrast, the payload provider focuses solely on the needs of the payload and its interface with the launch vehicle, prioritizing environmental conditions, integration, and data handling. The launch site provider, on the other hand, is primarily concerned with safety, operational compliance, and logistical feasibility, ensuring that the mission can be conducted smoothly within the constraints of their infrastructure and regulations. The ERT sponsors primarily emphasize visibility and adherence to the project timeline.

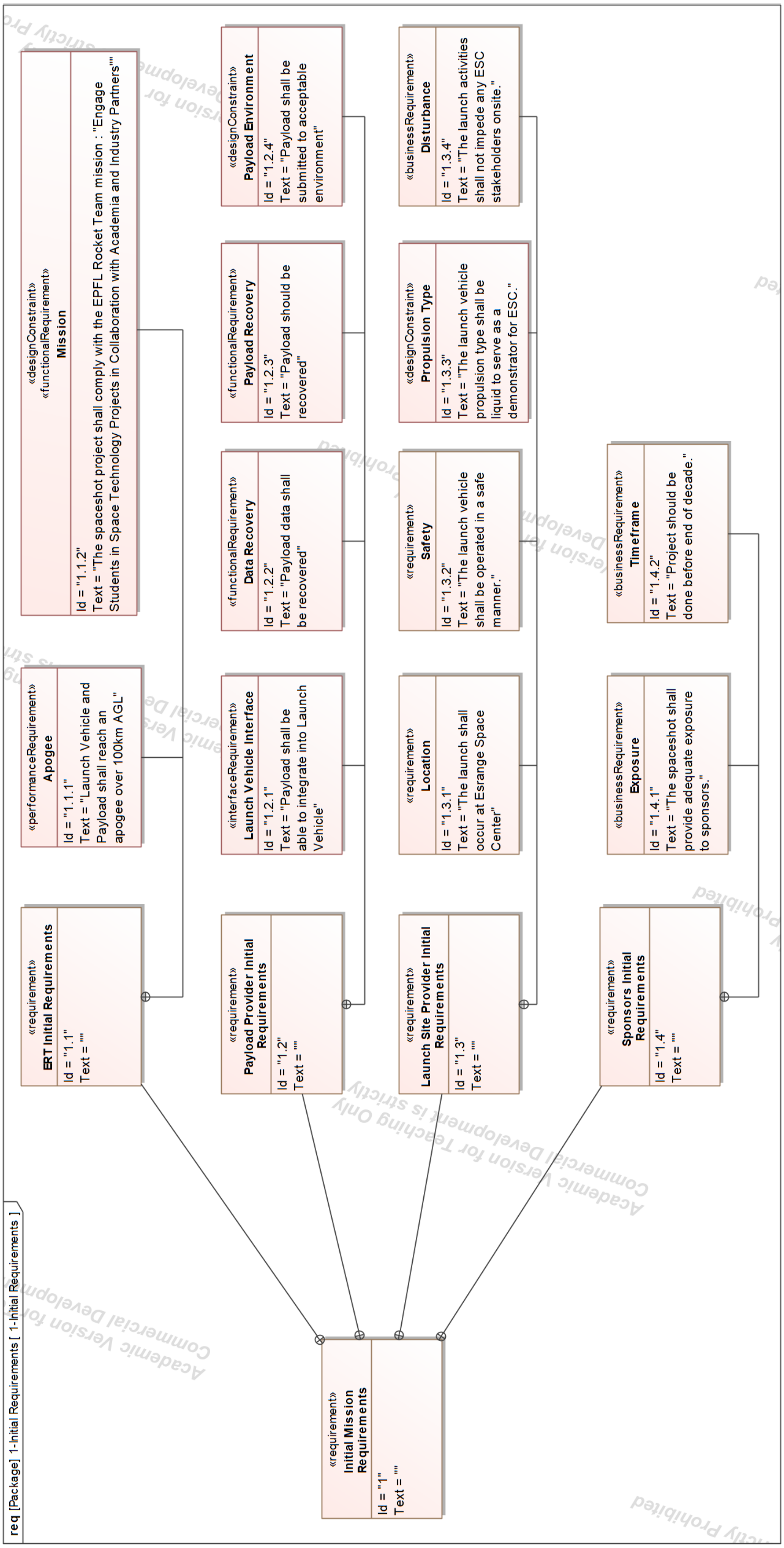


Figure 20: Mission Requirements Diagram

4.2.4 Refined Mission Requirements

Building on the preliminary mission requirements, a refined set of mission requirements was developed. These refined requirements are more detailed and structured, allowing for translation into measurable, verifiable parameters. As part of the systems engineering approach, emphasis was placed not only on defining these artifacts but also on maintaining clear traceability, ensuring that each refined requirement can be linked back to its originating stakeholder need or objective. This traceability supports validation, consistency, and alignment throughout the mission development process.

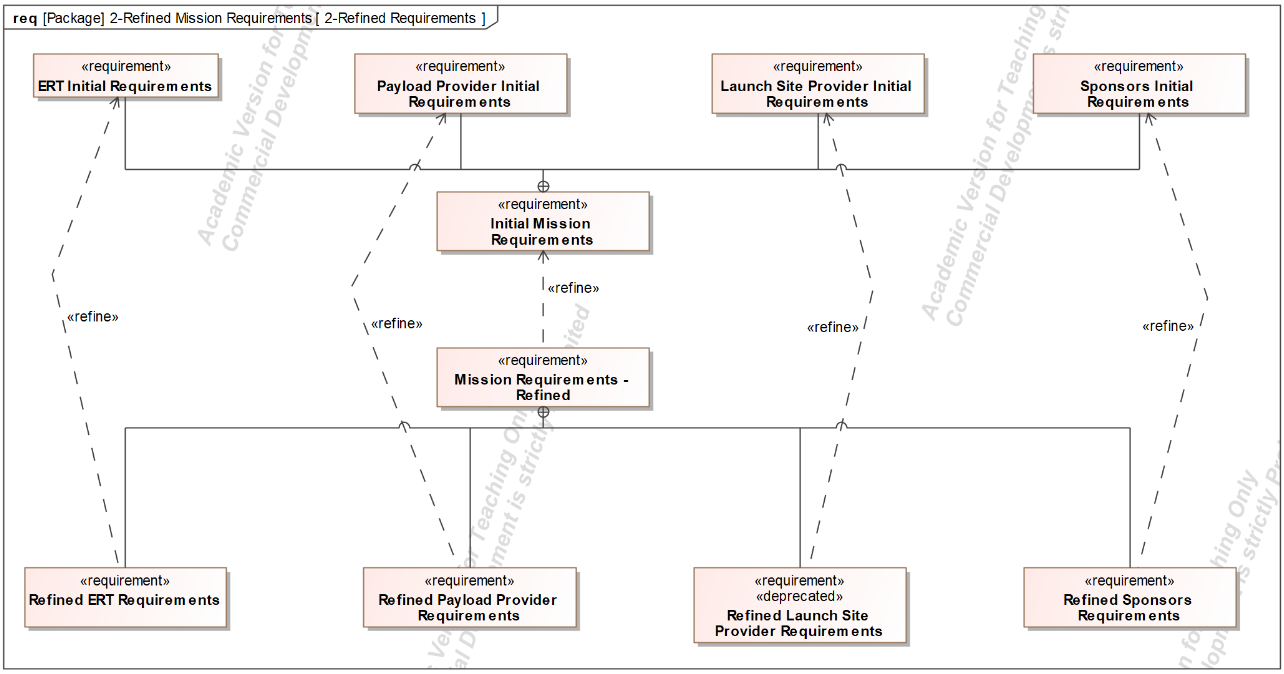


Figure 21: Refinement Process Diagram

Traceability

The traceability table is structured to show the relationship between the preliminary and refined mission requirements. Preliminary mission requirements are listed on the left, while the derived, more detailed requirements are presented across the top. Arrows indicate refinement paths, illustrating how high-level stakeholder needs evolve into actionable requirements.

This visualization highlights that each preliminary requirement typically branches into several refined ones, reinforcing the layered nature of the requirement development process. Notably, requirements from the payload provider tend to translate directly into technical specifications, such as interface constraints and environmental tolerances. In contrast, those from the launch site provider more often evolve into logistical, financial, or legal requirements, which remain high-level but are essential for operational feasibility and compliance.

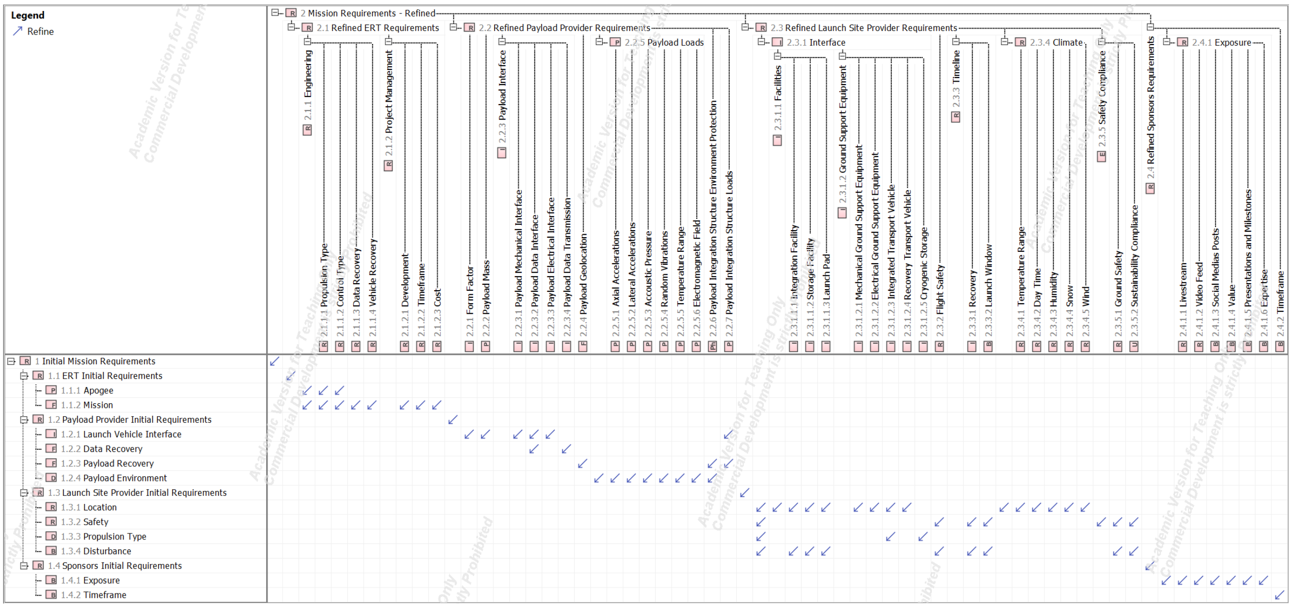


Figure 22: Refined Mission Requirements Traceability Table

Requirements

From an initial set of 12 mission requirements, a total of 63 refined mission requirements were derived. These are compiled into a comprehensive table that specifies the type of each requirement, such as mission, business, or design, along with a structured hierarchical ID. This artifact consolidates all refined requirements into a single view, providing a comprehensive overview of the project scope. To improve readability and highlight stakeholder-specific concerns, additional requirements diagrams were created for each stakeholder group. These targeted visualizations offer clearer insights into individual expectations and priorities, making the requirements easier to interpret and manage.

#	Name	Text
1	2 Mission Requirements - Refined	
2	2.1 Refined ERT Requirements	
3	2.1.1 Engineering	
4	2.1.1.1 Propulsion Type	The launch vehicle should use liquid propulsion as it's main propulsive mean.
5	2.1.1.2 Control Type	The launch vehicle should use active control.
6	2.1.1.3 Data Recovery	The flight data shall be recovered.
7	2.1.1.4 Vehicle Recovery	The launch vehicle should be recovered in a condition suitable for subsequent exhibition.
8	2.1.2 Project Management	
9	2.1.2.1 Development	The launch vehicle should be developped using the lessons learned from the Competition project's iterations
10	2.1.2.2 Timeframe	The spaceshot launch should take place no more than two years after being designated as the EPFL Rocket Team's main project.
11	2.1.2.3 Cost	The spaceshot project cost shall be under TBD CHF, including TBD CHF of cash cost.
12	2.2 Refined Payload Provider Requirements	
13	2.2.1 Form Factor	Shall be able to integrate a payload with size of TBD U
14	2.2.2 Payload Mass	Shall be able to lift a payload of up to TBD kg
15	2.2.3 Payload Interface	
16	2.2.3.1 Payload Mechanical Interface	Payload shall not be inextricably connected to other launch vehicle associated components than its supporting structure
17	2.2.3.2 Payload Data Interface	should not have any electrical data interface to the payload
18	2.2.3.3 Payload Electrical Interface	should not have any electrical power interface to the payload
19	2.2.3.4 Payload Data Transmission	Should allow payload to transmit its own data
20	2.2.4 Payload Geolocation	Should provide means to locate payload after landing
21	2.2.5 Payload Loads	Payload shall be submitted to acceptable loads
22	2.2.5.1 Axial Accelerations	Shall apply max axial acceleration of TBD g
23	2.2.5.2 Lateral Accelerations	Shall apply max lateral acceleration of TBD g
24	2.2.5.3 Accoustic Pressure	Shall apply max accoustic pressure of TBD Pa
25	2.2.5.4 Random Vibrations	Random vibrations at interface shall not exceed spectrum TBD
26	2.2.5.5 Temperature Range	Max temperature shall remain within TBD range
27	2.2.5.6 Electromagnetic Field	Applied magnetic field shall not exceed TBD
28	2.2.6 Payload Integration Structure Environment Prote	Shall protect payload from landing environment
29	2.2.7 Payload Integration Structure Loads	Shall be able to protect payload from recovery loads
30	2.3 Refined Launch Site Provider Requirements	
31	2.3.1 Interface	The launch vehicle shall operate with ESC facilities and equipment.
32	2.3.1.1 Facilities	
33	2.3.1.1.1 Integration Facility	The Launch Vehicle shall be integrated in an Integration Facility provided by ESC.
34	2.3.1.1.2 Storage Facility	The Launch Vehicle shall be stored on a dedicated storage facility provided by ESC.
35	2.3.1.1.3 Launch Pad	The Launch Vehicle shall be operated on a dedicated launch pad provided by ESC.
36	2.3.1.2 Ground Support Equipment	
37	2.3.1.2.1 Mechanical Ground Support Equipm	
38	2.3.1.2.2 Electrical Ground Support Equipment	
39	2.3.1.2.3 Integrated Transport Vehicle	After integration the launch vehicle shall be moved from the integration facility to the launch pad by a TBD ESC vehicle
40	2.3.1.2.4 Recovery Transport Vehicle	After recovery the launch vehicle shall be moved from the recovery site to the integration facilityh by a TBD ESC vehicle
41	2.3.1.2.5 Cryogenic Storage	The Launch Vehicle shall be compatible with the ESC cryogenic storage.
42	2.3.2 Flight Safety	The launch vehicle shall comply with the Esrange Safety Manual "Flight Safety" section requirements.
43	2.3.3 Timeline	Flight shall occur within a TBD timeframe imposed by ESC
44	2.3.3.1 Recovery	Recovery shall take be done within a TBD h window after landing.
45	2.3.3.2 Launch Window	Flight shall take place within a 2 day window (TBD), with daily operations beginning at a TBD h CET and ending at a TBD h CET
46	2.3.4 Climate	
47	2.3.4.1 Temperature Range	The launch vehicle shall whistand temperature ranges from TBD to TBD °C
48	2.3.4.2 Day Time	The launch vehicle should be operated during ESC work day time
49	2.3.4.3 Humidity	The launch vehicle shall whistand rain exposure of at least TBD mm/h
50	2.3.4.4 Snow	The launch vehicle equipments shall whistand snow exposure of at least TBD m
51	2.3.4.5 Wind	The launch vehicle shall whistand windspeeds from TBD to TBD m/s
52	2.3.5 Safety Compliance	The launch vehicle shall comply with the Esrange Safety Manual guidelines
53	2.3.5.1 Ground Safety	The launch vehicle shall comply with the Esrange Safety Manual "Ground Safety" section requirements.
54	2.3.5.2 Sustainability Compliance	The launch vehicle shall comply with the environmental framework imposed by Esrange Space Center
55	2.4 Refined Sponsors Requirements	
56	2.4.1 Exposure	The spaceshot shall provide adequate exposure to sponsors.
57	2.4.1.1 Livestream	The spaceshot launch shall include a livestream of major events such as pre-launch, launch and recovery activities.
58	2.4.1.2 Video Feed	The launch vehicle shall record at least 2 recoverable HD video flux of the flight.
59	2.4.1.3 Social Medias Posts	The spaceshot project shall support contracted social media posts including sponsors equipment and / or services.
60	2.4.1.4 Value	The spaceshot should seek to use a TBD percent "value"/"cash cost" sponsoring ratio, to reduce the cash cost.
61	2.4.1.5 Presentations and Milestones	The spaceshot project shall include at least TBD major presentations and milestones where sponsors are invited to attend.
62	2.4.1.6 Expertise	The spaceshot project should actively leverage sponsor expertise whenever applicable.
63	2.4.2 Timeframe	The spaceshot flight should be done before end of decade.

