POLITECNICO DI TORINO

Master's Degree in Aerospace Engineering

Master's Degree Thesis

Implementation and Validation of a Corporate Concurrent Engineering Framework through a Solar Sail-Propelled CubeSat for a NEA Survey Mission

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Abstract

Space mission design represents a complex challenge due to the vast and highly non-linear trade spaces, the complex and interconnected analyses required, and the need to address every mission phase, from procurement to end-of-life, while considering both technical and programmatic aspects. This thesis work was carried out within the Research & Development Unit of the Italian company Argotec and aims to implement a Concurrent Engineering (CE) framework in a corporate environment to enhance the efficiency and effectiveness of mission formulation and design, referred to as the *Advanced Concepts Laboratory* (*ACLab*). Unlike traditional sequential approaches, which can lead to late-stage redesigns, missed opportunities, or suboptimal designs, CE promotes teamwork and real-time design sessions, enabling simultaneous progress across all aspects of a space mission. CE enhances trade space exploration, decision-making, and the concurrent evaluation of all relevant factors, resulting in valuable, feasible, and consistent designs while reducing the overall effort required.

This work addresses the challenges of implementing CE in a corporate context, which include managing relationships with clients and potential external partners, dealing with limited resource availability due to staff being frequently engaged in other flight projects, staff training, and integrating technical aspects with programmatic ones. The work initially focused on implementing tools to support mission design and integrating the COMET tool within the framework to support data and study management. Additionally, a methodology was developed to encompass multiple aspects, from client relations and session planning to trade space exploration and point design. The implemented CE framework also introduces innovative elements, including the adoption of a SCRUM-based approach to prioritize tasks, improve session planning and identify critical areas that require more time and resources, as well as the integration of a RAG (Retrieval-Augmented Generation) pipeline, a tool from the field of Large Language Models (LLM), to optimize the systems engineering process, particularly for information retrieval.

The methodology and tools were tested through a Phase 0 study of a solar sail-propelled CubeSat mission for near-Earth asteroid survey and were refined based on the feedback gathered. The results of the case study demonstrate the benefits of designing a mission through this new approach while also analyzing the challenges encountered, tracing their causes and proposing possible solutions.

Sommario

Il design delle missioni spaziali rappresenta una sfida complessa a causa degli ampi e altamente non lineari spazi di trade-off, della richiesta di analisi complesse e interconnesse e della necessità di affrontare ogni fase della missione, dal procurement al fine vita, considerando al contempo aspetti tecnici e programmatici. Questo lavoro di tesi è stato svolto all'interno dell'unità Ricerca e Sviluppo dell'azienda italiana Argotec e ha come obiettivo l'implementazione e l'integrazione di un framework di Concurrent Engineering (CE) in un contesto aziendale. Questo framework, denominato *Advanced Concepts Laboratory (ACLab)*, mira a migliorare l'efficienza e l'efficacia nella formulazione e nel design delle missioni spaziali. A differenza dell' approccio sequenziale tradizionale, che può portare a riprogettazioni tardive, opportunità mancate o design subottimali, il CE promuove il lavoro di squadra basandosi su sessioni di design in tempo reale, consentendo progressi simultanei in tutti gli aspetti della missione. Il CE migliora l'esplorazione degli spazi di trade-off, il processo decisionale e la valutazione simultanea di tutti i fattori rilevanti, portando come risultato progetti di valore, fattibili e coerenti, riducendo al contempo lo sforzo complessivo richiesto.

Questo lavoro affronta le sfide dell'implementazione del CE in un contesto aziendale, che includono la gestione delle relazioni con i clienti e i potenziali partner esterni, la gestione della limitata disponibilità di risorse dovuta al personale spesso impegnato in altri progetti di volo, la formazione del personale e l'integrazione degli aspetti tecnici con quelli programmatici. Il lavoro si è concentrato inzialmente sull'implementazione di tools a supporto del design di missione e sull'integrazione del tool COMET come supporto alla gestione dei dati e degli studi. Inoltre è stata sviluppata una metodologia che abbraccia molteplici aspetti, dalle relazioni con i clienti e pianificazione delle sessioni, all'esplorazione degli spazi di trade-off fino al point design. Il framework implementato introduce anche elementi innovativi, tra cui l'adozione di un approccio basato su SCRUM, il quale prioritizza le attività, migliora la pianificazione delle sessioni e identifica le aree critiche che richiedono più tempo e risorse, oltre all'integrazione di una pipeline RAG (Retrieval-Augmented Generation), uno strumento nel campo dei Large Language Models (LLM) per ottimizzare i processi di system engineering, in particolare per il recupero di informazioni.

La metodologia e i tools sono stati poi testati attraverso uno studio di Fase 0 di una missione CubeSat propulsa con vela solare per l'esplorazione di asteroidi vicini alla Terra e sono stati affinati in base ai feedback ricevuti. I risultati del caso studio dimostrano i vantaggi nel progettare una missione attraverso questo nuovo approccio, analizzando anche i problemi incontrati, tracciandone le cause e proponendo possibili soluzioni.

Acknowledgements

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A heartfelt thanks to my parents for always encouraging me to pursue my aspirations and supporting me every day, even from afar. It is thanks to you that my dream of working while looking beyond the Earth is increasingly becoming a reality. Thank you for believing in me and always pushing me to aim higher. Special thanks as well to my sister and the rest of my family for the love and constant support you show me.

Thank you to all the friends I met during these years in Turin, who have been with me from day one, sharing many great moments and helping me through the tough times. I also want to thank my long-time friends, who have always brought me happiness and ease. Your genuine affection and constant encouragement mean the world to me, and I'm deeply grateful for your unwavering support.

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Acronyms

ADCS Attitude Determination & Control System
AOGNC Attitude and Orbit, Guidance Navigation and Control
AU Astronomical Unit

BOL Begin Of Life

CDF Concurrent Design Facility
CE Concurrent Engineering
CER Cost Estimation Relationship
CoP Center of Pressure
CoM Center of Mass
COMET COncurrent Model-based Engineering Tool
ConOps Concept of Operations

DoE Domain of Expertise

ECSS European Cooperation for Space Standardization
EOL End Of Life
EPS Electrical Power System
ESA European Space Agency
ESTEC European Space Research and Technology Center

FOM Figure Of Merit
FSW Flight SoftWare

GNC Guidance Navigation and Control

HDRM Hold-Down and Release Mechanism

IDM Integrated Design Model

IME Integrated Model Environment

JPL Jet Propulsion Laboratory

LEO Low Earth Orbit
LLM Large Language Model
LSE Lead System Engineer

MiCRA Mission Concept and Requirements Assessment
MVP Minimum Viable Product

NASA National Aeronautics and Space Administration
NEA Near Earth Asteroid

OBC On Board Computer
OBDH On Board and Data Handling
OCDT Open Concurrent Design Tool

PCDU Power Conversion and Distribution Unit
PI Principal Investigator
PS Propulsion System

RAG Retrieval-Augmented Generation
RCS Reaction Control System
RDT&E Research, Development, Test and Evaluation
RMA Rapid Mission Architecture
RSS Root Sum of Square
RTD Research and Technological Development

s/c SpaceCraft
SL Study Lead
SMAD Space Mission Analysis and Design
SME Subject Matter Expert
SPL Study Progress Level
STM System Trade Model

TATER Tool for Architectural Tradespace Exploration and Refinement
TBD To Be Determined
TBC To Be Confirmed
TLC Telecommunication
TM Team Member
TT&C Tracking Telemetry and Command

Chapter 1

Introduction

1.1 Space Mission Phases

At the heart of every successful space mission lies a meticulously planned project cycle, characterized by distinct phases. Each phase plays a crucial role in guiding the project from conception to execution, with early stages laying the foundation for subsequent development and implementation. NASA (and similarly ESA) divides the life cycle into phases, starting from Phase 0 (or Pre-phase A) to Phase F, each separated by Key Decision Points (KDPs), as shown in Figure 1.1. These KDPs mark events where decision authorities assess the readiness of a program/project to advance to the next phase of the life cycle. Phase boundaries are delineated to provide natural points for "go" or "no-go" decisions [1]. Decomposing the project life cycle into phases organizes the entire process into more manageable pieces. This approach gives managers periodic insights into the project's progress, ensuring these updates align with both management and budgetary requirements.

The phases of the project life cycle are:

Program Pre-Formulation

- Pre-Phase A: concept studies

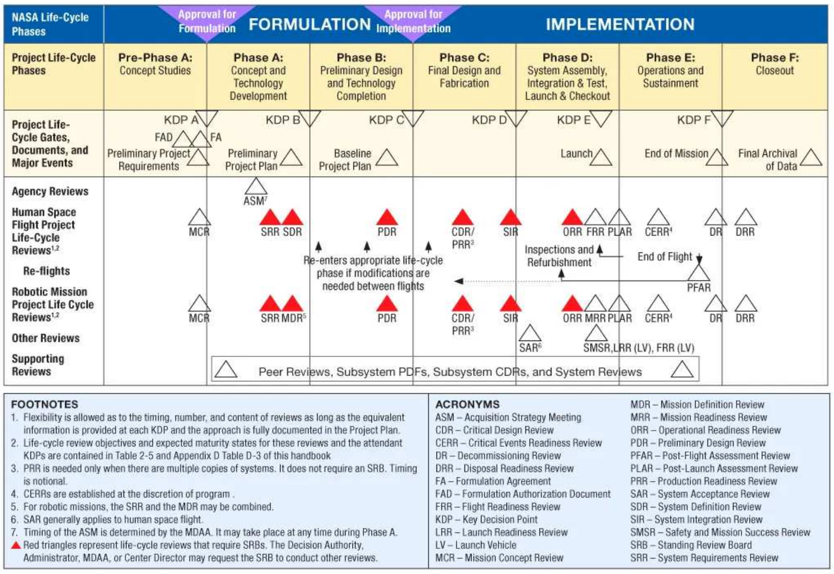
Program Formulation

- Phase A: concept and technology development
- Phase B: preliminary design and technology completion

Program Implementation

- Phase C: final design and fabrication

- Phase D: system assembly, integration and test, launch
- Phase E: operations and sustainment
- Phase F: closeout



FOOTNOTES

1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan.
2. Life-cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5 and Appendix D Table D-3 of this handbook
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of program .
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA. It may take place at any time during Phase A.

▲ Red triangles represent life-cycle reviews that require SRBs. The Decision Authority, Administrator, MDAA, or Center Director may request the SRB to conduct other reviews.

ACRONYMS

ASM – Acquisition Strategy Meeting
CDR – Critical Design Review
CERR – Critical Events Readiness Review
DR – Decommissioning Review
DRR – Disposal Readiness Review
FA – Formulation Agreement
FAD – Formulation Authorization Document
FRR – Flight Readiness Review
KDP – Key Decision Point
LRR – Launch Readiness Review
LV – Launch Vehicle
MCR – Mission Concept Review
MDR – Mission Definition Review
MRR – Mission Readiness Review
ORR – Operational Readiness Review
PDR – Preliminary Design Review
PFAR – Post-Flight Assessment Review
PLAR – Post-Launch Assessment Review
PRR – Production Readiness Review
SAR – System Acceptance Review
SDR – System Definition Review
SIR – System Integration Review
SMSR – Safety and Mission Success Review
SRB – Standing Review Board
SRR – System Requirements Review

FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E

Figure 1.1: NASA space flight project lifecycle
[1]

Pre-Phase A provides crucial insights into the mission's feasibility, guiding stakeholders in making informed decisions regarding resource allocation and risk management. Meanwhile, Phases A and B lay the groundwork for detailed design and implementation, fostering collaboration among interdisciplinary teams and ensuring that the mission's technical requirements are met with precision. The principal activities conducted during phases 0/A are:

- objectives definition and requirements analysis;
- feasibility assessment;
- preliminary risk identification;
- concept study;
- preliminary cost and schedule assessment.

The significance of the initial phases of a space project cannot be overstated, as they establish the overarching framework and direction for subsequent development efforts. Designing a space mission is challenging due to several factors: the vast and highly non-linear trade space, complex and interconnected analyses, and the difficulty in estimating concepts' values. Therefore, it is crucial to develop feasible, consistent, and robust designs in the initial phases; doing so helps anticipate potential issues and minimize the need for late redesigns caused by missed opportunities, suboptimal designs, or unconsidered factors.

1.2 Sequential vs Concurrent Engineering

As stated before, the early phases 0/A are highly significant as crucial decisions are made, and a baseline design is frozen. If conducted properly they allow for time and cost savings which are key factors in the successful implementation of a mission. Analyses conducted during these phases account for approximately 80% of the total cost and drive major decisions regarding system configuration, technology, and operations [2].

The traditional and classical design approach involves the individual and independent execution of tasks by each specialist, utilizing separate tools. Once the task is completed it is handed over to the next team member and design iterations occur through meetings held at intervals of several weeks. This approach employs a parametric and iterative framework that concludes upon the mathematical convergence of the design. While this approach offers advantages such as flexibility in work and resources, it also poses significant drawbacks: it greatly diminishes the potential for finding quick solutions because real-time monitoring of the design may not occur, necessitates multiple iterations to achieve convergence and fails to keep all specialists informed of the overall design progress.

The alternative that has emerged to the classical approach is provided by **Concurrent Engineering (CE)** which has been mainly adopted in the space sector for performing phase 0/A assessment studies. Concurrent engineering, also called simultaneous or collaborative engineering, is a work methodology emphasizing the parallelization of tasks. CE has been defined by Bandecchi in [3] as follows:

"Concurrent engineering is a systematic approach to integrated product development that emphasizes responsiveness to customer expectations. It embodies team values of cooperation, trust, and sharing in such a manner that decision-making is by consensus, involving all perspectives simultaneously from the beginning of the product life cycle."

This innovative approach is based on controlled and shared data and on the management of decision making during early design phases. A concurrent approach entails conducting collaborative design sessions, where a carefully selected team advances the designs simultaneously using interconnected design tools and paying close attention to dependencies among various elements. A CE approach can be described as a think tank where rapid iterations lead to more rapid convergence. CE is well-suited for space engineering due to the multitude of requirements that push the design in different directions. Implementing this approach has demonstrated that the primary advantage lies in cost and time savings, additionally it allows for the quicker identification of potential problems and failures in the design process through improved communication methods. This leads to a reduction in design changes in later stages, risk reduction, and increased productivity. Conversely, with a sequential approach, design errors are only identified during reviews, resulting in more work being lost if it is necessary to backtrack in the design process. The advantages of CE are because the whole team, composed of experts from different fields like engineering, production, marketing, etc., is involved from the beginning of the study. The differences between the sequential and concurrent approach are outlined in Figure 1.2.

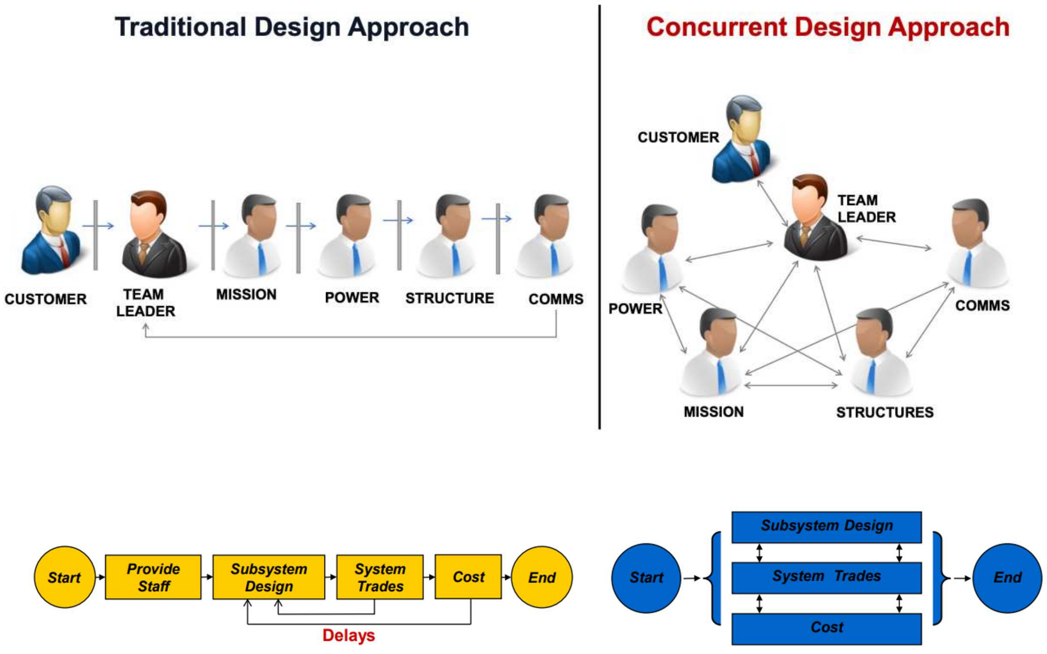


Figure 1.2: Traditional and Concurrent design approaches
[2] [4]

Figure 1.3 compares the development time with the number of design changes and clearly shows how the concurrent approach identifies and resolves issues earlier. CE experiences design changes in the early stages of development, while the sequential approach undergoes more changes at a later stage of development. If the number of design changes increases also the time for starting the production increases.

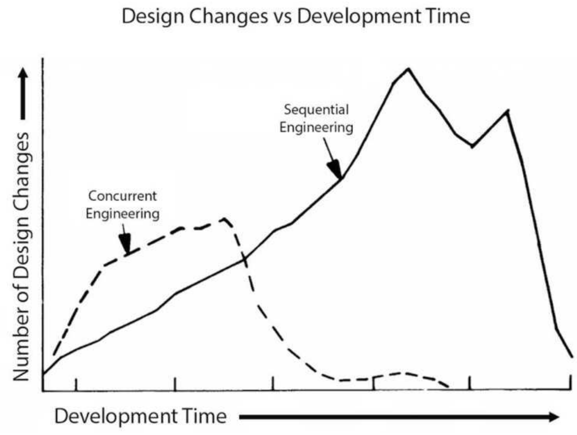


Figure 1.3: Design changes: Concurrent vs Sequential engineering [5]

Figure 1.4, instead, shows how only in the early stages of development the concurrent approach costs a little more than the sequential one while it leads to much higher savings in the later stages. Month 0 corresponds to the product launch time in the market.

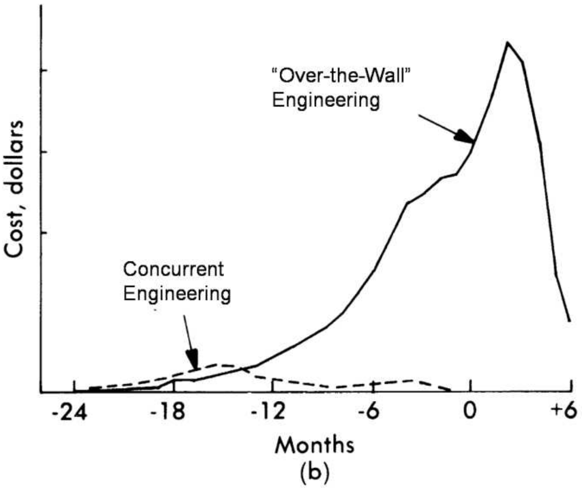


Figure 1.4: Cost savings: Concurrent vs Sequential engineering [5]

1.3 Aim of the Thesis Work

The objective of this thesis is to detail the implementation of a CE framework, named *Advanced Concepts Laboratory* (*ACLab*), within Argotec's corporate environment to enhance the efficiency and effectiveness of mission formulation and design. Introducing CE in a corporate setting is both innovative and challenging. The primary challenges include:

- managing client relationships and adapting to fast-changing needs and goals;
- engaging potential external partners in the design process;
- addressing the limited availability of resources, as personnel are often busy on flight missions;
- training staff, particularly those without a systems engineering background;
- integrating programmatic aspects with technical ones.

The "New Space" paradigm and the context of commercial space companies require valuable mission design within a short time and limited resources. Technological advancements and increased market competitiveness necessitate that companies adopt methodologies and frameworks suited to these conditions. Additionally, while missions' feasibility studies were previously conducted primarily by space agencies, research centers, and universities, in recent years private companies are increasingly taking part in this process. The New Space environment also emphasizes the need for quicker analyses and estimations, enabling companies to respond more efficiently to fast-evolving project demands and market needs.

In light of these changes, implementing a CE framework at Argotec becomes essential and aligns with the company's goals of conducting faster and more efficient feasibility studies, being innovative and competitive in the market. Moreover, previous studies conducted within the company have demonstrated the benefits of adopting Agile approaches to optimize resource allocation and mitigate the issue of limited resources.

Considering what has been discussed so far, the objectives set for the development of this thesis are:

- create a first Minimum Viable Product (MVP) of the *ACLab*;
- implement a flexible methodology tailored to a corporate environment;
- develop and integrate mission design tools to support the design;

- integrate in the CE framework a task prioritization approach inspired by Agile methodology like SCRUM;
- integrate a LLM tool to support information retrieval.

Regarding the final objective, another thesis has been developed in parallel at Argotec, focusing on the integration of an AI-based tool, specifically a LLM tool, within the CE framework. The LLM tool leverages an architecture called Retrieval-Augmented Generation (RAG) to enhance information retrieval, a critical but highly time-consuming task during trade space exploration and early phase design.

This thesis is organized into six chapters. Chapter 1 introduces the problem, followed by an overview of the state of the art among the major CE players in Chapter 2. Chapter 3 focuses on the implementation of the *ACLab*, detailing the development of its tools and methodology. Chapter 4 presents the case study used to validate the framework, while Chapter 5 provides a critical analysis of the results obtained. The thesis concludes with a summary of findings and recommendations for *ACLab* future improvements in Chapter 6.

Chapter 2

State of the Art

The concept of concurrent engineering made its debut in the space sector during the early 1990s at California's Jet Propulsion Laboratory (JPL). It was introduced as a direct response to NASA's imperative to produce mission designs that were both rapid and efficient, aligning with the agency's ethos of "Faster, Better, Cheaper". Over the years, various players, especially in the USA and Europe, began adopting a CE approach during the design process. Figure 2.1 shows the main CE centers in Europe, including those in agencies, industries, and universities.

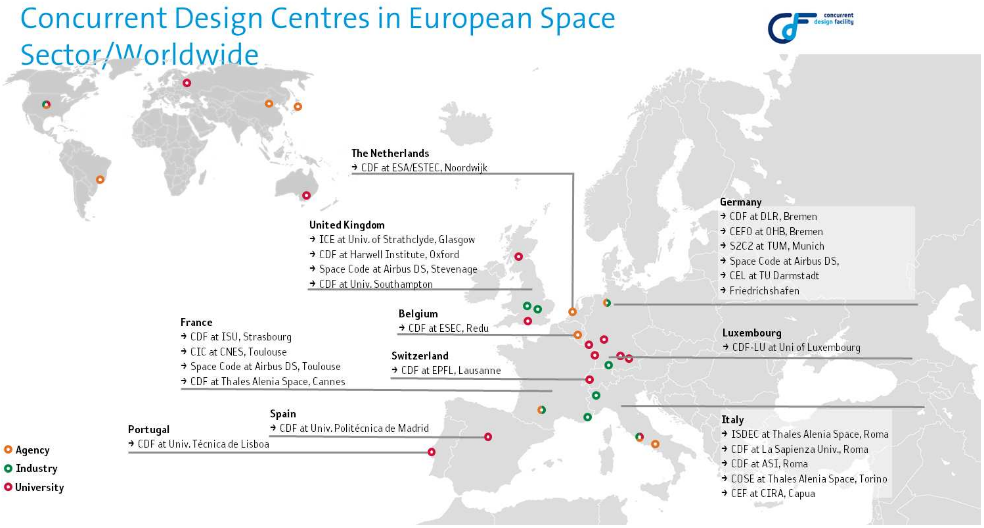


Figure 2.1: Concurrent Engineering facilities in Europe [6]

This chapter illustrates the main features of what, according to the author opinion, are the major players in adopting CE and enabling its spread worldwide: JPL and

ESA. Additionally, it provides an overview of the Agile/Scrum methodology, its integration with CE, and a brief look at the current state of the use of AI-powered virtual assistants to aid engineers during spacecraft mission design.

2.1 Concurrent Engineering at NASA JPL

At JPL early stage concept development is performed in a specially formulated environment called **Innovation Foundry** created in 2011 to respond to the space sector's evolving challenges. From an organizational perspective, Innovation Foundry is situated between Program Offices which identifies needs for new missions and Line Organizations which provide staff and tools to formulate them.
The framework for the activities of JPL's Innovation Foundry is based on the Concept Maturity Level (CML) scale, explained in detail in 2.1.1. This scale was created in 2009 and is used for mission formulation concepts and can be considered as an analogue of the Technology Readiness Level (TRL) scale (Figure 2.2) used for the assessment of technology maturation.

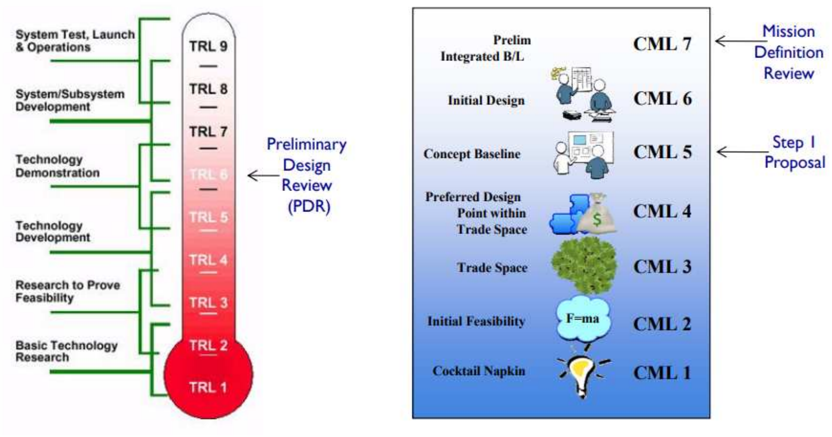


Figure 2.2: TRL and CML scale
[7]

The Innovation Foundry is divided into three main areas as described in [8]:

1. *Concept Shop* (from CML 1 to 4): assesses feasibility and matures concepts to a level where they can be proposed
2. *Proposal Shop* (CML 5): puts formal proposal together ready for implementation.
3. *Strategy Shop*: advises JPL's senior leadership on long-term strategy options.

Concept Shop consists of two design environments: **A-Team** and **Team X**. The activities of the A-team range from CML 1 to CML 3 and consist in ideation, initial feasibility studies and trade space exploration. A-Team studies are followed by Team X ones at about CML 4 which corresponds to a point design. Although Team X follows the work of the A-Team from a conceptual standpoint, the former was actually founded earlier, in 1995, followed by the latter only in 2008.

2.1.1 Concept Maturity Level

CMLs are at the base of a method implemented at JPL since 2008 aiming at measuring and communicating the maturity of a space concept. Teams involved in the development and exploration of mission concepts use this method before the concept enters the Phase A/B. Many advantages connected to the use of a method based on CML exist [9]:

- determine how much work is placed into a mission concept;
- explicitly know where the advancement of the concept is located in the project's life-cycle;
- determine which concepts had the same level of maturity in order to be compared;
- know how much and what achievements are required to proceed to a subsequent level.

Figure 2.3 shows the evolution of the CMLs and the main activity at each level.

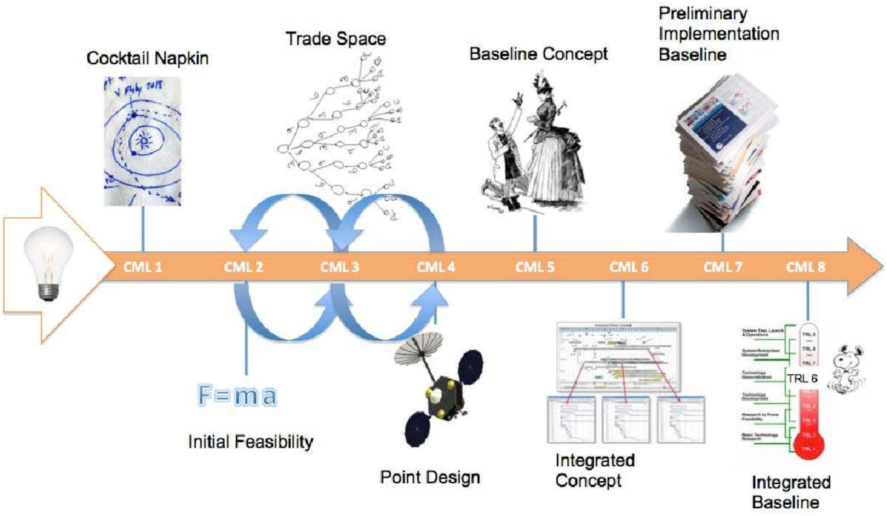


Figure 2.3: Concept Maturity Levels evolution
[9]

JPL's definition of CMLs is reported in Table 2.1.

