Methods for Improving User Needs Incorporation in Conceptual Design Phases of Systems Engineering

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Methods for Improving User Needs Incorporation in Conceptual Design Phases of Systems Engineering

By

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Preface

The completion of this thesis closes a chapter that has been, by some margin, the most demanding and the most rewarding of my life. Carried out alongside my work at Telespazio, this research project would not have reached its conclusion without the support and contributions of a number of people, whom I would like to acknowledge here.

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Finally, to my **family, friends**, and **loved ones**, thank you for the infinite support through both the good and the difficult moments. None of this would have been possible without you. A particular thought goes to **Nonna**, who cared deeply about my education and whom I know would have been proud to see this work completed.

It is my hope to carry forward, into both my career and my life, everything that this thesis, and the people who have accompanied me through it, have taught me along the way.

Matteo Manieri
Delft, May 2026

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Abstract

The New Space economy stresses the importance of accurately identifying and fulfilling user needs in Earth observation mission design. Traditional systems engineering lacks effective mechanisms for user engagement and needs determination during early development phases. This study explores how novel methods for user needs collection and transformation can be integrated into systems engineering to enhance the formulation of mission requirements in conceptual design phases.

32 user-centric methodologies were identified, from which a trade-off analysis involving eleven experts selected two as most promising: Iterative Prototyping and Design Thinking. Both were adapted for integration into systems engineering and validated through a real-world Posidonia use case.

Results show that both methods improve early-stage user engagement and promote the elicitation of user needs. Iterative Prototyping supports continuous feedback and facilitates the derivation of mission requirements directly driven by user needs, while Design Thinking effectively frames problems but lacks a traceable path to technical specifications.

1 Introduction

The aerospace industry is undergoing a significant transition, driven by the rise of private-sector participation in space activities, commonly referred to as the New Space movement. Traditionally dominated by governmental bodies such as NASA, ESA, and other institutional actors, the space sector is now increasingly characterized by the participation of commercial organizations that prioritize agility, cost-efficiency, and market responsiveness [1]. This shift is particularly visible in the Earth observation domain, where the market's growing demand for data-driven applications has fostered innovation and an emphasis on rapid service deployment [2].

The traditional space industry relies heavily on structured systems engineering frameworks, which have been designed to manage the complex requirements of large-scale, government-driven space missions. These frameworks are systematic, formalized, and tailored for missions with long timelines and high stakes [3], [4], [5]. They excel in ensuring technical accuracy and accountability in projects that serve large, well-defined institutional customers, such as governments and research institutions. These stakeholders are integrated into the project lifecycle through formal processes like requirements elicitation, validation, and verification, ensuring that mission objectives align with their high-level needs and constraints [3], [4].

However, in the New Space sector, the customer base is diversifying. Rather than focusing solely on institutional customers, New Space companies cater to a wide array of clients, including private businesses, small enterprises, and even individual users [6], [7], [8], [9]. These users often require faster turnaround times and customized solutions, prompting New Space companies to adopt more flexible, user-centric approaches [1], [10]. In this environment, companies prioritize rapid prototyping, iterative development, and agile methodologies to stay competitive and responsive to shifting market demands. This shift towards a more commercial and user-driven environment presents a major challenge for traditional space industry practices. The problem lies in the disconnect between the traditional systems engineering processes and the dynamic, market-driven methodologies used by New Space organizations [11]. Traditional systems engineering frameworks are ill-suited for the flexibility required by New Space missions, as they are often too rigid to adapt to the evolving needs of a diverse and fast-changing user base. Moreover, the methods used by New Space companies to gather and transform user needs into actionable system requirements lack standardization, making it difficult to assess their potential for integration into more structured systems like those used in the traditional space sector.