Figure 23: Refined Mission Requirements Table

EPFL Rocket Team

To align with the EPFL Rocket Team's educational mission, a set of refined requirements was developed to ensure strong integration of the Spaceshot project within the association's structure. These requirements promote collaboration across internal projects, notably by mandating the use of liquid propulsion to engage the Hyperion project and proposing active control systems to involve the Icarus project. Data recovery was identified as a critical requirement, given the high value flight data holds for future iterations and cross-project learning.

The requirements also provide guidance on project management, encouraging an iterative development approach that builds on the foundation of the competition project to mature into the Spaceshot initiative. Cost constraints are acknowledged, with a target value to be defined in future phases. Given the student-driven nature of the EPFL Rocket Team, the project is required to conclude within two years of being designated as the team's main focus. This time limit helps prevent knowledge loss due to student turnover, a risk observed in previous projects such as Firehorn 1 and Icarus, which confirmed that two years is the practical upper boundary for sustainable student-led development.

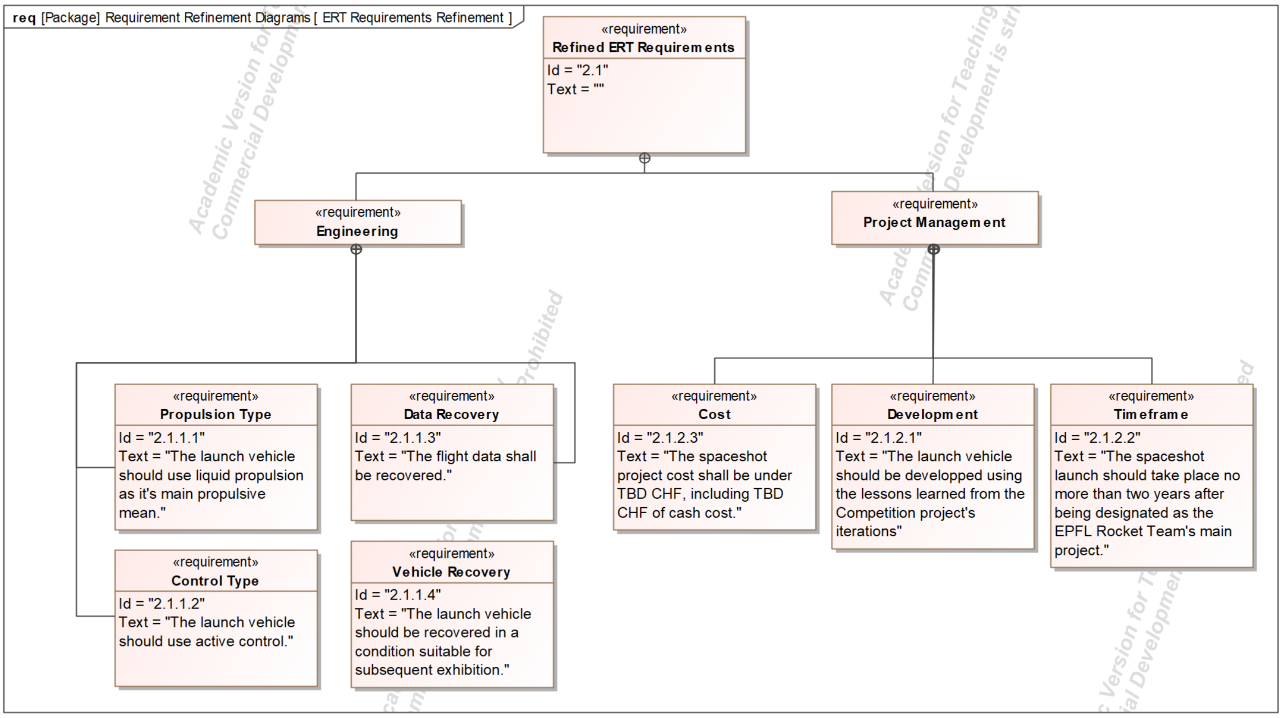


Figure 24: EPFL Rocket Team Refined Mission Requirements Diagram

Payload Provider

Several of the payload provider refined requirements fall under interface definitions, such as the mechanical, data, and electrical interfaces, reflecting the payload provider's emphasis on minimizing dependency on the launch vehicle and maximizing plug-and-play capability. Performance requirements address the mechanical and environmental loads the payload must endure, including acceleration, vibration, temperature, and electromagnetic exposure. These ensure the payload remains operational through the mission lifecycle.

Additionally, functional requirements such as data recovery and geolocation illustrate the importance of post-flight data access and payload retrieval. Compared to other stakeholders, the payload provider's requirements rapidly translate into detailed technical constraints, showing a direct path from stakeholder expectation to engineering specification. This reflects the payload provider's tight scope of concern: ensuring that their payload can be integrated, protected, operated, and recovered with minimal compromise or adaptation.

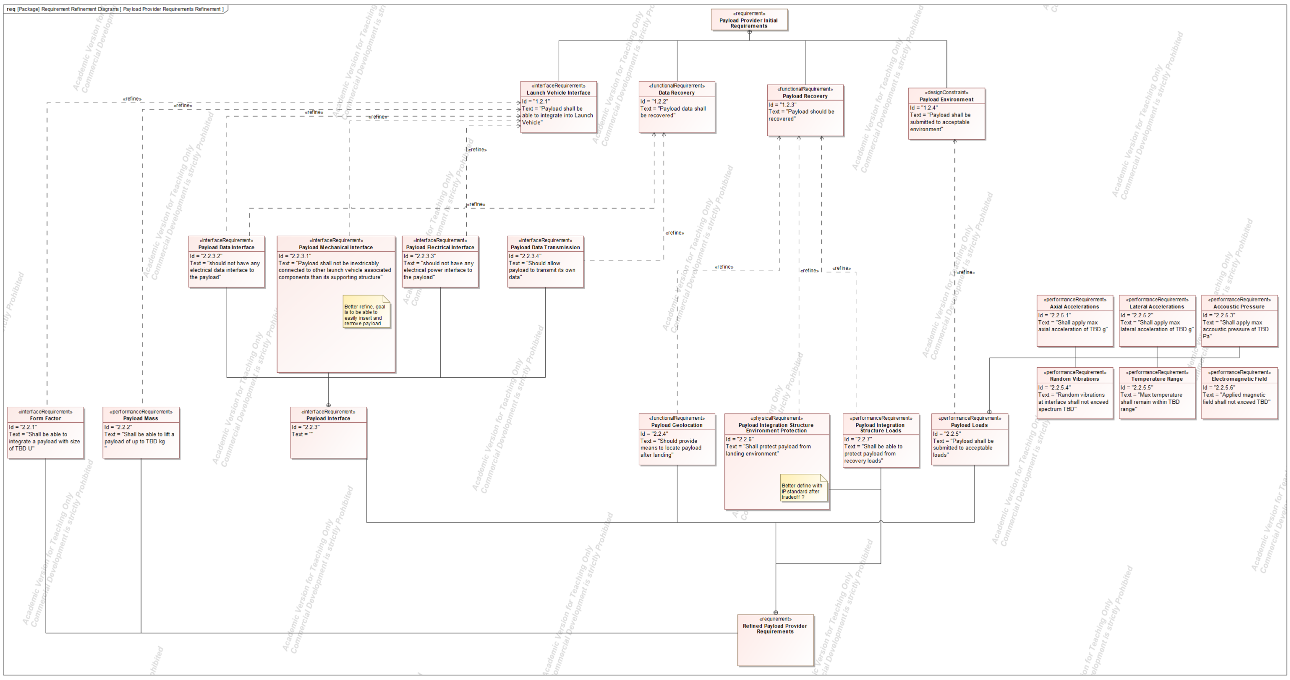


Figure 25: Payload Provider Refined Mission Requirements Diagram

Launch Site Provider

The Launch Site Provider refined requirements are broadly organized into interface, compliance, logistical, and environmental categories. A significant portion focuses on ground infrastructure compatibility, including integration, storage, and launch pad facilities, as well as support vehicles for cryogenic handling and transport. These interface requirements reflect the provider's need for integration into existing site operations.

Another key branch concerns safety and regulatory compliance. Requirements related to flight safety, sustainability, and ground safety are prominent, reinforcing the importance of adhering to established procedures and standards. These are essential not only for risk mitigation but also for protecting the reputation and operating license of the site.

Time-sensitive and logistical constraints are also detailed, with requirements specifying launch windows, recovery timing, and demobilization, reflecting the operational efficiency expected by the site. Finally, environmental requirements ensure that the vehicle can withstand local weather conditions, such as wind, temperature variations, snow, and rain.

Overall, the refined requirements from the launch site provider remain relatively high-level compared to those of the payload provider, but they form a crucial framework for enabling mission feasibility, regulatory acceptance, and logistical execution.

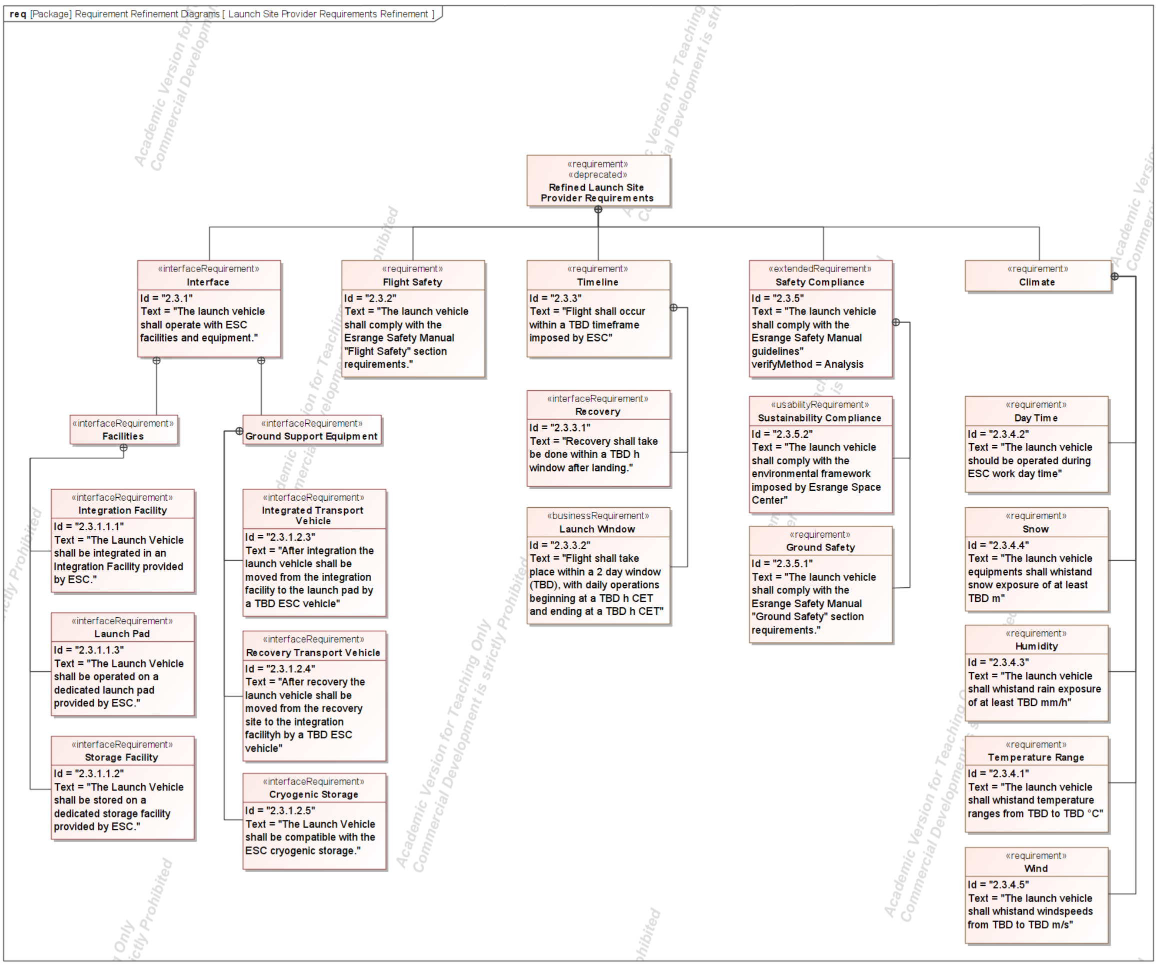


Figure 26: Launch Site Provider Refined Mission Requirements Diagram

Sponsors

The Sponsors refined requirements highlights two primary areas of concern: visibility and timeline adherence. These requirements reflect the sponsors' interest in return on investment, public exposure, and structured collaboration throughout the mission.