CML	Name	Definition
1	Cocktail Napkin	A complete idea. The level needed for an articulation of: the merit of the goals of the proposed project; and the technical, management, and cost feasibility of the proposed project implementation.
2	Initial Feasibility	The level needed for an initial assessment of feasibility from a customer desirability, technical, and programmatic viewpoint. Basic calculations have been performed that, to first order, establish the viability of the concept.
3	Trade Space	Exploration has been done around the project goals and objectives, the engineering architecture, and the implementation modes.
4	Point Design	A specific design and cost that meets the desired goals and objectives has been selected within the trade space and defined (scientifically, technically, and programmatically) down to the level of major subsystems with acceptable margins and reserves.
5	Baseline Concept	The level needed for competed projects to hold their Baseline Concept Review (BCR), or for assigned projects to hold their Mission Concept Review (MCR).
6	Integrated Concept	The level needed for competed projects to complete their NASA Step 2 Concept Study Report (CSR), or for assigned projects to hold their System Requirements Review (SRR).
7	Preliminary Implementation Baseline	The level needed for competed projects to hold their Preliminary Mission System Review (PMSR), or for assigned projects to hold their Mission Definition Review (MDR).
8	Project Baseline	The level needed for projects to hold their Preliminary Design Review (PDR).

Table 2.1: CML definitions
[10]

Here a more detail description of CML 1-5 is given, from [9], as they are the levels directly involved in Phase 0/A studies and connected with the application of CE.

- CML 1: the question and context of the study (e.g., scientific question) and a sketch of the mission concept have been articulated. The idea of what make the concept meaningful and unique has been captured.
- CML 2: the idea is expanded and a feasibility assessment is done from a

science, technical and programmatic point of view. Lower level objectives, performance parameters are specified and basic calculations are performed.

- CML 3: the trade space is explored around the reference point design. Different mission architectures and system design are identified and compared in terms of science return, performance, cost and risk.
- CML 4: a preferred concept is selected from the trade space and further defined down to the major subsystems.
- CML 5: implementation approach has been defined including contracting mode, integration and test approach, cost and schedule. This level represents the level needed to write a NASA step 1 proposal (for competed projects) or hold a Mission Concept Review (for assigned projects).

2.1.2 A-Team

The Architecture team applies CE throughout the concept ideation and trade exploration at CML from 1 to 3 as shown in Figure 2.4. The A-Team matures a concept from a “Cocktail Napkin” level to a defined mission concept; its process is designed to be rapid and efficient lasting approximately 6 weeks and costing the equivalence of 1/1.5 work-months of a full-time employee [11]. The study begins with a detailed plan with the client and is organized in sessions that can last half or whole day.

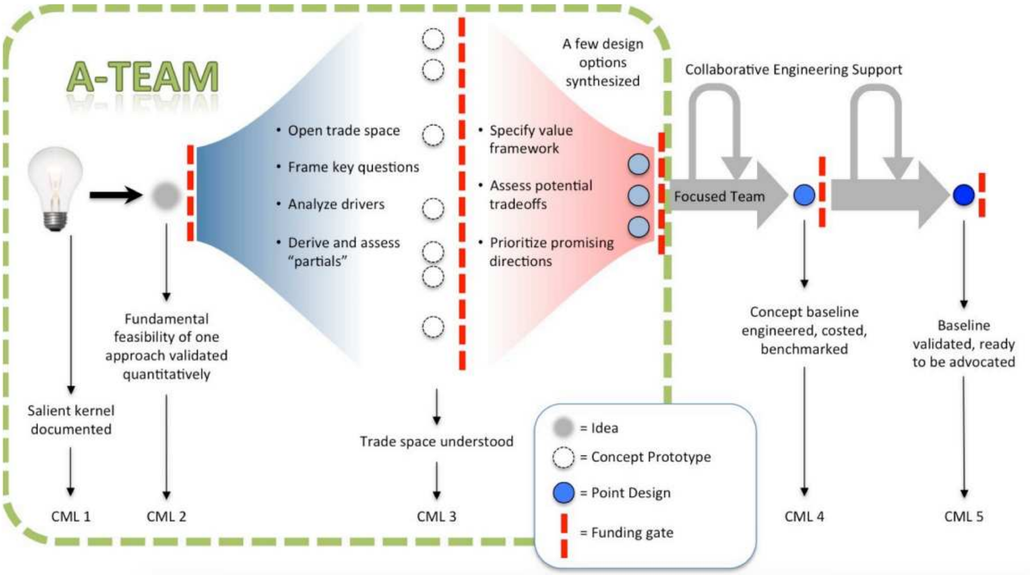


Figure 2.4: CML in A-Team process
[11]

A-Team has become a reliable and configurable process where people, ideas and concepts come together to foster innovation. In about 2 years from the establishment of the team over 50 A-Team studies have been conducted with a peak of 1 study per week during the summer of 2013.

Process

An A-Team study starts with an idea or question that can come from different sources including Principal Investigator, Program Office, Directorate, etc. within JPL/NASA or externally in some cases. The initial inquiry can vary and lead to different types of investigations, whether scientific, technological, or programmatic in nature. After the idea has been proposed and sponsored by one of the programs of JPL or NASA, the planning begins through a meeting between the client and the JPL Innovation Foundry. During this meeting, the context of the study, goals, objectives, staff, and required timelines are defined. At this point JPL Innovation Foundry Office assigns to the A-Team a *Study Lead (SL)*, who is the person that will guide the working sessions. The SL, with the client lead, plans all the studies, including participants, schedule, budget, methodology description, tools and facilities that will be used and how results will be handled. When the study plan is reviewed and approved, study pre-work begins and sessions occur in the next few weeks. Sometimes, time for research on previous studies or papers and some basic analyses are required before the team meets for the first time. The SL is also part of a small team called “Nucleus” which manages the sessions and assigns tasks. Once the sessions are completed, the study Nucleus team generates the final report within 1-3 weeks [11].

A-Team’s study methods are structured according to the CML scale, with each level utilizing distinct environments, conversation management techniques, staffing strategies, and analysis tools to achieve efficient and valuable outcomes. At CML 1, studies concentrate on generation of ideas; sessions at this level generate numerous ideas from a single question or topic, which are then organized and potentially ranked based on their merit. At CML 2 studies focus on initial feasibility assessment, employing basic information such as science objectives, payload description, mission details, and high-level subsystem specifications. Sessions at this level quantitatively analyze ideas for technical and programmatic feasibility using advanced tools. At CML 3 studies delve into exploring the trade space of options, evaluating factors like science return, cost, and risk.

The initial feasibility is based on an assessment across multiple dimensions. The selectability of a concept come form the union of three aspects (Figure 2.5):

- Customer desirability
- Technical feasibility
- Economic viability

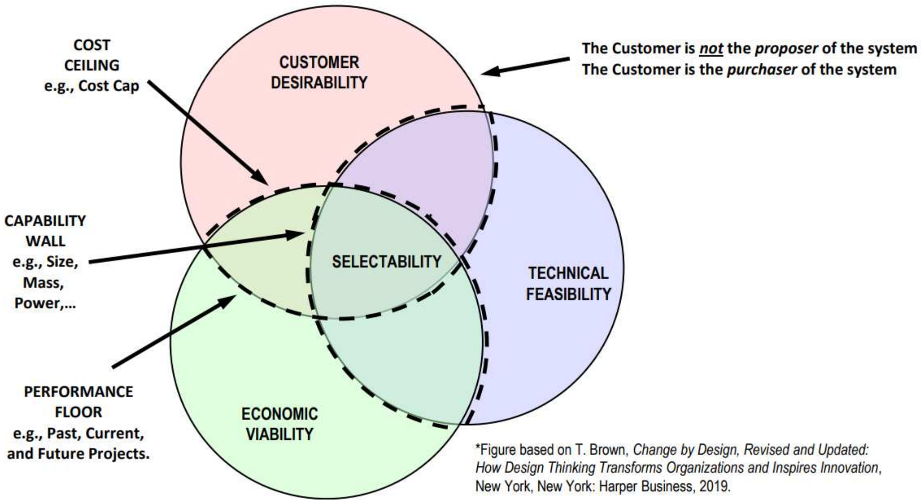


*Figure based on T. Brown, *Change by Design, Revised and Updated: How Design Thinking Transforms Organizations and Inspires Innovation*, New York, New York: Harper Business, 2019.

Figure 2.5: Concept selectability criteria
[10]

Roles

The A-Team follows a simple rule: everyone present participates; for this reason the team size is deliberately kept small, between 8 and 12 members. As described in [11], for each A-Team study there is a “Nucleus” of 3-6 members that lead methods design, study implementation, architectural guidance and technical work. The client and any additional Subject Matter Experts (SMEs) required for the study are also considered part of the team. A SME is a specialist with deep knowledge in a specific area who provide technical guidance and support throughout the design process. However, while the Nucleus members attend every session, the participation of the SMEs, depends on the specific goals of each session. In addition to the Nucleus and SMEs, there is a Core Group, which helps develop the team’s processes, methods, and tools to ensure efficient studies.

The **Nucleus** includes six roles filled by 3-6 people along an A-Frame with the two legs based on methods and technical expertise as shown in Figure 2.6.

Methods roles, who hold the control of the study process and methods, are: Facilitator, Study Lead and Assistant Study Lead.

1. *Facilitator*: is responsible for understanding the client's objectives and designing sessions to achieve study goals. They set session agendas, methods, and guide conversations, using facilitation and team-building techniques. The Facilitator must have broad expertise and lead conversations on complex topics. They also contribute to high-level planning, determining the number and type of sessions needed to meet objectives.

2. *Study Lead*: manages the study, working with the client to set goals, staffing, tasks, budget, and schedule. They conduct sessions, oversee analyses, and ensure the final product is delivered on time and within budget. This role requires proactive planning, formulation experience, and strong communication and management skills, coordinating the team to deliver study results.

3. *Assistant Study Lead (ASL)*: manages daily information flow, organizing ideas and work from sessions and tasks, and distributing it to the study team. They maintain study wikis, implement tools, and produce intermediate products like session's reports. This role requires initiative and strong organizational skills, assisting the Facilitator with agendas and the Study Lead in generating the final report.

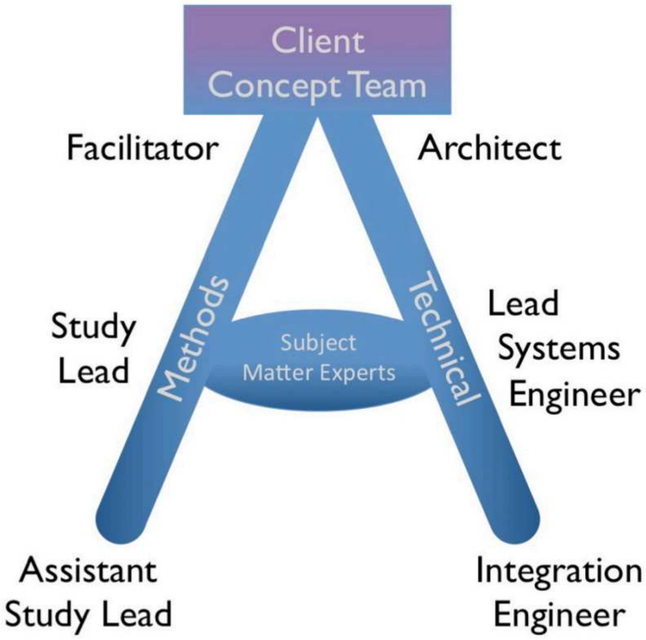


Figure 2.6: A-Team Nucleus roles
[11]

Technical roles manage the technical content of the study and are: the Architect, the Lead System Engineer (LSE) and the Integration Engineer. Each role is responsible for a different layer of assessing feasibility and exploring the trade space.

1. *Architect*: grasps the client's objectives and makes architectural decisions throughout the study. They define the study's scope, boundaries and trade space branches, determining which concept seeds or prototypes receive priority. With access to a network of subject matter experts, they guide the study toward a mission architecture aligned with the client's needs. The Architect contributes to session planning, provides guidance during sessions, and reviews the final report.

2. *Lead System Engineer*: ensures the technical validity of spacecraft and instrumentation approaches in the study. They make engineering decisions shaping mission, spacecraft and payload design, considering subsystems in detail to provide information that guides the Architect's decisions. Leveraging their expertise and contacts, they select tools and analyses to understand spacecraft and instrument drivers. The LSE collaborates with the study lead in planning and is responsible for the final report's technical content.

3. *Integration Engineer*: manages the A-Team study's day-to-day technical aspects, implementing technical-based tools. They collect analyses from team members, collaborating with the LSE to identify study drivers. Additionally, they assist in generating configurations for concept prototypes and organize technical data for comparisons. The Integration Engineer ensures consistency in assumptions and data throughout the study, supporting fundamental decisions and contributing to all phases of planning and product development.

In some smaller studies, Nucleus members may take on multiple roles, such as Assistant Study Lead also serving as Integration Engineer, Study Lead as Facilitator, or combining the roles of Lead System Engineer and Architect.

In addition to the Nucleus team, **Subject Matter Experts** play a crucial role in every A-Team study in areas such as science, instruments, mission design, operations, spacecraft subsystems, technology, and programmatics. While some SMEs may contribute to multiple studies, new SMEs are often introduced for each study. Participation in A-Team studies doesn't require specific training, thus allowing for a wide pool of potential candidates from JPL, academia, and industry. The inclusion of appropriately chosen SMEs can significantly streamline analysis tasks, leveraging their expertise, flight project experience, and specialized tools. SMEs offer invaluable insights to Principal Investigators (PIs) and clients when assessing feasibility and exploring options, within a managed environment that encourages innovation. Additionally, SMEs bring their own networks and best practices, enhancing the quality of early formulation work and fostering knowledge exchange among study participants across the Laboratory.

Finally, the **A-Team Core group** comprises 12 members tasked with refining the A-Team process, methods, tools, and products. Selected for 1-2 year rotational positions, Core A-Team members possess expertise across various disciplines crucial for formulation activities. These experts, already integrated into JPL's knowledge network, are dedicated to advancing formulation and innovation within the lab. While A-Team studies draw members from this core group, not all members participate in every study. In cases where core team members with specific expertise are unavailable, they assist in finding suitable replacements. The Core A-Team represents diverse disciplines including facilitation, study leadership, tools and infrastructure, flight systems, mission architecture, instrumentation, technology, and cost management. Core A-Team members have access to plans and products from all A-Team studies, enhancing study design and serving as a repository of best practices. They review client feedback to improve study performance and are expected to lead multiple A-Team studies during their tenure. Pilot studies involving the Core A-Team are conducted annually to refine skills, methods, and gain experience. Additionally, core members lead tools development activities and contribute to other formulation work, offering feedback and strategic direction for ideas entering the Foundry.

Tools

The A-Team developed new tools, described in [11], which are currently focused on four key areas: knowledge capture and management; science traceability; mission, flight system and payload design; and cost, complexity and risk assessment. Each tool is designed based on stakeholder requirements and intended for use during sessions to facilitate conversation.

- *Knowledge Capture and Management*: these tools involves capturing and organizing information generated during A-Team sessions. Various techniques are used, such as mind mapping tools and electronic whiteboards, and information is shared in a wiki-based environment to ensure it is well organized and distributed.

- *Science Traceability*: these tools facilitate the early examination of mission requirements and the categorization of science concepts based on their potential impact and value. This process helps identify key science objectives and their influence on mission architecture.

- *Mission, Flight System, and Payload Design*: these tools are employed at different CMLs to aid in mission design and subsystem selection. They range from basic mass equipment lists to parametric design relationships, leveraging JPL's expertise in trajectory optimization and navigation.

- *Cost, Complexity, and Risk Assessment*: the various tools have been developed and utilized to estimate mission costs and assess complexity. These tools help in understanding mission concept complexity and identifying potential cost-saving measures.

Facility

The A-Team infrastructure is composed of three main dedicated spaces for its studies: Left Field, Out There and PI Lounge (Figure 2.7). Left field is the main design room with floor-to-ceiling and wall-to-wall whiteboards on one wall and multiple rollaway whiteboards, tables and desks. The room is configured for each study depending on the type, session focus and number of people expected to attend. The room also contains projectors, cameras to take images and provide movies about the progress of the study. Out There is a patio adjacent to the Left Field that hosts an outdoor location for side meetings. The last space is the PI Lounge equipped with a large seating area for visiting PIs or external study participants [11].

Figure 2.7: From left to right: Left Field, Out There, PI Lounge [11]

A-Team precursors

The creation of the tools currently used within the A-Team stems from previously developed approaches and tools; a high-level description of these is provided below.

In 2007 JPL created the **Rapid Mission Architecture (RMA)** a team-based approach precursor of the A-Team. The purpose of the team was to approach the generation of new mission architectures, explore trade space options with a novel collaborative approach. As described in [12] the RMA integrated a small team of typically 6-10 people to explore a wide-ranging trade space of mission architectures driven by mission objectives. The advantage of RMA is the possibility to identify innovative and unforeseen paths in the trade space in order to avoid tending to drive to an architecture prematurely. This approach helps avoid getting constrained early on and spending significant study resources on a concept that does not fit the initial objectives and constraints. Historical approaches often suffer from inefficiencies due to their use of larger teams or much more detailed analyses that are not necessary in the early stage of trade space exploration. Participants in the RMA team have a “system-level” mindset and include a mix of roles and responsibilities. The process operates on a rapid time scale, usually from 1 to 3 weeks, depending on the scope of the study. Studies include 4 to 8 concurrent working sessions of 2 to 3 hours each. The general RMA process is shown in Figure 2.8. Multiple mission architectures are assessed simultaneously throughout the process to enhance efficiency; this approach contrasts with a method that sequentially evaluates individual point designs, which tends to be less efficient and consistent. Additionally, incorporating feedback loops in the process allows for the exploration of new ideas at different stages. Intermediate results are recorded both in real-time during sessions and outside of them, evolving between stages as the study progresses. The impact on key metrics, such as scientific value, cost, and risk, is continually assessed throughout the process, guiding the development and refinement of the architectures being studied.

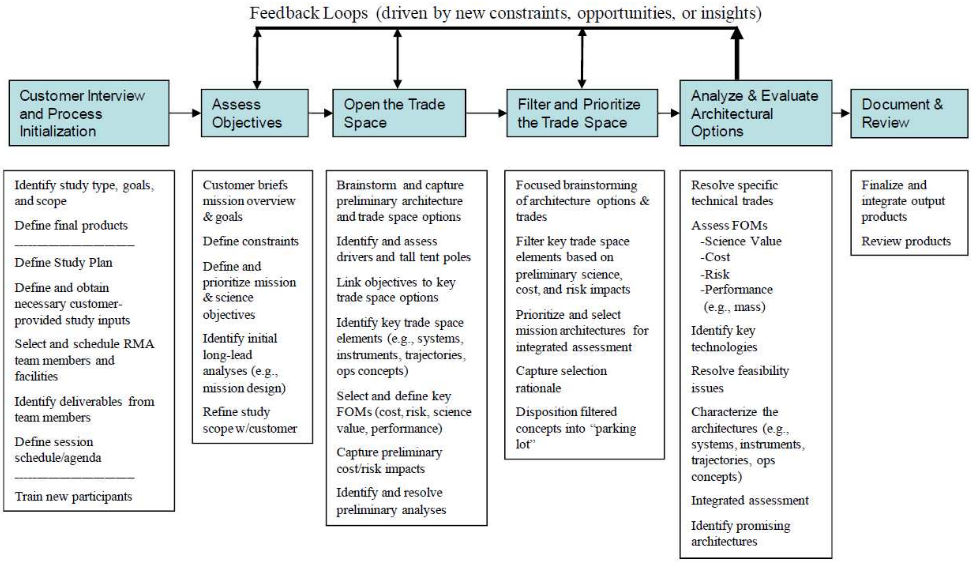


Figure 2.8: RMA process
[12]

The study begins with identifying the specific needs of the customer, which includes study objectives, product schedules, and costs. Once the study planning is completed, group sessions begin with the goal of assessing and prioritizing mission objectives and open the trade space. During these sessions, the team identifies and prioritizes a high-level list of objectives. Next, the trade space is decomposed into key trade dimensions (trajectories, flight systems, instruments, etc.), where different possibilities for each dimension are considered and collected into an RMA Key Trade Matrix. The next stage involves prioritizing mission concepts derived from the major trade dimensions using selected figures of merit.

The science value of missions is estimated through group assessments employing the JPL RMA Science Value Matrix approach. Top-level science objectives are provided and grouped by the customer science team representatives and iterated with the RMA team if necessary. An example of an RMA Science Value Matrix can be found in [12]. Mission costs are estimated at the mission element and system level using parametric cost models, previous study data, and relevant flight system analogies. Mission risks (operational risks affecting the ability to accomplish mission objectives) and implementation risks (development risks affecting the consumption of cost, schedule, and performance resources) are identified and assessed by team members using NASA 5x5 risk matrices (likelihood versus severity). These risks are rated and aggregated for the various mission architectures. Critical risks are mitigated by modifying the architectures upon identification during the assessment process.

Key metrics, including science value, total mission cost, and risk, are evaluated consistently across the set of architectures and compared in an integrated view. In the final part of the RMA process, the best candidate architectures for further study are identified in conjunction with the customer/science lead representative. This concurrent interaction ensures that the integrated results appropriately balance science benefits, cost-effectiveness, and acceptable risk. Key results and preliminary products are then compiled into a final report or presentation. These are high-level results, providing mass estimates at the flight system level rather than the more precise subsystem or component level, typical of a detailed point design study.

To enhance the RMA process, the **System Trades Model (STM)** [13] was incorporated to improve the integration of analyses and facilitate faster, more effective exploration of the trade space, also addressing the fact that engineers often rely on their experiences and intuition to identify potential preliminary concepts. A trade space modeling tool can organize and track various architecture, component, and system options; it also has the flexibility to incorporate trades that were not initially considered and to reassess and modify the design.

The development of STM began in 2005 and has undergone several iterations. The primary capability of STM lies in its proficiency to store designs at the component level and utilize this data to evaluate the effects of trade-offs across the system, subsystem, and component levels. Its main strength is its foundational architecture, which efficiently organizes subsystem analyses, records mass equipment lists at the component level, manages power mode variations, and tracks costs based on the Work Breakdown Structure. Additionally, it comprehends the interconnections between these mission parameters. The STM is an Excel-based tool that provides a straightforward method for accessing each specific subsystem; further details on its composition is described in [13].

Over the past ten years, the Innovation Foundry has developed a new software environment called the Foundry Furnace. This web-based platform includes study management tools, a hardware data catalog, a database of common entity and property definitions, and a concurrent engineering design environment known as the Integrated Modeling Environment (IME). A more detailed description of the Foundry Furnace environment will be given in section 2.1.3. One of the tools integrated within the IME is the **Tool for Architecture Tradespace Exploration and Refinement (TATER)**, developed around 2019 and continuously refined. As described in [14], TATER is an analysis suite designed for rapid design, feasibility assessment, and trade space exploration from the lowest concept maturity levels. This tool can be used by anyone in the JPL formulation community but it is primarily designed for the A-Team. TATER encompasses analyses for flight system design, trajectory visualization, science value and risk assessment, and low-CML costing. It uses physics-based and regression-based analyses to generate self-consistent subsystem-level designs with minimal inputs, dynamically adjusting and reconverging as more details are added. TATER's primary output is a flight element-level mass, used for early formulation cost models.

TATER implements a hierarchical structure within the Integrated Modeling Environment (IME), consisting of data blocks and analysis blocks. Data blocks hold information and can contain other data or analysis blocks. Analysis blocks, containing Python or spreadsheet-based models, perform calculations using inputs from users or linked parameters. Streamlining TATER aimed to reduce the time required to complete a baseline design. By consolidating models and optimizing logic, the engineering team reduced the number of common user inputs by 32% without compromising accuracy. The latest version of TATER consolidates all summary information (mass, power, system modes, cost, and notes) into a single model that can display multiple tables. This centralization allows engineers to rapidly evaluate and present concepts, avoiding information overload and improving communication with the concept team. The summary table enhances modeling efficiency, enabling users to quickly check designs as modeling progresses. A more detailed description of how TATER is implemented can be found in [14] and [15].

2.1.3 Team X

Established in 1995 during NASA's "Faster, Better, Cheaper" era, Team-X was created to rapidly design space missions for principal investigator-led competitive proposals. Its success and longevity stem from its unique business model, tailored to JPL's specific needs. Initially focused on planetary missions, Team-X has expanded its services to include Earth science, astrophysics, heliophysics, human exploration, operations missions, and space technology development. Team-X excels in delivering value to clients through its rapid and cost-effective approach. It has extended its value by forming teams to develop Instrument (the Instrument Team) and SmallSat Concepts (Team Xc), and by enhancing its review process and pre-design architecting capabilities. Its success is further attributed to its infrastructure, including skilled personnel, advanced tools and robust IT infrastructure. In March 2020, Team-X marked its 25th anniversary as the longest-standing CE design team for space mission concept formulation. From conducting 20 studies in its first year to 77 in its 25th year, it has completed over 1500 studies [16].

Methods

The team possesses a predefined set of standard products, although custom products can be generated upon request to meet specific study requirements. Prior to the study sessions, non-concurrent pre-work is initiated to lay the groundwork and ensure efficiency during the sessions. The study sessions typically span three hours each, with the number and schedule tailored to the nature of the study and the products needed. Following the sessions, post-study activities ensue, during which Systems Engineers (SEs) and the SL collaborate to finalize and complete the study report [4].

Team X operates within the methodology based on the CML scale at levels CML 4 and 5, characterized by a subsystem point design starting from a predefined concept. Prior to the beginning of the main design sessions, any subsystems requiring preliminary study are identified. At the conclusion of CML4, the typical deliverables presented to the client include: Master Equipment List, Power Equipment List, power modes, orbit/trajectory design, high-level mission cost range, science/mission requirements and traceability, schedule or project timeline, link budget, End-to-End Information System design, identification of ground stations, assessment of software complexity level, risk analysis, identification of heritage missions and/or components, and structural design. In CML 5 an independent design review is planned to be conducted with the client.

Roles

One of the strengths of Team-X and of the CE in general is having a team working together to solve a problem. Team X comprises approximately 20 regular “chairs”, each led by a designated lead member supported by at least two backups; these chairs represent the major subsystems of the spacecraft. Notably, these individuals often juggle responsibilities on ongoing flight projects alongside their involvement in Team X activities. As necessary, additional experts are incorporated into the team to provide specialized knowledge and support, ensuring comprehensive coverage of all aspects of the spacecraft design process [4].

Tools

Since its establishment, the modeling tool infrastructure has primarily relied on a collection of older Excel workbooks, which have been interconnected using an evolving code base. The content within these workbooks has evolved over time through the efforts of various line organizations at JPL, each taking ownership and responsibility for their maintenance. These workbooks encompass a range of functionalities, including hardware databases, analysis tools, and institutional cost models, all developed independently within the Excel environment [16]. Due to the increasing difficulty in maintenance and management of these worksheets, in 2011, the Innovation Foundry created an entirely web-based software environment named **the Foundry Furnace**, specifically designed for spacecraft mission formulation. This Furnace provides a range of tools encompassing technical and programmatic aspects as shown in Figure 2.9 and as fully described in [17].

It includes the Study Management System, which is instrumental in organizing and supervising the more than 100 studies carried out annually by the Innovation Foundry. Additionally, there is the Mission and Cost Database (MCDB), utilized for storing data related to both past and proposed missions, along with the Domain Model Registry (DMR), where analysis models are housed. Furthermore, the Furnace incorporates the Integrated Modeling Environment (IME) for conducting CE design studies, the Hardware Catalog (HWC) containing a database of spacecraft hardware items, and the Common Resources Database (CRDB), which serves as a repository facilitating communication among all components of the Furnace.

Talking in particular about the IME, it is a system utilized by engineers for constructing, analyzing, and building spacecraft technical designs. It offers a flexible interface accessible via web browsers, allowing subsystem chairs within a study to collaborate seamlessly across different computer systems. IME encompasses both the data constituting a spacecraft design, such as mass and power, and the analysis models crucial for sizing the system and ensuring it meets mission requirements. IME's strength lies in its ability to link values across workspaces dynamically through point-to-point and query-based links, enabling flexible and adaptive design evolution. Behind IME there is a model execution engine that efficiently converges the spacecraft design, ensuring consistency and providing up-to-date information to all stakeholders during CE studies [17].