This research addresses the question of how user needs collection and transformation methods and practices identified in and outside of the New Space sector can be integrated into the systems engineering framework used by the traditional space industry to improve the integration of user needs into mission designs. By exploring the differences in approaches between New Space and traditional space organizations, this study seeks to bridge the gap between these methodologies and identify best practices that could enhance the overall process of user needs collection and requirements generation in Earth observation mission. For traditional space organisations, the integration of user-centric methods offers a means of shifting toward a more demand-pull approach, in which end users exert greater influence on the requirements that shape mission design, without compromising the rigour and traceability that characterise their engineering practice. For New Space organisations and new market entrants, conversely, alignment with established systems engineering frameworks provides a more formalised structure within which to embed their existing user-driven practices. By examining how the strengths of both domains can be combined, this research seeks to contribute to a more effective and user-aligned approach to requirements generation for Earth observation missions.

1.1 Research Question

The problem statement arises from the growing need to bridge the gap between the innovative, flexible practices of New Space organizations and the structured, model-based frameworks of traditional space organizations [11]. By identifying and integrating the best user needs collection and transformation methods from New Space into (Model-Based) Systems Engineering, traditional space entities can enhance their responsiveness to these evolving user requirements, improve mission success, and remain competitive in a market increasingly driven by end-user needs [8].

The state of the art highlights that while both NASA and INCOSE systems engineering frameworks provide robust methodologies for requirements generation, they often fall short in accommodating the rapidly changing needs and flexible approaches required in today's commercial space environment [7], [10], [11]. Furthermore, their traditional focus on institutional customers does not adequately address the rising importance of individual users and businesses in the New Space sector [8]. New Space organizations on the other hand, utilize more user-driven approaches, which are not integrated into a structured engineering framework, but are able to align user needs more effectively with system requirements [8], [11], [12], [13]. Thus, the main research question focuses on exploring how best practices from the New Space sector, with its emphasis on user-driven design, can be adapted and incorporated into (Model-Based) Systems Engineering to improve the overall effectiveness of the space industry in addressing this broader and more diverse range of user needs.

Main Research Question: *How can user needs collection and transformation methods and practices identified in and outside of the New Space sector can be integrated into the systems engineering framework used by the traditional space industry to improve the integration of user needs into mission designs.*

The main research question is driven by the need to integrate the agile, user-driven methods of New Space with the rigor of traditional (Model-Based) Systems Engineering approaches. This integration is crucial for maintaining relevance and competitiveness in the evolving space sector, where the ability to collect and effectively transform user needs into system requirements can determine the success of Earth observation satellite missions. The question reflects the overarching goal of the research: to explore how these sectors can complement each other by combining New Space's agility with the robustness of (Model-Based) Systems Engineering. This integration will help streamline the transformation of user needs into actionable mission and system requirements and enhance the overall mission design process.

1.2 Sub-research Questions

To effectively address the main research question, it is decomposed into a set of sub-questions, each targeting a distinct component of the problem. Together, these sub-questions are structured such that their combined answers are intended to fully resolve the overarching research question. These sub-questions will guide the research, providing a structured approach to understanding the methods used by New Space organizations and their potential integration into (Model-Based) Systems Engineering frameworks. To answer these sub-questions, a second literature study is conducted, directed at answering the sub-questions and the identification of methodologies for the collection and transformation of user needs.

Sub-question 1: *What widely adopted methods for user needs collection and transformation are used by New Space organizations?*
This sub-question aims to explore the methods and practices that New Space organizations employ for gathering and transforming user needs into technical requirements. Given the commercial focus of New Space, where missions are often user-driven, it is important to investigate whether standardized or widely adopted tools and methodologies exist across the industry. If such methods are not present, this gap must also be identified and addressed. This question will aid in determining which methods, if any, could be adapted or integrated into traditional (Model-Based) Systems Engineering processes. By analysing these methods, their suitability for use within the more structured frameworks of traditional space projects, particularly in Earth observation missions, can be evaluated.