The left branch focuses on exposure, which is further refined into tangible communication deliverables such as livestreaming key mission events, capturing and recovering HD video footage, and supporting contracted social media posts featuring sponsor equipment and services. These requirements underline the importance of media presence and brand visibility tied to the mission.

The right branch captures business-oriented requirements, such as adhering to a launch timeline within the current decade, maintaining a healthy value-to-cash cost ratio for sponsorships, and including sponsors in key milestones and presentations. Additionally, it encourages the project team to actively leverage sponsor expertise when relevant, promoting meaningful engagement beyond financial support.

Compared to other stakeholder clusters, the sponsors' requirements remain largely non-technical but are critical to maintaining strong external partnerships. They ensure the project delivers reputational value and professional reliability in exchange for funding and support.

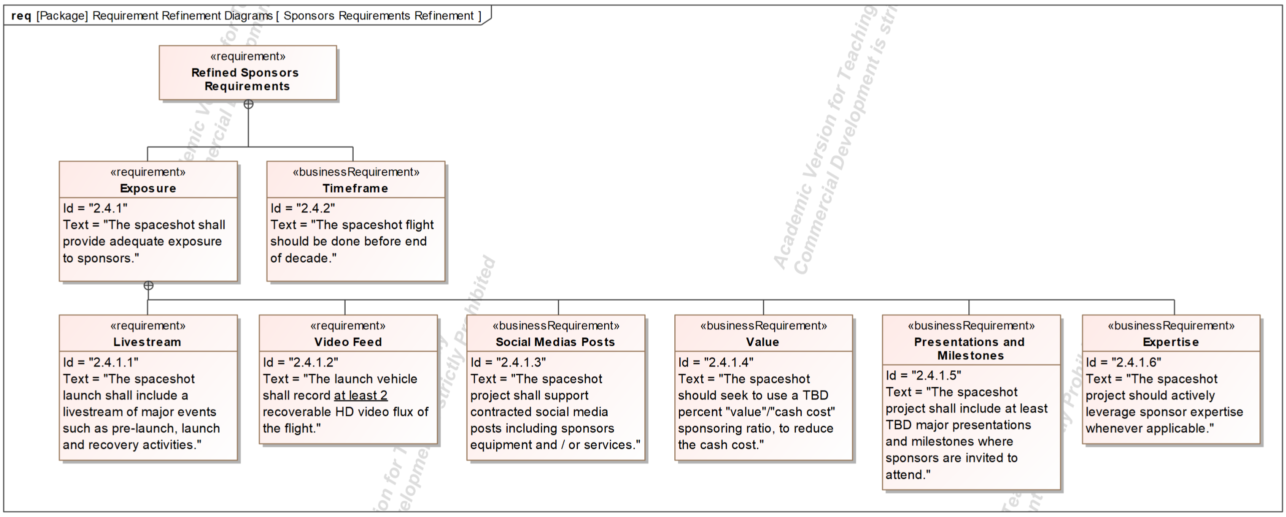


Figure 27: Sponsors Refined Mission Requirements Diagram

5 Trade-Offs

5.1 Methodology

The methodology used to perform the tradeoffs is the one described in the *ECSS-E-ST-10C Rev.1 - Systems engineering general requirements*[1] standard, annex L, Trade-off report DRD. When applied to this project in a reduced form, it consists of the following steps:

- **Tradeoff goal:** brief description of the purpose of the trade-off study and its context
- **Evaluation criteria:** list the selected evaluation criteria and precise the justification for selecting those criteria, and provide the weighting of criteria and their justifications
- **Presentation of the alternative design solutions:** present every different alternative design solutions
- **Evaluation of the alternative design solutions:** present the result of the evaluation of every identified alternative design solution with regard to the evaluation criteria, and with respect to the reference solution
- **Conclusion:** recommend one solution and explain the reason for this choice

5.2 Mission-Level Tradeoffs

As the stakeholders were being analyzed and the model was being developed, every time it was identified that there are multiple ways to fulfill an objective or a function, the identified tradeoff was noted in a list to be performed later. These tradeoffs were listed into different levels: mission, system and below system. This subsection describes the content of the mission-level tradeoffs. The system level tradeoffs and below were not performed as they intrinsically rely on having done at list a black box specification of the system, which wasn't done during this project.

At the mission level, the following tradeoffs were identified:

- **Payload mass:** Decide what payload total mass to design the system for
- **Payload electrical interface:** Decide if the payload should have an electrical interface with the LV or be electrically independent
- **Apogee:** Decide what apogee to design the system for
- **Recovery scope:** Decide whether only to payload or the entire launch vehicle should be recovered

5.3 Evaluation Criteria

In order to be able to evaluate all the mission level tradeoffs in a similar manner, a standardized set of evaluation criteria was derived. No clearly established criteria list was found in NASA or ESA literature. Therefore, this set of criteria was selected based on what were estimated to be the most important factors for the project success.

- **Performance:** How much is the solution able to fulfill its mission objectives
- **Programmatic:**
  - **Non-recurring costs:** How expensive is the solution expected to be in term of non-recurring costs.
  - **Recurring costs:** How expensive is the solution expected to be in term of recurring costs.
  - **Schedule:** How much time is the solution expected to require.
  - **Development needs:** How technologically mature/how much experience does ERT have with this solution.
  - **Learning opportunity:** How interesting to work on for students is this solution.
  - **Exposure:** How much media exposure the solution is expected to bring.
- **Risks & Safety:**
  - **Technical risks:** How reliable is this solution expected to be.
  - **Safety issues:** How safe to work on is this solution expected to be.

All criteria are evaluated on a quantitative scale that compares the alternative solution(s) to the reference one as follows:

- Alternative is significantly worse than reference.
- Alternative is slightly worse than reference.
- Alternative is equivalent to reference.
- Alternative is slightly better than reference.
- Alternative is significantly better than reference.

5.4 Results

Since no sizing tool of the launch vehicle currently exists, these tradeoffs were performed qualitatively. It is intended that they are revisited in a quantitative manner as part of the upcoming systems engineering workpackages described in section 6.

5.4.1 Payload Mass

- **Goal:** Qualitatively determine how much payload mass the LV shall be designed to carry during flight.
- **Criteria:** All criteria defined in subsection 5.3. For the performance criteria, the apogee is considered.
- **Solutions:**
  - **3-6[kg] (Reference):** This mass range corresponds to a 3U CubeSat payload, which have a mass of typically 1-1.3kg/U but that doesn't exceed 2kg/U[6][22].
  - **<3[kg] (Alternative 1):** This mass range corresponds to a payload smaller than 3U.
  - **>6[kg] (Alternative 2):** This mass range corresponds to a payload larger than 3U.
- **Evaluation:**
  - **Table:**

	3–6 kg	**<3 kg**	**>6 kg**
Performance	3	4	1
Non-recurring costs	3	4	2
Recurring costs	3	3	3
Schedule	3	3	2
Development needs	3	3	2
Learning opportunity	3	3	4
Exposure	3	3	4
Technical risks	3	3	3
Safety issues	3	3	3
Total	**27**	**29 (+7.4%)**	**24 (-11.1%)**

  - **Justification:** Slightly lighter payload is expected to have an impact on apogee and on costs, because it will require a smaller LV to reach the target altitude. Larger payloads is expected to have a significant impact on the required LV size to reach the same altitude, it is expected to require more time to develop the required interfaces and to analyze them as the team ERT has only worked with payloads of up to 3U so far. However, it could also bring in more exposure to media and potential sponsors, and the added complexity could be of interest for students.
- **Conclusion:** Based on this qualitative tradeoff, we recommend going for a light payload in order to end up with interfaces that are easier to develop and analyze, and with a LV that is lighter and less expensive to develop. The differences are however not significant, and this tradeoff must be performed again later down the line once a proper sizing tool has been developed, and once the payload SE has identified actual experiments.

5.4.2 Payload Electrical Interface

- **Goal:** Qualitatively determine whether the payload should have electrical interfaces with the LV or be electrically independent.
- **Criteria:** All criteria defined in subsection 5.3. For the performance criteria, the impact on apogee, the ability to enable the payload to operate and the impact on payload data transmission are considered.
- **Solutions:**
  - **No electrical interface (Reference):** The payload has no electrical connections to the rest of the LV whatsoever.
  - **Power interface, no data (Alternative 1):** The payload power is provided by the LV, but the payload doesn't transmit any data to the LV.
  - **Data interface, no power (Alternative 2):** The payload is self-powered but transmits some data to the LV.
  - **Both power and data interface (Alternative 3):** The payload power is provided by the LV and it transmits some data to the LV.
- **Evaluation:**
  - **Table:**

	No Interface	Only Power	Only Data	Both Power & Data
Performance	3	2	4	3
Non-recurring costs	3	2	3	2
Recurring costs	3	3	3	3
Schedule	3	2	2	1
Development needs	3	2	2	1
Learning opportunity	3	4	4	5
Exposure	3	3	3	3
Technical risks	3	2	2	1
Safety issues	3	3	3	3
Total	**27**	**23 (-14.8%)**	**26 (-3.7%)**	**22 (-18.5%)**

  - **Justification:** If the payload needs to rely on the LV for its power supply, we believe that it adds complexity to the power architecture as well as extra mass and risk, with no significant upsides to compensate for it. For the data interface, while it adds some technical complexity and does require additional development, we believe that is also enhances the chances of successful payload data recovery. Having both interfaces at the same time compounds these risks and technical difficulties.
- **Conclusion:** We recommend to the future SE to impose either no electrical interface or a data interface between the payload and the LV. Like for the payload mass however, this tradeoff must be performed again as part of both the payload and avionics systems engineering work.

5.4.3 Apogee

- **Goal:** Qualitatively determine what altitude to aim for.
- **Criteria:** All criteria defined in subsection 5.3. For the performance criteria, the ability to expose the payload to a space environment is considered.
- **Solutions:**
  - **100 km (Reference):** Designing the LV to reach an apogee of 100km, which is the most common definition of the start of space.
  - **80 km (Alternative):** Designing the LV to reach an apogee of 80km, which is an alternative definition of the start of space that also offers exposure to a valuable environment for experiments[18].
- **Evaluation:**
  - **Table:**

	100 km	**80 km**
Performance	3	2
Non-recurring costs	3	4
Recurring costs	3	3
Schedule	3	3
Development needs	3	3
Learning opportunity	3	3
Exposure	3	1
Technical risks	3	3
Safety issues	3	3
Total	**27**	**25 (-7.4%)**

  - **Justification:** While 80 km does offer some interesting conditions for experimental payloads, flying lower also means less exposure time to desired conditions. Additionally among the rocketry community, a proper spaceshot is only achieved if the Kármán line (100 km) has been reached, which would make a 80 km flight a lesser achievement. However, a smaller LV is also cheaper and slightly less complex to develop.
- **Conclusion:** Considering all this, we recommend sticking to the initial goal of 100 km. If money must be saved, it should be saved elsewhere in the project, for example by implementing less complex technologies or by carrying a lighter payload. In fact, to account for uncertainties, the team should probably design the LV for a target altitude of slightly above 100 km, such as for example 100 km.

5.4.4 Recovery Scope

- **Goal:** Qualitatively determine what parts of the launch vehicle to recover.
- **Criteria:** All criteria defined in subsection 5.3. For the performance criteria, the impact on the launch vehicle mass is considered.
- **Solutions:**
  - **Payload only (Reference):** Only recover the payload itself.
  - **Payload and flight data recorder (Alternative 1):** Recover the payload as well as the LV part of the avionics stack that records the flight data, but not the rest of the vehicle.
  - **Entire LV (Alternative 2):** Recover the entire LV including the payload.
- **Evaluation:**
  - **Table:**

	Payload Only	Payload and Avionics	Entire LV
Performance	3	2	1
Non-recurring costs	3	3	2
Recurring costs	3	3	3
Schedule	3	3	2
Development needs	3	3	1
Learning opportunity	3	3	4
Exposure	3	4	5
Technical risks	3	3	4
Safety issues	3	3	3
Total	**27**	**27 (±0%)**	**25 (-7.4%)**

  - **Justification:** We don't expect avionics recovery to add much complexity or cost to a recovery system that is already able to carry the loads due to the payload recovery. However, we believe that being able to fully recover the LV would add significant costs, mass and technical complexity. Being able to slow down a vehicle that will likely be multiple hundred kg all the way from space down to a safe touchdown is likely a very difficult task that requires extensive development, analysis and testing. Fully recovering the LV however offers a significant advantage in terms of public communication.
- **Conclusion:** We recommend that only the payload and avionics stack are recovered, unless the team has significant financial resources and the timeline allows for the development of a full-LV recovery system. This tradeoff can however be revisited again after a sizing tool has been developed.

6 Spaceshot Project Perspective

During this semester project, we defined a set of workpackages that can be assigned to future Systems Engineers. Although the Systems Engineering tasks were beyond the scope of the current project, they contribute to establishing a solid foundation for the next phase. In parallel, a timeline was developed to indicate when each workpackage should ideally be addressed. Recognizing that future projects will be completed asynchronously and depend on student availability, we also propose an iterative development approach and the creation of a supervisory "Spaceshot Committee" to maintain coherence across teams and milestones.