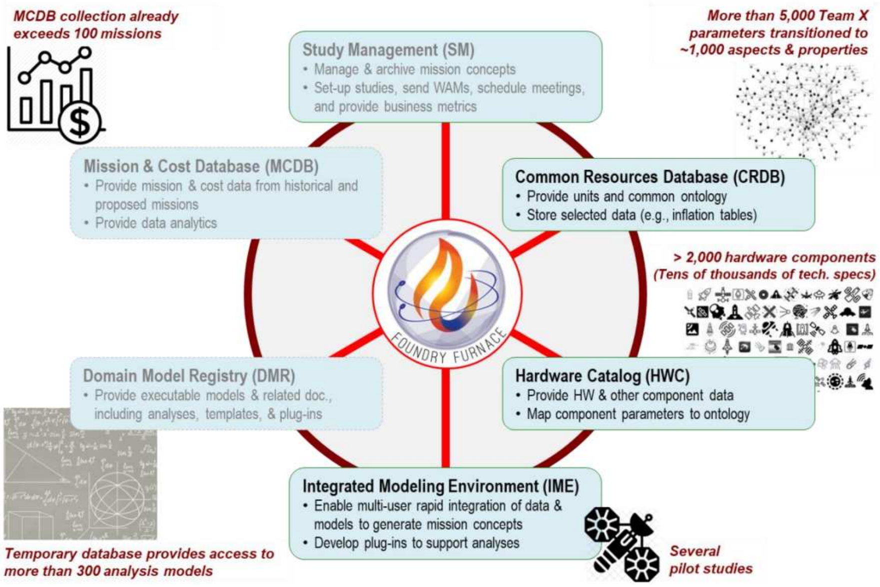


Figure 2.9: Foundry Furnace tools architecture
[16]

The Hardware Catalog is a web-based database designed to store data for specific spacecraft hardware items. It includes both common parameters like mass and power, as well as more specific parameters tailored to individual items such as specific impulse for thrusters or maximum torque for reaction wheels. Engineers can access the Hardware Catalog within IME using a plug-in called the "hardware picker", which interfaces with the catalog in real-time during study sessions. The hardware picker, residing on each data block, allows engineers to specify components to search for in the catalog, displaying a list of relevant hardware items in the IME. Engineers can then select items from this list to automatically populate the data block with relevant parameters, streamlining spacecraft design in accordance with mission requirements [17].

Facility

The Foundry presents also an IT infrastructure that integrates parameters across numerous design and analysis models, requiring robust facilities for data management and training. Special-purpose theaters, equipped with networked engineering workstations and display screens, facilitate comprehensive discussions, multi-specialist sidebars, and simultaneous individual work. In 2009, the Foundry significantly renovated and upgraded its Team X facilities, resulting in the establishment of two fully capable study theaters, as shown in Figure 2.10.

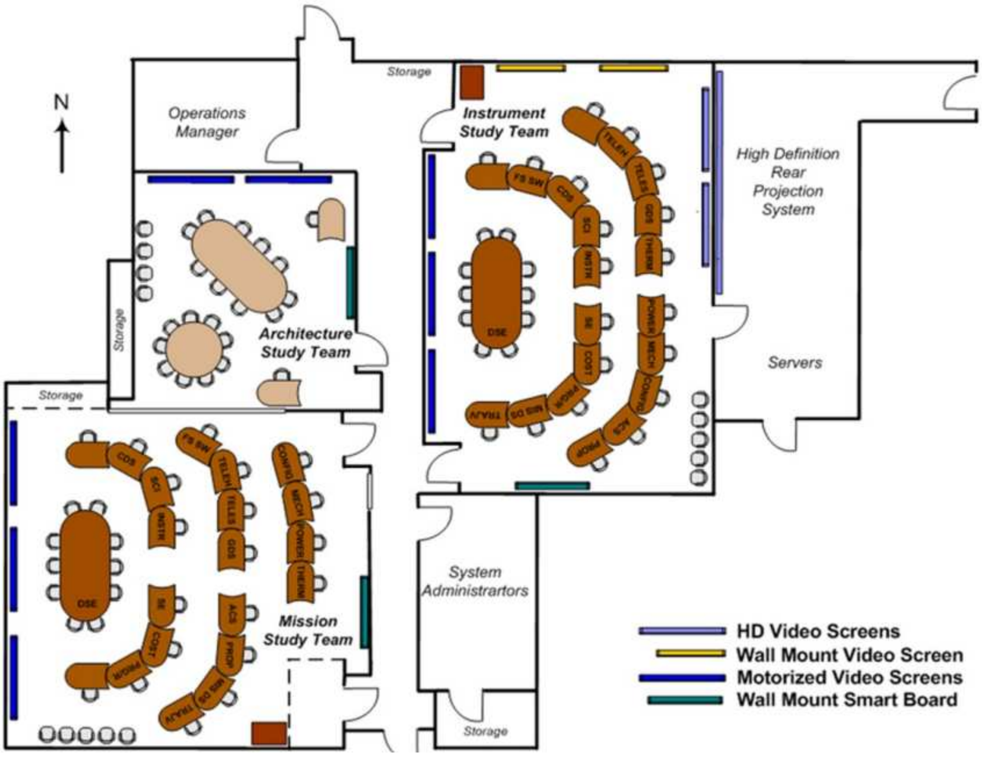


Figure 2.10: Team X facility
[18]

2.2 Concurrent Engineering at ESA

Under the inspiration of Team-X's success, ESA also introduced an alternative to the traditional approach to space mission design by establishing in 1999 a CE facility in ESTEC called CDF (Concurrent Design Facility). Initially, the facility was created experimentally with the aim of organizing the tools and human resources already used for assessment studies in a more efficient manner. ESA conducts a high number of pre-Phase A studies each year, and the use of a classical approach required up to 6-9 months, which became incompatible with the growth of the space sector and the shortened development timelines.

The first case study was provided by the Central European Satellite for Advance Research (CESAR) performed from January to March 1999, which ESA had undertaken jointly with the Italian Space Agency (ASI). From about 2012 in response to the need for preliminary mission concept assessment, the CDF has introduced MiCRA (Mission Concept and Requirements Assessment) studies. These studies aim to provide a comprehensive understanding of novel mission ideas by identifying key drivers, constraints, and trade-offs, as well as assessing system sizing and technology needs. MiCRA, conducted over a period of approximately two weeks, engages a smaller team and fewer sessions compared to standard CDF studies. Nevertheless, it yields valuable insights and preliminary mission objectives. MiCRA activities complement the range of services offered by ESA CDF, enhancing early-stage mission concept assessment and paving the way for follow-up full CDF studies or industrial activities [19].

Process

The design process for space systems involves multiple interdependent components, as illustrated in Figure 2.11 and described in [3]. Changes to one component affect others, necessitating early assessment of impacts. The process starts with a few meetings involving a restricted number of specialists to refine mission requirements, define constraints and design drivers, and estimate resources. The iterative process ensures comprehensive and timely consideration of all aspects, minimizing incorrect assumptions and allowing disciplines that traditionally are involved later in the design to participate from the beginning. Customers participate throughout, contributing to study assumptions and correcting deviations in real-time. In the first design sessions, the costumer presents the mission requirements and constraints to the team. Flexibility is crucial, allowing alternative paths and professional estimates to prevent process blockages due to data or decision constraints.

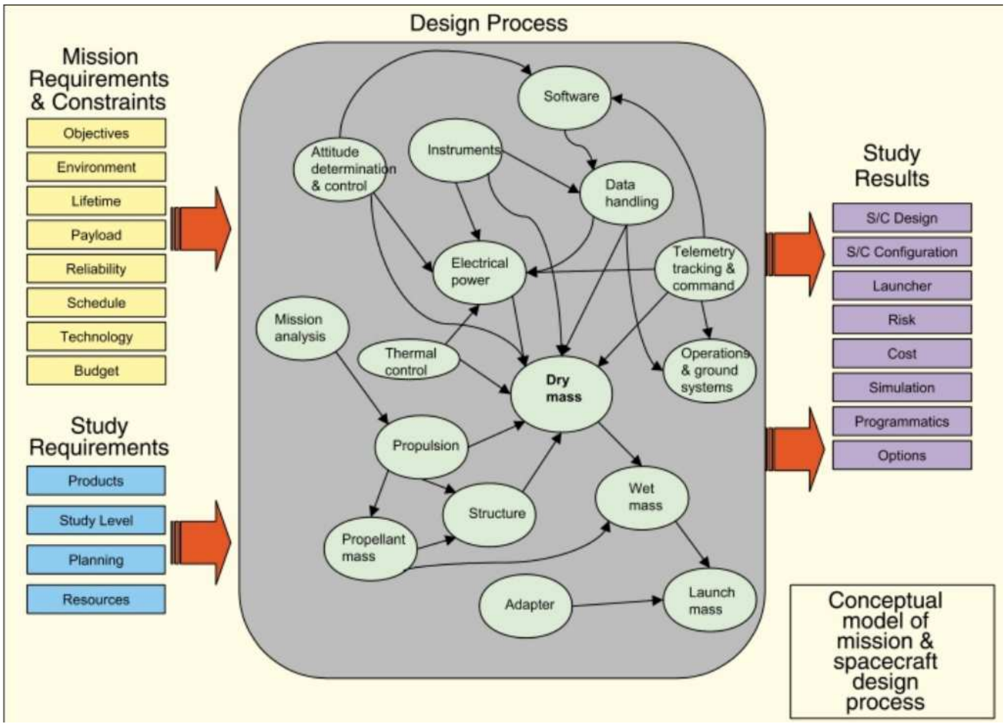


Figure 2.11: Conceptual model of the design process
[3]

Team

The essential element of the CDF is a group of engineering specialists working together in one room; it's important to create a highly motivated, multidisciplinary team since people are the most important element. To work effectively the team must accept to adopt a new method of working, perform design work and provide answers in real time, cooperate and contribute to the team spirit. It is more difficult than it might appear because it puts more pressure on the participants, that has to perform the design with the facility's specific tools, identify influences other domains may have on their own, adapt and be ready to change the subsystem design according to the mission baseline changes. For each discipline there is an assigned position in the facility for a particular technical domain and the choice of the disciplines depends on the study's level of detail. The team typically comprises 15-20 specialists selected based on their experience relevant to the type of study being conducted. Importantly, the team members represent all ESA member states nationalities, fostering diversity and collaboration. Being part of the CDF team offers several motivations, including the opportunity for team members to learn from each other, gain insights into new and future ESA missions, and work in an innovative and dynamic environment [3].

Tools

The first tool developed by ESA's General Studies Program to support CDF activities was the **Integrated Design Model (IDM)** [20]. It extends Microsoft Excel's functionality through macros to address CE challenges. In operation for a decade, it has supported over 100 ESA studies. IDM serves as both a hierarchical space system model and as a distributed Excel implementation. In the hierarchical model, each study case contains Elements (e.g., transport vehicle, lander), each with general Element Information and composed of Subsystems. Subsystems are then further divided into Units (e.g., transmitter, receiver) which are described by Parameters (e.g., power consumption, weight). Practically, IDM is split into separate Excel workbooks, each representing a subsystem or a specific discipline (e.g., cost calculation, power management) to enable concurrent editing by engineers. Every workbook contains:

- output sheet listing parameters calculated and provided to other workbooks;
- input sheet listing required parameters;
- calculation sheet with formulas for calculation;
- presentation sheet for visual representation.

Parameter exchange between output and input sheets is managed by Excel macros via a central Data-Exchange workbook, as shown in Figure 2.12. When the session leader initiates it, this process copies output parameters so engineers can update their local input values.

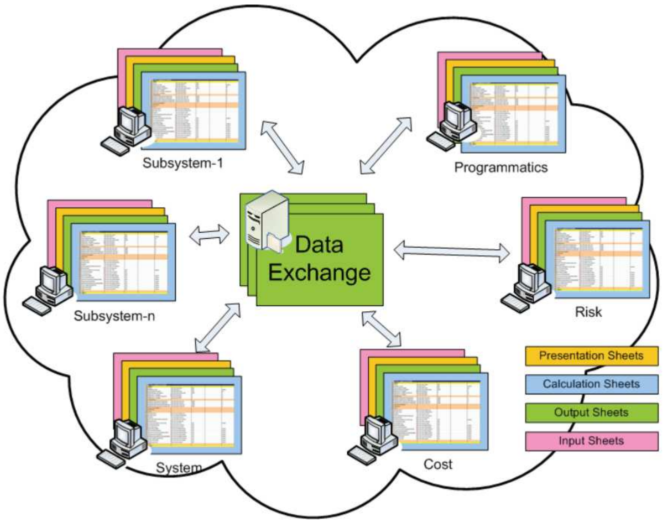


Figure 2.12: IDM architecture
[20]

The IDM approach worked well, but also clearly had limitations, in particular with respect to interactive performance, scaling and extension to larger system design problems and later life cycle phases, software verification, configuration control and maintenance. Therefore a new, more robust and better performing toolset was needed, so ESA developed a second generation CE software package called the **Open Concurrent Design Tool (OCDT)**.

It is an easy-to-use add-in for Microsoft Excel that performs simple analyses and simulations. Moreover, other tools for engineering analysis and simulation can be integrated, through the use of OCDT adapters. The server is able to support concurrent teams of more than 20 users and synchronize their engineering model content twice a minute or faster. Typically each user would represent a different domain of expertise. Apart from use in the ESTEC CDF, OCDT was intended for users in the community of CE centers in the European space sector. In order to create an interoperable environment, OCDT implements the conceptual data model defined in Annex A of the *ECSS-E-TM-10-25* Technical Memorandum, titled *System Engineering - Engineering Design Model Data Exchange.* This ECSS Technical Memorandum was developed by a working group in which representatives from all major European space organizations with a stake in concurrent design cooperated. This tool after 150 application cases in just over 8 years was completely replaced in the ESA CDF by the **Concurrent Model-based Engineering Tool (COMET)**.

CDP4-COMET [21] is a tool developed by *REHA Group* through ESA's General Support Technology Programme. COMET offers a more modern user interface and enhanced report generation capabilities, including automatic reporting of mass and power budgets. It is also compatible with the previous tool OCDT, so all existing models can be reused. The transition to COMET began in August 2022 and became the baseline for all future studies. As OCDT, COMET is freely available in open source and its adoption aligns with ESA's Agenda 2025, particularly in achieving Model Based System Engineering throughout all phases of mission development. The adoption of COMET enables the use of spacecraft digital twins beyond the design phase, extending to assembly, integration, and test phases of development. This allows for smoother and faster progress, early anomaly identification, detailed simulations replacing costly physical testing, and data collection throughout the production cycle to improve future design phases. The COMET architecture is illustrated in Figure 2.13, with further details provided in [22].

One of the main new features of COMET is the integration with so-called domain specific tools; software applications used by the various engineering domains that make up the concurrent design team. Through this, they can benefit from an automated link/data exchange with the COMET server. The key tools that COMET can integrate into include: Capella, MagicDraw–SysML, Enterprise Architect–SysML, Catia v5, Ecosim Pro, Matlab and ASTOS.

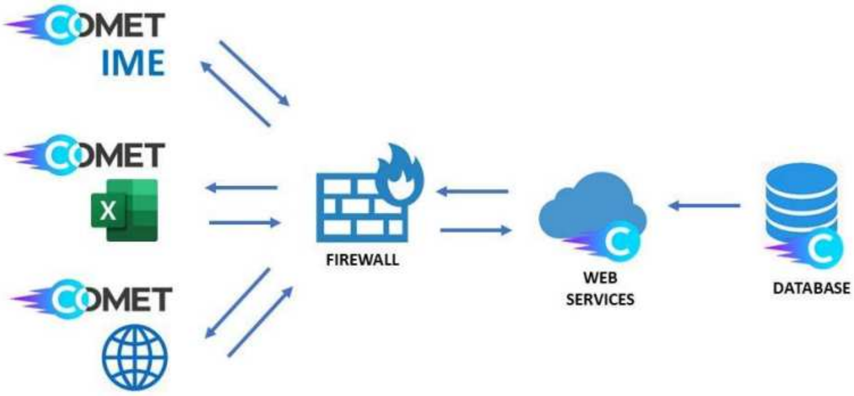


Figure 2.13: CDP4-COMET architecture
[22]

Facility

Initially housed in temporary barracks, the CESAR study proved successful, leading to the establishment of an operational facility available to all ESA programs. Over 70 assessment studies and 12 industrial reviews were conducted in the temporary facility (Figure 2.14), demonstrating its value and effectiveness.

In December 2007, the CDF transitioned to a purpose-built facility (Figure 2.15), becoming a reference point for other European partners in space mission design. The CDF is equipped with comprehensive hardware, software, and communication tools to facilitate multidisciplinary and concurrent design activities. The facility consists of 4 design rooms with a number of support rooms grouped around a central foyer. The main design room with 30 workstations is used as the primary room for large mission and large instruments studies. Additionally, there are two identical design rooms known as the project design room and the MiCRA room, separated by a glass wall, primarily used for smaller studies or reviews and splinter meetings. The support design room can function as a conventional meeting space or be converted into a design room as needed. All rooms are interconnected via an audiovisual network, allowing data sharing among screens and workstations, and feature full video conferencing capabilities via IP.

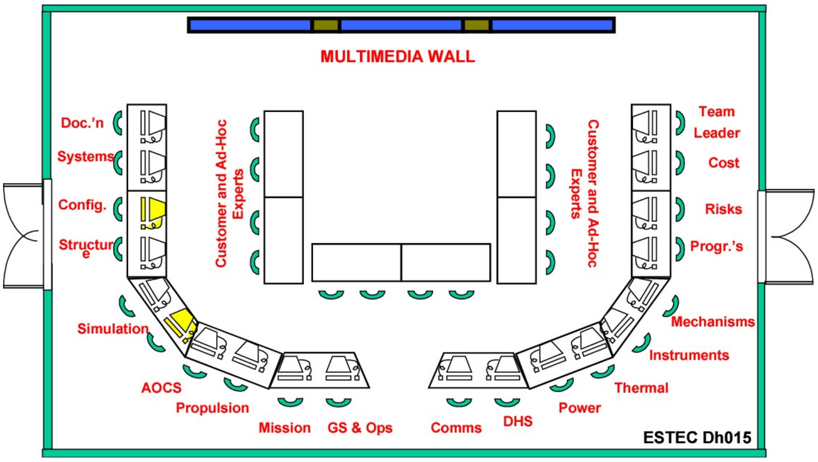


Figure 2.14: CDF layout of the temporary barracks [23]

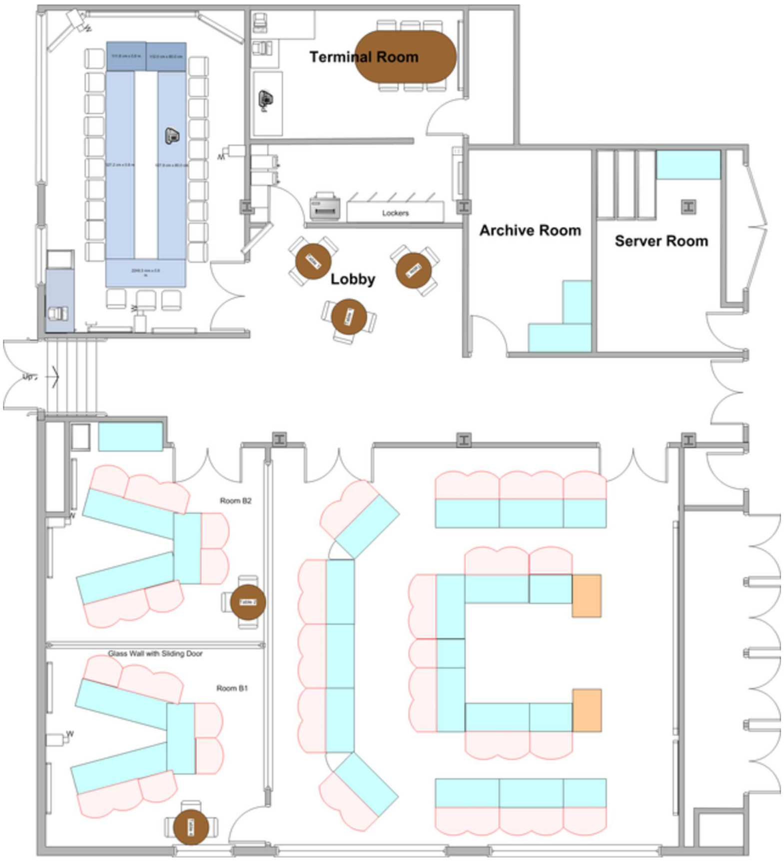


Figure 2.15: CDF facility [24]

2.3 Overview of Scrum Approach and its Integration in CE

Scrum is an Agile framework used for managing and completing complex projects. Introduced in the early 1990s, Scrum originated in the software development sector as a part of Agile methodologies. It focuses on enhancing productivity and quality by enabling teams to adapt quickly to changes and deliver value iteratively and incrementally so that problems that may arise are solved as soon as possible.

The Scrum framework defines three key roles: the Product Owner, responsible for maximizing the product's value and managing the Product Backlog; the Scrum Master, who supports and promotes Scrum practices; and the Development Team, a cross-functional group responsible for delivering a product increment at the end of each Sprint.

Scrum organizes work into Sprints, which are time-boxed iterations typically lasting between one and four weeks. Each Sprint includes a Sprint planning session to define the work to be done, daily Scrum meetings to synchronize activities, a Sprint Review to showcase completed work and gather feedback, and a Sprint Retrospective to reflect on the past Sprint and identify improvement areas (Figure 2.16). The primary artifacts in Scrum are the Product Backlog, an ordered list of everything needed in the product; the Sprint Backlog, a selection of Product Backlog items for the Sprint, along with a plan for delivering them; and the Increment, the sum of all completed Product Backlog items at the end of a Sprint [25] [26].

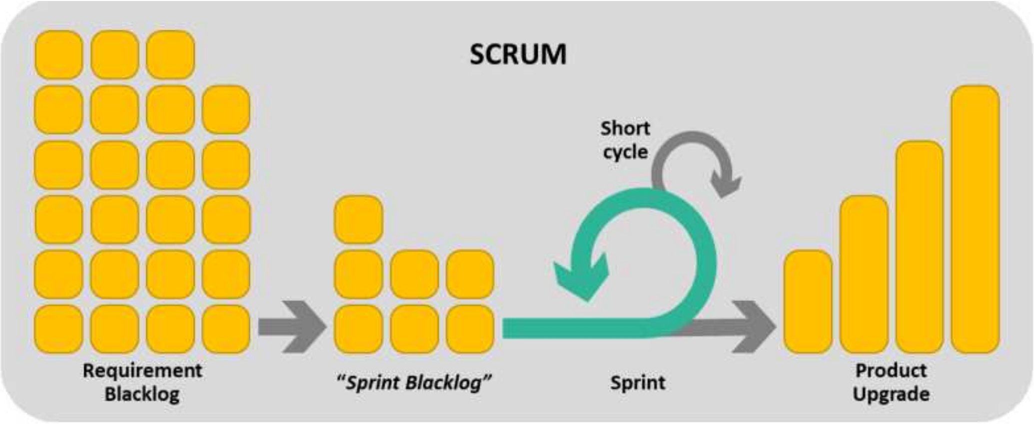


Figure 2.16: SCRUM methodology
[27]

CE and Scrum methodology share several common aspects, such as advancing tasks in parallel, working through sessions and sprints, and engaging in continuous design iterations. Initially developed for software applications, Scrum might not seem inherently suitable for application in space engineering projects characterized by physical systems and hardware. However, this limitation is less pronounced in the early stages of mission design, which primarily involve ideas and concepts without immediate reliance on physical systems. The traditional concurrent design methodologies currently used by the top players in the field of Space CE (e.g., ESA's Concurrent Design Facility, JPL's A-team and Team X) don't envisage a formal and systematic estimation of the effort of the technical and programmatic activities involved in the mission design: the effort is distributed simultaneously across all participants and no prioritization of critical activities is foreseen. Until now, to the author's knowledge, only one work has been published by the Polytechnic University of Madrid about the implementation of a Scrum methodology in space mission CE studies [27]. The work focused on prioritizing mission requirements, establishing a hierarchical order for subsystem design, and reallocating resources accordingly, assigning a greater number of design experts to disciplines with higher priority during the design phases (e.g., mission analysis, payload, ConOps). The result observed through the application of this methodology was an increase in the optimization of the spacecraft under design (in terms of mass, power, ΔV, etc.) for a team using the Scrum methodology with respect to a team using classical concurrent design approach. What Scrum methodology adds to CE is a task hierarchy that facilitates better resource allocation across different disciplines. In contrast, CE runs the risk of allocating resources to tasks that may require prior completion of other tasks or access to data that are not yet available.

Two additional works have been published on integrating an Agile approach with CE, not specifically in the space sector, but in the general corporate environment. Article [28] highlights the drawbacks CE faces in the industrial context and how these could be addressed by adopting more flexible methodologies, such as Agile/Scrum, proposing an Agile Concurrent Engineering (ACE) approach. It argues that ACE is more applicable to product development, especially in medium-sized or small companies. Also [29] proposes a hybrid Agile-Concurrent framework that utilizes Scrum. The integration of the Scrum approach provides greater flexibility and a quicker response to changes in product development, particularly in private companies. In the proposed hybrid framework, the project teams for each cycle are multidisciplinary, with each cycle representing a full iteration of the various project phases. Within each project team, three Scrum development teams are formed, with each team responsible for delivering a specific output from one of the phases involved in the cycle. The product development loop is shown in Figure 2.17. Effective communication and continuous information exchange between teams are achieved through daily meetings, shared data environments, and other appropriate information and communication technologies.

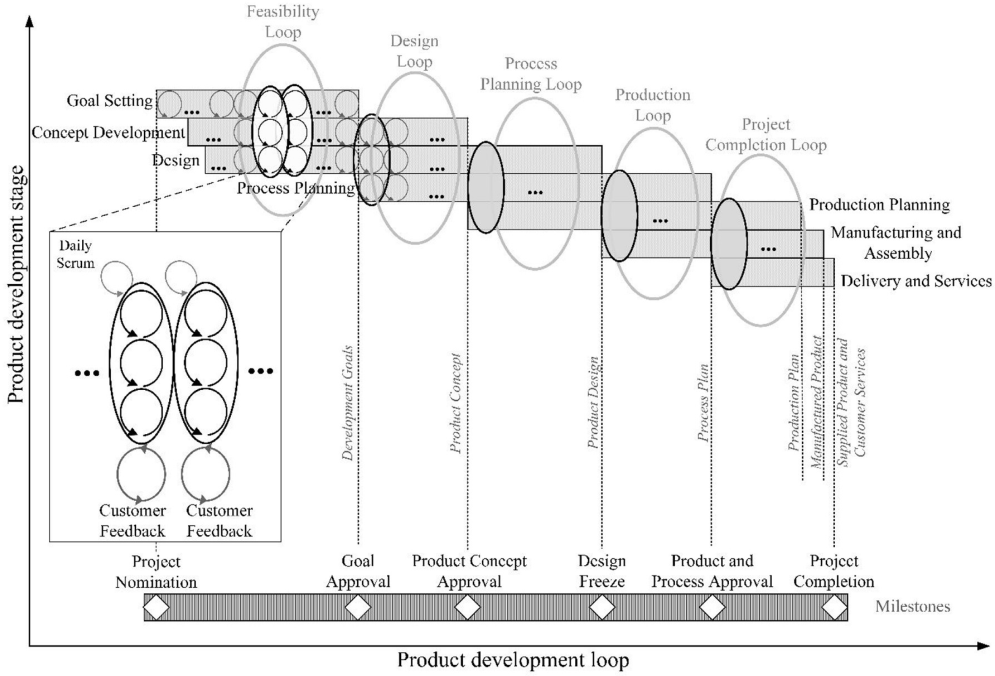


Figure 2.17: Agile-Concurrent hybrid
[15]

2.4 Artificial Intelligence for Mission Design

The integration of AI in the design and analysis of space missions is a growing area of research, particularly focusing on improving the efficiency and capabilities of CE. Several projects have explored the use of AI-powered virtual assistants to aid engineers during spacecraft mission design. Notable examples are Daphne [30], [31] and SpaceQA [32]. Daphne [30] is a virtual assistant for designing Earth observation distributed spacecraft missions. Its comprehensive question-answering system and cognitive assistance features were assessed through a study at JPL involving nine people. The findings suggest that Daphne can improve performance during system design tasks compared to traditional tools. Reference [31] delves into the application of Knowledge Representation, Reasoning, and Expert Systems as Design Engineering Assistants. It emphasizes the utility of converting unstructured, legacy data into structured data stored in Knowledge Graphs to enhance design processes in CE sessions. This study also explores the use of Ontology Learning methods to automate the knowledge base generation, addressing the challenges of manual data curation. SpaceQA [32] is the first open-domain question-answering system specifically designed for space mission design. Developed under the ESA initiative, SpaceQA utilizes an architecture combining dense retrieval and neural reading, with an emphasis on transfer learning due to the scarcity of domain-specific annotated data. Preliminary evaluations indicate the effectiveness of this approach, though further fine-tuning is necessary for optimal reading comprehension. Collectively, these works underscore the transformative potential of AI-driven tools in streamlining and augmenting the complex processes involved in space mission design, paving the way for more efficient and informed decision-making within concurrent design facilities.