Sub-question 2: *Which New Space organizations have successfully validated their Earth observation satellite services against the initially collected user needs, and what methods were used in this validation process?*
This sub-question focuses on identifying successful case studies where New Space organizations have validated their satellite services to ensure they meet the needs initially identified by users. Validation is a critical component of systems engineering, ensuring that the system operates as intended and fulfils user requirements. In addition to providing insights into how user needs collection is tied to mission success, these case studies will also help determine which methods were used for both collecting and transforming user needs into system requirements. By examining these organizations and their validation methods, this sub-question will not only highlight practices that could enhance validation processes in traditional (Model-Based) Systems Engineering frameworks but also assist in scouting for appropriate case studies to perform the validation of the proposed method

Sub-question 3: *What methods can be used to evaluate the effectiveness of user needs collection and transformation processes for Earth observation missions, and what criteria or metrics support this evaluation?*
Evaluating the effectiveness of user needs collection and transformation processes is essential to ensuring that the method proposed by this research is both efficient and reliable. This sub-question explores the criteria, tools, methods, and KPIs that can be applied to measure the success of these processes in Earth observation satellite missions. The effectiveness of these methods can be assessed using various potential criteria such as time to deployment, user satisfaction, and accuracy of requirements generation. By identifying and evaluating these criteria, this question will help determine which metrics are most relevant to measuring the potential success of the proposed method. Furthermore, these criteria are critical for defining what constitutes an "effective" method, providing a basis for answering the next two sub-research questions, which evaluate the effectiveness of the identified user needs collection and transformation methods. Finally, these criteria will form the foundation for conducting a trade-off analysis between the identified methods later in the research, ensuring that the most effective methods are selected for integration.

Sub-question 4: *To what extent have the user needs collection methods used by New Space organizations in the past ten years been effective in identifying the needs for operational Earth observation satellites?*

The success of any satellite mission begins with accurately identifying user needs. This sub-question investigates the effectiveness of user needs collection methods used by New Space organizations over the past decade. Operational Earth observation satellites differ from research satellites in that they are fully integrated into continuous, real-world applications and are typically owned and operated by the users or operational partners after development [20]. These satellites focus on delivering consistent, reliable services for applications such as environmental monitoring and disaster management. In addition to evaluating the effectiveness of these methods using the criteria from the previous sub-research question, this question will also identify which specific methods have been employed for user needs collection. This will provide a basis for determining how such methods can be adapted or improved for use within traditional space organizations and will inform the potential alignment with (Model-Based) Systems Engineering processes.

Sub-question 5: *To what extent are the user needs transformation methods used by New Space organizations in the past ten years effective in converting user needs into system requirements for operational Earth observation satellites?*

This sub-question focuses on a key aspect of systems engineering by evaluating the effectiveness of methods that transform user needs into concrete system requirements. It examines how the methods used by New Space organizations convert user needs into mission requirements that guide the design and operation of Earth observation satellites. The effectiveness criteria established in the previous sub-research question will be used to assess these transformation methods, ensuring a consistent evaluation approach. Additionally, this sub-question will identify which specific methods have been employed by New Space organizations for transforming user needs into system requirements. Understanding the effectiveness of these methods will help determine which practices can be beneficially integrated into traditional (Model-Based) Systems Engineering frameworks.

Sub-question 6: *In what way can the proposed methodology be integrated into the requirements generation processes of (Model-Based) Systems Engineering?*

The final sub-question focuses on the practical integration of the proposed methodology into the existing (Model-Based) Systems Engineering frameworks. This question aims to explore how the insights gained from New Space practices, specifically in user needs collection and transformation methods, can be adapted for use in the structured process of requirements generation in the traditional systems engineering framework as used by traditional Earth observation missions. It will help define the steps needed to modify and align these methods with existing (Model-Based) Systems Engineering processes, ultimately contributing to a more agile and responsive engineering approach that results in missions which better meet user needs. This sub-question is key to ensuring that the outcomes of this research can be applied in practice and drive improvements in the systems engineering design-cycle of Earth observation missions.

The sub-questions establish the investigative framework of this research, building the knowledge required to address the main research question in a structured and substantiated manner. Together, they guide the investigation into how user needs collection and transformation methods from the New Space sector can enhance traditional systems engineering practices.