6.1 Workpackages

- **General Systems Engineering**
  - *Inputs:* Mission requirements, Previous Spaceshot work
  - *Outputs:* Preliminary Requirements Review / System Requirements Review compliant Systems Engineering artifacts
- **Flight Dynamics Systems Engineering**
  - *Inputs:* Mission requirements, Previous Spaceshot work, ERTSim
  - *Outputs:* Sizing methodology, Preliminary Launch Vehicle sizing (mass and dimensions), Preliminary Flight Dynamics analysis (trajectory)
- **Propulsion Systems Engineering**
  - *Inputs:* Mission requirements, Previous Spaceshot work, Hyperion lessons learned, Launch Vehicle sizing
  - *Outputs:* Propulsion technology selection methodology, Preliminary propulsion budgets (thrust, propellant, pressurization)
- **Structure Systems Engineering**
  - *Inputs:* Mission Requirements, Previous Spaceshot work, Competition structure lessons learned, Launch Vehicle sizing
  - *Outputs:* Structural load analysis methodology, Load requirements
- **Avionics Systems Engineering**
  - *Inputs:* Mission requirements, Competition avionics lessons learned
  - *Outputs:* Architecture layout
- **Payload Systems Engineering**
  - *Inputs:* Mission requirements, Previous Spaceshot work, Launch Vehicle sizing
  - *Outputs:* Identified payloads, Quantitative payload load analysis and methodology, Preliminary design of a payload bay

- **Recovery Systems Engineering (TBC)**
  - *Inputs:* Mission requirements, Previous Spaceshot work, Competition recovery lessons learned, Launch Vehicle sizing
  - *Outputs:* Preliminary recovery strategy and architecture
- **GNC Systems Engineering**
  - *Inputs:* Mission requirements, Previous Spaceshot work, Icarus lessons learned, Launch vehicle Sizing
  - *Outputs:* GNC Solution Proposal and Methodology
- **MGSE Systems Engineering**
  - *Inputs:* Mission requirements, Suborbital Launch Rail System work
  - *Outputs:* MGSE Solution Proposal and Methodology
- **EGSE Systems Engineering**
  - *Inputs:* Mission requirements
  - *Outputs:* EGSE Solution Proposal and Methodology

6.2 Timeline

As the semester project concludes, establishing a clear roadmap for future development was identified as a priority. To address this, we created a Gantt chart [11] outlining the proposed timeline and hierarchy of the workpackages necessary to bring the Spaceshot project to maturity.

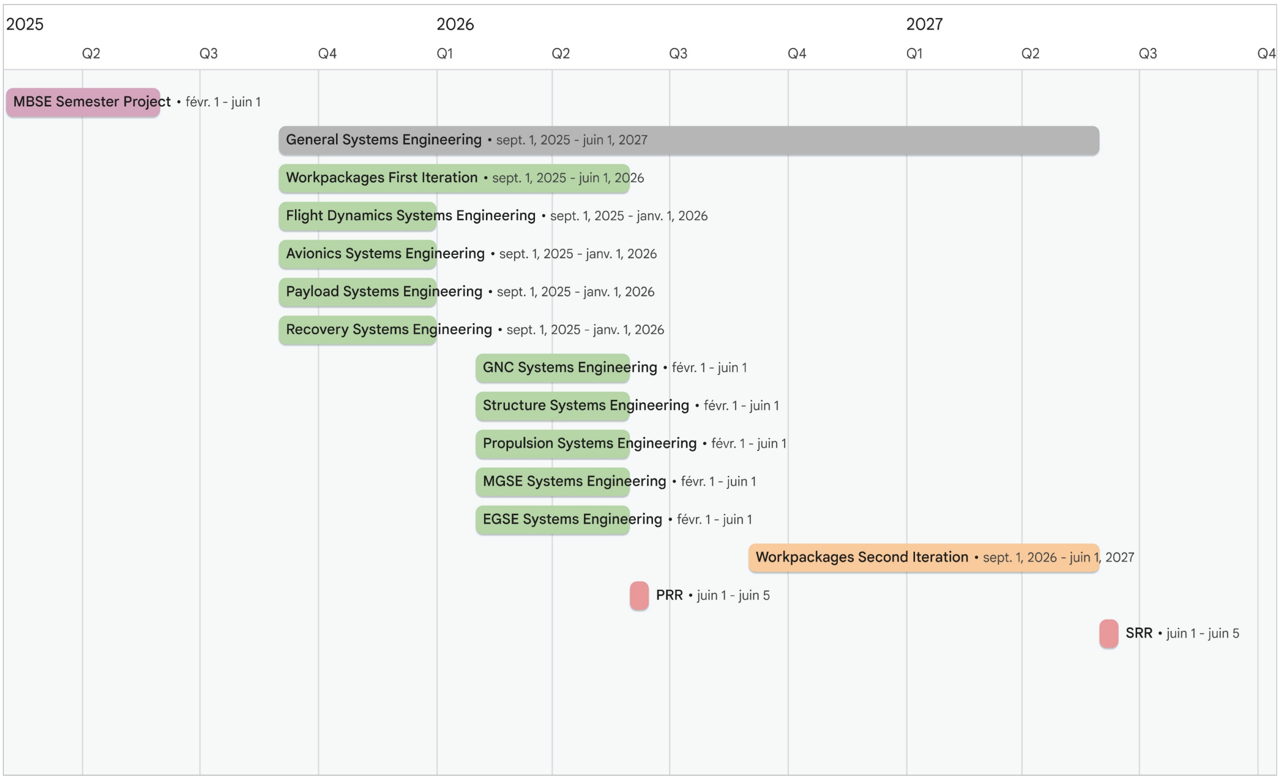


Figure 28: Workpackages Timeline

The timeline spans two years, targeting System Requirements Review (SRR) readiness by June 2027. The first year focuses on achieving Preliminary Requirements Review (PRR) readiness by June 2026. During this period, an initial iteration of workpackages is scheduled, beginning with Flight Dynamics Systems Engineering. In parallel, independent packages such as Avionics, Payload, and Recovery Systems Engineering will be carried out. These are followed by more dependent workpackages, GNC, Structural, Propulsion, MGSE, and EGSE Systems Engineering, which rely on the outcomes of the flight dynamics phase. A dedicated systems engineer will oversee and coordinate progress across teams to ensure PRR-level documentation and consistency.

In the second year, these workpackages will be iterated and refined as needed, consolidating into a complete system architecture and verification baseline, with the objective of reaching SRR readiness and formally positioning the Spaceshot project for full-scale development within the EPFL Rocket Team.

6.3 Coordination

A critical insight raised during the project presentation concerns the dependencies between Systems Engineering workpackages and how their sequencing may affect the consistency of the overall architecture. While the project timeline proposes an ideal order of execution, in practice, the realization of these workpackages depends heavily on student availability and interest. As such, it is neither feasible nor desirable to enforce a strict project sequence across semesters.

To address this challenge, the team identified the need for an iterative approach. A second iteration is explicitly planned following the initial completion of all workpackages. This will enable cross-checking, refinement, and resolution of any interface or consistency issues that may have emerged due to the asynchronous and parallel nature of student-led development.

In addition, the idea of implementing a *Spaceshot Committee* was introduced. This committee, composed of past contributors, would act as a supervisory body to provide continuity, maintain institutional knowledge, and support key Systems Engineering milestones across semesters.

A further recommendation includes the organization of Concurrent Engineering sessions during the second iteration. These sessions would involve representatives from each subsystem and could be structured as multiple smaller design iterations. This method, inspired by practices from the ENG-411 course, would enhance interdisciplinary collaboration and promote more cohesive integration of subsystem interfaces.

7 Semester Project Retrospective

7.1 Goals and Results

7.1.1 Goals

When the project was defined and the goals were established before the beginning of the semester, the following goals were listed, in order of most to least important:

1. **Learn MBSE**
2. **Lay the groundwork** for the future of the Spaceshot project
3. Complete the **Phase 0 and the Phase A** of the Spaceshot project
4. Create a **SysML model of the launch vehicle** at the system level

7.1.2 Results

1. **Learn MBSE (Partially Achieved):** We believe that this objective has been partially achieved. This is because we both now have an introductory understanding of the topic, whereas neither of us knew anything about MBSE at the beginning of the semester. With such a vast and difficult topic, it is clear that how much could be learned from a semester project would always be limited. However, due to the above mentioned difficulties, we both could learn less than what we initially wanted to.

2. **Spaceshot Project Groundwork (Achieved):** We consider this objective achieved. It has been multiple times in the past that ERT project's early phases have been done very fast, often leading to required rework. While the project scope has been reduced, we believe that the achieved work is of good quality and can be reused in the future. In particular, the 63 mission requirements, the identified tradeoffs, the stakeholder analysis and the workpackages described in section 6 create a good basis for future work on the Spaceshot project.

3. **Phase 0 / A (Partially Achieved):** We consider that the Spaceshot initiative is currently at a MDR compliant stage, but that the Phase A of the project was not really started. This is again due to the difficulties listed above. In order to be PRR/Phase A compliant, this would have required white-box modeling at the system level. The required workpackages to reach this state have been identified and listed in section 6. This goal is therefore considered a partial success.

4. **SysML Model of the System (Not Achieved):** As stated earlier in the report, only modeling of the problem domain could be achieved, and neither black-box nor white-box modeling of the system itself could be started. This goal is therefore considered to be a failure. On top of the encountered difficulties, we also believe that this goal was likely overly ambitious. Even if we had received the software from day 1, aiming for a coherent and comprehensive model at the system level for a very first experience in MBSE is likely doable, but very difficult. Therefore, this failure should be taken with a grain of salt. Moreover, the mission modeling that was performed is reusable for later stages of the project.

7.2 Main Difficulties and Obstacles

Tool Procurement

The single biggest difficulty we have had by far is regarding the tool procurement. Because Cameo was not part of the EPFL software suite, we had to go through eSpace to get a license for it. We are extremely grateful for the support of eSpace and all its personnel for getting the software, but this process took a very long time. Despite trying to get a license at the very beginning of the semester, we got the software at the end of week 9 of the semester. This left us with very little time to learn and practice a difficult topic, which has had drastic consequences regarding the outcomes of the project.

MBSE Specific Supervision

As stated multiple time in this report, MBSE is an advanced topic that is not taught at EPFL as of doing this project. ERT also had no solid prior experience in either MBSE or SysML. While we are both extremely grateful for the support of Emmanuelle David which could provide guidance for the traditional SE aspects of the project, we had no MBSE expert that we could turn towards for feedback and advice. This means that every time that we weren't sure how to do a certain diagram, or what its content should be, or what the ultimate purpose of the diagram was, internet was the only place we could turn to for information. Most importantly, continuous feedback from an experienced MBSE engineer would have been invaluable, as all the artifacts produced are SysML compliant, but we have no idea if they follow the best practices.

Availability

Both students taking part in the project had a very busy semester. Michaël was away for over 2 weeks of the semester due to military duties. Antoine was heavily involved in the B1 liquid engine test campaign that took place during the first two thirds of the semester. Both students had multiple other responsibilities related to ERT's Firehorn project, which had to take priority over the Spaceshot project. This overall means that both students could invest less time than would have been required to reach the initial goals. Note that this has been very frustrating for both of us, as this has reduced how much we could learn from the project. However, some Firehorn work was utilized for the semester project, such as the first meetings with ESC that yielded a better understanding of the launch site provider needs.

7.3 Lessons Learned

This last subsection aims to share some of the lessons learned during the project so that future students can best learn from our work.

MBSE Feasibility Model-based systems engineering is absolutely feasible for students, provided they already have a solid grounding in traditional systems engineering. Trying to draw models without understanding what the traditional SE artifacts are and what they bring to a project is likely to be too much.

Scope and Iteration It's better to aim for a reduced model scope and iterate frequently than to try modeling everything at once. In our case, rather than aiming for a model scope up to system level white-box, it would have been better to aim for a reduced scope. If time allowed it, iterating on achieved work again instead of increasing the scope could help to catch errors and increase overall quality of the model.

Clear Goals The goal of the model needs to be clearly defined from the very beginning. Ask: What questions should this model answer, and what is its purpose? What level of fidelity is needed? Without a sharp goal, you'll drift into modeling details that don't add value. While for us the goal was always clearly to *learn*, we could still feel the many directions that we could bring the model towards. Therefore, we strongly recommend taking the time to define clear objectives, as described in the early chapters of [10].

Specialized MBSE Supervision It's not hard to do some MBSE—but doing good and useful MBSE requires proper mentorship. We recommend students who wish to learn the topic to find a subject-matter-expert who can review their SysML diagram, validate their architecture decisions, inform them of the best-practices, and keep them on-track.

Value in MBSE Even in the context of a student association, MBSE can bring a lot of benefits:

- Diagrams are easy to read and facilitate communication between SEs. It was very easy for each student to understand the decisions made by the other because all artifacts are derived in SysML. This might not apply to students who haven't been introduced to SysML.
- It forces a strict methodology and approach to SE work.
- A lot of other benefits exist but weren't explored during this project, such as executable (simulation-ready) model

	that can be used to perform Multidisciplinary Design Optimization or the use of automated requirements / design traceability functionalities. • It however requires as significant amount of time to pick up the discipline and perform MBSE activities. We therefore believe that ERT SE should only do MBSE as part of semester projects and not as part of their regular SE routine.
Google Drive Desktop	It is a great tool to have multiple students work on the same model without always having to send the updated files to eachother.

8 Conclusion

This semester project marked a key milestone in introducing Model-Based Systems Engineering (MBSE) into the EPFL Rocket Team's long-term Spaceshot initiative. With the ambitious objective of reaching space using a student-developed bi-liquid launch vehicle, the project aimed to establish a solid systems engineering foundation while offering a rigorous and meaningful learning experience.

The work was conducted in alignment with early-phase ECSS standards and applied the SysML language within the Magic Systems Architect tool. Despite a delayed start due to tool procurement challenges, significant progress was made during Phase 0 activities, culminating in the successful delivery of tangible systems engineering artifacts. The team produced a structured mission definition, completed comprehensive stakeholder analyses, derived 63 refined mission requirements, and created initial MBSE artifacts such as viewpoints, mission objectives, and traceability diagrams. Complementary trade-off studies were also performed at the mission level, exploring payload mass, apogee targets, recovery scope, and electrical interfaces. While qualitative, these studies introduced a structured decision-making framework for future design iterations.

A forward-looking development roadmap was also proposed. It includes a breakdown of systems engineering workpackages, a two-year timeline to reach System Requirements Review (SRR) readiness, and multiple solutions to support continuity across student-led projects, address asynchronous involvement, and manage complex interface dependencies.

While the original goal of producing a complete system-level model was not achieved, the project successfully delivered several foundational modeling artifacts and offered a deep, hands-on learning experience. Work remained focused on the problem domain, stopping short of internal block diagrams, functional architecture, or parametric modeling—largely due to delayed tool access and the steep learning curve associated with MBSE. These challenges reinforced critical lessons: the need for early access to modeling tools, the importance of realistic project scoping, and the value of dedicated mentorship. Equally, the experience demonstrated that MBSE is both feasible and beneficial in a student-led context—especially when students are supported by strong systems engineering fundamentals, a well-defined scope, and a sustainable development framework.

Ultimately, this report is a practical reference for future contributors. It consolidates the methodology, decisions, and insights developed throughout the semester and offers a structured path for continued progress. As the Spaceshot project evolves, this work lays a durable foundation to help future teams move closer to realizing the vision of reaching space with a student-built rocket.

9 Acknowledgements

We would like to express our sincere gratitude to Emmanuelle David for her invaluable guidance throughout this semester project, as well as for her ongoing support and supervision of the EPFL Rocket Team. Her insights and availability played a key role in the success of our work.

We are also grateful to eSpace for providing financial support for the Magic Systems of Systems Architect software, a critical tool that enabled us to apply MBSE methodologies effectively during the project.