Chapter 3

ACLab Implementation

After reviewing the state-of-the-art application of CE at major space agencies and detailing the processes, methodologies, and tools they employ, this chapter focuses on the implementation of CE at Argotec within the *ACLab*, particularly in addressing the challenges of a corporate environment. It outlines the tools, methodologies and roles implemented for the *ACLab*, which have been validated through a real case study discussed in Chapter 4.

The R&D unit, especially the systems engineering team, typically handles the development of innovative and disruptive feasibility studies and the formulation of new phase 0/A mission concepts. Study submissions generally originate from Argotec's management or as responses to projects funded by public entities or space agencies. Until a few years ago, Argotec primarily relied on a sequential methodology for mission design; however, in recent years, the company has adopted a more concurrent one. Consequently, the introduction of a new design approach has become both necessary and essential.

3.1 *ACLab* Tools

The first activity focused on analyzing and developing tools to support the design process. Specifically, the focus was initially on technical tools, like ones for system budgets, followed by the analysis and selection of a tool for data exchange and session management.

3.1.1 System Design Tools

The main goal was not just to develop design tools, but also to identify the key inputs and outputs needed by the different domains and to highlight the interconnections between the spacecraft subsystems. This work is important because subsystem engineers, particularly those without a systems engineering background, often lack awareness of where the necessary inputs for their subsystem design originate and who requires the outputs of their design. This understanding is crucial in the design process, especially in CE, which advances the design process simultaneously and in parallel. Another reason for developing an initial version of these tools was to achieve internal standardization within the company, creating a readily accessible repository for everyone. This standardization ensures that tools can be used not only within the *ACLab* context but also helps engineers avoid duplicating existing tools that they might not be aware of.

The analysis of tool interconnections followed the same logic shown in Figure 2.11, but focused on the interaction between system budgets rather than the interconnections during the design process. Figure 3.1 shows all the main interconnections found and the main inputs required for each analysis.
The different tools have been developed using Excel, as it is already widely used in the company and all engineers are familiar with it. The implemented tools are about:

- Configuration
- Cost estimation
- ΔV budget
- EPS design
- Mission Analysis
- Momentum budget
- Single-node Thermal Analysis

Some of these tools have been developed from scratch, while others are based on existing tools that have been analyzed and adjusted as needed. The Excel worksheets are not interconnected; however, the interconnection between the various domains and data is achieved through the COMET tool, described in Section 3.1.2. Additionally, since these tools are meant to be used during design sessions, each team member can directly interface with the relevant domain expert to obtain data and information. In the future, it is conceivable to enhance and interconnect these tools, either through Excel or other platforms, and develop a tool for design optimization.

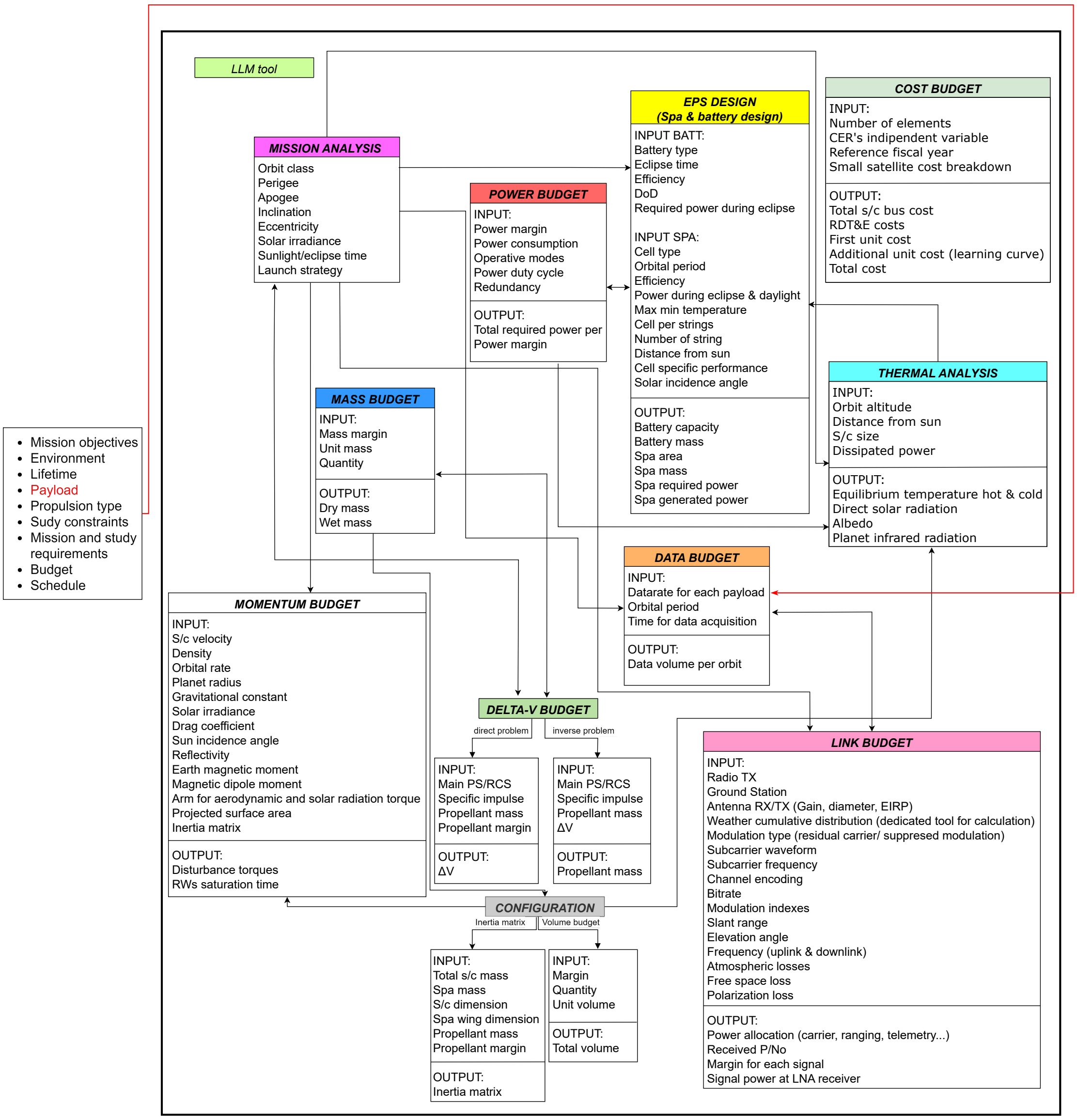
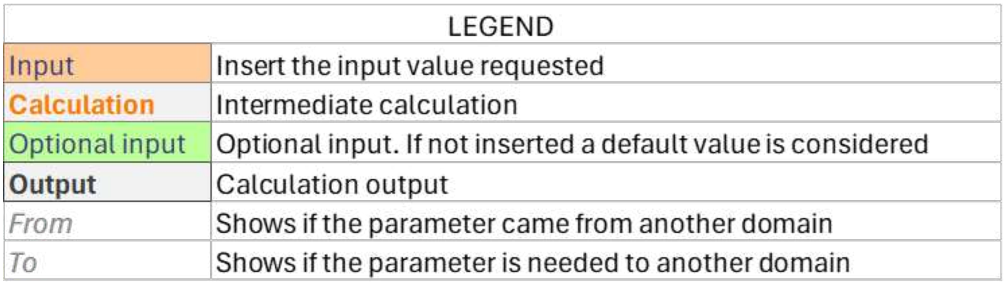


Figure 3.1: Interconnection of tools

Each tool consists of an initial worksheet containing a user guide that explains the tool's architecture, how it should be used within a CE session, and highlights the interconnections with other subsystems in the form of inputs and outputs. The other worksheets represent the actual calculation sheets. All the tools follow the same legend (Figure 3.2), which uses different colors to identify cells representing user inputs, calculation cells, output cells and optional input cells where the required parameter can be entered if known, otherwise, a default value is used.



LEGEND	
Input	Insert the input value requested
Calculation	Intermediate calculation
Optional input	Optional input. If not inserted a default value is considered
Output	Calculation output
From	Shows if the parameter came from another domain
To	Shows if the parameter is needed to another domain

Figure 3.2: Worksheets legend

Configuration

The configuration tool is composed of two calculation worksheets. The first one is intended to provide a preliminary calculation of the inertia matrices of a spacecraft similar to the one shown in Figure 3.3, considering both deployed and non-deployed solar panels. The second worksheet, instead, provides a volume budget tool.

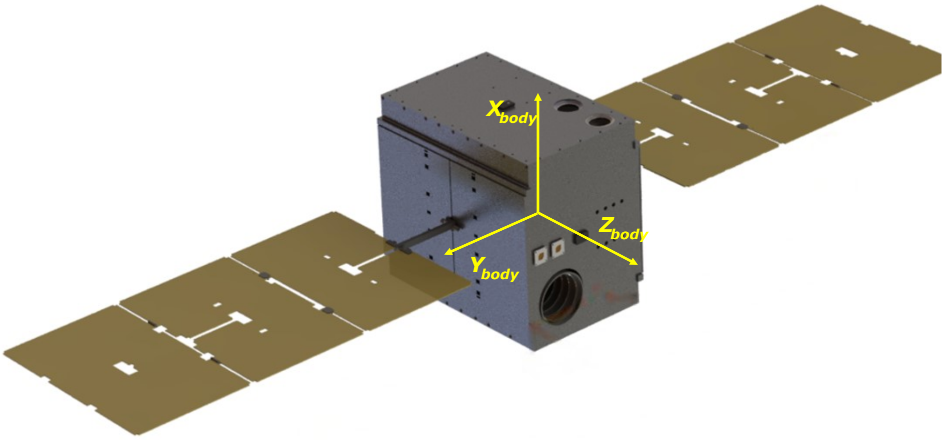


Figure 3.3: Spacecraft model with reference frame

The inputs required for the inertia matrices calculation are: total spacecraft mass, single wing mass, dimensions of the main body of the spacecraft and dimensions of the panels. It is also necessary to indicate the distance along the three axes between the start of the panel's boom and the center of the spacecraft (where the reference frame is located). The resulting matrices are the inertia matrix of the spacecraft without panels, the inertia matrix of the spacecraft with deployed panels, and the inertia matrix of the spacecraft with folded panels. It is also possible to specify, as an input, the rotation angle of the panel around the Y-axis. As stated in [33] the inertia matrix of the spacecraft, considering only the main body, is calculated as follows; where a, b, and c are the dimensions of the spacecraft along x, y, and z respectively.

$$J_{s/c} = \frac{m_0}{12} \begin{bmatrix} b^2 + c^2 & 0 & 0 \\ 0 & a^2 + c^2 & 0 \\ 0 & 0 & a^2 + b^2 \end{bmatrix} [\text{kgm}^2] \tag{3.1}$$

The inertia matrix of a single panel, calculated with respect to its center of mass as the origin of the reference frame, is determined as follows:

$$J_{wing} = \frac{m_w}{12} \begin{bmatrix} b_1^2 + c_1^2 \cos^2\theta + a_1^2 \sin^2\theta & 0 & 0 \\ 0 & a_1^2 + c_1^2 & 0 \\ 0 & 0 & b_1^2 + c_1^2 \sin^2\theta + a_1^2 \cos^2\theta \end{bmatrix} [\text{kgm}^2] \tag{3.2}$$

with θ being the panel's rotation angle around the y-axis and a_1, b_1, and c_1 being the dimensions of the panel along the x, y, and z axes respectively. To calculate the inertia matrix of the entire system, with both deployed and folded panels, the panel inertia matrix (3.2) is first translated into the reference frame centered at the spacecraft's center, and then added to the spacecraft's inertia matrix (3.1). It should be noted that the dimensions a_1, b_1, and c_1 as well as the distance between the reference frame centered on the panel and the one centered on the spacecraft's center change between the deployed and folded panel configurations.

The second worksheet contains a table that calculates the volume of each component. The user needs to enter the component's dimensions in meters, either as [*length* × *width* × *height*] or [*diameter* × *height*]. Additionally, the user must input the margin and specify the number of components. The worksheet automatically calculates the unit volume of the component and the total volume, including the margin. Finally, it displays the total volume as the sum of the volumes of all components both in m^3 and in CubeSat unit.

Cost estimation

The cost model implemented is a parametric one and provides an initial assessment of the mission cost. While it may not be the most accurate, it offers a valuable preliminary estimate in the early stages of the mission and serves as a useful support tool for *ACLab* activities. Other types of cost models include the bottom-up method and analogy-based estimation. The bottom-up method sums the cost of each component and, although it is the most accurate, is also the most time-consuming and unsuitable for the early design phase. On the other hand, analogy-based estimation faces implementation challenges due to the lack of a dataset and reference models.

A parametric cost model consists of a series of mathematical relationships that link the cost of the spacecraft with physical and technical parameters. These relationships are called Cost Estimation Relationships (CERs) and highlight how the system cost varies with the characteristic parameters. In the described tool the CERs from the Small Satellite Cost Model (SSCM) version 8.0 have been implemented for the calculation of the spacecraft bus cost (Table 3.1). This is the result of a weighted average among the results of the individual CERs with weights inversely proportional to the associated error.

Independent Variable(s)	**CER for Total Bus Cost (FY94$M)**	**Applicable Range**	**Std. Error (%)**
r: EOL power (W) s: Pointing accuracy (deg)	$c = 6.47r^{0.1599}s^{-0.356}$	r: 5-500 s: 0.05-5	29.55
r: TT&C mass (kg) s: Payload power (W)	$c = 0.702r^{0.554}s^{0.0363}$	r: 3-50 s: 10-120	35.68
r: Downlink data rate (kbps) s: Average power (W) p: Prop system dry mass (kg)	$c = 1.44r^{0.0107}s^{0.509}1.0096^{p}$	r: 1-2000 s: 5-410 p: Prop system dry mass (kg)	35.66
r: Spacecraft dry mass (kg) s: Pointing accuracy (deg)	$c = 0.6416r^{0.661} - 1.5117s^{0.289}$	r: 20-400 s: 0.05-5	37.19
r: Solar array area (m^2) s: ACS type (3-axis or other)	$c = 4.291r^{0.255}1.989^{s}$	r: 0.3-11 s: 0=other, 1=3-axis	38.53
r: Power subsys mass (kg)	$c = 0.602r^{0.839}$	r: 7-70	37.07

Table 3.1: CERs for total bus cost
[34]

The cost of the entire space segment is calculated by summing RDT&E (Research, Development, Test, and Evaluation), First Unit, and Additional Unit costs. The first two are derived from the SMAD Small Satellite Cost Breakdown Table 3.2, which outlines the various costs (Payload, Spacecraft bus, Integration Assembly & Test, Program Level, Ground Support Equipment, and Launch & Orbital Operations Support) expressed as a percentage of the total spacecraft bus, as reported in the second column of Table 3.2. This percentage is then divided into Non-Recurring (RDT&E) and Recurring (First Unit) costs.

Small Satellite Cost Breakdown	**Fraction of S/C Bus Cost**	**Non-Recurring Percentage**	**Recurring Percentage**
Payload	40.0%	60.0%	40.0%
Spacecraft Bus	**100.0%**	**60.0%**	**40.0%**
ADCS	18.4%	37.0%	63.0%
C&DH	**17.0%**	**70.0%**	**30.0%**
Power	23.3%	62.0%	38.0%
Propulsion	8.4%	50.0%	50.0%
Structure	18.3%	70.0%	30.0%
Thermal	2.0%	50.0%	50.0%
TT&C	12.6%	**70.0%**	**30.0%**
Integration Assembly & Test	13.9%	0.0%	100.0%
Program Level	22.9%	50.0%	50.0%
Ground Support Equipment	6.6%	100.0%	0.0%
Launch & Orbital Ops Support	6.1%	0.0%	100.0%

Table 3.2: Small Satellite Cost Breakdown
[35]

The process above does not account for Additional Unit costs, which are calculated using the Learning Curve. This mathematical method accounts for increased productivity as more units are produced. The production cost of the additional units is given by the formula:

$$\text{ProductionCost} = \text{TFU} \times L \tag{3.3}$$

where TFU is the Theoretical First Unit cost and $L = N^B$, where N is the number of unit produced and B is calculated as follows:

$$B = 1 - \frac{\ln(\frac{100\%}{S})}{\ln 2} \tag{3.4}$$

S indicates the learning curve slope and varies depending on N as shown in Table 3.3.

N	S
< 10	95%
10-50	90%
> 50	85%

Table 3.3: Learning Curve slope values

ΔV budget

The ΔV budget tool implements two types of problems: direct and indirect. The direct problem calculates the ΔV given the propellant mass, while the indirect problem calculates the required propellant mass given the ΔV. In practice, the indirect problem is more commonly used during mission design because ΔV is an input that directly derives from the mission analysis.
The necessary inputs for the ΔV calculation in the direct problem are the total mass before the maneuver (m_0), the propellant mass (m_P), and the specific impulse (I_{sp}). Moreover, the ΔV is calculated separately for the Main Propulsion System (PS) and the Reaction Control System (RCS).

$$\Delta V = -I_{sp} \cdot g_0 \cdot \ln\left(1 - \frac{m_p}{m_0}\right) \tag{3.5}$$

In the indirect problem, instead, the key input is the required ΔV for each maneuver. Other inputs users need to provide to the tool are about the number and type of propulsion systems, specific impulse, and propellant margin. The tool accepts up to 15 firing times for the mission and it calculates the propellant mass for each propulsion system, rearranging equation 3.5. The calculation starts from the last firing time because the total mass after the last maneuver equals the spacecraft's dry mass, which is given as an external input. For each firing time, the necessary propellant mass for each propulsion system is calculated in sequence. For earlier firing times, the total mass after the maneuver is equal to the total mass before the next firing time's maneuver. This sequential approach ensures that the propellant mass for each maneuver is accurately calculated. Summing the propellant mass calculated for each firing time gives the total propellant mass needed for the mission.

Electrical Power System (EPS) design

The tool for the EPS design performs calculations for sizing both solar panels and secondary batteries. For the solar panels, the tool includes an initial section that outputs the generated BOL (Begin of Life) and EOL (End of Life) power, the area, and the mass of the solar array. The required inputs are the power needed by the system during eclipse (P_e) and daylight (P_d). These inputs are derived from the power budget, which calculates the power consumed by the system in each operational mode. For daylight power, it is advisable to consider the maximum power consumption value to be more conservative. The other inputs come from the mission analysis and include: orbital period, eclipse duration (T_e), daylight duration (T_d), lifetime, and efficiencies during eclipse and daylight. The power required from the solar array during the day to sustain the spacecraft is calculated as follows:

$$P_{\mathrm{sa}} = \frac{\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}}{T_d} \quad [\mathrm{W}] \tag{3.6}$$

The terms X_e and X_d indicate the eclipse and daylight efficiency and depend on the type of regulation (Direct Energy Transfer DET and Peak Power Tracking PPT). Moreover, in the tool, by indicating the solar cell type and the cell regulation type from a drop-down list, values like ideal solar efficiency and cell degradation per year are automatically imported from reference tables.
The generated power BOL is:

$$P_{\mathrm{BOL}} = P_o I_s \cos(\theta) \quad [W/m^2] \tag{3.7}$$

where P_o is the power generated if the sun were normal to the cell surface, I_s is the inherent degradation factor accounting for various degradation factors of the cell, and θ is the angle between the incident ray and the normal vector to the surface. This power also depends on the spacecraft's distance from the Sun, as P_o decreases with the square of that distance. To calculate the EOL power, P_{BOL} is multiplied by the lifetime degradation factor. Finally, the area and the mass of the solar panels are estimated.

$$A_{\mathrm{sa}} = \frac{P_{\mathrm{sa}}}{P_{\mathrm{EOL}}} \quad [\mathrm{m}^2] \tag{3.8}$$

$$m_{\mathrm{sa}} = \frac{P_{\mathrm{EOL}}}{\alpha} \quad [\mathrm{kg}] \tag{3.9}$$

where α is the cell specific performance in W/Kg.
It is important to note that this calculation worksheet is not well-suited for deep space or interplanetary missions, because the spacecraft is almost always illuminated by the sun, with absent or very little eclipse periods compared to the mission's lifetime.

Another worksheet for the preliminary sizing of the solar array is introduced. In this case, the inputs are the type of solar cell with its characteristics like efficiency, V_{oc}, V_{mp}, I_{sc}, I_{mp} (respectively Voltage open circuit, Voltage max power, Current short circuit and Current max power), the number of cells per string, the number of strings, the temperature range, the loss factors and the distance from the sun. The main output of interest is the maximum power generated in BOL and EOL at different temperature conditions which can be compared with the required power. By knowing the total number of cells and the cell area, it is possible to estimate the total area of the panels, and using equation 3.9, the mass of the solar panels can be derived. This approach does not account for eclipse time so it is more suitable for deep space missions.

For the preliminary sizing of the battery, the inputs needed are the power required by the system during eclipse and the eclipse duration. By selecting the battery type (Lithium-Ion, Nickel-Hydrogen, or others) from a drop-down menu, the tool automatically considers the values for bus voltage, cell-specific energy (E_{sc}), efficiency (η), depth of discharge (DOD), and self-discharge per day. The battery capacity and mass are then calculated as follows, where N indicates the number of batteries considered:

$$C = \frac{P_e T_e}{DOD \cdot N \cdot \eta} \quad \text{[Wh]} \tag{3.10}$$

$$m = \frac{C}{E_{sc}} \quad \text{[kg]} \tag{3.11}$$

Even in this case, the calculation is suboptimal for deep space/interplanetary missions due to the absence of a real eclipse period as stated before. This issue can be bypassed by considering as eclipse power the difference, if negative, between the power in the worst operative mode and power generated by the solar panel.

Mission Analysis

The Mission Analysis Tool is an evolving tool designed to gather all necessary inputs for the other design tools and outline the required mission maneuvers along with their respective ΔV values. These ΔV values are essential for calculating the propellant needed within the ΔV budget. By selecting the reference planet, the tool automatically considers all key planetary parameters from reference data tables. Furthermore, by inputting the satellite's orbital parameters, the tool can calculate a range of critical metrics, including the orbital period, eclipse and daylight time, satellite velocity and orbital rate. It also incorporates formulas to determine solar irradiance based on the distance from the Sun (in AU) and to calculate atmospheric density based on the perigee altitude.

Momentum budget

The support tool for the Attitude Determination and Control System (ADCS) includes an initial worksheet that allows the evaluation of the total disturbance torque acting on the spacecraft which is divided into four components [35]:

- aerodynamic torque;
- solar pressure torque;
- gravity gradient torque;
- magnetic torque.

The aerodynamic torque acts only on spacecraft orbiting at an altitude where atmospheric presence and aerodynamic drag are still significant, primarily in LEO. The aerodynamic drag force is given by:

$$F_a = 0.5\rho V^2 C_D A \quad [\mathrm{N}] \tag{3.12}$$

where:

- ρ is the density;
- V is the velocity;
- A is the frontal area of the spacecraft;
- C_D is the drag coefficient.

The torque is calculated by multiplying the force by the arm of the force (r_{cp}), which corresponds to the distance between the aerodynamic center of pressure and the center of gravity.

$$T_a = F_a \cdot r_{\mathrm{cp}} \quad [\mathrm{Nm}] \tag{3.13}$$

The necessary inputs for calculating this first torque come from the mission analysis (velocity and density) and configuration (frontal area and torque arm).

The solar pressure torque T_{sp} is highly dependent on the type of surface illuminated. The worst-case scenario for solar radiation torque is:

$$T_{sp} = F\left(C_{ps} - cg\right) \quad [\mathrm{Nm}] \tag{3.14}$$

$$F = \frac{F_s}{c} \cdot A_s(1+K)\cos l \quad [\mathrm{N}] \tag{3.15}$$

where:

- F_s is the solar constant, 1367 W/m^2;
- c is the speed of light, $3 \times 10^8\,\mathrm{m\,s^{-1}}$;
- A_s is the area of the surface;
- C_{ps} is the position of the solar pressure center;
- cg is the position of the center of gravity;
- K is the reflectivity factor;
- l is the Sun incidence angle.

The reflectivity factor value is automatically considered by the tool by indicating the type of material from those listed in a specific table. The inputs necessary for calculating the solar pressure contribution come from mission analysis (solar irradiance and Sun incidence angle) and configuration (frontal area and force arm).

The torque due to the gravity gradient is calculated as:

$$T_g = \frac{3\mu}{2R^3} \left| I_z - I_y \right| \sin(2\theta) \quad [\text{Nm}] \tag{3.16}$$

where:

- μ is the Earth's gravitational constant, $3.986 \times 10^{14}\,\text{m}^3/\text{s}^2$;
- R is the orbital radius (m);
- I_z and I_y are the moments of inertia about the z and y axes (or x, if smaller) in kgm^2;
- θ is the maximum deviation of the z-axis from the local vertical in radians.

The inputs from mission analysis are the gravitational constant and the orbital radius while the ones from configuration are the largest and smallest moments of inertia.

Finally, the torque generated by the magnetic field is:

$$T_m = D \cdot B \quad [\text{Nm}] \tag{3.17}$$

where D is the residual dipole on the spacecraft in Am^2 and B is the Earth's magnetic field expressed in Tesla (T). The magnetic field B can be approximated as:

$$B = \frac{2M}{R^3} \quad [\text{T}] \tag{3.18}$$

where M is the Earth's magnetic moment and R is the distance between the Earth and the center of the spacecraft expressed in meters.

In addition to the disturbance torques, the tool also allows for the calculation of the Slewing Torque:

$$T_s = 4\theta \frac{I}{t^2} \quad [\text{Nm}] \tag{3.19}$$

where:

- θ is the maximum slew angle;

- I is the largest moment of inertia;
- t is the minimum maneuver time.

The sum of the disturbance torques, along with the slewing torque, allows for sizing the spacecraft's attitude control actuators, such as reaction wheels and thrusters.

Single-node thermal analysis

This tool solves the heat equation under steady-state conditions, considering both the worst-case hot and cold scenarios. It is assumed that the entire system can be represented by a single node (or point) with a uniform temperature. By solving the equation, the maximum equilibrium temperature (in the hot case) and the minimum equilibrium temperature (in the cold case) reached by the spacecraft are calculated. The equation accounts for the balance between the heat generated internally and absorbed from the external environment with the heat rejected externally.

$$Q_{out} = Q_{\text{solar\_direct}} + Q_{\text{solar\_albedo}} + Q_{\text{planet\_IR}} + Q_{int} \tag{3.20}$$

The terms on the right side of the equation consider the contribution of direct solar radiation on the spacecraft ($Q_{\text{solar\_direct}}$), the albedo ($Q_{\text{solar\_albedo}}$), the infrared radiation emitted by the atmosphere/surface of the planet ($Q_{\text{planet\_IR}}$), and the heat generated internally (Q_{int}). $Q_{\text{solar\_albedo}}$ indicates the percentage of reflected solar radiation relative to the incident radiation that mainly depends on the optical properties of the surface. The equation, as written, considers a satellite orbiting a planet; however, for deep space missions, the terms $Q_{\text{solar\_albedo}}$ and $Q_{\text{planet\_IR}}$ become negligible and can be omitted from the equation. Moreover, $Q_{\text{solar\_albedo}}$ and $Q_{\text{solar\_direct}}$ decrease with the square of the distance from the Sun. Examining the various terms in the equation in detail:

$$Q_{\text{out}} = A_{S/c} \cdot \epsilon \cdot \sigma \cdot T^4 \quad [\text{W}] \tag{3.21}$$

where:

- $A_{S/c}$ is the spacecraft surface exposed to space [m^2];
- ϵ is the spacecraft emissivity;
- σ is the Stefan-Boltzmann constant, $5.670 \times 10^{-8} \left[\frac{\text{W}}{\text{m}^2\text{K}^4}\right]$;
- T is the equilibrium temperature [K].

$$Q_{\text{solar\_direct}} = A_{\perp} \cdot \alpha \cdot I_S \quad [\text{W}] \tag{3.22}$$

where:

- $A_\perp$ is the spacecraft surface perpendicular to Sun vector [m^2];
- α is the spacecraft absorptance;
- I_S is the solar irradiance [Wm^{-2}].

$$Q_{\text{solar\_albedo}} = A_p \cdot \alpha \cdot I_a \quad [\mathrm{W}] \tag{3.23}$$

where:

- A_p is the spacecraft projected area to the planet [m^2]
- $I_a = I_S \cdot a \cdot F$ is the solar albedo [Wm^{-2}], where a is the planet's albedo and F is the visibility factor which indicates the fraction of albedo intercepted by the satellite. This factor depends on the orbit altitude, beta angles, and the view factor between the body and the planet.

$$Q_{\text{planet\_IR}} = A_p \cdot \epsilon_{S/c} \cdot I_p \cdot F_{\text{view}} \quad [\mathrm{W}] \tag{3.24}$$

where:

- $I_p = \epsilon \cdot \sigma \cdot T_p^4$ [Wm^{-2}] is the planet emission and T_p is the planet surface temperature [K];
- F_{view} is the view (or shape) factor. It is a measure of the fraction of radiation emitted from surface i and intercepted by surface j.