1.3 Thesis Report Structure

This thesis follows a paper-based structure, in which the core research contribution is presented as a standalone scientific publication embedded within a broader report framework. Chapter 2 presents the conference paper "Methods for Improving User Needs Incorporation in Conceptual Design Phases of Systems Engineering", which was submitted to, accepted by, and presented at the IEEE Aerospace Conference 2026 on 9 March 2026 [14]. As such, Chapter 2 is self-contained and includes its own introduction, methodology, results, discussion, and conclusions.

Chapter 1 provides the broader research context that motivates the study, elaborating on the problem statement, main research question, and six sub-research questions that together guided the research. Chapter 3 synthesises the findings of Chapter 2 in relation to these sub-questions and presents overarching conclusions and recommendations for future work.

The appendices provide supporting material referenced throughout the report. Appendix A lists the 32 identified methodologies considered during the collection phase. Appendix B contains the methodology trade-off description sheets presented to the expert panel. Appendix C details the trade-off evaluation criteria and their descriptions, followed by the full trade-off scoring results per expert in Appendix D. Appendix E presents the raw outputs of both validation exercises, including the final Iterative Prototyping prototype and the Design Thinking ideation and concept results.

The research underlying this thesis was carried out under a formal project structure, in which the work was decomposed into five principal work packages, themselves subdivided into sub-work packages and scheduled according to a project plan developed prior to the research. Each work package was associated with multiple sub-research questions formulated in Section 1.2, ensuring traceability between the planned activities and the research questions they were designed to address.

2 Journal Paper

Methods for Improving User Needs Incorporation in Conceptual Design Phases of Systems Engineering

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Abstract— **The New Space economy, characterized by financial models increasingly driven by private investment and paying end-users, stresses the importance of accurately identifying and fulfilling user needs. The success of Earth observation mission design critically depends on the effective collection and translation of user needs into mission and system requirements. Traditional Systems Engineering practices, however, often lack effective and efficient mechanisms to address this during the early phases of mission development. This study explores how novel methods for user needs collection and transformation can be integrated into the Systems Engineering framework to enhance the formulation of mission requirements in the conceptual design phase.**

Innovative methodologies for improving user needs identification and transformation, drawn from both within and outside the space sector, were identified and systematically assessed. Additionally, three previously undescribed methods for mission requirements generation were developed based on practices currently employed by New Space organizations. A total of 32 methodologies, characterized by strong user integration, were identified and further analyzed on their suitability for application in the space domain. Through a trade-off analysis involving eleven experts and 20 evaluation criteria, the two most promising methods were identified: Iterative Prototyping (a newly developed method) and Design Thinking. These two methods were subsequently adapted to facilitate their integration into the Systems Engineering process, ensuring their outputs align with the required process inputs and maintain validation and verification traceability. Next, their performance was evaluated using a real-world Earth observation use case focused on seagrass monitoring. This case involved a user group comprising European domain experts on climate and maritime anthropogenic impacts, who worked towards generating mission requirements using the two selected methodologies.

This study reveals that numerous methodologies exist to improve user engagement, yet few address the transformation of needs into formal requirements. Traditional Systems Engineering does not sufficiently engage users in its front-end practices as highlighted by the results of the trade-off analysis. Both selected methodologies, Iterative Prototyping and Design Thinking, allow for enhanced early-stage user engagement and needs collection. Iterative Prototyping supports continuous feedback loops and validation and facilitates the derivation of mission-level requirements. Instead, Design Thinking effectively frames user problems and promotes inclusive dialogue but lacks a (traceable) path to technical specifications and mission requirements.

This study finds that spatial and temporal mission requirements can be derived using Iterative Prototyping. Spectral and radiometric requirements, however, still depend on conventional techniques and expert judgment.

In conclusion, the study demonstrated that the use of novel methods, such as Iterative Prototyping and Design Thinking, applied in the early phases of the conceptual design process improves user engagement and promotes the elicitation of user needs. The study's trade-off analysis indicates that Iterative Prototyping also facilitates the derivation of mission requirements directly driven by user needs.