We also thank Mathieu Udriot from eSpace and Martin Lemaire for their feedback and involvement on the Spaceshot project.

Finally, we would like to thank Matthieu Tonneau and Ryan Svoboda for their professionalism and constructive feedback in the context of their own semester projects related to the Spaceshot initiative. Their collaboration and shared insights greatly enriched our work.

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11 Appendix

Disclaimer

The information contained in this appendix may be outdated or not fully applicable to the current semester's project scope. Nevertheless, it has been included as it provides valuable context and insight into the underlying thought process.

11.1 MBSE Artifacts

This appendix collects all diagrams and tables presented in the MBSE Artifacts section for convenient visibility.

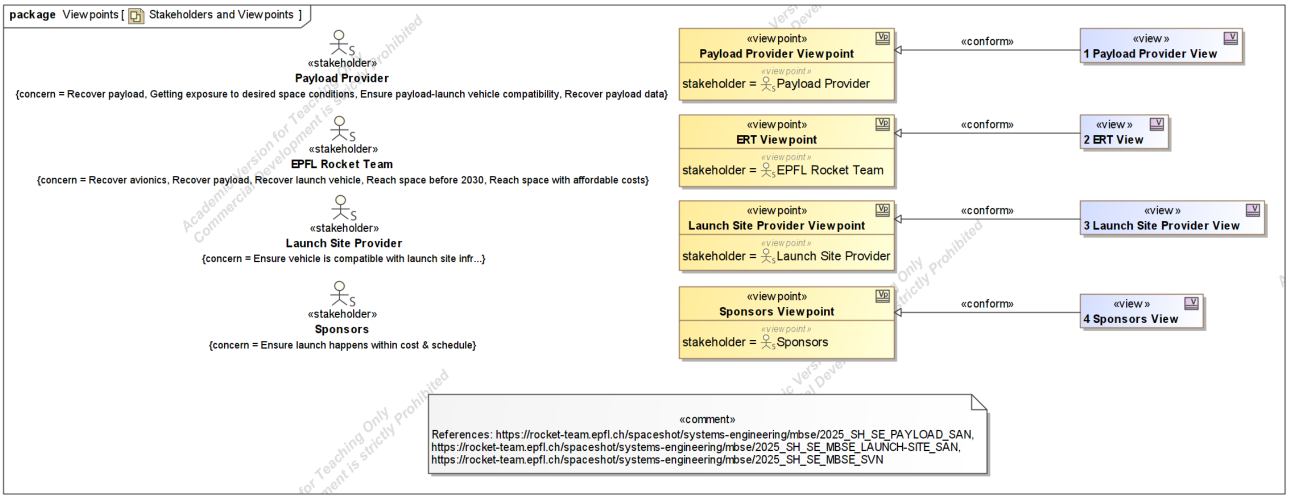

Figure 29: Viewpoints Diagram

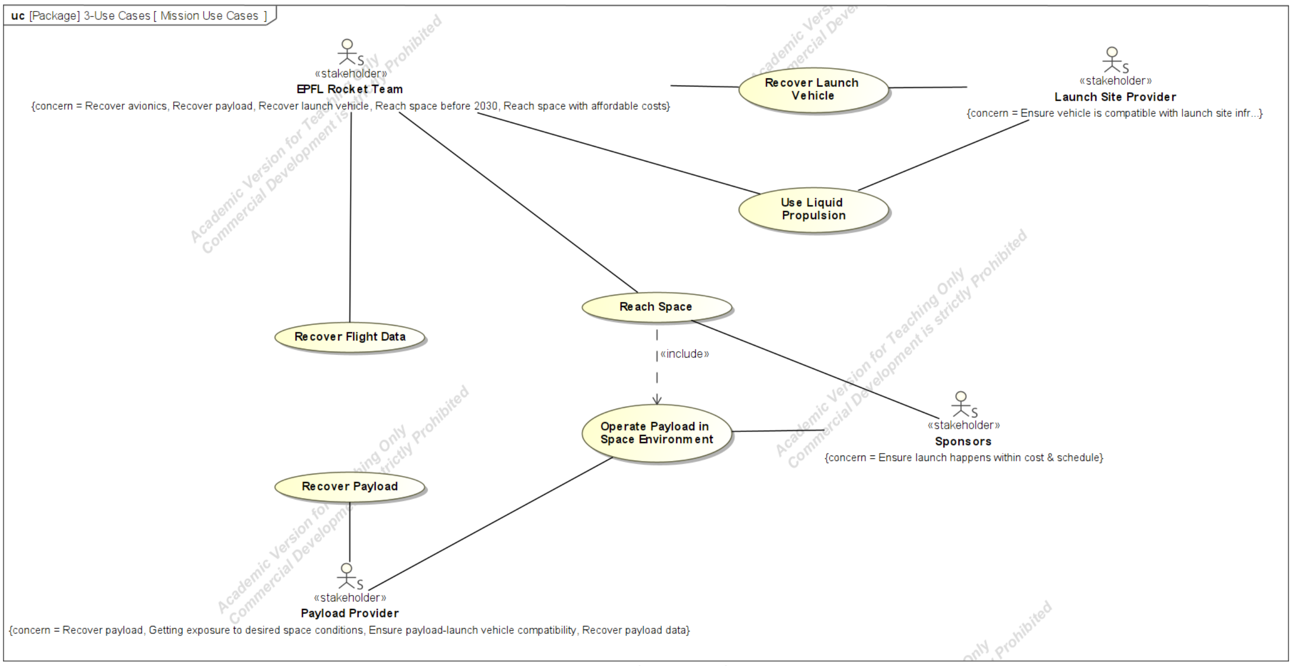

Figure 30: Mission Use Cases/Objectives Diagram

#	Name	Text
1	1.1 ERT Initial Requirements	
2	1.1.1 Apogee	Launch Vehicle and Payload shall reach an apogee over 100km AGL
3	1.1.2 Mission	The spaceshot project shall comply with the EPFL Rocket Team mission : "Engage Students in Space Technology Projects in Collaboration with Academia and Industry Partners"
4	1.2 Payload Provider Initial Requirements	
5	1.2.1 Launch Vehicle Interface	Payload shall be able to integrate into Launch Vehicle
6	1.2.2 Data Recovery	Payload data shall be recovered
7	1.2.3 Payload Recovery	Payload should be recovered
8	1.2.4 Payload Environment	Payload shall be submitted to acceptable environment
9	1.3 Launch Site Provider Initial Requirements	
10	1.3.1 Location	The launch shall occur at Esrange Space Center
11	1.3.2 Safety	The launch vehicle shall be operated in a safe manner.
12	1.3.3 Propulsion Type	The launch vehicle propulsion type shall be liquid to serve as a demonstrator for ESC.
13	1.3.4 Disturbance	The launch activities shall not impede any ESC stakeholders onsite.
14	1.4 Sponsors Initial Requirements	
15	1.4.1 Exposure	The spaceshot shall provide adequate exposure to sponsors.
16	1.4.2 Timeframe	Project should be done before end of decade.