What varies between the hot case and the cold case is the internally generated power and the fact that, in the cold case, the contributions from albedo and direct solar radiation are null, considering the satellite is in eclipse. The inputs required by the tool derive from mission analysis (planet parameters, distance from the Sun, orbit altitude), spacecraft configuration (s/c size), and power budget (internally dissipated power).

3.1.2 COMET

As described in 2.2, the new CDP4-COMET tool is utilized by ESA and other European entities during the conceptual phases of project design, based on the principles of CE. After an initial evaluation of the tool and possible alternatives, COMET was found to be well-suited for integration within the *ACLab*. This tool features a central repository, allowing data to be transmitted and received through a single channel, thereby eliminating the need for multiple individual data exchanges. All information is formally collected, enabling users to input data specific to their domain and access relevant data from other domains.

COMET was selected for *ACLab* because it serves as a single source of truth for data storage and exchange. Each mission domain has an assigned owner responsible for editing components and modifying parameters specific to their area. The system engineer can review data prior to publication, ensuring its accuracy and reducing the risk of errors due to potential oversights. Additionally, COMET offers the advantage of creating a catalog that functions as a database, addressing a significant gap frequently encountered across Argotec's various activities; as studies progress, the catalog is updated. Furthermore, the tool enables the automatic generation of reports, such as the mass and power budget.

One of the drawbacks is the need to train engineers to use the tool and become familiar with it. Additionally, there is some overhead involved in introducing the program within the company, managing and maintaining the server, and inputting the various components and associated parameters during the sessions. Alternative solutions considered included Excel, which has the significant disadvantage of lacking a central repository and control over data publication, as well as verbal data sharing, which was quickly dismissed due to its informal and confusing nature.

COMET is based on the creation of a *Study Model* that contains all the mission-defining information such as orbital parameters, equipment, instruments, ground stations, spacecraft, etc. In the *Study Model*, all these elements are defined as **Element Definitions**, while the mission structure depends on how these elements are assembled. Lower-level Element Definitions can be nested within higher-level ones; in this case, the nested Element Definitions are referred to as **Element Usages** (for example the spacecraft is an element usage of the space segment, and the solar panel is an element usage of the spacecraft).

Different types of models can be created:

- *Study Model*: a model that will be used for the actual representation of the mission during the design phase.
- *Template Model*: a base model to be used as a template, which can be modified as needed to avoid creating a model from scratch each time.
- *Catalogue Model*: a model that collects all the main components and equipment along with their parameters, essentially serving as a database.

The creation of the *Study Model* is under the responsibility of the SL, who is in charge of editing the DoEs (Domains of Expertise), creating *Person* profiles, and adding *Participants* to the study.
During the study phase for integrating COMET in *ACLab* studies, a *Template Model* was created to offer a predefined and standardized framework for missions. This template can be adjusted as needed to accommodate the specific characteristics of each study. The structure of this template is illustrated in Figure 3.4.

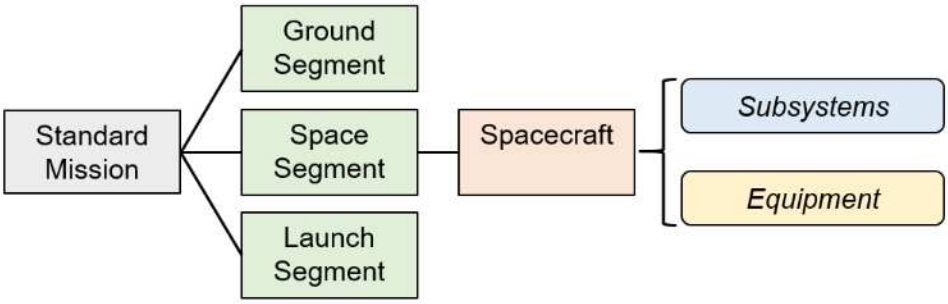


Figure 3.4: *Study Model* architecture
[36]

Moreover, each *Study Model* can contain several *Options* that identify the mission's different characteristics: for example, the default option might feature a chemical propulsion system, while another option might include an electrical one. Therefore, it is possible to concurrently conduct the design of both options to perform analyses that help identify the optimal choice. *Finite States*, on the other hand, are operative modes that the spacecraft assumes during the mission and are applied to specific parameters like power consumption.

Regarding the report creation tool, it consists of three main parts: Code Editor, Report Designer and Report Explorer. The Code Editor allows using data from the model through the C# language; ESA provides code for the mass budget, power budget and equipment list reports in the dedicated Git-hub repository. These were taken as a starting point for creating *ACLab* reports and modified based on specific needs that arose. The mass budget sums up the mass Parameter Values and adds the maturity margin values of all Element Usages inside a specific Element Definition (likely the Flight Element). Additional mass allocations for the harness mass, systems margin and propellant mass will be handled directly in the report designer section.

The power budget calculates the average power and maximum power of equipment or subsystems for each operational mode (Finite State).

The calculation is performed using three parameters:

- Power while on (P_{on}): power consumed by the component when active.
- Power in standby (P_{stby}): power consumed when the component is neither active nor off but in standby mode.
- Power duty cycle ($P_{\text{duty\_cyc}}$): this parameter is associated with the Finite States list, so a value for each state is indicated. $P_{\text{duty\_cyc}}$ can take a value between 0 and 1 or be equal to -1. A value of 0 indicates that the equipment is in standby. Other values between 0 and 1 describe the percentage of time the equipment is active during a given state. A value of -1 indicates that the equipment is off.

Other parameters considered for the power budget calculation are related to the redundancy concept and are shown in Table 3.4.

Name	**Value**	**Meaning**
redundancy.scheme	active passive standby	hot redundancy - all units always on cold redundancy - k units on and $n-k$ off k units on and $n-k$ standby
redundancy.type	internal external	redundant units all in a single package/box redundant units explicitly modeled in design
redundancy.k	integer ≥ 1	number of units needed for nominal operation
redundancy.n	integer $> k$	total number of units in the system

Table 3.4: Redundancy parameters
[36]

Taking into account the aforementioned considerations regarding duty cycle and redundancy, the average power (P_{mean}) and maximum power (P_{max}) are calculated as follows:

- If $P_{\text{duty\_cyc}} \neq -1$, external redundancy, passive scheme:

$$P_{\text{mean}} = \frac{r_k}{r_n} \cdot N \cdot (P_{\text{on}} \cdot P_{\text{duty\_cyc}} + P_{\text{stby}} \cdot (1 - P_{\text{duty\_cyc}})) \cdot \left(1 + \frac{PM}{100}\right)$$

$$P_{\text{max}} = \frac{r_k}{r_n} \cdot N \cdot P_{\text{stby}} \cdot \left(1 + \frac{PM}{100}\right)$$

- If $P_{\text{duty\_cyc}} \neq -1$, external redundancy, active scheme:

$$P_{\text{mean}} = \frac{r_k}{r_n} \cdot N \cdot (P_{\text{on}} \cdot P_{\text{duty\_cyc}} + P_{\text{stby}} \cdot (1 - P_{\text{duty\_cyc}})) + \left(\frac{r_n - r_k}{r_n} \cdot N \cdot P_{\text{stby}}\right) \cdot \left(1 + \frac{PM}{100}\right)$$

$$P_{\text{max}} = \frac{r_k}{r_n} \cdot N \cdot P_{\text{on}} + \left(\frac{r_n - r_k}{r_n} \cdot N \cdot P_{\text{stby}} \right) \cdot \left(1 + \frac{PM}{100} \right)$$

- If $P_{\text{duty\_cyc}} \neq -1$, internal redundancy:

$$P_{\text{mean}} = N \cdot (P_{\text{on}} \cdot P_{\text{duty\_cyc}} + P_{\text{stby}} \cdot (1 - P_{\text{duty\_cyc}})) \cdot \left(1 + \frac{PM}{100} \right)$$

$$P_{\text{max}} = N \cdot P_{\text{on}} \cdot \left(1 + \frac{PM}{100} \right)$$

N indicates the number of items while PM stands for Power Margin.
Figure 3.5 provides a schematic overview of all the steps and actions the SL must complete in COMET before the first session of the study.

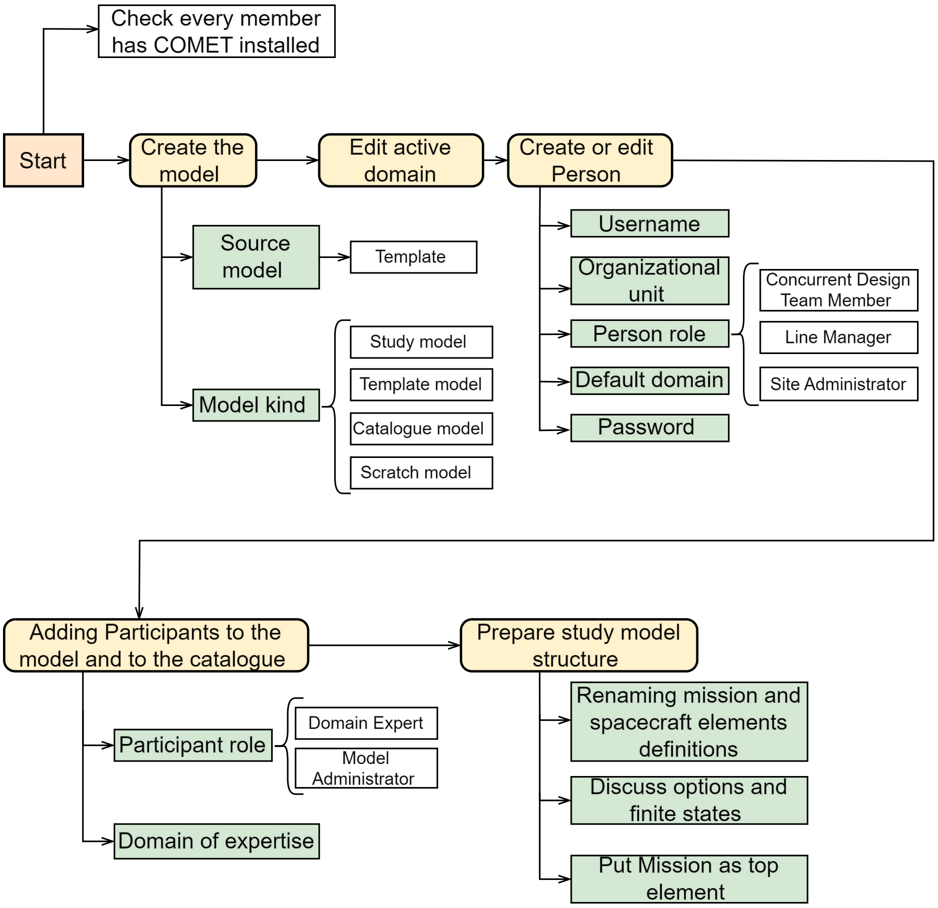


Figure 3.5: COMET set up workflow

3.2 Roles

This section describes the roles that constitute the *ACLab* team. Three main roles, present in every study, are identified along with a series of SMEs whose presence depends on the characteristics of the mission (e.g., EO, Telecommunication, etc.) and the maturity level of the study. The three main roles are:

- **Study Lead (SL)**: responsible for understanding the client's requests, preparing the study from team assembly to session planning to ensure that the predetermined objectives are met, and guiding the conversation during the sessions.
- **Lead System Engineer (LSE)**: responsible for overseeing the technical design of the mission, making engineering decisions, understanding the boundaries of the trade space to be explored, and managing the system budgets.
- **Assistant System Engineer (ASE)**: responsible for managing and implementing the technical tools (COMET, system budgets, Excel sheets, etc.) and handling all other technical aspects.

These roles represent the nucleus of the *ACLab* team. In addition to these, SMEs representative of each subsystem required by the study are included. They are responsible for performing more specific analyses within their respective domains. The number of domain experts varies depending on the type of study and on the expertise required. It often happens that one person covers more than one main role (e.g., serving as both SL and LSE), and almost always, they are also given ownership of one or more specific domains. This happens because, in a corporate setting, it is challenging to have a dedicated person for each domain available for the entire duration of the study, as they are often engaged in other projects. Therefore, the main roles of the *ACLab* team are typically covered by system engineers who also have a broad understanding of subsystem design. Additional support from SMEs can be requested, but usually for a limited period (e.g., 1-2 sessions), as will be discussed in the Chapter 4.

There is also a group named *Core Team*, responsible for managing and organizing studies. This group is the initial point of contact for clients looking to start a study. Currently, it consists of the team implementing the framework, and it will soon be responsible for promoting and disseminating the CE methodology within the company.

3.3 *ACLab* Methodology

The methodology presented here has undergone several iterations to ensure optimal adaptation to Argotec's corporate environment. It incorporates innovative elements by adopting an Agile approach, utilizing story points and task prioritization, and is supported by an AI-based tool to enhance information retrieval.

The *ACLab* methodology draws inspiration from NASA's methodology, which is based on CMLs which indicate the maturity level of a concept (see 2.1.1). In the context of *ACLab*, a similar scale is employed based on **Study Progress Levels (SPLs)**. Each SPL marks the achievement of a specific objective and a point in the design process where the results obtained up to that moment are consolidated. As this is the first instance of implementing a framework that applies CE, it is envisaged that the methodology presented will undergo further modifications and refinements over time, particularly as an increasing number of studies are conducted. Table 3.5 briefly describes the actions and the goals for each SPL.

SPL	**Description**	**Goal**
1	Consolidation of the study proposal with the client Definition of study objectives and constraints	Study proposal consolidated
2	Study preparation: tasks quotation, team assembly, sessions' planning Study presentation Mission objectives flowdown	Study planned (sessions scheduled, resources allocated) Mission objectives defined
3	FOMs (Figures Of Merit) selection Trade space exploration – concept push Trade-off analysis – concept pull	Trade space explored Mission concepts ranked/selected
4	Technical and programmatic analyses	Point design System budgets consolidation

Table 3.5: *ACLab* SPL description

To better organize the various activities and especially the people involved, the *ACLab* CE framework is also divided into phases in which the different SPLs are identified. An high level methodology is shown in Figure 3.6.

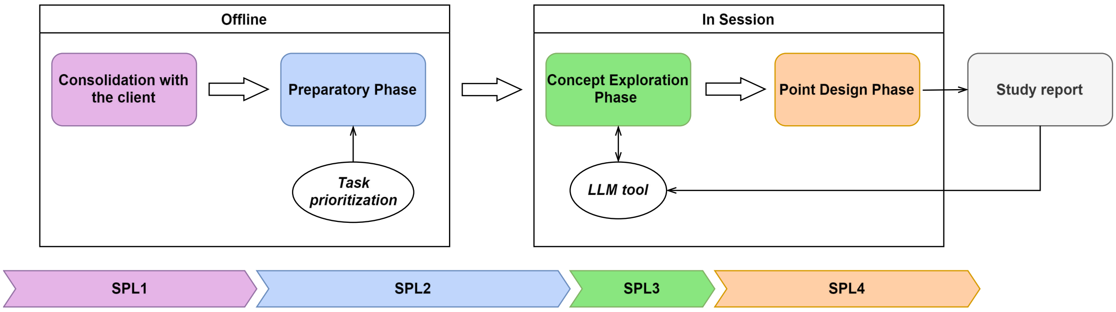


Figure 3.6: *ACLab* high level framework

3.3.1 Consolidation with the Client

Before starting the study, the *ACLab* workflow requires multiple iterations with the client to consolidate and clearly define the study objectives and constraints. This step is crucial for gaining a better understanding of the client's needs and avoiding studies with unclear objectives, which in the past have led to an overly broad solution space and inefficiencies within the company. To start a study, whether it originates internally within the company or from an external client, a specific submission form must be filled in. This form must include the following details:

- Mission scenario: class of the mission, class of the spacecraft, etc.
- Study objectives: required deliverables/output
- Study constraints: effort, output (starting and ending SPL of the study), and timeline

A SL is assigned once Argotec's management approves the study, considering factors such as the company roadmap. The objectives and constraints of the study are finalized through an iterative process with the client, culminating in the achievement of SPL1. The workflow differs between internal and external study requests: internal studies originate directly from Argotec's management, which automatically assigns a SL, while external studies require management approval before a SL can be designated. Throughout this process, the core team manages and coordinates the proposals but does not have a decision-making authority. A schematic of this process is shown in Figure 3.7.

During this phase, the AI-powered LLM tool finds its first application. The SL can use the developed tool to gather information to understand better the client's request, such as reviewing similar missions, before finalizing and initiating the study.

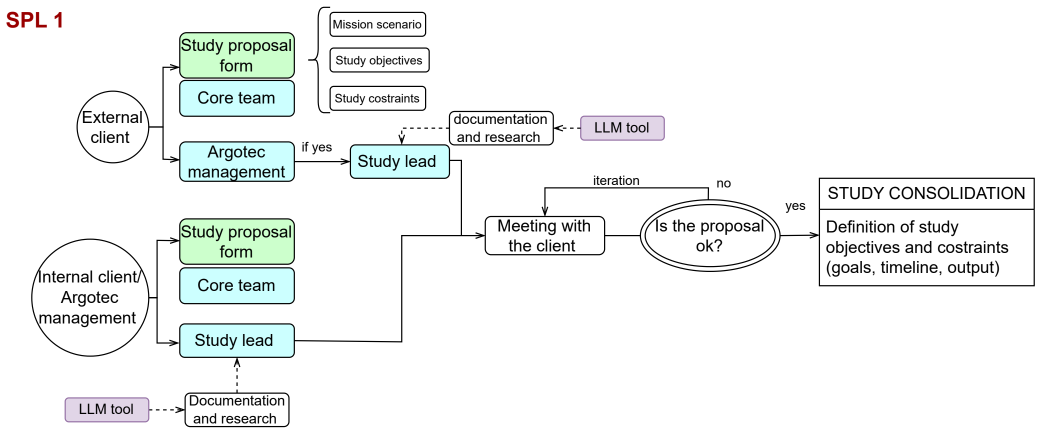


Figure 3.7: Consolidation with the client

3.3.2 Preparatory Phase

Once the study is approved, it moves to SPL2. The preparation of the study is delegated to the SL whose main tasks are:

- roles and DoEs identification;
- team assembly;
- session plan.

All the action required for the preparation of the study are summarized in Figure 3.8.

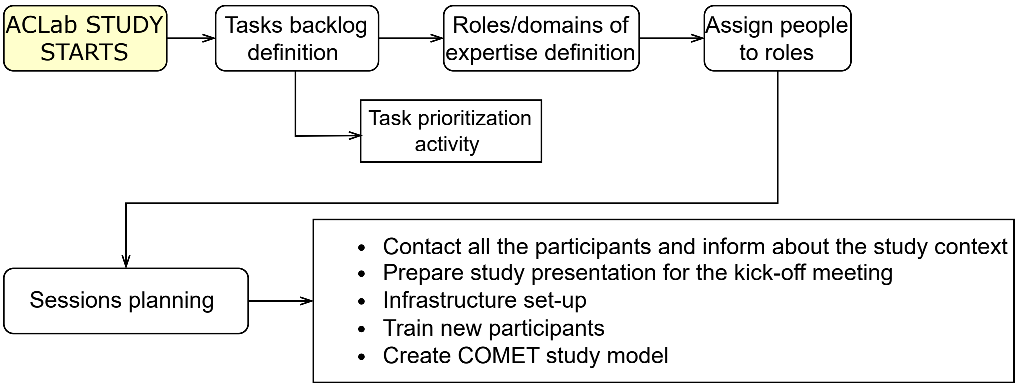


Figure 3.8: Preparatory phase actions

Before identifying roles and assembling the team, all the tasks required for the completion of the study are outlined in a backlog. This process is enhanced by a task prioritization activity, introduced in the Argotec CE framework inspired by Agile/SCRUM principles. It involves identifying and prioritizing tasks based on the required effort, ensuring appropriate allocation of time and resources for optimal session planning.

Task Prioritization in *ACLab*

The first integration of task prioritization into the *ACLab* is here presented. The task prioritization activity is conducted by the SL with the support of 2-3 other experts (typically system engineers), during a study pre-meeting. In this meeting, a backlog of tasks is compiled and reviewed. Then each team member has a limited amount of time (usually 1 minute) to assign story points to each task, considering effort, complexity, and associated risks as evaluation parameters. Story points can be assigned based on a scale from 0 to 100 (0, 0.5, 1, 2, 3, 5, 8, 13, 20 ,40, ...); this sequence is used because its non-linear increments help teams differentiate between task sizes, manage increasing uncertainty in larger tasks, and avoid prolonged debates over estimates. However, other scales such as the Fibonacci scale (1, 2, 3, 5, 8, 13, 21, 34, ...), the power of two scale (1, 2, 4, 8, 16, 32, ...) or the T-shirt size scale (XS, S, M, L, XL) can also be used. If the team disagrees with the story point allocation, a brief discussion follows, and voting is repeated until an agreement is reached. During this discussion, the opinions and viewpoints of the team members who assigned the highest and lowest scores are taken into consideration. This allows for the identification of any overlooked aspects, which may lead to a reassessment of the previously assigned points.

Figure 3.9: Task Prioritization - initial methodology

The process, represented in Figure 3.9, helps identify the most critical tasks and the areas which require a highest effort. Following the estimation process, the SL converts story points into session hours. This begins by defining the time needed to complete a task with the minimum story points, and then scaling that time proportionally for other tasks. For example, if a task with 0.5 story points takes 15 minutes, a task with 5 story points would take 7 hours and 30 minutes, and so on.

This conversion allows the SL to create a session schedule, assigning tasks to each session according to the estimated time needed for their completion.

3.3.3 Concept Exploration Phase

After all the preparatory activities described above, the design sessions can begin with the team assembled. Before the actual design work begins, the SL presents the study context to the entire team, outlining the design drivers and the expected outputs. Then the first activity consists of deriving and formalizing the mission objectives based on the inputs provided by the client. This is achieved through a flowdown process that typically includes an initial brainstorming phase followed by a reorganization and clustering of ideas. The formalization of the mission objectives marks the achievement of SPL2 and the transition to SPL3, which involves the exploration of the trade space and the selection of possible mission concepts.

Before proceeding with the concept push, which involves expanding ideas and exploring all possible solutions, the Figures of Merit (FoMs) are identified. These FoMs are used to compare and select the optimal concept, for this reason are defined priorly to avoid being influenced by past experiences or personal biases that might skew the decision towards a specific concept. The standard classes of figures of merit identified for each study include:

- technical feasibility;
- adherence to mission objectives;
- programmatic compliance.

Others can be added depending on the study.

The initial exploration of the trade space involves identifying key trade options that define the elements of the concept that can be expanded. The primary elements include mission architecture, which covers factors such as payload type, data products, satellite class, orbit class, and programmatic considerations like cost and schedule. Additionally, the concept push helps to identify potential critical aspects of the mission. Following the exploration of the trade space and the expansion of various concepts, a clustering is performed, grouping similar concepts to have a limited final list.

Then, the concept pull phase involves conducting a trade-off analysis, which, based on the previously chosen FoMs, results in the identification of an optimal mission baseline. The trade-off process involves assigning weights to the selected FoMs and then scoring each concept (for example on a scale from 1 to 5, where 1 indicates unfeasibility and 5 indicates complete feasibility) with respect to each specific FoM. Finally, the overall score for each concept is calculated as a weighted average, where the scores assigned to each concept for the various FoMs are weighted according to the importance of each FoM. The scores are then compared to identify the optimal concept. At this point SPL3 is completed. A summary flowchart of the concept exploration phase is shown in Figure 3.10.

Even during the trade space exploration, the LLM tool is useful for obtaining data to conduct initial analyses based on analogies with other missions and make quick estimates.

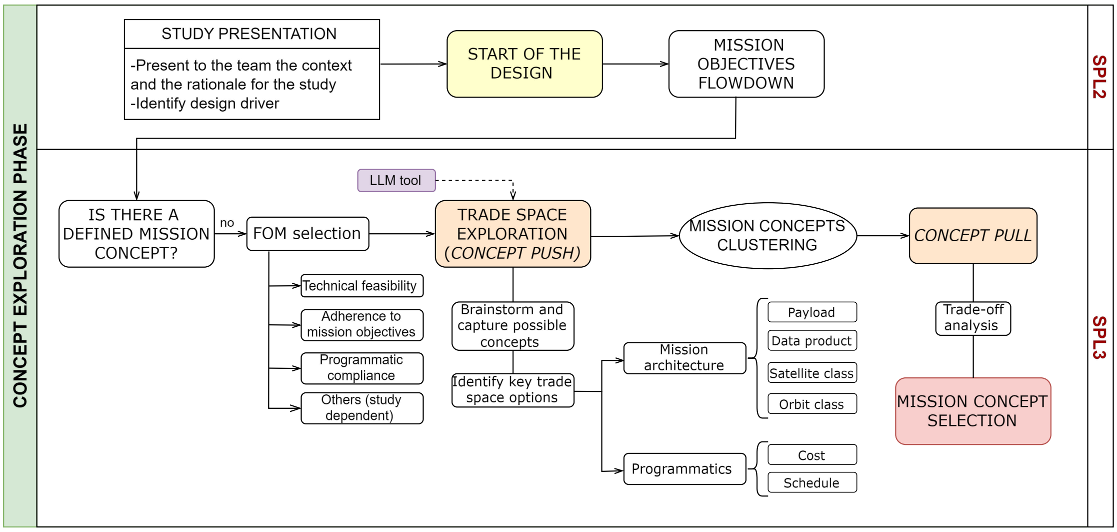


Figure 3.10: Concept Exploration phase

3.3.4 Point Design Phase

The Point Design Phase encompasses the SPL 4 and can be compared to the work carried out by Team X at JPL (2.1.3). This phase involves delving deeper into the technical design of subsystems, ideally requiring a more comprehensive team with an expert for each domain of expertise. However, assembling such a specialized team can be challenging in a corporate environment as stated in the Section 3.2. Initially, the design focuses on three aspects:

- ConOps
- Payload
- Mission analysis

These elements are considered priorities and serve as essential inputs for progressing with the design of various subsystems. Therefore, the team's initial effort is totally focused on these three elements. While the aspects mentioned above are identified as priority elements for a general study, other aspects may be prioritized depending on the specific study. For instance, in a telecommunications mission, the communication system design would likely be considered a priority. Subsequently, the design of the various subsystems proceeds concurrently, with each expert focusing on the design of the subsystem under its ownership.
Various budgets are calculated, and subsystem design iterations are conducted. Figure 3.11 shows this process with the various subsystems and the main connections between them (dashed line). At the end of each session, considerations regarding mass, power and volume, are made. If the design does not meet the initial requirements and constraints, design iterations are performed until all budgets are closed and the study objectives are achieved.

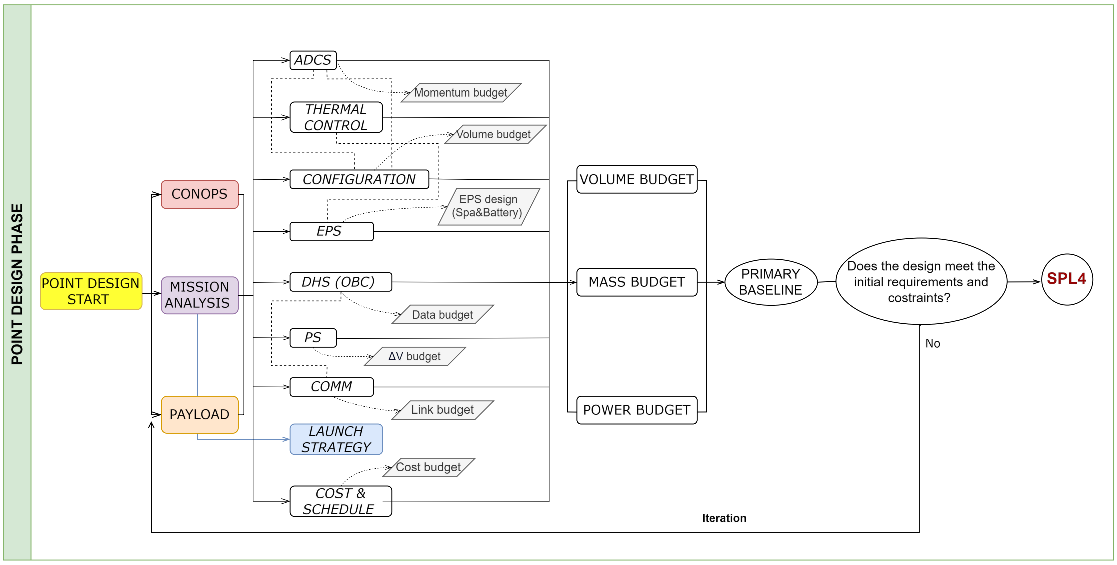


Figure 3.11: Point Design phase

At the end of the study, a final report is prepared and given in input to the RAG knowledge base of the LLM tool, keeping the model's knowledge up to date for future sessions.

Chapter 4

ACLab Validation: Case Study

The methodologies and tools presented in Chapter 3 have been validated through a case study involving a mission for a Near-Earth Asteroid (NEA) investigation using a CubeSat propelled by a solar sail. The objective is to conduct a Phase 0 feasibility study, primarily aimed at validating the work done in this thesis, while also holding significant scientific and technological value. The study of NEAs has become crucial for several reasons: planetary defense and space situational awareness, resource exploitation for sustainable long-term space exploration, and the acquisition of important scientific data for understanding the evolution of the solar system. Moreover, using a solar sail as a propulsion system presents a substantial technological challenge but offers a highly innovative solution. The solar sail leverages the Sun's radiation pressure as a driving force, which imposes no restrictions on ΔV. This provides greater flexibility in terms of trajectory planning and launch windows, ensuring the spacecraft can reach in any case at least one asteroid.

4.1 Study Overview

For this case study it was assumed that the *Core Team*, consisting of three system engineers, act as the client, defining the objectives and constraints of the study; as a result the study started with the SPL1 already achieved. The objective of the study is, therefore, the feasibility study of a CubeSat mission with the following characteristics:

- 6U/12U form factor
- solar sail propulsion;

- orbital and attitude control systems suitable for a CubeSat with a solar sail;
- autonomous navigation and control system;
- communication system suitable for the deep space environment ;
- CubeSat ensuring a long operational life in deep space;
- systems and subsystems capable of being mass-produced.

Some constraints were established at the beginning: the study must be completed within 36 session hours, divided into a kick-off meeting and 8 ACLab sessions, each lasting 4 hours while the required outputs of the study are a system design report and a technical requirements specification. Offline work may also be planned if necessary, either as preparation for the sessions or for tasks that do not require a concurrent execution.

4.2 Session Description

The following section will outline the activities carried out during each session, the results achieved, and the feedback received from the participants. A comparison will be made between the initial planning of each session and its actual execution. The overall results will then be discussed and analyzed in the next chapter. The sessions were conducted in the meeting rooms available in the Argotec headquarters since a dedicated facility is not yet available. However, all the meeting rooms are fully equipped with the necessary tools (smart boards, whiteboards, etc.) for this first case study.

4.2.1 Kick-off Meeting and Task Prioritization Activity

The study team is composed of three systems engineers from the R&D unit (the same members who make up the *ACLab* Core Team); this small number highlights the challenge of assembling a complete team within the corporate environment. As a result, each team member is responsible for multiple domains of expertise. For the type of mission under analysis, the Study Lead identified the following domains of expertise:

- AOGNC
- Configuration & Structures
- Communication
- Mechanism

- Mission Analysis
- On-board Control & Data Handling
- Payload
- Power
- Programmatics
- Propulsion
- Thermal

Table 4.1 provides an overview of the team and their respective roles. The domains were allocated according to each member's experience and availability, with an effort to group together the most interconnected domains.

Person	**Role(s) / Ownership**
Team Member 1	Study Lead Lead System Engineer Power Configuration & Structures Thermal
Team Member 2	AOGNC Propulsion Programmatic
Team Member 3	Assistant System Engineer Payload Telecommunication On-board Control & Data Handling Mission Analysis

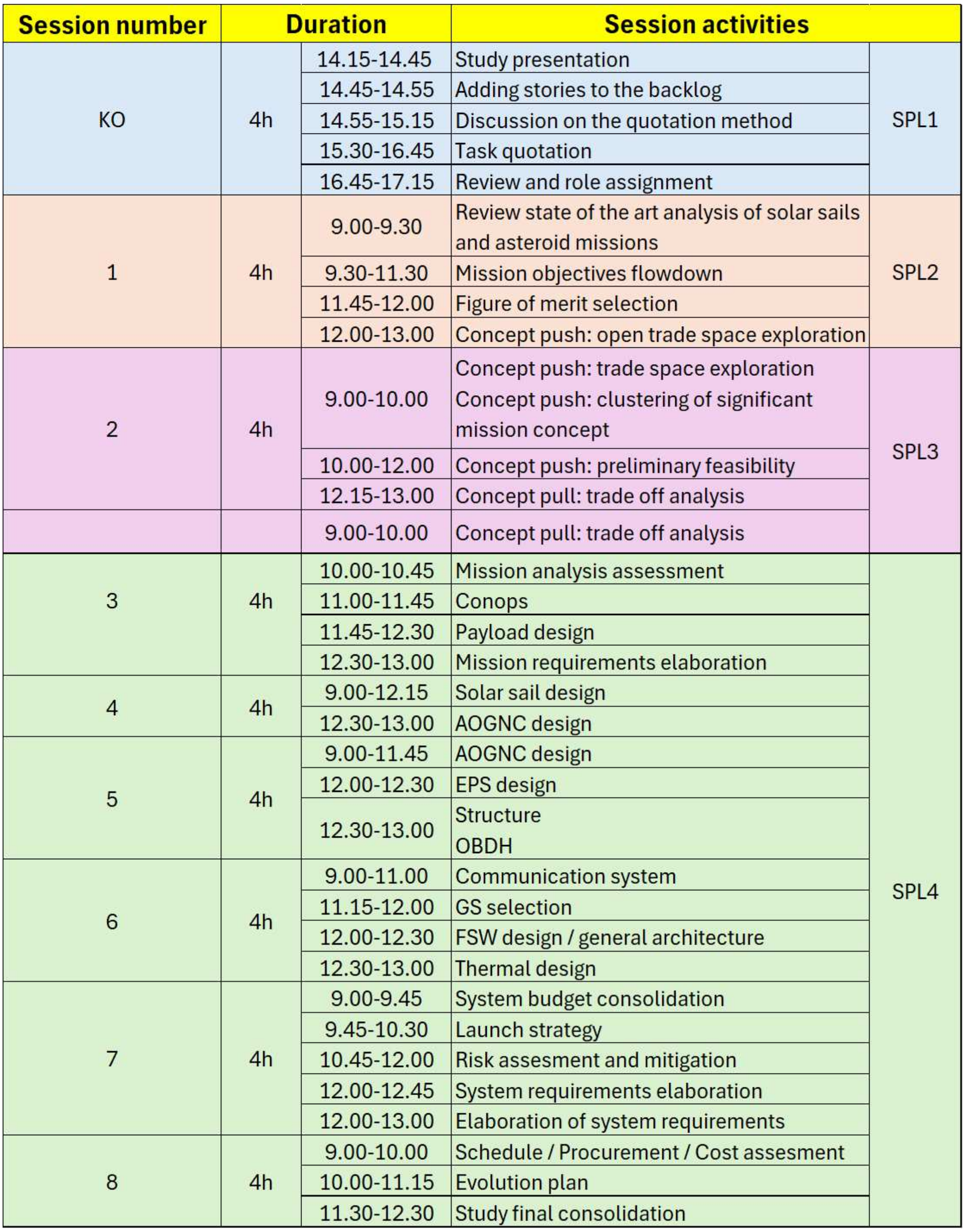
Table 4.1: Roles and Ownership within the team

During the kick-off meeting, the Study Lead presented the study's objectives and constraints to the other team members before moving on to the task prioritization activity. The latter began with a review of the task backlog, previously compiled by the SL, and followed by the assignment of story points to each task. Table 4.2 shows the task backlog along with the corresponding story points assigned to each task. Both tasks to be performed during the sessions and those to be completed offline outside of the sessions were considered. During the quotation process, a debate arose regarding the effort required for the mission analysis task, as the team lacked the resources and capability to perform a complete analysis, and it was uncertain whether it could be completed offline by another expert due to the lack of expert availability. Ultimately, a score was assigned that reflected the effort as if an expert were available to complete the work offline.

Tasks	**Story points**	**Type**
State of the art of solar sails/asteroid missions	5	Offline
Mission objectives flowdown	8	In-session
Figure of merit selection	0.5	In-session
Concept push: open trade space exploration	5	In-session
Concept push: clustering of significant mission concepts	1	In-session
Concept push: preliminary feasibility	8	In-session
Elaboration of mission requirements	3	Mixed (50% in-session)
Concept pull: trade-off analysis	5	In-session
Mission Analysis	80	Offline
ConOps	3	In-session
Solar sail design	13	In-session
AOGNC design	13	In-session
Communication system	8	In-session
EPS	2	In-session
Structure	0.5	In-session
OBDH	0.5	In-session
Configuration	8	In-session
Thermal	3	In-session
System budget (consolidation)	1	Mixed
Elaboration of system requirements	3	In-session
Study final consolidation	3	Mixed
Report writing	5	Offline
Payload definition	3	In-session
FSW design/general architecture	2	In-session
Risk assessment and mitigations	5	In-session
Schedule/procurement/cost assessment	8	Mixed
Evolution plan (activities, partners, gaps, technology maturation plan, distribution)	5	In-session
Launch strategy assessment	3	In-session
Ground Segment preliminary definition	3	In-session

Table 4.2: Task backlog and story points

After estimating the task effort, the SL developed a detailed schedule for the sessions (Figure 4.1), converting story points in hours required to complete each task.



Session number	Duration		Session activities	
KO	4h	14.15-14.45	Study presentation	SPL1
		14.45-14.55	Adding stories to the backlog	
		14.55-15.15	Discussion on the quotation method	
		15.30-16.45	Task quotation	
		16.45-17.15	Review and role assignment	
1	4h	9.00-9.30	Review state of the art analysis of solar sails and asteroid missions	SPL2
		9.30-11.30	Mission objectives flowdown	
		11.45-12.00	Figure of merit selection	
		12.00-13.00	Concept push: open trade space exploration	
2	4h	9.00-10.00	Concept push: trade space exploration Concept push: clustering of significant mission concept	SPL3
		10.00-12.00	Concept push: preliminary feasibility	
		12.15-13.00	Concept pull: trade off analysis	
		9.00-10.00	Concept pull: trade off analysis	
3	4h	10.00-10.45	Mission analysis assessment	SPL4
		11.00-11.45	Conops	
		11.45-12.30	Payload design	
		12.30-13.00	Mission requirements elaboration	
4	4h	9.00-12.15	Solar sail design	
		12.30-13.00	AOGNC design	
5	4h	9.00-11.45	AOGNC design	
		12.00-12.30	EPS design	
		12.30-13.00	Structure OBDH	
6	4h	9.00-11.00	Communication system	
		11.15-12.00	GS selection	
		12.00-12.30	FSW design / general architecture	
		12.30-13.00	Thermal design	
7	4h	9.00-9.45	System budget consolidation	
		9.45-10.30	Launch strategy	
		10.45-12.00	Risk assesment and mitigation	
		12.00-12.45	System requirements elaboration	
		12.00-13.00	Elaboration of system requirements	
8	4h	9.00-10.00	Schedule / Procurement / Cost assesment	
		10.00-11.15	Evolution plan	
		11.30-12.30	Study final consolidation	

Figure 4.1: Initial session planning

Feedback gathered after the kick-off meeting highlighted that the task estimation activity is quite time-consuming, both in terms of hours and number of people involved, in fact, it took 9 man-hours almost equivalent to an entire session; this clashes with CE's principles of time and cost reduction. To address this concern and optimize the resources involved in the activity, the team scheduled a test that was conducted after the study's conclusion, with the support of other experts, which will be explained in more detail in Section 4.3. Task prioritization proves to be very useful for identifying critical areas that require more effort and resource allocation. On the other hand, it was observed that converting story points into hours would likely not be very effective, as it doesn't support concurrent work and instead encourages sequential scheduling. Despite these doubts, the team chose to adhere to the initial schedule to evaluate its effectiveness in practice, as no better approach for planning the sessions based on story points had been identified.

4.2.2 Session 1

According to the schedule, the tasks to be completed in the first session were:

- review of the state of the art of solar sails and asteroid missions;
- mission objectives flowdown;
- FoM selection;
- concept push: open trade space exploration.

Session 1 began with a review of the current state of solar sail missions to asteroids. The mission closest to the one under study is NASA's *NEAScout*, which was used as a reference mission [37]. Next, the mission objectives were defined, divided into technological objectives related to demonstrating solar sail propulsion, and scientific objectives related to the asteroid survey.

The mission objectives are:

ID	Objective	Priority
TO-01	Integration of a solar sail in a 6U/12U CubeSat	
TO-02	In-space deployment of solar sail	
TO-03	Use of solar sail for controlled propulsion to reach a target asteroid	
TO-04	Demonstration of control technologies suitable for solar sail system	
TO-05	Demonstration of autonomous GNC for solar sail system	
TO-06	Demonstration of autonomous sail management techniques	Nice-to-have
TO-07	Having at least 6 m^2/kg of solar sail area to overall mass ratio	
TO-08	Validate solar sail propulsion models	Maximization*

Table 4.3: Technological objectives

ID	Objective	Priority
SO-01	Perform an asteroid flyby for scientific investigation	
SO-02	Perform multiple asteroid flybys for scientific investigation	Nice-to-have
SO-03	Characterize asteroid shape, size, rotational state	Maximization*
SO-04	Characterize surface morphology of the asteroid(s)	Maximization*
SO-05	Characterize surface topography of the asteroid(s)	Maximization*
SO-06	Characterize chemical and mineralogical composition of the asteroid(s)	Maximization*
SO-07	Characterize internal and bulk properties of the asteroid(s)	Maximization*
SO-08	Characterize dust/debris environment in the vicinity of the asteroid(s)	Maximization*
SO-09	Characterize orbital properties of the asteroid(s)	Maximization*
SO-10	Characterize thermal properties of the asteroid(s)	Maximization*

Table 4.4: Scientific objectives

TO-7 allows to have continuous opportunities in terms of trajectories, according to *NEAScout* analyses.

Maximization* indicates that not all of these objectives can be achieved simultaneously in a single mission. A trade-off is needed to select objectives that maximize the mission's success by achieving the highest possible number.

SPL2 is therefore completed after the elaboration of the mission objectives. Following that, the FoMs were identified and assigned weights (Table 4.5), and the concept push phase began with a discussion about the type of transfer, which is strongly linked to the presence or absence of an additional (chemical) propulsion system. The identified possible types of transfers are: tug, piggyback, or direct launch to points such as Second Sun-Earth Lagrange Point, Moon and directly to deep space. The discussion also included aspects regarding the spacecraft's attitude, the type of sail and the method of controlling the high torques generated.

FoM	Description	Weight
Technical feasibility	All technical budgets and analyses preliminarily show that the mission is feasible from a technical perspective	1/3
Adherence to mission objectives	All required technical and scientific objectives are met. The highest possible number of scientific objectives is achieved, with additional points awarded for fulfilling optional objectives	1/3
Programmatic feasibility	All preliminary analyses show that the mission is implementable in terms of schedule and budget	1/3

Table 4.5: Figures of Merit

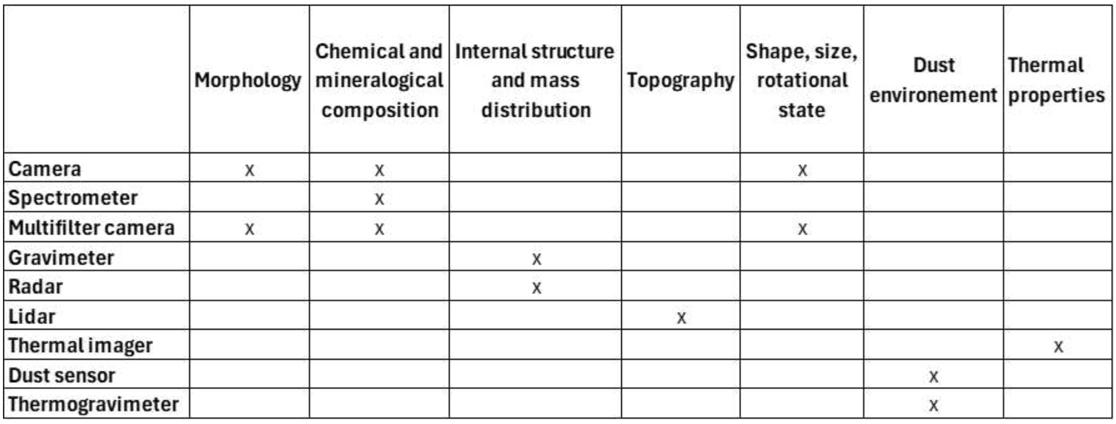
The activities carried out were consistent with the planned ones, and no critical issues emerged. It was therefore crucial that all participants remained engaged throughout the session.

4.2.3 Session 2

From the schedule, Session 2 included the completion of the following tasks:

- Concept push:
  - trade space exploration
  - clustering of significant mission concepts
  - preliminary feasibility analysis
- Concept pull first part: start of the trade-off analysis

Session 2 was conducted by only two team members (TM1 and TM3) due to the unavailability of the other member, who was occupied with another flight project. This once again highlights the challenges and limitations of conducting a CE study in a corporate environment. Despite this, the session proceeded as scheduled and was successfully completed by the remaining team members, as the planned activities did not require a division of the work across the various domains.
During this session, the team advanced the concept push by first analyzing the different types of payloads suitable for the mission, using data from previous asteroid missions as a reference. The focus was on evaluating how each payload could meet the previously defined mission objectives. Figure 4.2 shows the type of information each payload can gather during a flyby of the asteroid. For the main categories of payloads, a brief collection of data on mass, power, and volume was also compiled.



	Morphology	Chemical and mineralogical composition	Internal structure and mass distribution	Topography	Shape, size, rotational state	Dust environement	Thermal properties
Camera	x	x			x		
Spectrometer		x					
Multifilter camera	x	x			x		
Gravimeter			x				
Radar			x				
Lidar				x			
Thermal imager							x
Dust sensor						x	
Thermogravimeter						x	

Figure 4.2: Payloads capabilities overview

At this point, potential mission concepts were outlined, differing in: form factor (6U or 12U), inclusion or not of a chemical propulsion system for correction maneuvers and attitude control, and type of payload. The identified concepts are:

A. 6U s/c with propulsion, *NEAScout* like, 0.5U of payload allocation

  - **A1:** camera
  - **A2:** two gravimeters

B. 6U s/c without propulsion, up to 2U of payload allocation

  - **B1:** hyperspectral imager
  - **B2:** hyperspectral imager + camera
  - **B3:** thermal imager

C. 12U s/c with propulsion

  - **C1:** camera + 2 gravimeters
  - **C2:** hyperspectral imager

D. 12U s/c without propulsion

  - **D1:** hyperspectral imager + camera + gravimeter
  - **D2:** thermal imager

A gravimeter can be added in each concept as an option.

Initially, without further formal analysis, it was evident that a 6U CubeSat would be challenging to realize due to limited available volume, and would require a detailed feasibility study if pursued. For this reason, concept A was discarded as it seemed unfeasible to allocate propulsion system, sail and payload in a 6U form factor.

During the session, it was decided to conduct a preliminary technical feasibility analysis of a 12U concept, focusing on the calculation of the spacecraft's mass, power, and volume. Between the C and D configurations, C1 was chosen to maintain a more conservative approach, given the stricter weight and volume limitations imposed by the presence of the propulsion system. Data on the various subsystems and components were approximated based on information from similar missions or on the heritage of previous company CubeSat missions. This analysis was guided by "educated guesses" to complete it within the available time that will be further investigated offline or as the design progresses.

The concept push required more time than initially planned (4 hours instead of 3), which caused a delay in the schedule; in fact, the original plan included also starting the concept pull during this session. The delay can be attributed to the absence of a components database, which would have significantly reduced the time needed for information gathering, as well as the fact that it was the first time setting up a concept push with this new approach. To get back on schedule, offline work was assigned to complete the preliminary feasibility analysis of the other concepts and to try to make an assessment of the mission analysis in anticipation of the next session.

The overall results of the concepts preliminary analysis are reported in the following Table 4.6:

Concept	**Mass [kg]**	**Volume [U]**	**Average Power [W]**
B1	20.36	6.33	57
C1	28.5	12.75	101.7
C2	27.46	12.28	99.324
D1	27.94	11.78	105.174
D2	30.01	11.05	112.82

Table 4.6: Concepts preliminary feasibility analysis summary

4.2.4 Session 3

Session 3 involved the completion of the following tasks:

- concept pull second part: trade-off analysis conclusion;
- mission analysis considerations;
- ConOps definition;
- mission requirements elaboration.

Before proceeding with the trade-off analysis, there was a discussion on how to evaluate the programmatic aspects of cost and schedule. The cost of the various concepts was estimated using the parametric tool described in Section 3.1.1. However, it appears that the tool may overestimate the cost accounting for approximately \$43M for concepts C and D and \$37M for concept B. This overestimation may be due to the assumption of certain input parameters and the exclusion of some CERs from the calculation, as their inputs fell outside the range of their applicability.

The schedule, on the other hand, was considered by evaluating the following aspects:

- RTD: consider the time for research and technological development
- Engineering: consider the system complexity in the system design (e.g., having more subsystems is more onerous)
- Long lead items: consider the time for the component's procurement
- System test

To evaluate the schedule for each concept, a score from 1 to 5 was assigned based on its adherence to the aspects mentioned above, with 5 given to the best concept and the others scaled accordingly. This approach allowed for a ranking of the concepts from the best to the worst in terms of schedule.

After analyzing the technical and programmatic feasibility of each concept, a trade-off analysis was conducted. The previously identified FoMs include: technical feasibility, programmatic compliance, and adherence to mission objectives, each weighted equally at 1/3. Technical feasibility encompasses system budget closure and, for the case study at hand also how navigation is performed (concepts with an optical camera facilitate it). For the programmatic compliance, due to the unsatisfactory initial cost estimation, 90% of the 1/3 score assigned to the FoM will be based on the schedule aspect, while 10% will focus on cost.

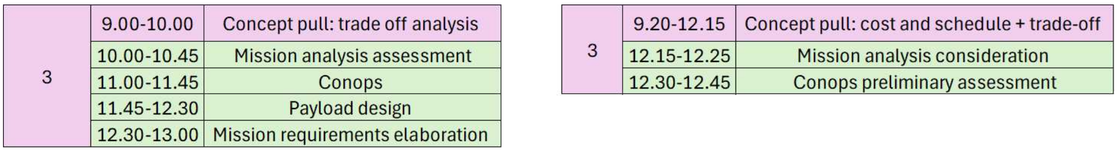
FoM	**Weight**	**B1**	**C1**	**C2**	**D1**	**D2**
Technical feasibility	0.33	1	3.5	3	2.5	1.5
Adherence to mission objectives	0.33	3	3.5	3.5	5	2.5
Cost	0.033	2	1	1	1	1
Schedule	0.3	5	3	3	4	4
Final score		**2.9**	**3.27**	**3.1**	**3.73**	**2.56**

Table 4.7: Trade-off results

The concept that emerged with the highest value from the trade-off is D1, closely followed by C1 and C2, while B1 and D2 are excluded due to both technical feasibility issues and their adherence to mission objectives. Although D1 proved to be the most valuable concept, a comparison between the D1 and C concepts was conducted. Concerns about the D1 concept regard the absence of a propulsion system. At this point in the design, it is unknown if it is feasible to have control laws based only on the sail and if all the spacecraft manoeuvres can be carried out by the sail. On the other hand, the C concepts are technically safer due to the presence of a propulsion system. For these reasons, it was decided to proceed with the analysis using concept C1, which has a higher score than C2. However, concept D1 is not completely excluded; its analysis is postponed until there is a better understanding of sail management and mission analysis. The main results of the trade-off indicate that the spacecraft will likely be a 12U size, with a preferred payload of a camera, spectrometer, or gravimeter. This point marks the completion of SPL3.

Lastly, the team member who had ownership of the mission analysis presented his assessment, highlighting that literature examples or other tools could not be used as references since they are based on impulse maneuvers. It was suggested that considerations from the *NEAScout* mission could be applied, demonstrating that it is possible to find a flyby opportunity given the defined sail area-to-mass ratio of 6 m^2/kg regardless of the launch date. Then the very last part of the session was devoted to a preliminary draft of the ConOps.

The evaluation of the programmatic aspects and the trade-off analysis consumed almost the entire time allocated for the session. Feedback from this session indicates that more time was spent on the concept pull than planned, particularly on the programmatic evaluation. This was largely because the cost analysis tool had never been used or validated before, and the parameters for considering the schedule had never been defined previously. Therefore, future studies are expected to be more time-efficient and align more closely with the planned schedule. Figure 4.3 illustrates the comparison between the planned activities and those that were actually carried out. The design of the payload and the development of the mission requirements were not completed during Session 3.



3	9.00-10.00	Concept pull: trade off analysis
	10.00-10.45	Mission analysis assessment
	11.00-11.45	Conops
	11.45-12.30	Payload design
	12.30-13.00	Mission requirements elaboration

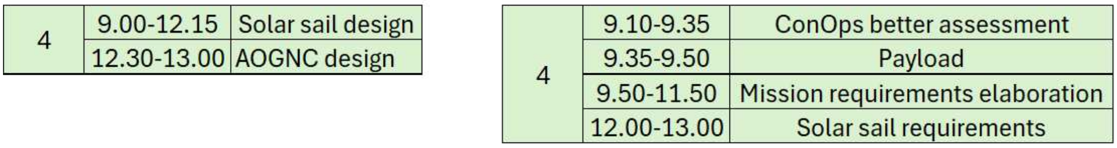
3	9.20-12.15	Concept pull: cost and schedule + trade-off
	12.15-12.25	Mission analysis consideration
	12.30-12.45	Conops preliminary assessment

Figure 4.3: Comparison of Session 3 planned and actual schedule

4.2.5 Session 4

Due to the delays accumulated in Session 3, the tasks that were not completed were carried over to Session 4, which was attended by only two team members. In the first part of the session, the ConOps were further refined, with a particular focus on the cruise and approach phases in preparation for the flyby. Additionally, the characteristics of the payload were briefly discussed. Following this, mission requirements were elaborated, and an additional tool was developed to calculate the target identification distance and maximum relative speed during the flyby. The tool's inputs are based on the flyby parameters (such as asteroid size, minimum number of pixels required for identification, and the time from the target identification to the end of the flyby) as well as camera specifications (including half-aperture FOV and pixel count). The preliminary sail requirements were also identified, which are still considered, at this stage of the design, at a high level of detail. Therefore, the focus was more on the requirements relevant to system design (such as mass, area, volume, solar reflectance, etc.) rather than on those concerning the actual sail system (such as material, deployment mechanism, control method, etc.). The preliminary ConOps and the mission and sail requirements are reported in the Appendices A.1 and A.2.

The progression of this session deviated significantly from the original plan, which was to focus on the design of the sail and the AOGNC system as shown in Figure 4.4.