Figure 31: Mission Requirements Table

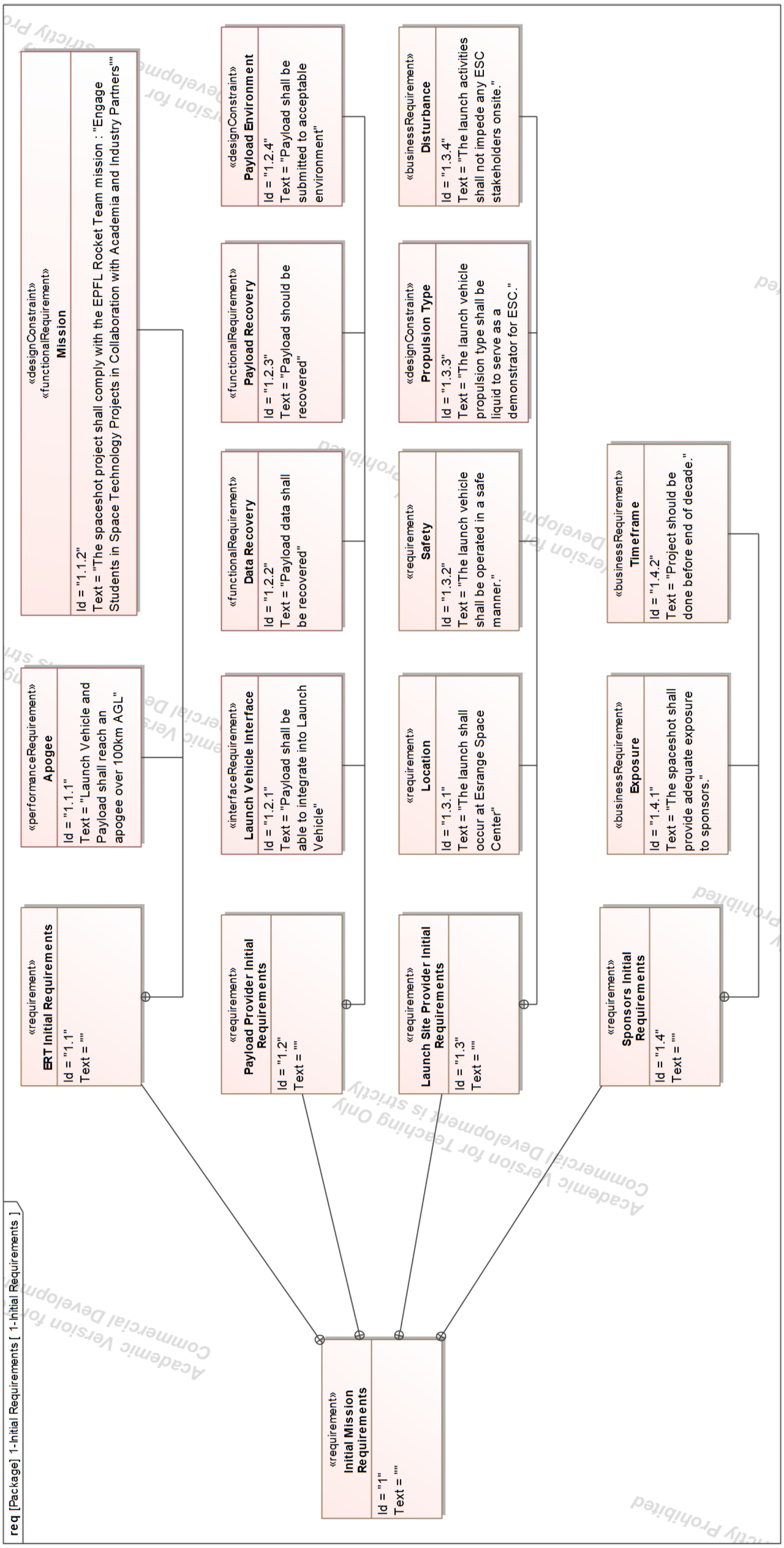

Figure 32: Mission Requirements Diagram

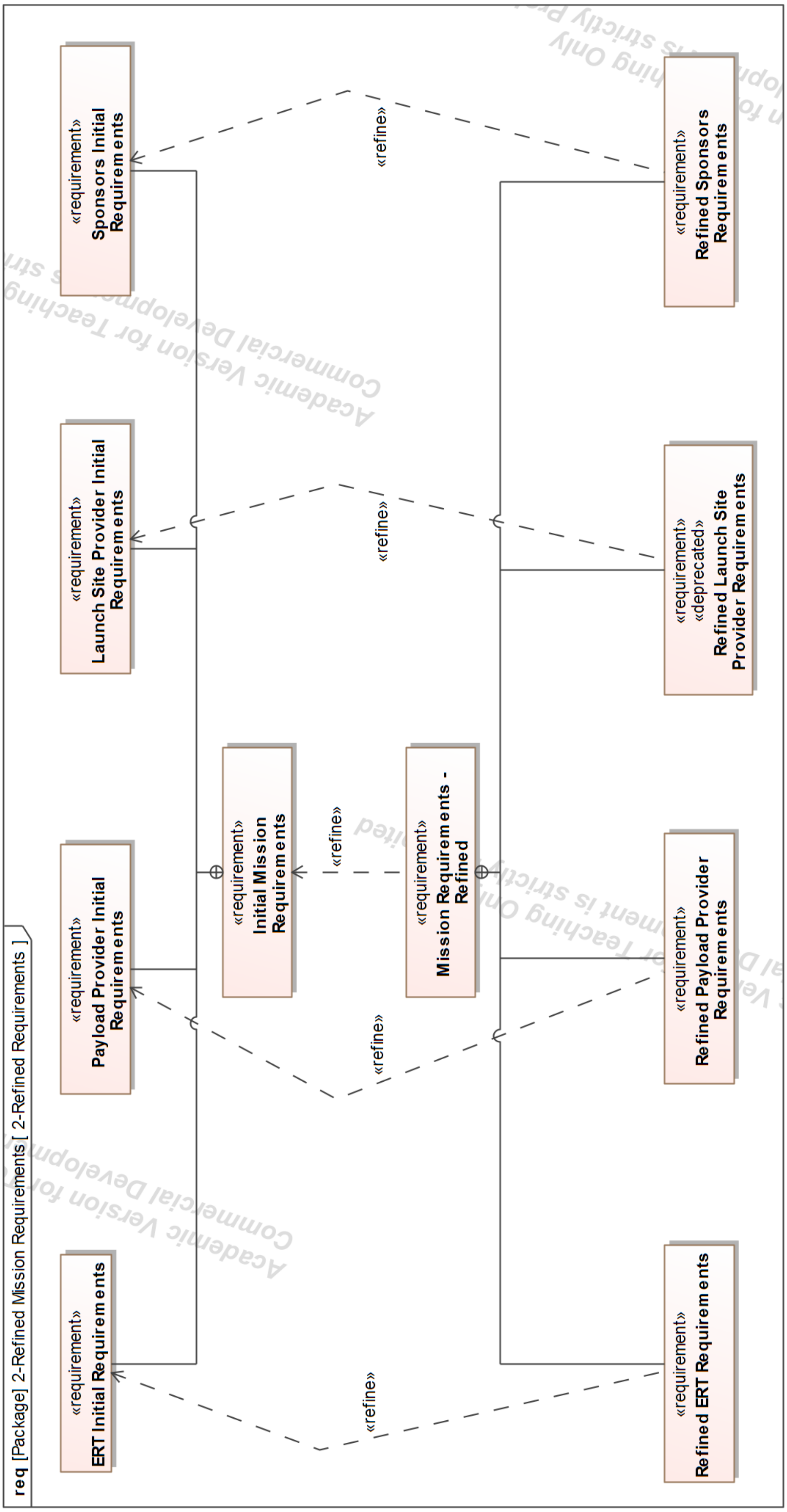

Figure 33: Refinement Process Diagram

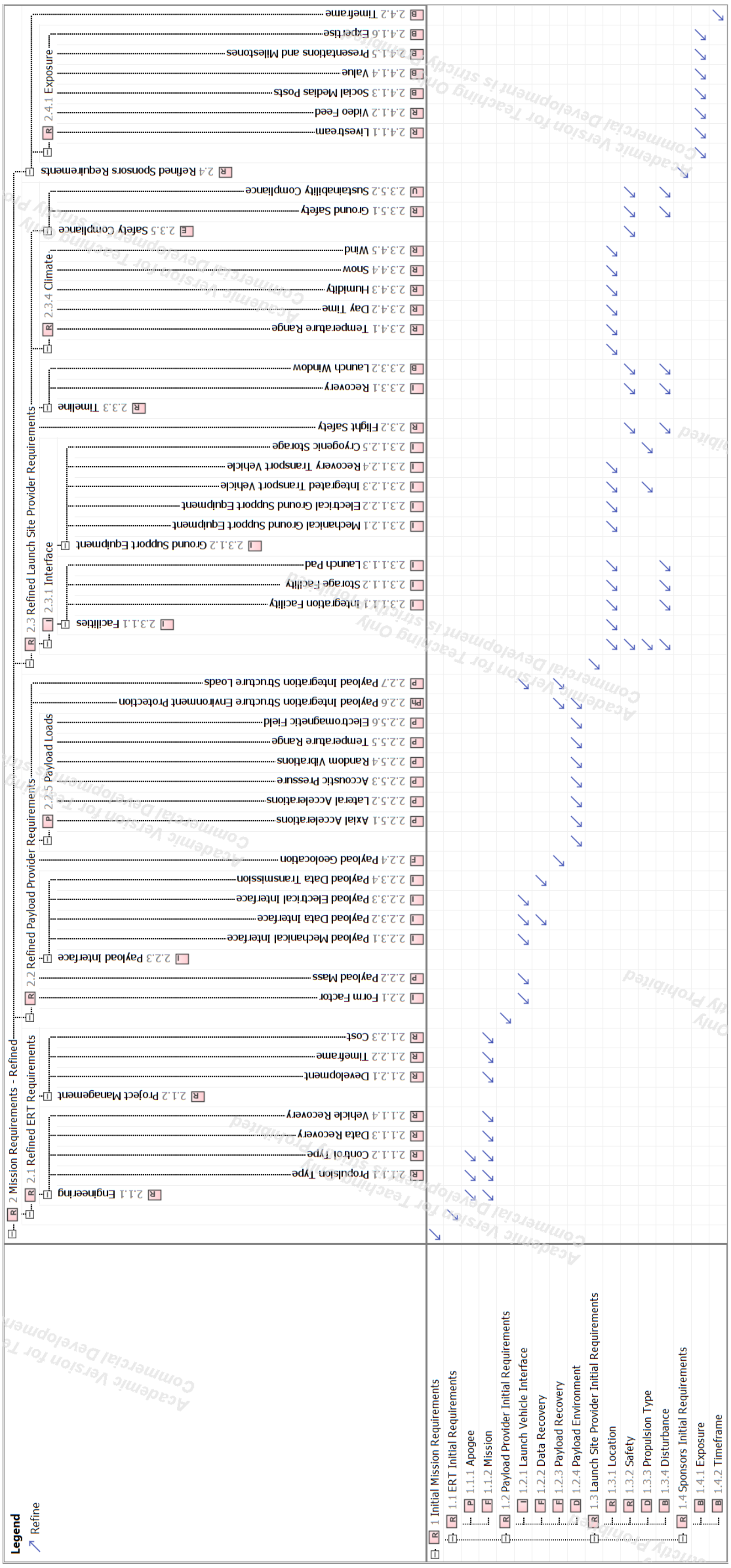

Figure 34: Refined Mission Requirements Traceability Table

#	Name	Text
1	2 Mission Requirements - Refined	
2	2.1 Refined ERT Requirements	
3	2.1.1 Engineering	
4	2.1.1.1 Propulsion Type	The launch vehicle should use liquid propulsion as it's main propulsive mean.
5	2.1.1.2 Control Type	The launch vehicle should use active control.
6	2.1.1.3 Data Recovery	The flight data shall be recovered.
7	2.1.1.4 Vehicle Recovery	The launch vehicle should be recovered in a condition suitable for subsequent exhibition.
8	2.1.2 Project Management	
9	2.1.2.1 Development	The launch vehicle should be developped using the lessons learned from the Competition project's iterations
10	2.1.2.2 Timeframe	The spaceshot launch should take place no more than two years after being designated as the EPFL Rocket Team's main project.
11	2.1.2.3 Cost	The spaceshot project cost shall be under TBD CHF, including TBD CHF of cash cost.
12	2.2 Refined Payload Provider Requirements	
13	2.2.1 Form Factor	Shall be able to integrate a payload with size of TBD U
14	2.2.2 Payload Mass	Shall be able to lift a payload of up to TBD kg
15	2.2.3 Payload Interface	
16	2.2.3.1 Payload Mechanical Interface	Payload shall not be inextricably connected to other launch vehicle associated components than its supporting structure
17	2.2.3.2 Payload Data Interface	should not have any electrical data interface to the payload
18	2.2.3.3 Payload Electrical Interface	should not have any electrical power interface to the payload
19	2.2.3.4 Payload Data Transmission	Should allow payload to transmit its own data
20	2.2.4 Payload Geolocation	Should provide means to locate payload after landing
21	2.2.5 Payload Loads	Payload shall be submitted to acceptable loads
22	2.2.5.1 Axial Accelerations	Shall apply max axial acceleration of TBD g
23	2.2.5.2 Lateral Accelerations	Shall apply max lateral acceleration of TBD g
24	2.2.5.3 Accoustic Pressure	Shall apply max accoustic pressure of TBD Pa
25	2.2.5.4 Random Vibrations	Random vibrations at interface shall not exceed spectrum TBD
26	2.2.5.5 Temperature Range	Max temperature shall remain within TBD range
27	2.2.5.6 Electromagnetic Field	Applied magnetic field shall not exceed TBD
28	2.2.6 Payload Integration Structure Environment Prote	Shall protect payload from landing environment
29	2.2.7 Payload Integration Structure Loads	Shall be able to protect payload from recovery loads
30	2.3 Refined Launch Site Provider Requirements	
31	2.3.1 Interface	The launch vehicle shall operate with ESC facilities and equipment.
32	2.3.1.1 Facilities	
33	2.3.1.1.1 Integration Facility	The Launch Vehicle shall be integrated in an Integration Facility provided by ESC.
34	2.3.1.1.2 Storage Facility	The Launch Vehicle shall be stored on a dedicated storage facility provided by ESC.
35	2.3.1.1.3 Launch Pad	The Launch Vehicle shall be operated on a dedicated launch pad provided by ESC.
36	2.3.1.2 Ground Support Equipment	
37	2.3.1.2.1 Mechanical Ground Support Equipm	
38	2.3.1.2.2 Electrical Ground Support Equipment	
39	2.3.1.2.3 Integrated Transport Vehicle	After integration the launch vehicle shall be moved from the integration facility to the launch pad by a TBD ESC vehicle
40	2.3.1.2.4 Recovery Transport Vehicle	After recovery the launch vehicle shall be moved from the recovery site to the integration facilityh by a TBD ESC vehicle.
41	2.3.1.2.5 Cryogenic Storage	The Launch Vehicle shall be compatible with the ESC cryogenic storage.
42	2.3.2 Flight Safety	The launch vehicle shall comply with the Esrange Safety Manual "Flight Safety" section requirements.
43	2.3.3 Timeline	Flight shall occur within a TBD timeframe imposed by ESC
44	2.3.3.1 Recovery	Recovery shall take be done within a TBD h window after landing.
45	2.3.3.2 Launch Window	Flight shall take place within a 2 day window (TBD), with daily operations beginning at a TBD h CET and ending at a TBD h CET
46	2.3.4 Climate	
47	2.3.4.1 Temperature Range	The launch vehicle shall whistand temperature ranges from TBD to TBD °C
48	2.3.4.2 Day Time	The launch vehicle should be operated during ESC work day time
49	2.3.4.3 Humidity	The launch vehicle shall whistand rain exposure of at least TBD mm/h
50	2.3.4.4 Snow	The launch vehicle equipments shall whistand snow exposure of at least TBD m
51	2.3.4.5 Wind	The launch vehicle shall whistand windspeeds from TBD to TBD m/s
52	2.3.5 Safety Compliance	The launch vehicle shall comply with the Esrange Safety Manual guidelines
53	2.3.5.1 Ground Safety	The launch vehicle shall comply with the Esrange Safety Manual "Ground Safety" section requirements.
54	2.3.5.2 Sustainability Compliance	The launch vehicle shall comply with the environmental framework imposed by Esrange Space Center
55	2.4 Refined Sponsors Requirements	
56	2.4.1 Exposure	The spaceshot shall provide adequate exposure to sponsors.
57	2.4.1.1 Livestream	The spaceshot launch shall include a livestream of major events such as pre-launch, launch and recovery activities.
58	2.4.1.2 Video Feed	The launch vehicle shall record at least 2 recoverable HD video flux of the flight.
59	2.4.1.3 Social Medias Posts	The spaceshot project shall support contracted social media posts including sponsors equipment and / or services.
60	2.4.1.4 Value	The spaceshot should seek to use a TBD percent "value"/"cash cost" sponsoring ratio, to reduce the cash cost.
61	2.4.1.5 Presentations and Milestones	The spaceshot project shall include at least TBD major presentations and milestones where sponsors are invited to attend.
62	2.4.1.6 Expertise	The spaceshot project should actively leverage sponsor expertise whenever applicable.
63	2.4.2 Timeframe	The spaceshot flight should be done before end of decade.