4	9.00-12.15	Solar sail design
	12.30-13.00	AOGNC design

4	9.10-9.35	ConOps better assessment
	9.35-9.50	Payload
	9.50-11.50	Mission requirements elaboration
	12.00-13.00	Solar sail requirements

Figure 4.4: Comparison of Session 4 planned and actual schedule

This session also marked the point where it became clear that this approach of planning sessions was not effective. Up until SPL3, during the Concept Exploration Phase, session planning logic was effective because the entire team worked on the same tasks, regardless of assigned roles, as the sessions focus on expanding concepts and ideas. On the contrary, the process of converting story points into session hours was found to be inefficient for tasks in SPL4, in fact, it diminishes the ability to perform activities concurrently. Creating a session schedule based on the hours allocated to tasks almost inevitably leads to planning the session design process sequentially or otherwise inefficiently. For example, Figure 4.5 shows how the planning for Sessions 4, 5, and 6 involves a sequential execution of activities without a concurrent division of work among the team members.

Session 4	9.00-12.15	Solar sail design
	12.30-13.00	AOGNC design
Session 5	9.00-11.45	AOGNC design
	12.00-12.30	EPS design
	12.30-13.00	Structure OBDH
Session 6	9.00-11.00	Communication system
	11.15-12.00	GS selection
	12.00-12.30	FSW design / general architecture
	12.30-13.00	Thermal design

Figure 4.5: Session 4, 5, and 6 schedule

For this reason, starting from Session 5, the focus shifted from completing specific tasks in each session to achieving broader goals. The initial plan was still useful in identifying which subsystems were a priority in the design, as the small team could only parallelize the design of a few subsystems at a time. The role of task prioritization, therefore, was to identify, through the quotation, which areas required the most effort. This major effort could be translated into more time dedicated by the team or in the allocation of additional resources for a limited time (e.g., 1 session) necessary for the execution of the task.

4.2.6 Session 5

As discussed above, the new approach defines the goals to be achieved in the session rather than specifying the time allocated to each task. Following this logic, the goals that the SL outlined for Session 5 were:

- finalization of the sail's requirements;
- first iteration of the subsystem design, including a draft of the system budgets and the identification of any potential gaps.

At this point, the estimation of story points was used to identify critical areas that required additional support in the design process. For these areas, SMEs were engaged starting from Session 5 to assist with the design. The critical areas identified were: AOGNC, Telecommunication, Configuration, Mission Analysis, and Cost; a SME for each area of interest was found available. The threshold for requesting a SME support was set at 8 story points (see Table 4.2) for the tasks to be conducted in SPL4. During Session 5 a SME supported the mission analysis, the area with the highest story point allocation. The SME presented a first assessment conducted offline and also helped the rest of the team review and add requirements for the sail.

Then the team entered the Point Design phase (SPL4), which involved the first iteration of subsystem design; the COMET tool was introduced, and domain responsibilities were distributed as initially defined among the team members. Various tools previously described, such as the Momentum Budget Tool and Configuration Tool, proved useful in this phase. The goal of this first design iteration was also to identify the critical points of each subsystem, which would be addressed in the next session with additional SME support.

The initial use of COMET in the session was quite successful, though a bit of training on the program is needed to make its use more fluent and efficient. A preliminary version of the component database had already been created within COMET, which proved valuable for extracting data and simplifying searches during the study. This database, which is an essential element in a CE session, is continuously updated as new components are considered throughout the study or through other projects.

Feedback highlighted the need to better understand how to truly approach the design in a concurrent way and how to interact efficiently throughout the different domains. What proved helpful was reviewing the outcomes from the various domains at the end of the session, which allowed the team to track progress and better understand how to iterate. Given the new approach, based on setting goals at the beginning of each session, it is no longer possible to directly compare the initial schedule with the actual one, but the goals achievement can still be evaluated: in this session, all the set goals were achieved.

4.2.7 Session 6

For Session 6, the core team of three system engineers was joined by two SMEs: a TLC engineer and an AOGNC engineer, who participated respectively for 3 and 4 hours. The goals set for this session were:

- second iteration of the system design;
- consolidation of the system budgets.

The entire session was dedicated to the design of the subsystems. Not all the subsystems were analyzed during the session, the design focused on: ADCS, Communication, Propulsion System, and EPS. The main results of these subsystems design can be found in the Appendices A.3, A.4, A.5 and A.6 . By the end of the session, the system budgets were not fully finalized, meaning the goal was only partially achieved, particularly with regard to the sizing of the attitude control system. The ADCS design became more complex due to the presence of the sail, necessitating further analysis outside the session to determine how to manage higher torques and perform the slew maneuver during the fly-by. The analysis of the Telecommunication system was completed by verifying the link budget across various configurations. The Thermal system and the spacecraft configuration were not covered in this session and were briefly addressed in the following session. Additionally, during a short segment of the session, the mission analysis SME presented the final results of the offline research on the mission transfer strategy. The conclusion is that it would be optimal to have a trajectory that allows for Earth escape, for example through a dedicated launch with $C3 > 0$ (indicating the energy required for escaping Earth's gravity), or via a rideshare to the Second Sun-Earth Lagrange Point (SEL2), reducing transfer time.

4.2.8 Session 7

The goals set for Session 7 were:

- system design consolidation and budget closure;

- risk assessment closure;
- elaboration of system requirements.

To complete the system design, considerations regarding the spacecraft configuration and thermal analysis were still needed. Therefore, a SME was engaged for 2 hours during this session. The first part of the session was dedicated to reviewing the design of all subsystems, highlighting critical points and unresolved issues. The team then focused on high-level considerations regarding the spacecraft configuration and thermal design. Although these are crucial aspects, they will be more thoroughly analyzed in a potential future Phase A of the project, with additional analysis. Overall, the proposed configuration is similar to that of *NEAScout*, with the sail stowed in the central part of the spacecraft, separating the propulsion system from the avionics and payload [38]. Various alternatives were considered, including the possibility of placing part of the avionics between the propulsion system and the sail for thermal reasons. However, no significant issues were found with the thermal system, but it will be necessary to assess, in future phases, how the sail affects the spacecraft's thermal environment and heat dissipation. At the end of the technical design, the spacecraft achieved a wet mass of 34.4 kg, an average power of 60W, and a volume of approximately 12.6 U (more detailed budgets can be found in the Appendix A.9).

After finalizing the technical design of the spacecraft, the system engineers focused on identifying mission risks, categorized into operational, design, and technological risks (Appendix A.8). Each engineer then elaborated the initial system requirements for their respective subsystems.

The goals set for this session were achieved. From the feedback collected, it was noted that the configuration and thermal analysis could have been conducted concurrently with the design of other subsystems in the previous session. This was not feasible due to the limited number of participants and the availability of SMEs. This situation highlights the challenges of conducting a study in a corporate environment and the need for flexibility in planning and executing sessions.

4.2.9 Session 8

The following goals were set for the last session:

- schedule/procurement/cost assessment;
- evolution plan;
- study final consolidation.

For the cost, schedule and procurement aspects, support from a SME has been requested. The initial cost analysis was carried out using the parametric tool previously described, which was also employed during the preliminary feasibility analysis of the various concepts (Session 3), despite some identified issues. The tool's inputs were updated, taking into account the various analyses conducted in the interim, and even inputs that were slightly out of scale were included in the calculation. The resulting estimate was \$29M, lower than the previous estimate of \$37M, which appeared more accurate and consistent. This indicates that it is crucial to consider all inputs and CERs, even those slightly out of scale, to achieve a more accurate cost estimation.

In addition to this estimate, a further analysis was conducted using a different tool developed by the reference SME, which also incorporates the project schedule. This tool allocates costs across various phases (Phase A, Phase B, etc.), detailing the duration of each phase and calculating the total costs for manpower, hardware, and services. For manpower cost calculations, the input required is the number of FTEs (Full-Time Equivalents) for each design section (e.g., system engineering, software, science, etc.), while hardware and service costs are directly specified. One of the main challenges encountered when using this tool was obtaining data on hardware costs, underscoring the need for an updated and well-structured company database of components. Due to the lack of data on some component costs, the completion of the cost estimate had to be deferred for offline work. The mission cost derived from this tool was \$29.8M, which is consistent with the cost calculated using the parametric tool. This result demonstrates that both tools are valuable for preliminary mission cost estimation. The second tool provides visibility into the various phases of the project and is based on absolute values rather than CERs, which can vary and not be applicable depending on the type of mission and spacecraft.

After the cost analysis, a technology maturation plan was compiled for the various phases, with the sail design progressing ahead of the other subsystems' designs, as it is the most critical system. For example, in Phase B, the plan includes the consolidation of the sail design and the start of component testing. In contrast, for the payload and other subsystems, Phase B includes design consolidation if produced, or procurement if purchased.

Due to the considerable time required for the cost analysis, a final consolidation of the study was not conducted. In general, the technical consolidation of the design had already been completed earlier; only the final analysis and considerations for the programmatic and schedule aspects need to be concluded. At the end of the study, an offline study report was prepared, compiling all the results and analyses from the design. The study can not be considered complete until a final report is written.

4.3 Task Prioritization Test

As previously described in the validation study, the task quotation activity was carried out by the three members who also participated in the study sessions (Section 4.2.1). Based on the quotation, the SL planned the activities to be performed during the different sessions. However, the quotation activity proved to be very time-consuming, requiring more than 9 man-hours (3 participants for 3 hours). To reduce time and effort, it was suggested that the activity could be performed solely by the SL. However, this approach would eliminate discussions among participants and the opportunity to consider multiple viewpoints and areas of expertise, which typically contribute to a more objective evaluation of task effort.

To evaluate whether it is more effective to perform the task quotation in a small group or individually by the SL, a test was conducted with five system engineers from the company who had not participated in the previous validation study and were completely external to it. Of these five engineers, three worked as a team, while the remaining two completed the test individually. The division into teams took into account the participants' level of experience, allowing those with more experience to work independently. Each team was asked to perform the task prioritization and planning activity on the same case study described earlier. The teams began by compiling the task backlog, then estimating the task effort using story points, and finally planning the activities, all within a 4-hour timeframe.

The following constraints were given to the teams:

- use a maximum of 10 sessions, each lasting 4 hours;
- allocate three people to participate in all study sessions, whose domain of expertise is to be defined;
- plan for the eventual presence of additional SMEs for up to 35 man-hours;
- plan for eventual individual offline work for up to 35 man-hours.

Individual participants were allowed to consult other employees within the company (excluding members of the other teams) to gather additional information about the effort required for certain tasks on which they lacked direct knowledge or visibility. An Excel file was prepared to collect the required outputs: the task backlog with the corresponding effort estimates, the session plan with goals, activities, and participants listed for each session, and a log for individual participants, documenting the experts they consulted, the nature of their inquiries, and the approximate time spent on each consultation.

A few days before the test, participants were given an overview of the CE approach, the *ACLab* methodology, and the test rules. Instead, the mission scenario, study constraints and group divisions were revealed on the day of the test to prevent any preparation or consultation among team members. The test rules included no interactions within teams, no interactions with the people involved in the already concluded *ACLab* study and no preparation.

Chapter 5

Results

5.1 Study Results

This chapter summarizes the main results obtained at the conclusion of the study. The initial objective, which required a Phase 0 feasibility study of the mission, was achieved within the predetermined timeframe, and the required outputs (system design report and technical requirements specification) were also delivered. The study was finished over the course of all 8 planned sessions, with additional offline work used both for tasks initially scheduled to be done offline, such as mission analysis, and to finish activities that were not completed during the sessions. A summary of the man-hours spent on the study is shown in the Table 5.1.

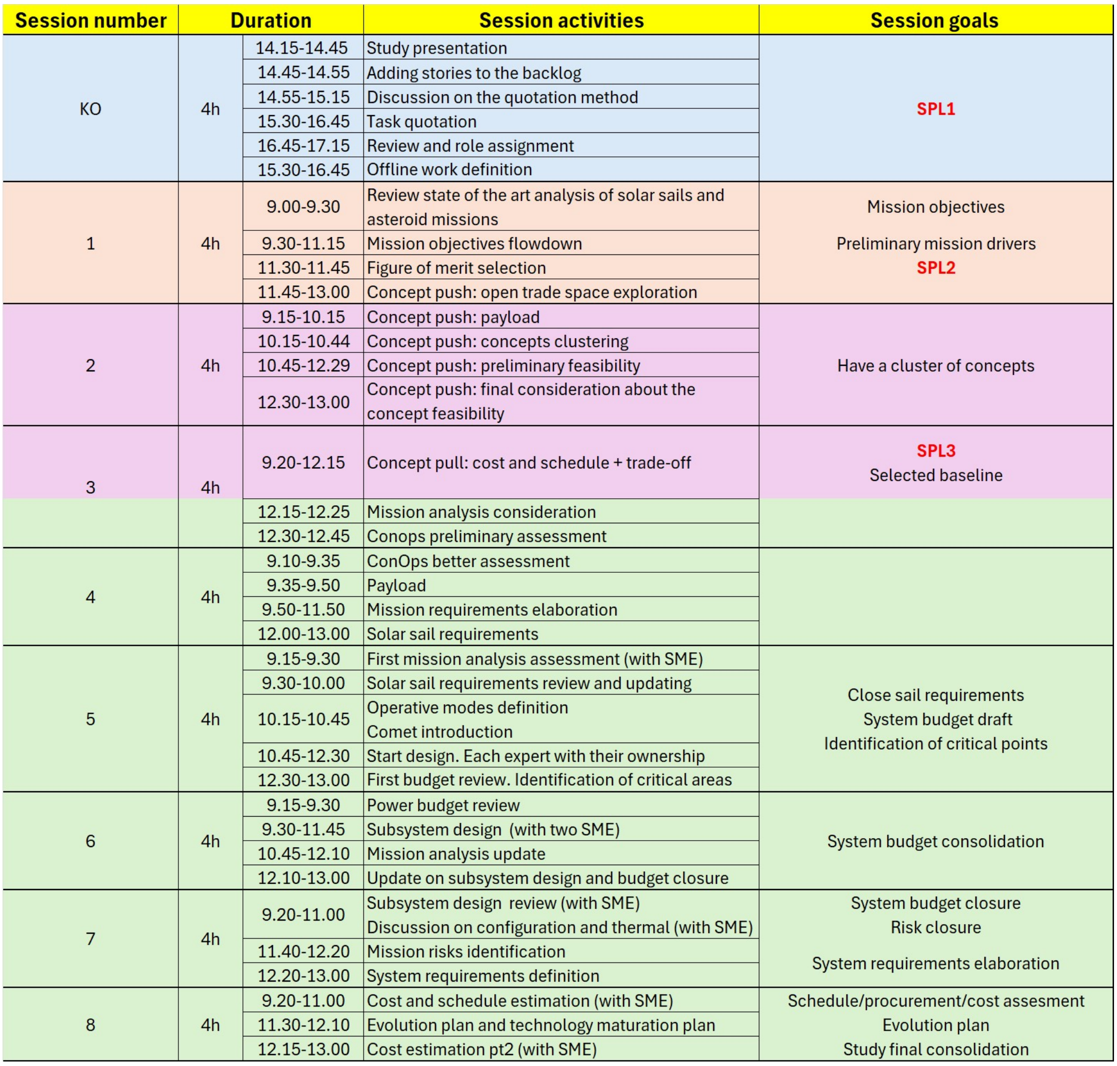
	TM1	TM2	TM3	SMEs	**Total**
Hours in-session	34	26	34	13	**108**
Hours offline	19.5	3	4	7	**33.5**

Table 5.1: Study hours summary

The SMEs provided support during the last four sessions of the study, with the following contributions:

- mission analysis in Session 5 for 1 hour, plus 5 hours of offline work;
- AOGNC in Session 6 for 4 hours, plus 2 hours of offline work;
- TLC in Session 7 for 3 hours;
- configuration and thermal analysis in Session 7 for 2 hours;
- cost analysis in Session 8 for 3 hours.

One of the study's main results arises from the comparison between the originally planned schedule (Figure 4.1) with the one that was actually carried out (Figure 5.1). It is evident that up until SPL3, completed during Session 3, the two schedules are similar, with only minor delays between sessions. However, significant differences arise in SPL4 during the Point Design phase, making the two schedules no longer comparable. As previously mentioned, the issue with the initial schedule stemmed from an inefficient method of planning sessions based on story points. Converting story points into the hours required to complete a task works well if the task does not belong to a specific domain and all participants are involved in its completion; this approach was successful up to SPL3 during the Concept Exploration activities.



Session number	Duration		Session activities	Session goals
KO	4h	14.15-14.45	Study presentation	**SPL1**
		14.45-14.55	Adding stories to the backlog	
		14.55-15.15	Discussion on the quotation method	
		15.30-16.45	Task quotation	
		16.45-17.15	Review and role assignment	
		15.30-16.45	Offline work definition	
1	4h	9.00-9.30	Review state of the art analysis of solar sails and asteroid missions	Mission objectives Preliminary mission drivers **SPL2**
		9.30-11.15	Mission objectives flowdown	
		11.30-11.45	Figure of merit selection	
		11.45-13.00	Concept push: open trade space exploration	
2	4h	9.15-10.15	Concept push: payload	Have a cluster of concepts
		10.15-10.44	Concept push: concepts clustering	
		10.45-12.29	Concept push: preliminary feasibility	
		12.30-13.00	Concept push: final consideration about the concept feasibility	
3	4h	9.20-12.15	Concept pull: cost and schedule + trade-off	**SPL3** Selected baseline
		12.15-12.25	Mission analysis consideration	
		12.30-12.45	Conops preliminary assessment	
4	4h	9.10-9.35	ConOps better assessment	
		9.35-9.50	Payload	
		9.50-11.50	Mission requirements elaboration	
		12.00-13.00	Solar sail requirements	
5	4h	9.15-9.30	First mission analysis assessment (with SME)	Close sail requirements System budget draft Identification of critical points
		9.30-10.00	Solar sail requirements review and updating	
		10.15-10.45	Operative modes definition Comet introduction	
		10.45-12.30	Start design. Each expert with their ownership	
		12.30-13.00	First budget review. Identification of critical areas	
6	4h	9.15-9.30	Power budget review	System budget consolidation
		9.30-11.45	Subsystem design (with two SME)	
		10.45-12.10	Mission analysis update	
		12.10-13.00	Update on subsystem design and budget closure	
7	4h	9.20-11.00	Subsystem design review (with SME) Discussion on configuration and thermal (with SME)	System budget closure Risk closure
		11.40-12.20	Mission risks identification	System requirements elaboration
		12.20-13.00	System requirements definition	
8	4h	9.20-11.00	Cost and schedule estimation (with SME)	Schedule/procurement/cost assesment Evolution plan Study final consolidation
		11.30-12.10	Evolution plan and technology maturation plan	
		12.15-13.00	Cost estimation pt2 (with SME)	

Figure 5.1: Effective session schedule

In contrast, during SPL4 the planning method proved ineffective. The tasks were scheduled to be executed sequentially, preventing the concurrent approach in which experts work simultaneously on the design of their subsystems. A possible solution could be to adopt parallel task planning, continuing to convert story points into hours, even if they require different amounts of time to be completed. However, this approach might not be effective, as tasks with different durations make it difficult to efficiently manage the work. It was ultimately concluded that this conversion method is not ideal, even for the Study Lead responsible for organizing the sessions. With a detailed and fixed schedule, it is difficult to stick to the plan, as potential changes that may arise are not taken into account. For all these reasons a more flexible methodology is needed.

During the execution of the case study, a more optimal method for the task prioritization activity was identified, as shown in Figure 5.2, keeping the initial task quotation unchanged. Task quotation proves useful in pinpointing the most critical areas that require increased time or resource allocation, such as engaging a SME for a duration proportional to the story point value. This approach is particularly beneficial in corporate environments where assembling a complete team to cover all areas of interest, for the entire duration of the study, is often challenging. The case study demonstrated that the areas identified as most critical during the estimation process indeed proved to be so. Moreover, this new approach allows session planning to focus on the goals to be achieved by the end of each session, without relying on the previous method of converting story points into hours necessary for task completion. The task estimation helps to fine-tune those goals based on the required effort. Conducting sessions based on achievable goals makes the methodology more flexible and adaptable, especially when participants need to cover multiple domains. A flexible methodology is also essential given the evolving needs and demands of clients and the involvement of potential external partners. This revisited approach was applied in the second half of the study (from session 5 to 8) and proved more efficient and easier to conduct, in fact all goals set for the sessions were achieved.

Figure 5.2: Task Prioritization - final methodology

Another finding highlights that the tools developed during the framework implementation were useful in the sessions, where they were tested and refined according to the needs that emerged. The study also revealed the lack of some tools, leading to the creation of new tools including one for single-node thermal analysis, flyby velocity calculation, and cost estimation. Lastly, one of the most frequently raised issues during the sessions was the lack of a comprehensive component database: implementing such a database would significantly reduce time and allow to focus more on the actual design process.

To summarize, the final methodology envisages always the division of the design process into SPL to track the progress of the study. After the study consolidation with the client, the task prioritization activity allows for identifying the most critical areas for a better allocation of time and resources. The work sessions are then divided into two parts: the first dedicated to the generation of ideas and concepts exploration, and the second to the point design of the various subsystems. Future mission studies, especially Phase 0 ones, are expected to be conducted by a small group of participants, with each person responsible for the design of more than one domain. Additionally, SMEs are involved depending on the areas identified as most critical through to the task prioritization activity.

5.2 Task Prioritization Test Results

Following the test introduced in Section 4.3, the outputs collected were analyzed and evaluated by the three members of the *ACLab* core team. All teams submitted the required outputs within the appointed time and immediately after the test, a debriefing was held with the participants to gather feedback, identify any challenges or difficulties encountered, and provide a brief explanation of the test's objective. The analysis of the results was conducted based on five evaluation criteria, each with a relative weight (Table 5.2). Each of the three evaluators assigned scores on a scale from 1 to 10. The scores shown for each criterion under the columns Team A, Team B, and Team C in the Table 5.2, correspond to the arithmetic average of the scores given by the three evaluators. Team A is the team that performed the test in a group of three people, while Teams B and C worked individually. The final score is a weighted average based on the importance assigned to each criterion. The highest weight was given to criterion C4, as it evaluates how the study was planned, which is considered the most important output. Lower weights were assigned to criteria C3 and C5, as they are more challenging to assess objectively and tend to vary significantly depending on how each team worked, while criteria C1 and C2 were considered of medium importance.

Evaluation Criteria	**Relative weight**	**Team A**	**Team B**	**Team C**
C1: Task backlog completeness compared with the case study	1	8.67	5.83	7.67
C2: Any improvements compared with the case study	1	7.33	6.33	8
C3: Task quotation compared with the real effort required in the case study	0.8	6.33	5	8
C4: Session planning compared with the case study actual plan	1.2	8	8.17	6.83
C5: Alignment between task backlog, quotation and session planning	0.8	8.17	7.83	7.67
	Weighted average	**7.75**	**6.75**	**7.58**

Table 5.2: Teams evaluation

The scores assigned to criteria C4 and C5 were not given through an objective comparison of the data but rather in a more subjective manner, considering various factors. For criterion C4, the factors considered included the alignment between the planned activities and the case study real activities, the consistency between the tasks performed and the SMEs involved, the adherence to the *ACLab* workflow (mission objectives flowdown, concept push, concept pull, etc.), and whether the activities were planned considering a concurrent approach. Criterion C5 was much more challenging to evaluate; in this case, the allocated story points for each session with the involved SMEs were compared to check for a correlation between the areas identified as most critical in the task estimation and the allocation of time and resources in the planning.

The results show that all teams delivered satisfactory outcomes, with the scores overall aligned. The team with the highest score is Team A, closely followed by Team C, which achieved a very similar score. Analyzing the graph (Figure 5.3), which highlights in red the range between the highest and lowest scores assigned by the evaluators, it is clear that Team A's scores remained consistently similar across all evaluators, indicating low variability, while Team C exhibited a higher variability range. Team A performed better than the others in criterion C1, which measures the completeness of the backlog, demonstrating how teamwork allows for a broader consideration of various aspects, thanks to the diverse experiences and backgrounds of the team members. In contrast, for criteria C2 and C3, one individual team (Team C) performed better than the group while for criterion C4, Team B achieved the highest score. Finally, the results for criterion C5 are, on average, comparable. Although Team B has the lowest overall score, it stands out for achieving a higher score in criterion C4 (the one with the highest weight), which refers to session planning activities. Its lower performance is primarily due to less effective backlog compilation and task estimation. It was not possible to assess the effectiveness of any potential external support because both teams that worked independently (Teams B and C) either did not request support or, if they did, did not receive a response to their requests within the four hours allocated for the test.

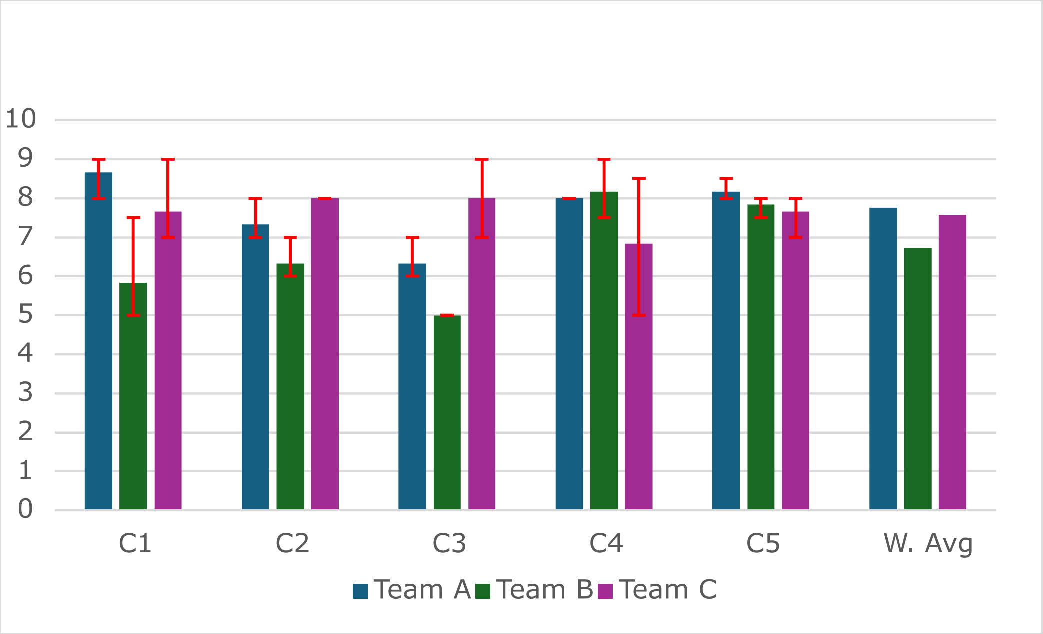


Figure 5.3: Teams evaluation results

Overall, the test data indicate that performing this activity in a group is more efficient, however, the results achieved by the individual teams should not be underestimated, as they remain competitive with those of Team A. This suggests that, with the same resources, the task quotation activity and session planning could be effectively managed by a single person, typically the Study Lead, with additional support potentially provided for backlog completion and review of the work done.

It is important to note that the results of this test should not be considered absolute, as there was no statistically significant sample size to draw definitive conclusions, and the outcomes are highly dependent on the participants' experience. Nonetheless, the test was valuable in understanding how others approached the same problem and in providing insights to improve task prioritization activities. Assigning this activity to a Study Lead with strong expertise would likely lead to even better results. In this test, it was not possible to involve more experienced participants, but there are plans to do so in the future to gather additional data samples and establish another parameter for comparison.

Chapter 6

Conclusions and Future Improvements

At the conclusion of the work, an evaluation was conducted to determine whether the objectives set at the beginning of the thesis were achieved.

	Objective	**Accomplished**
1	Create a first MVP of the *ACLab*	Yes
2	Implement a flexible methodology tailored to a corporate environment	Yes
3	Develop and integrate mission design tools	Yes
4	Integrate a task prioritization approach inspired by Agile methodology like SCRUM	Yes
5	Integrate a LLM tool to support information retrieval	Partially

Table 6.1: Summary of objectives achieved

All the objectives set for the development of this thesis have been successfully achieved with satisfactory results (Table 6.1). The first MVP of a CE framework, named *ACLab*, was created as set by Objective 1; this framework includes a series of methodologies and tools, tested through a case study, aimed at delivering valuable and efficient space mission designs in the early project phases, helping to save both time and resources. The developed methodology was specifically adapted to the Argotec corporate environment (Objective 2), which presents different constraints compared to traditional CE contexts. These include the inability to have a full team with an expert for every domain, the management of the relationship with clients and external partners and the need to consider programmatic aspects alongside technical ones from the very beginning of the process.

Furthermore, as outlined in Objective 3, new tools have been developed to support system design, along with the integration of a tool like COMET for data and ownership management during the sessions.

Objectives 4 and 5 have introduced innovative elements to *ACLab*, aiming to address the challenges of a corporate environment highlighted in the first chapter. The task prioritization activity was integrated into the methodology (Objective 4); its effectiveness was evaluated thanks to the case study which revealed the weaknesses of the initial approach and enabled refinements to make it more adaptable and aligned with the needs of the team. Moreover, to determine whether it would be more efficient in terms of time and resource savings to conduct the task quotation and subsequent session planning activity in a small group or individually, a dedicated test was carried out with the support of other system engineers.

Objective 5 was partially achieved: the LLM was developed, tested, and integrated into the methodology, but it was not utilized during the case study. The validity of the tool was assessed by asking 16 questions related to the previously conducted case study. The study participants, who were familiar with the correct answers, formulated the questions and then evaluated the tool's responses based on four factors: coverage, consistency, accuracy, and clarity. The results indicate that the tool effectively meets user needs by delivering comprehensive and accurate answers and facilitating quicker information retrieval. This can accelerate analyses and estimations, enabling companies to respond more swiftly to market demands and technological advancements. The next step involves actively using the tool in future CE sessions to enhance its performance. At a later stage, the tool can be further enhanced by integrating idea and concept generation, thereby extending its usefulness beyond information retrieval.

After the conclusion of the study, thanks to the feedback gathered from the participants, some areas of improvement were highlighted. The first suggestion consider improving the work conducted by SMEs by scheduling it in advance and providing an overview of the study progress beforehand. This would ensure the expert is well-prepared for the session and able to use the available time as effectively as possible. Additionally, the role and responsibilities of the SL were identified as critical, requiring strong communication and team management skills; future consideration should be given to training programs for SLs. Finally, a further improvement of *ACLab* involves standardizing existing tools and developing new ones to support the design process, addressing any needs that may arise.

Of the challenges related to the corporate environment mentioned in Chapter 1, this thesis addressed the issues regarding the lack of resources and available personnel, the integration of programmatic aspects with technical ones, and the need for rapid research and estimates. The next steps for the *ACLab's* development will focus on further integrating Agile-based methodologies to tackle remaining challenges, including better management of relationships with clients and external partners. Since these stakeholders may not always be available during the sessions and the objectives and constraints of the study can sometimes be unclear to the technical team, it would be beneficial to hold brief meetings at key design milestones (such as at the conclusion of each SPL). This approach would facilitate gathering feedback and provide a better understanding of the client's requirements, constraints, or goals. These idea will be tested in future *ACLab* studies and will help increase the methodology's flexibility while mitigating the challenges posed by the industrial environment.

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Appendix A

Technical Design Results

A.1 ConOps

→ **Launch & Early-Orbit Phase (LEOP)**
The LEOP phase considers all the activities between the spacecraft deployment from the launcher and the first communication with the ground segment. It includes:

- release from launcher and first power-up;
- detumbling (to reduce angular velocities on the three axes);
- opening of solar panels;
- set-up of the TT&C system, to prepare the satellite for the first communication.

→ **Commissioning**
This phase immediately following the LEOP includes:

- initial acquisition and first communication between spacecraft and ground;
- checkout of all subsystems and possible in-orbit testing;
- desaturation of reaction wheels, if necessary.

→ **Initial Insertion Maneuver**
The insertion maneuver towards the transfer orbit is performed. It is still to be determined how this will take place, as it depends on the launch strategy and the mission analysis.

→ **Sail Deployment/Maneuver**
It consists of the deployment of the solar sail through the booms (TBC). The timing of the deployment always depends on the launch and transfer strategy (e.g. *NEAScout* had a first moon flyby before the sail deployment).

→ **Cruise**
This phase considers the transfer to the asteroid using the sail propulsion system e and has these characteristics:

- duration of years (2 TBC);
- health checks every 2 months are expected, in which the spacecraft is Earth-pointing for telemetry communications. These checks can be held less frequently if there is onboard autonomy;
- radio always receiving.

→ **Approach**
The spacecraft approaches the target and prepares for the flyby:

- target search with NAVcam / widecam;
- target visual identification with NAVcam / widecam;
- onboard GNC (with chemical propulsion maneuver if needed).

→ **Target Recognition**

→ **FB & Science**
During this phase, it is essential that the spacecraft points the target and the payload acquires data.

→ **Science Downlink**
It considers the downlink of the science data gathered during the flyby. It has a duration of months, and the spacecraft must be Earth-pointing.

→ **Cruise (if mission extended)**
This phase considers another cruise in case the mission is extended, for example, for the flyby of another asteroid. Repeating of cruise, target approach, target recognition, FB, and science downlink.

→ **TBD**
In case of extension of the mission, further phases will be detailed.

→ **End of Life**
Once the operational phase is completed, end-of-life actions are planned:

- disposal maneuver to minimize Earth collision risk (TBD, size is very low, likely not hazardous);
- propellant offloading;
- battery passivation;
- other subsystem (S/S) decommissioning.

A.2 Mission and Solar Sail Requirements

ID	**Description**	**Note**
REQ-MIS-01	The CubeSat developed in the mission shall have a 12U or 6U form factor	From TO-01 Upgrade to a larger class could be beneficial
REQ-MIS-02	The mission shall deploy a solar sail from a CubeSat	From TO-02
REQ-MIS-03	The CubeSat shall have a solar sail area/overall mass ratio of at least 6 m^2/kg	From TO-07
REQ-MIS-04	The mission shall use solar sail propulsion to perform a flyby of its target	From TO-03
REQ-MIS-05	The mission target shall be a Near-Earth Asteroid	From TO-03
REQ-MIS-06	The mission should be compatible with mission extensions to other NEAs	
REQ-MIS-07	The mission shall demonstrate attitude control technologies for solar sail systems	From TO-04
REQ-MIS-08	The mission should demonstrate autonomous momentum management technologies for solar sail systems	From TO-06
REQ-MIS-09	The mission shall demonstrate autonomous GNC technologies for a solar sail propelled CubeSat	From TO-05
REQ-MIS-10	The mission shall characterize the morphology of the target asteroid during the flyby	From SO-04
REQ-MIS-11	The mission shall characterize the physical properties (shape, size, rotational state) of the target asteroid during the flyby	From SO-03
REQ-MIS-12	The mission shall characterize the mass and mass distribution of the target asteroid during the flyby	From SO-07. Internal structure could be derived indirectly. Navigation data can contribute to this measure
REQ-MIS-13	The mission shall characterize the orbital properties of the asteroid	From SO-09. This can be done via relative navigation data

REQ-MIS-14	The mission should characterize the chemical and mineralogical composition of the target asteroid during the flyby	From SO-06. This is done preliminarily/indirectly with a camera. Use of VNIR camera or imaging spectrometer can enhance this measure
REQ-MIS-15	The mission shall store telemetry, payload and other sensors/elaborated data until transmission to ground	
REQ-MIS-16	The mission shall transmit all relevant acquired data to ground before the EOL	Relevant data may be elaborated onboard, or may be selected from ground
REQ-MIS-17	The developed CubeSat should be composed of commercially available components and subsystems	From TO-09
REQ-MIS-18	The mission shall embark an optical payload	“Child” of REQ-MIS-10 and REQ-MIS-11
REQ-MIS-19	The mission shall embark two gravimeters	“Child” of REQ-MIS-12
REQ-MIS-20	The mission shall have a lifetime of at least 2.5 (TBC) years	
REQ-MIS-21	The flyby velocity at close approach shall be less than TBD m/s	Depending on target and trajectory, it could span from tens of m/s to the order of 1 km/s, based on *NEAScout* results
REQ-MIS-22	The distance at close approach shall be less than 1.5 km (TBC)	Based on *NEAScout*
REQ-MIS-23	The time from asteroid detection to end of possible detection shall be at least TBD hours	A RoM could be around 12 hours, based on *NEAScout*
REQ-MIS-24	The mission should be capable of performing on-board processing to reduce the downlinked data	
REQ-MIS-25	The total mission cost estimation shall be below TBD	
REQ-MIS-26	The mission shall be compatible with a launch with Ariane 6.2/6.4, Vega C, or alternatively other launchers of the same categories	
REQ-MIS-27	If piggyback opportunities are identified, the mission shall be compatible with these opportunities	

REQ-MIS-28	The total launch mass of the spacecraft shall be less than 36 (TBC) kg	
REQ-MIS-29	The system design shall guarantee target flexibility	
REQ-MIS-30	The mission shall perform a decommissioning after the beginning of the EOL phase	The decommissioning includes, at least, offloading of residual propellant, batteries passivation, and disposal maneuvers if needed/-foreseen
REQ-MIS-31	During the cruise to the Asteroid the mission shall foresee health status checks (with telemetry downlink) every TBD month	Depending on the autonomous level of the spacecraft
REQ-MIS-32	The mission shall be able to receive commands from ground at any time during the cruise phase (provided that the spacecraft is visible)	
REQ-MIS-33	The solar phase angle between the sun and the spacecraft shall be less than 50° (TBC)	From *NEAScout*
REQ-MIS-34	The spacecraft should be released at $C3 \geq 0$ or in a trajectory towards SEL2	
REQ-MIS-35	The spacecraft shall be released on a trajectory such that a 37 m/s delta-V (TBC) allows Earth-Moon system escape within 2 months from the end of commissioning (TBC)	

Table A.1: Mission requirements

ID	**Description**	**Note**
REQ-SSL-01	The sail shall weigh less than 6 kg (TBC) including margin	Limit impact on system design
REQ-SSL-02	The sail shall have a deployed reflective area of at least 171 m^2 (TBC)	Guarantee a minimum thrust
REQ-SSL-03	The sail shall occupy a stowed volume less than 3U (TBC)	Limit impact on system design
REQ-SSL-04	In-space deployment shall have a reliability above 99%	

REQ-SSL-05	The sail shall be able to compensate thrust asymmetries from structural defects. Note: rotation around the axis/rotation of the whole spacecraft can be used to compensate for asymmetries	
REQ-SSL-06	The sail material shall have a solar reflectance above 0.85 (TBC) at BOL	Guarantee a minimum thrust
REQ-SSL-07	The sail material shall have a solar reflectance above TBD after 3 years of mission	Guarantee a minimum thrust
REQ-SSL-08	The sail should include sensors to measure temperature, sail extension, incoming solar radiation pressure	Investigation of solar sail thrust model
REQ-SSL-9	The sail should include sensors to measure the status of the sail, including deployment status, attitude with respect to the spacecraft	
REQ-SSL-10	The sail should be able to control the torque generated on the spacecraft	
REQ-SSL-11	The sail shall be able to manage the momentum generated on the spacecraft (e.g., change CoP wrt CoG)	
REQ-SSL-12	The sail shall include mechanical interfaces for the CubeSat	
REQ-SSL-13	The sail shall include power interfaces for the CubeSat	
REQ-SSL-14	The sail shall include data interfaces for the CubeSat	
REQ-SSL-15	The sail shall include thermal interfaces for the CubeSat	
REQ-SSL-16	The sail shall guarantee a solar torque of less than 50 mNm	Limit need for desaturation

Table A.2: Solar Sail requirements

A.3 Electrical Power System

The EPS system is responsible for generating, storing, and distributing the power necessary for the operation of the various subsystems of the platform. It consists of three main elements: solar panels, battery, and PCDU (Power Conversion and Distribution Unit). Each of these components fulfills one of the previously mentioned tasks, and their selection is guided by mission requirements and potential design constraints.

The solar panels are responsible for the primary power generation for the satellite. The sizing of the panels was carried out according to the mission power budget. The power budget A.3 identifies the platform's power demand in the various operational modes. Using the Excel EPS tool, the solar panels have been sized and have the following characteristics: 2 wings, each with 3 strings (TBC, with the possibility to consider four wings). The panels are composed of 96 triple-junction AZUR 3G30A cells with an efficiency of 30%. The panels consist of a total of six strings, each with 16 cells. To determine the area and mass of the panels and to verify that they could generate the power required by the power budget, various analyses were conducted at different distances from the Sun. The power budget (A.3) requires 77W in the worst-case scenario, which is during the communication mode.

The results calculated in the best case at 1 AU from the Sun are shown here:

- Power EOL hot case: 95 W
- Mass of 2.7 kg (considering a specific performance of 35 W/Kg)
- Area of 0.35 m^2

Moreover, two SADA (Sola Array Drive Assembly) mechanisms are mounted to ensure that the panels are always oriented perpendicularly to the Sun. Further analysis will investigate whether this is actually necessary, as the panels (which will be parallel to the sail) will be perpendicular to the Sun's direction for most of the time during cruise mode to maximize thrust.

The battery is responsible for storing energy within the platform. It is charged using the power generated by the solar panels, and the stored energy is distributed to the platform when necessary. These situations include:

- pre-deployment operations of the solar panels, such as detumbling;
- negative power margin of the platform, where additional power is needed beyond what the panels can provide.

To meet these requirements, a battery with a capacity of 124 Wh was selected.

The PCDU is responsible for receiving the input power from the solar panels and appropriately distributing it to the various subsystems to ensure power supply. At the same time, it provides protection against potential electrical failures, preventing them from affecting other subsystems. The PCDU chosen for the mission has a primary efficiency of 90%.

A.4 Attitude Determination and Control System

The ADCS subsystem is one of the most critical for the mission in question and required various analyses for sizing. Before selecting the actuators, the environmental torques (Table A.3) and the time required for saturation (Table A.4) were calculated based on the following assumptions:

- heliocentric orbit with radius 0.75 AU wrt sun;
- sail orthogonal to sun direction (worst case scenario to maximize parasite torque)
- inertia matrix estimated with Excel tool (see 3.1.1);
- center of pressure (CP) – center of mass (CM) offset equals to 1 mm.

Torque Source	Value (Nm)
Gravity gradient	4.160E-13
Solar radiation	2.738E-06
Magnetic	0
Aerodynamic	0
Total (RSS)	2.738E-06

Table A.3: Environmental torques

Parameter	Value
Integrated angular momentum	56.6554 Nms
Required hours for saturation	4.26 h
Required days for saturation	0.17 d

Table A.4: Torques and momentum in orbit (integration)

In a mission propelled by a solar sail, it is crucial to consider the offset between the center of mass (CoM) and the center of pressure (CoP), as it leads to the generation of significant torques that make it challenging to maintain proper sail orientation. For instance, *NEAScout* employs an Active Mass Translator (AMT) mechanism to autonomously manage the spacecraft's momentum, trim the dominant solar torques about the spacecraft's X and Y axes, and keep the resulting torque below a specified threshold. The AMT achieves this by adjusting the center of mass to align with the center of pressure. More detail about this mechanism can be found in [39] [40].

Assuming that the mission under analysis includes a control mechanism for the position of the CoP (or CoM), the focus has been on setting a requirement for the magnitude of the parasite torque. For instance, managing the CoP to maintain the Solar Radiation Pressure (SRP) torque below 50 nNm, while considering the momentum storage capacity of a pyramidal wheel configuration, would lead to saturation after 222 hours. This assumption allows for a four-wheel pyramidal configuration, with each wheel having an angular momentum capacity of 0.015 Nms. The selected configuration aligns the wheels along the X or Y axes to optimize agility and maximize momentum storage in those directions. This choice is based on the spacecraft's inertia matrix, where the greatest inertia is found in the direction perpendicular to the sail. As a result, maneuvers are executed around the X or Y axes to minimize the control torque required.

An additional analysis was conducted to determine whether the wheel torques were sufficient to achieve the agility required for the flyby maneuver depicted in Figure A.1. By varying the distance from the NEA and the spacecraft's velocity, the angular velocity and required torque were derived. This analysis allowed for the verification of whether the wheels could provide the necessary momentum and torque.

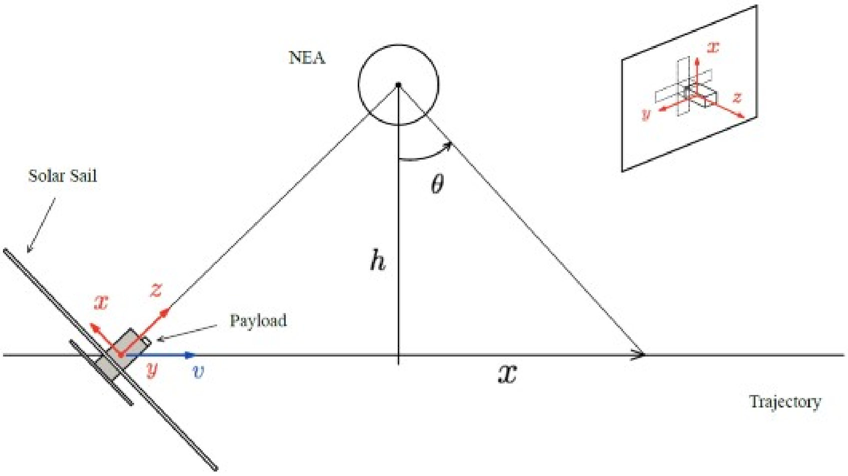


Figure A.1: Fly-by configuration

A.5 Telecommunication System

The preliminary communication architecture is composed by:

- X-band radio: 3.8/5 W
- Receiving Low Gain patch antenna: 7.8 dBi
- Transmitting 8×8 High Gain patch array antenna: 24 dBi

Considering the *NEAScout* mission, a minimum target of 1 kbps at a maximum distance of 1 AU is set [37]. The baseline for the ground segment is identified in the ESTRACK Cebreros-1 station. Other options are also identified and further analysis will be conducted in the next project phases. A link budget analysis was also conducted to assess the reliability of the communication system.

A.6 Propulsion System

For an initial sizing of the chemical propulsion system (PS), some assumptions on the ΔV needed to perform the mission were made; not having performed a detailed mission analysis. The *NEAScout* mission taken as reference, required a ΔV of 37 m/s for a transfer from Trans-Lunar Injection (TLI) to the target, taking approximately 700 days with additional 5 m/s for reaction wheel desaturation [41]. The sizing PS was performed without considering the launch phase, assuming the sole requirement of escaping the Earth-Moon system with the 37 m/s ΔV.

Although the system was sized based on the *NEAScout* transfer, it would be ideal to leverage a launch with a $C_3 \geq 0$ or towards the SEL2 point. Moreover, using the ΔV budget tool, a required propellant mass of 0.5 kg was calculated.

A.7 Spacecraft Configuration

As previously described, the preliminary configuration of the satellite follows that of *NEAScout*, with the sail stowed in the central bay and the avionics and propulsion system located in the side bays [37]. The solar panels are deployed from the side of the propulsion system, and the high-gain antenna is mounted on one of the four panels. To minimize the inertia during the flyby maneuver, the payload must be oriented with its pointing axis perpendicular to the sail. Additionally, to perform the momentum budget analysis, the satellite's inertia matrices were calculated using the designated tool. The inertia is derived from the sum of the sail, panels, and spacecraft inertia. The tool, described in 3.1.1, was originally implemented considering only the solar panels as appendages; it was subsequently modified to also account for the presence of the sail. The calculated inertia matrices are listed in Table A.5.

Body [kgm^2]		
0.365545	0	0
0	0.365545	0
0	0	0.211346

Solar panel [kgm^2]		
0.84243	0	0
0	0.013889	8.51×10^{-19}
0	8.51×10^{-19}	0.856313

Sail [kgm^2]		
11.30128	0	0
0	10.74818	6.58×10^{-16}
0	6.58×10^{-16}	22.04945

Total [kgm^2]		
24.65296	0	0
0	21.88968	1.32×10^{-15}
0	1.32×10^{-15}	46.02288

Table A.5: Spacecraft components inertia matrices

A.8 Mission Risks Identification

Operational

- Sail operations (deployment, sail management)
- Pointing during flyby
- Cruise phase operations
- Communication after flyby
- Power during flyby & autonomous operations

Technological

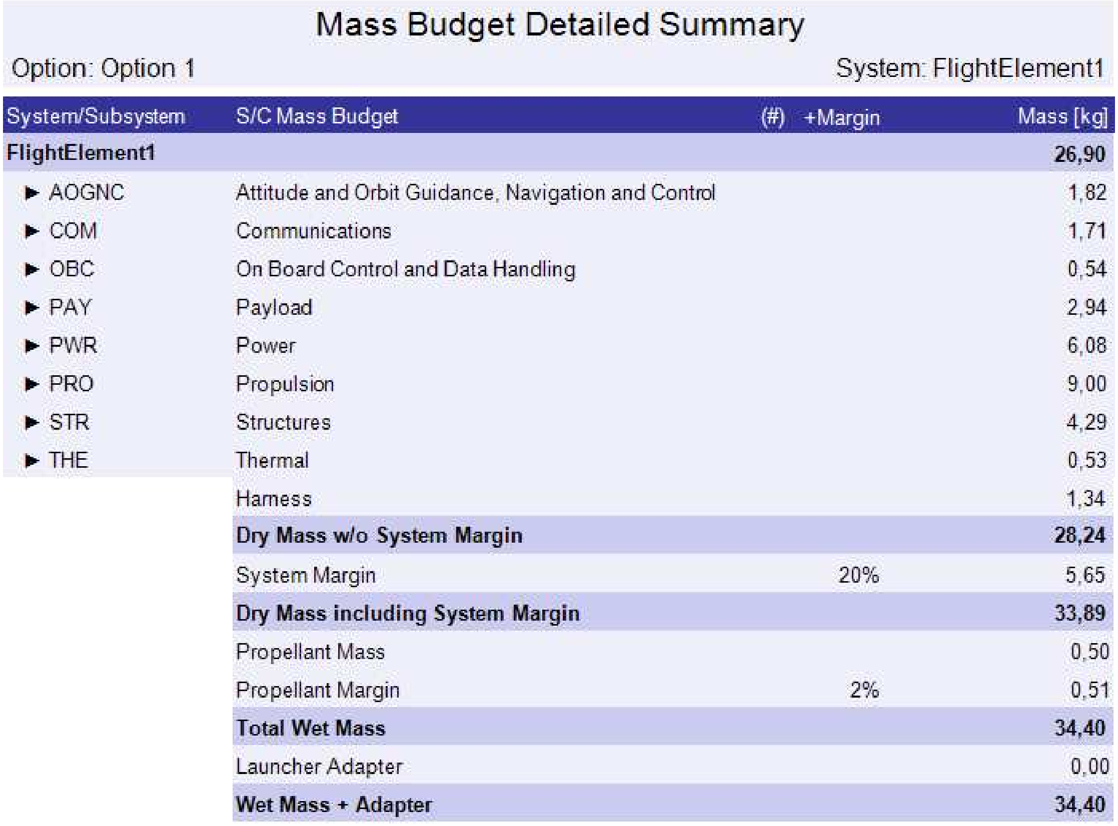
- AIT

  - Test of solar deployment
  - Sail testing with the ADCS
  - Possible integration of solar sail between two s/c buses

Design

- Sail maturation to TRL 9
- Autonomous GNC maturation
- Thermal management
- Lean transfer strategy vs mass increase

A.9 System Budgets



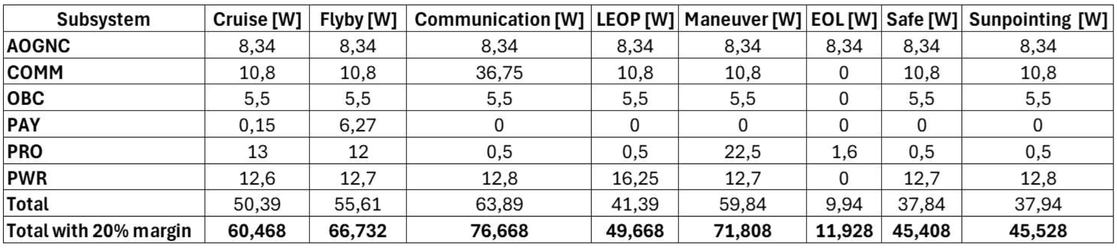
Mass Budget Detailed Summary

Option: Option 1

System: FlightElement1

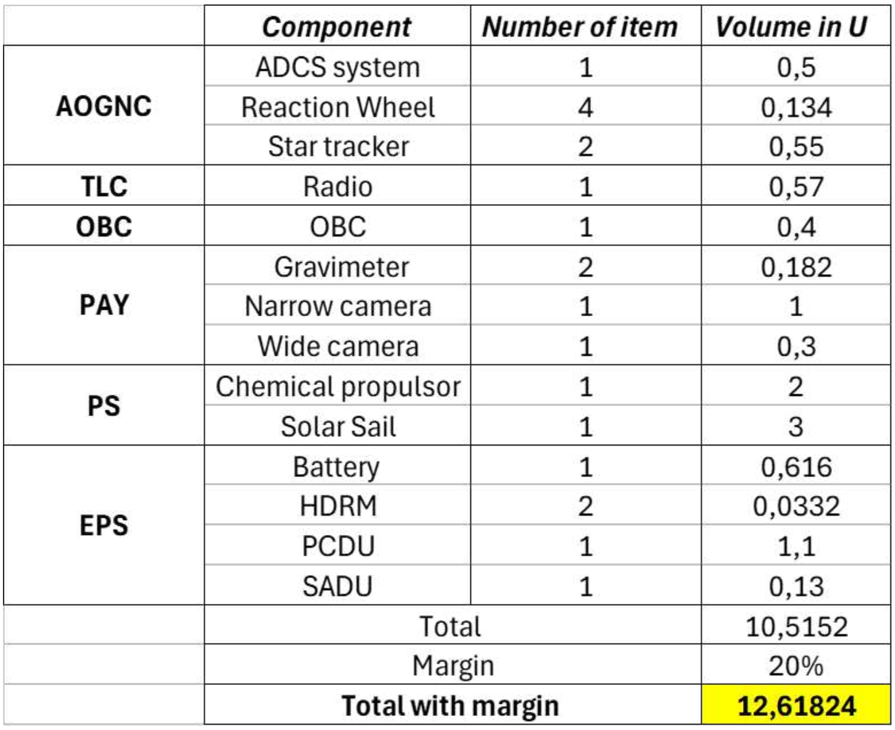
System/Subsystem	S/C Mass Budget	(#)	+Margin	Mass [kg]
FlightElement1				**26,90**
▶ AOGNC	Attitude and Orbit Guidance, Navigation and Control			1,82
▶ COM	Communications			1,71
▶ OBC	On Board Control and Data Handling			0,54
▶ PAY	Payload			2,94
▶ PWR	Power			6,08
▶ PRO	Propulsion			9,00
▶ STR	Structures			4,29
▶ THE	Thermal			0,53
	Harness			1,34
	Dry Mass w/o System Margin			**28,24**
	System Margin		20%	5,65
	Dry Mass including System Margin			**33,89**
	Propellant Mass			0,50
	Propellant Margin		2%	0,51
	Total Wet Mass			**34,40**
	Launcher Adapter			0,00
	Wet Mass + Adapter			**34,40**

Figure A.2: Mass budget



Subsystem	Cruise [W]	Flyby [W]	Communication [W]	LEOP [W]	Maneuver [W]	EOL [W]	Safe [W]	Sunpointing [W]
AOGNC	8,34	8,34	8,34	8,34	8,34	8,34	8,34	8,34
COMM	10,8	10,8	36,75	10,8	10,8	0	10,8	10,8
OBC	5,5	5,5	5,5	5,5	5,5	0	5,5	5,5
PAY	0,15	6,27	0	0	0	0	0	0
PRO	13	12	0,5	0,5	22,5	1,6	0,5	0,5
PWR	12,6	12,7	12,8	16,25	12,7	0	12,7	12,8
Total	50,39	55,61	63,89	41,39	59,84	9,94	37,84	37,94
Total with 20% margin	**60,468**	**66,732**	**76,668**	**49,668**	**71,808**	**11,928**	**45,408**	**45,528**

Figure A.3: Power budget



	Component	***Number of item***	***Volume in U***
AOGNC	ADCS system	1	0,5
	Reaction Wheel	4	0,134
	Star tracker	2	0,55
TLC	Radio	1	0,57
OBC	OBC	1	0,4
PAY	Gravimeter	2	0,182
	Narrow camera	1	1
	Wide camera	1	0,3
PS	Chemical propulsor	1	2
	Solar Sail	1	3
EPS	Battery	1	0,616
	HDRM	2	0,0332
	PCDU	1	1,1
	SADU	1	0,13
	Total		10,5152
	Margin		20%
	Total with margin		**12,61824**

Figure A.4: Volume budget