Figure 35: Refined Mission Requirements Table

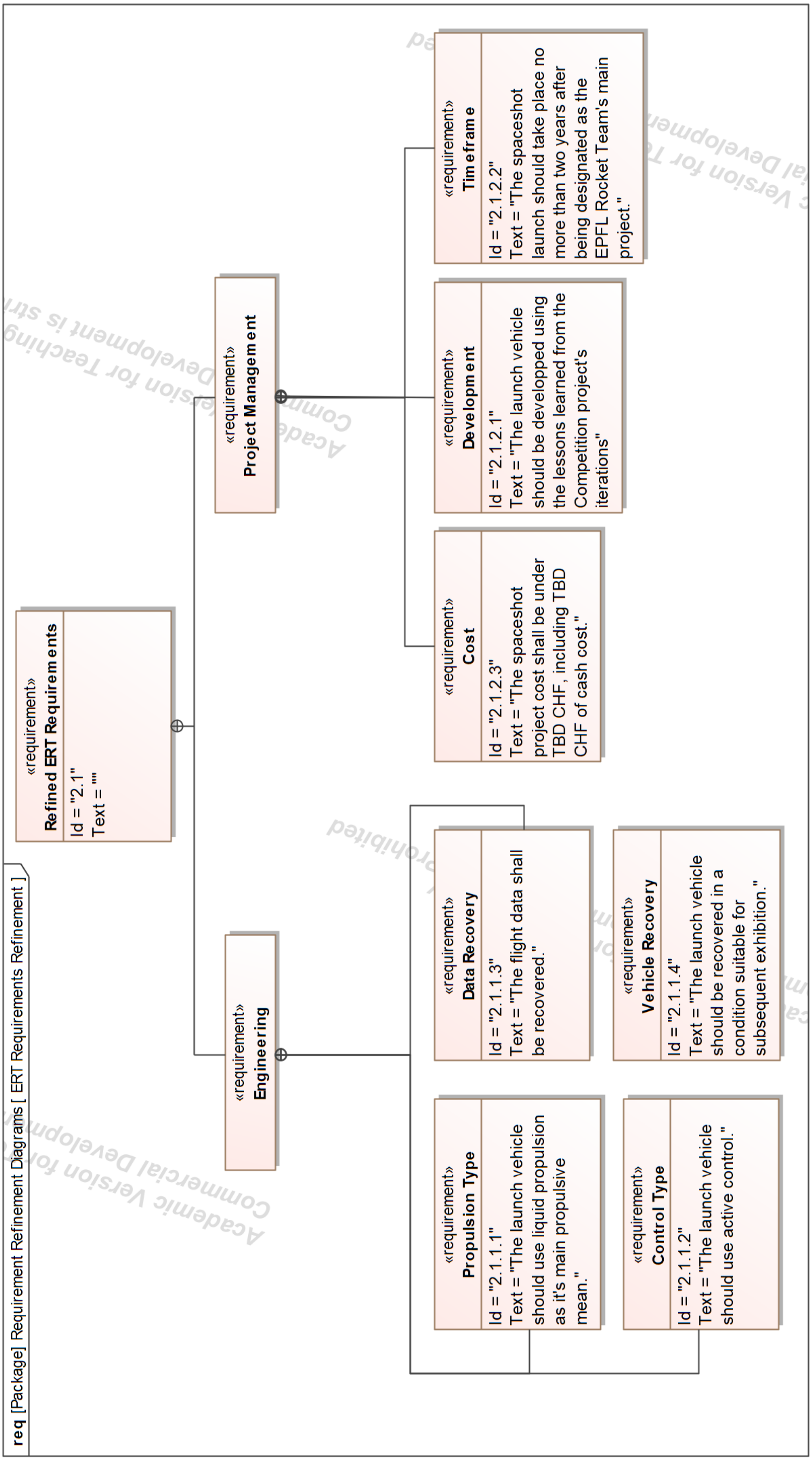

Figure 36: EPFL Rocket Team Refined Mission Requirements Diagram

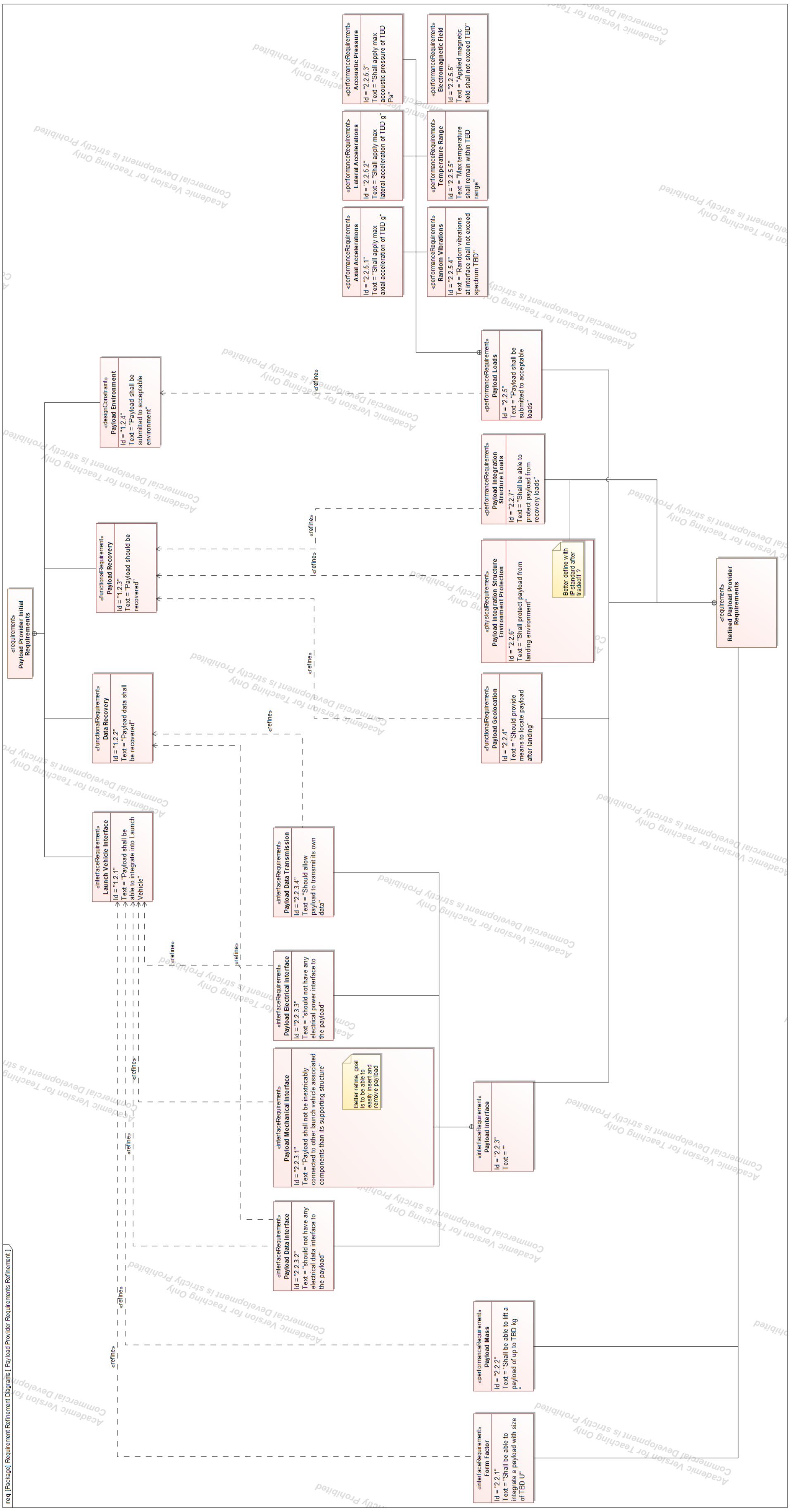

Figure 37: Payload Provider Refined Mission Requirements Diagram

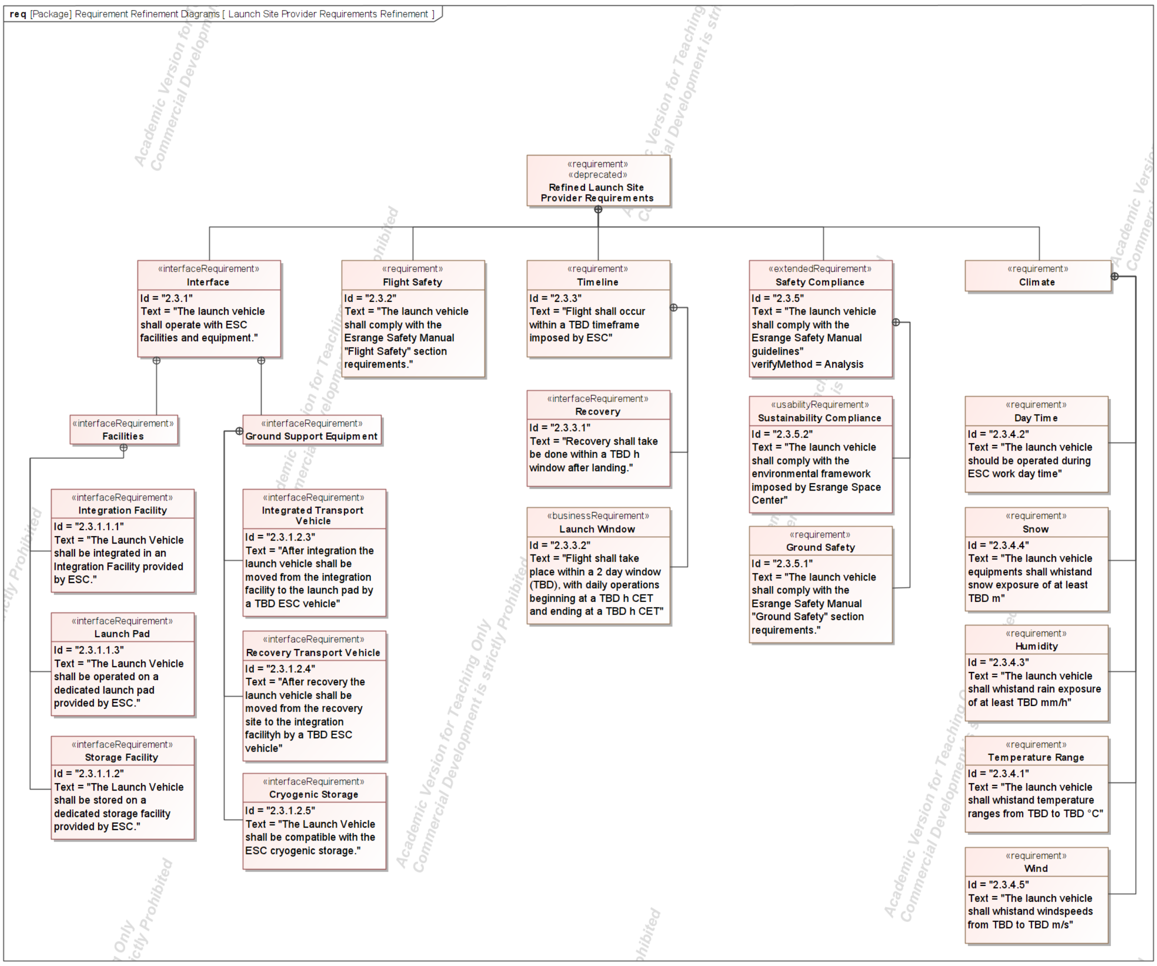

Figure 38: Launch Site Provider Refined Mission Requirements Diagram

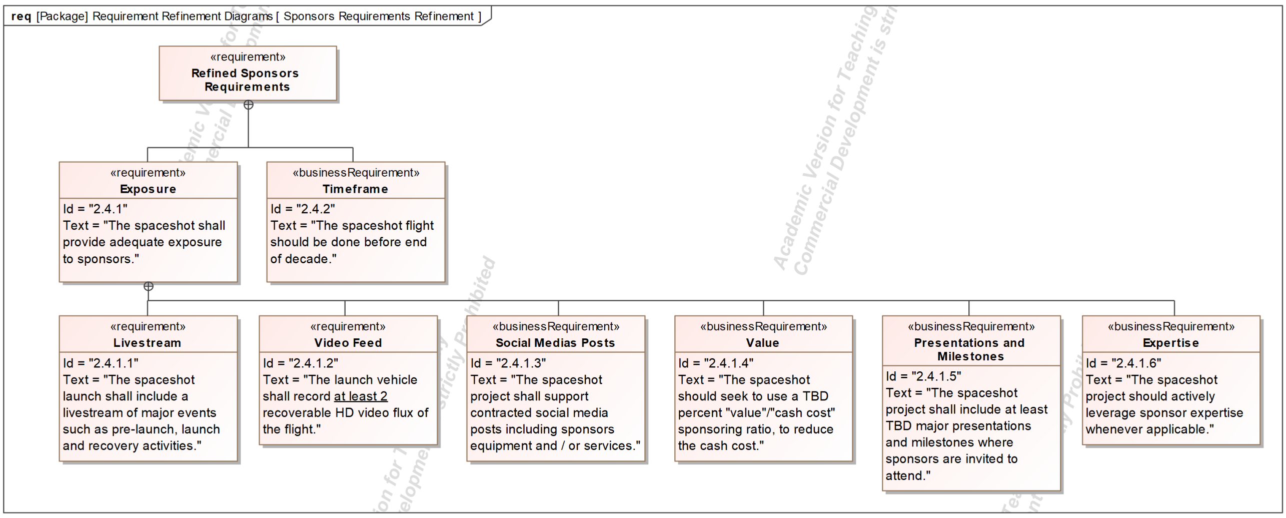

Figure 39: Sponsors Refined Mission Requirements Diagram

11.2 State Of The Art (SOTA)

11.2.1 Overview of Student-Led SpaceShot Projects

EPFL Rocket Team (ERT)

ERT has set an ambitious goal of launching a bi-liquid propulsion rocket to space by 2027. Their project, Spaceshot, involves a bi-liquid EthaLox propulsion system and aims to be the first student-led team to reach the Kármán line. The team has conducted structural analysis, trajectory simulations, and iterative rocket design improvements.

Princeton Rocketry Club (PRC)

PRC developed the SpaceShot Rev.2, a two-stage sounding rocket designed to reach over 125 km. The rocket employs composite airframes and optimized propulsion, achieving hypersonic speeds of Mach 5.8. The team has demonstrated success in aerodynamics, lightweight structural design, and high-altitude recovery systems.

Yellow Jacket Space Program (YJSP)

Based at Georgia Tech, YJSP is developing a suborbital vehicle with liquid propulsion. Their incremental approach includes testbeds for avionics and propulsion, with a focus on risk mitigation and iterative design.

11.2.2 Key Technologies

Propulsion Systems

- **Solid Rocket Motors (SRMs):** Used by USCRPL and PRC for their reliability and simplicity. They provide high thrust but lack throttle control and reusability.
- **Bi-Liquid Propulsion:** Employed by ERT and YJSP, offering controllable thrust and higher efficiency. EthaLox (ethanol-liquid oxygen) is a popular choice due to its storability and handling properties.
- **Hybrid Propulsion:** Combines elements of solid and liquid propulsion, with solid fuel and liquid oxidizers. It is being explored for its potential benefits in fuel efficiency and environmental impact.
- **Thrust Vector Control (TVC):** Some teams are developing TVC mechanisms to improve in-flight stability and trajectory precision.
- **Regenerative Cooling:** Advanced bi-liquid engines employ regenerative cooling to prevent overheating, a technology critical for prolonged burn times.

Structural Design

- **Composites:** CFRP and GFRP are used for their high strength-to-weight ratios, ensuring lightweight and durable rocket airframes.
- **Monocoque and Rib-Stringer Structures:** Princeton and Yellow Jacket teams utilize monocoque structures for load-bearing efficiency, while rib-stringer designs offer modularity and ease of integration.
- **Thermal Protection Systems (TPS):** Rockets operating at hypersonic speeds require TPS, such as ablative materials and ceramic coatings, to withstand aerodynamic heating.
- **Aerodynamic Optimization:** Nose cone shapes and fin designs are refined through CFD simulations to reduce drag and improve stability.

Avionics and Control Systems

- **GPS and Telemetry:** Real-time tracking and data transmission are critical for mission success.
- **Flight Computers:** Custom-built avionics with redundancy to ensure mission success. Many teams integrate fail-safe systems.
- **Active Stability Control:** Some teams, such as YJSP, experiment with thrust vectoring and aerodynamic control surfaces like canards for precision trajectory corrections.
- **Sensor Integration:** Accelerometers, gyroscopes, and altimeters provide critical flight data.
- **Software and Simulation Tools:** MATLAB, OpenRocket, and RASAero are commonly used.

Recovery Systems

- **Parachute Deployment:** Dual-stage systems reduce descent speed and impact forces.
- **Autonomous Navigation:** GPS-guided parachutes or parafoil designs for controlled descent.
- **Reusability Considerations:** Modular recovery bays allow for component reuse.

Competitions and Industry Collaboration

- **European Rocketry Challenge (EuRoC):** A major platform for student teams to test rockets.
- **Base 11 Space Challenge:** Former competition aiming for student-led space access.
- **Industry Partnerships:** Teams collaborate with aerospace companies for resources and expertise.

11.3 Concept of Operations (COP)

Figure 40: Pre-arrival ConOps

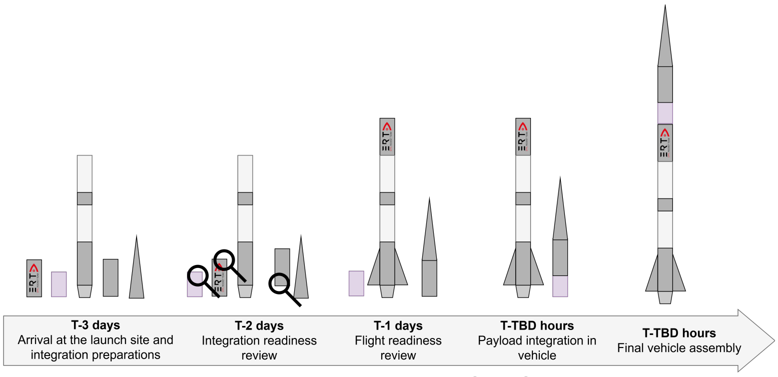

Figure 41: Pre-flight ConOps

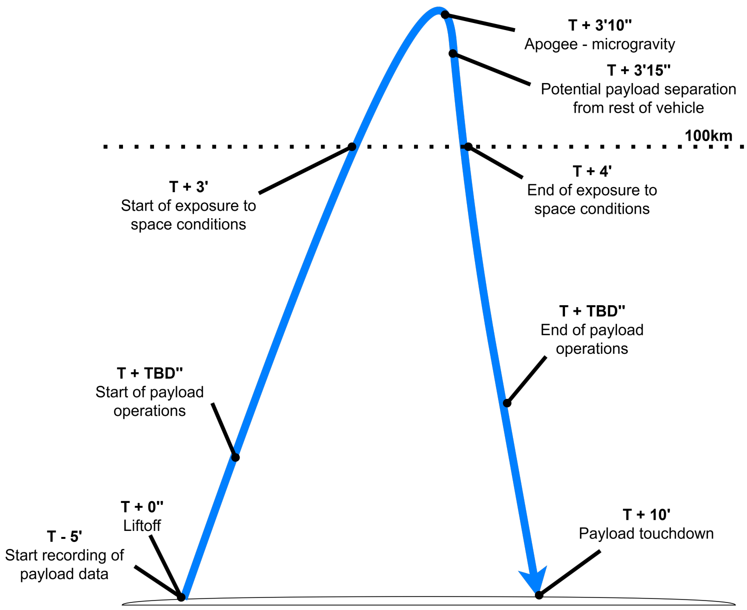

Figure 42: Mission Profile ConOps

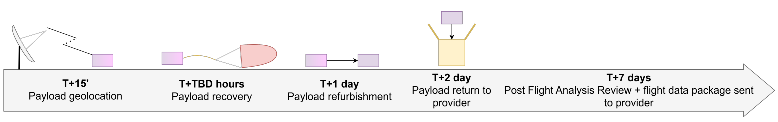

Figure 43: Post-flight ConOps

11.4 Mission Requirements List (MRL)

ID	Type	Title	Description	Rationale	Source	Stakeholders
1	Flight Performance	Apogee	The launch vehicle and the payload apogee shall exceed 100 [km].	*Rationale*	*Source*	Spaceshot, Hyperion, Icarus, Solaris, Space Race, EPFL, MAKE, eSpace, Workshops, Payload Provider, Launch Site, National Authorities, ESA, Rocketry Associations, ERT Alumni, Generic ERT Sponsors, GCM SA, Shipping Services
2	Flight Performance	Downrange Distance	The launch vehicle and the payload should land at most TBD [km] from the launch location.	Landing far away from the launch site induces a lot of stress on recovery operations, telemetry dimensioning, and reduces the chances of finding the payload and launch vehicle.	*Source*	eSpace, Payload Provider, Launch Site
3	Flight Performance	Launch Independance	The launch vehicle shall be capable of launching successfully even if the payload is not present or integrated.	While the payload mission objective is important, the logistic cost of bringing such a complex system onsite cannot be aborted or repeated, thus we must ensure that the launch vehicle is capable to fulfill it's mission target without a payload.	*Source*	Spaceshot, Payload Provider, Launch Site
4	Flight Performance	Flight Duration	The flight duration shall not exceed TBD [s]	A timeframe must be set to avoid energetic over-dimensionning of the launch vehicle and payload.	*Source*	Payload Provider, Launch Site, National Authorities
5	Flight Performance	Microgravity Duration	The flight path shall provide a high-quality microgravity environment with an absolute perceived acceleration of at most 10^-4 [g] for at least 60 [s]	Time above 90 [km], for a 100 [km] apogee.	https://ntrs.nasa.gov/api/citati	EPFL, MAKE, eSpace, Payload Provider
6	Launch Vehicle	Propulsion	The launch vehicle shall demonstrate in-flight performance of a SRAD bi-liquid propulsion system.	Hyperion needs to provide the bi-liquid system.	*Source*	Hyperion, EPFL, MAKE, eSpace, Workshops, Launch Site, National Authorities, ESA, Rocketry Associations, ERT Alumni, Generic ERT Sponsors, GCM SA
7	Launch Vehicle	Recovery	The launch vehicle should be recovered for reuse or post-flight analysis.	Recovery of such large sytems is appreciated regarding the sustainability efforts done EPFL-side	*Source*	Spaceshot, EPFL, MAKE, eSpace, Launch Site, National Authorities, ESA
8	Launch Vehicle	Refurbishment	The launch vehicle should be displayed as an ornative piece after it's flight with minimum hazards to visitors.	Being able to present the flown vehicle to the public has a positive effect on the association's image as well as other stakeholders such as ESA, EPFL or eSpace.	*Source*	Spaceshot, Hyperion, EPFL, MAKE, eSpace, Workshops, Launch Site, ESA, Rocketry Associations, ERT Alumni, Generic ERT Sponsors, GCM SA, Shipping Services
9	Launch Vehicle	Media Recording	The launch vehicle shall include visual and audio capture systems to document flight events.	Having medias such as video and audio to show to the public is essential as these are the most used in-beetween ERT's stakeholders.	*Source*	EPFL, MAKE, eSpace, Workshops, Payload Provider, Launch Site, National Authorities, ESA, Rocketry Associations, ERT Alumni, Generic ERT Sponsors, GCM SA, Shipping Services
10	Launch Vehicle	Flight Data Logging	The launch vehicle shall log it's flight computer data along the whole mission.	*Rationale*	*Source*	Spaceshot, Rocketry Associations
11	Launch Vehicle	Flight Data Retrieval	The launch vehicle shall enable the complete retrieval of flight computer data.	*Rationale*	*Source*	Spaceshot, Rocketry Associations
12	Launch Vehicle	Telemetry	The launch vehicle shall enable the payload to retrieve its data in real time	In case of an unexpected mission failure during flight at any stage, we want to still be able to recover something from the mission. Minimizing delay reduces data loss in case of mission failure.	2025_SH_SE_PAYLOAD_SAN	Payload Provider, Launch Site
13	Payload	Integration Schedule	The payload shall be integrated TBD [h] before launch	*Rationale*	2025_SH_SE_PAYLOAD_SAN	Payload Provider, Launch Site
14	Payload	Recovery Schedule	The payload should be recovered under TBD [h].	*Rationale*	2025_SH_SE_PAYLOAD_SAN	Payload Provider, Launch Site
15	Payload	Recovery	The launch vehicle shall enable payload recovery.	This allows for full data recovery, among other benefits of preserving the payload.	2025_SH_SE_PAYLOAD_SAN	EPFL, MAKE, eSpace, Payload Provider, Launch Site, ESA
16	Payload	Mass	The launch vehicle shall be able to lift a payload of maximum 18 [kg] to the target altitude.	1-1.5[kg] / U is the typical range the team is used to.	*Source*	Payload Provider
17	Payload	Volume	The launch vehicle shall provide a 12U cubsat (200 by 200 by 300 [mm]) volume for the payload.	12U	https://www.nasa.gov/what-are	Payload Provider
18	Payload	Interface	The launch vehicle shall only provide a mechanical interface to the payload.	Minimizing the different interfaces makes it much easier to integrate different types of payload providers.	2025_SH_SE_PAYLOAD_SAN	Payload Provider

ID	Type	Title	Description	Rationale	Source	Stakeholders
19	Payload	Quasistatic Accelerations	The launch vehicle shall maintain maximum acceleration loads on the payload to <(TBD)[g] along any axis during the entire flight duration.	Limit loads applied on payload to an acceptable level.	2025_SH_SE_PAYLOAD_SAN	Payload Provider
20	Payload	Accoustic Loads	The launch vehicle shall maintain accoustic loads experienced by the payload under a TBD threshold.	Limit loads applied on payload to an acceptable level.	2025_SH_SE_PAYLOAD_SAN	Payload Provider
21	Payload	Vibratory Loads	The launch vehicle shall maintain vibrational levels within a (TBD) PSD curve for the entire flight duration.	Limit loads applied on payload to an acceptable level.	2025_SH_SE_PAYLOAD_SAN	Payload Provider
22	Payload	Coast Phase Angular Frequency	The launch vehicle shall maintain an angular frequency below or equal to TBD [Hz] during the coast phase.	High angular frequency can induce unwanted centrifugal accelerations on the payload. Also medias can be unusable at high spin rates	https://www.space-propulsion.	
23	Payload	Pressure Range	The launch vehicle shall expose the payload to a pressure range of TBD to TBD [bars] during the coast phase.	Ambient conditions	*Source*	
24	Payload	Temperature Range	The launch vehicle shall expose the payload to a temperature range of TBD to TBD [K] during the coast phase.	Ambient conditions	*Source*	
25	Compliance	Cost	The total mission cost shall remain below [TBD] CHF.	*Rationale*	*Source*	Launch Site, National Authorities, ESA, Generic ERT Sponsors, Shipping Services
26	Compliance	Launch Site	The launch system shall be fully compatible with the available launch site equipment and facilities, verified through coordination with the site authorities.	*Rationale*	*Source*	Launch Site, National Authorities
27	Compliance	Range Safety Regulations	The launch and flight operations shall comply with all applicable local range safety regulations and standards.	*Rationale*	*Source*	Launch Site, National Authorities
28	Compliance	Flight Safety Reviews	The entire launch system and mission plan shall undergo and pass safety reviews by the launch site authority prior to launch approval.	*Rationale*	*Source*	Launch Site, National Authorities
29	Compliance	Environmental Compliance	The system design, materials, and operational procedures shall fully adhere to local environmental protection laws, guidelines, and enforcement standards.	*Rationale*	*Source*	Launch Site, National Authorities
30	Compliance	Airspace Compliance	The mission planning and execution shall strictly comply with applicable local and international airspace regulations and coordinate as required with aviation authorities.	*Rationale*	*Source*	Spaceshot, Launch Site, National Authorities, ESA
31	Compliance	Documentation Standards	All mission documentation should adhere to ECSS standards, specifically adapted and implemented by the EPFL Rocket Team.	*Rationale*	*Source*	EPFL, MAKE, eSpace, Launch Site, National Authorities
32	Compliance	Operator Safety	The mission, including pre-launch, launch, and recovery operations, shall not introduce unacceptable safety risks to personnel, operators, or observers.	*Rationale*	*Source*	EPFL, MAKE, eSpace, Launch Site, National Authorities
33	Compliance	Hazardous Materials	No hazardous materials prohibited by local launch site regulations shall be included in the launch vehicle or payload.	*Rationale*	*Source*	National Authorities, Shipping Services
34	Compliance	Export Control	The launch vehicle, payload, associated hardware, software, and documentation shall comply with all relevant international export control laws and regulations.	*Rationale*	*Source*	Spaceshot, Hyperion, Solaris, EPFL, MAKE, Launch Site, National Authorities, ESA, Rocketry Associations, ERT Alumni, Generic ERT Sponsors, GCM SA
35	Timeline	Timeline	The mission should be realised before the year 2030	*Rationale*	*Source*	

11.5 Launch Site Provider Refined Mission Requirements (Deprecated)

Disclaimer

Some of the requirements presented here place stronger constraints on the stakeholder than on the mission itself; these were subsequently transferred to Matthieu Tonneau's Spaceshot logistics semester project.

Name	Text
2.3 Refined Launch Site Provider Requirements	
2.3.12 Data	The mission shall comply with the Esrange Safety Manual "Esrange Space Center safety data requirements on range users" section requirements.
2.3.11 User Responsibilities	The mission shall comply with the Esrange Safety Manual "Range Users Responsibilities" section requirements.
2.3.10 Flight Safety	The mission shall comply with the Esrange Safety Manual "Flight Safety" section requirements.
2.3.7 Climate	The mission shall be compatible with ESC climate
2.3.7.6 Wind	ERT equipments shall whistand windspeeds from TBD to TBD m/s
2.3.7.5 Weather Forecasting	ESC shall provide weather forecasting to ERT
2.3.7.4 Snow	ERT equipments shall whistand snow exposure of at least TBD m
2.3.7.3 Humidity	ERT equipments shall whistand rain exposure of at least TBD mm/h
2.3.7.2 Day Time	Mission operations should occur during ESC work day time
2.3.7.1 Temperature Range	ERT equipments shall whistand temperature ranges from TBD to TBD °C
2.3.3 Safety Compliance	The mission shall comply with the Esrange Safety Manual guidelines
2.3.3.4 Ground Safety	The mission shall comply with the Esrange Safety Manual "Ground Safety" section requirements.
2.3.3.3 Pre-Arrival	The mission shall comply with the Esrange Safety Manual "Pre-arrival requirements on range users" section requirements.
2.3.3.2 Sustainability Compliance	The mission shall comply with the environmental framework imposed by Esrange Space Center
2.3.3.1 Legal Compliance	The mission shall comply with the TBD (The Work Environment Act (Arbetsmiljölagen)) legal framework imposed by Esrange Space Center
2.3.2 Timeline	The mission shall occur within a TBD timeframe imposed by ESC
2.3.8.2 Timeframe	The onsite mission operations shall occur within a 8 days timeframe
2.3.8.1 Launch Window	The flight shall take place within a 2 day window (TBD), with daily operations beginning at a TBD h CET and ending at a TBD h CET
2.3.2.1 Recovery	Recovery shall take be done within a TBD h window after landing.
2.3.1 Interface	
2.3.1.12 Ground Support Equipment	
2.3.1.12.2 Electrical Ground Support Equipment	
2.3.1.12.1 Mechanical Ground Support Equipment	
2.3.1.12.1.3 Cryogenic Storage	The Launch Vehicle and ERT GSE shall be compatible with the ESC cryogenic storage.
2.3.1.12.1.2 Recovery Transport Vehicle	After recovery the launch vehicle shall be moved from the recovery site to the integration facilityh by a TBD ESC vehicle
2.3.1.12.1.1 Integrated Transport Vehicle	After integration the launch vehicle shall be moved from the integration facility to the launch pad by a TBD ESC vehicle
2.3.1.11 Facilities	
2.3.1.11.4 Mission Control Room	The mission shall be controlled from a Mission Control Room provided by ESC.
2.3.1.11.3 Launch Pad	The Launch Vehicle and related GSE shall be operated on a dedicated launch pad provided by ESC.
2.3.1.11.2 Storage Facility	The Launch Vehicle and related GSE shall be stored on a dedicated storage facility provided by ESC.
2.3.1.11.1 Integration Facility	The Launch Vehicle shall be integrated in an Integration Facility provided by ESC.
2.3.1.11.5 Commodities	ESC shall provide ERT with basic commodities (kitchen, toilets...) necessary to ensure operators wellbeing onsite.
2.3.1.10 Supplies	
2.3.1.10.4 Working Fluids	ESC shall provide all working fluids onsite.
2.3.1.10.4.3 Pressurisant	ESC shall provide TBD u. of TBD L at TBD Bars of TBD gaz
2.3.1.10.4.2 Oxydizer	ESC shall provide TBD u. of TBD L at TBD Bars of TBD oxyidizer
2.3.1.10.4.1 Fuel	ESC shall provide TBD u. of TBD L of TBD fuel
2.3.1.10.3 Internet Access	ESC should provide ethernet access.
2.3.1.10.3.1 Interface	Internet interface shall be wired 1000Mbps ethernet
2.3.1.10.3.2 Speed	Speeds shall be at least TBD up and TBD down
2.3.1.10.3.3 Location	Internet access shall be accessible from the Mission Control Room, Integration Facility and if possible in the other ERT allocated locations.
2.3.1.10.2 Water Supply	ESC shall provide drinkable water supply to the Integration Facility and Mission Control.
2.3.1.10.1 Electrical Supply	ESC shall provide electrical supply to ERT locations.
2.3.1.10.1.1 High Power Electrical Supply	ESC shall provide 400 V TBD A electrical supply to the Integration Facility and Launch Pad
2.3.1.10.1.2 Low Power Electrical Supply	ESC shall provide 240 V TBD A electrical supply to all ERT locations