1. INTRODUCTION

The aerospace industry is undergoing a significant transition, driven by the rise of private-sector participation in space activities, commonly referred to as the New Space movement. Traditionally dominated by governmental bodies such as NASA, ESA, and other institutional actors, the space sector is now characterized by increased participation of commercial organizations and a concomitantly increased focus on agility, cost-efficiency, market responsiveness, and a greater tolerance for risk [1]. This shift is particularly visible in the Earth observation domain, where the market's growing demand for data-driven applications has fostered innovation and an emphasis on rapid service deployment.

The traditional space industry relies heavily on structured systems engineering frameworks, which have been designed to manage the complex requirements of large-scale, government-driven space missions. These frameworks are systematic, formalized, and tailored for missions with long timelines and high stakes. They excel in ensuring technical accuracy and accountability in projects that serve large, well-defined institutional stakeholders, such as governments and research institutions. NASA defines a stakeholder as anyone affected by or having an interest in a project, while a customer is a specific type of stakeholder who requests, pays for, and receives the product or service [3] [15]. The stakeholders involved in the traditional space industry are integrated into the project lifecycle through formal processes like requirements elicitation, validation, and verification, ensuring that mission objectives align with their high-level needs and constraints [3] [5] [4] [16].

However, in the New Space sector, the emphasis is more on customers and users rather than stakeholders as a whole. This customer base is diversifying, as New Space companies cater to a wide array of clients, including private businesses, enterprises, and even individual users [2]. These users often require faster turnaround times and customized solutions, pressing New Space companies to adopt more flexible, user-centric approaches [8]. In turn, New Space organizations show a high dependence on private capital and positive returns on investment, while also operating on a demand-pull framework rather than a technology-push one. Along with disruptive innovations, shorter lifecycles, and greater risk-taking, these organizations are radically transforming the space industry into a more dynamic and fast-paced market [9] [11].

In this environment, companies prioritize rapid prototyping, iterative development, and agile methodologies to stay competitive and responsive to shifting market demands. This shift towards a more commercial and user-driven environment presents a major challenge for traditional space industry practices. The problem lies in the disconnect between the traditional systems engineering processes and the dynamic, market-driven methodologies used by New Space organizations. Traditional systems engineering frameworks are ill-suited for the flexibility required by New Space missions, as they are often too rigid to adapt to the evolving needs of a diverse and fast-changing user base. Moreover, methods used by New Space companies to gather and transform user needs into actionable system requirements lack standardization, making it difficult to assess their potential for integration into more structured systems like those used in the traditional space sector.

Furthermore, the rise of New Space organizations highlights the need for new methodologies that prioritize aligning space services with end-user needs, driven by commercial business models that emphasize funding and market success. In contrast, traditional space programs have often struggled to fully leverage their infrastructure due to limited stakeholder engagement and a lack of user-centered approaches [8]. There is a gap between the potential value of space infrastructures and the enacted value as realized by users. This gap is largely due to insufficient user awareness, technical complexity, and a lack of integration between upstream space providers and downstream service users [8]. This disconnect is further emphasized in industries like Insurance, Finance, and Energy, where end-users struggle to actualize the strategic benefits of satellite data due to high transaction costs and limited expertise [17]. New Space organizations aim to bridge this gap by prioritizing user engagement and fostering collaboration between stakeholders. By addressing these challenges, New Space organizations are working to ensure their services meet the evolving needs of their diverse user base. The challenge of collecting user needs for requirements generation is not unique to the space industry but is also common in other sectors with similar commercial structures to New Space. Methods identified in other sectors could potentially prove valuable when integrated into New Space organizations for improved user needs collection.

This study identifies novel methods for user needs collection and transformation and explores how these methods can be integrated into the Systems Engineering framework to enhance the formulation of mission requirements in the conceptual design phase.

2. METHODOLOGY

The methodological framework that was adopted to identify, evaluate, and adapt user needs collection and transformation methods for integration into Systems Engineering with a focus on Earth observation mission design comprised of four phases:

1. Collection of relevant user needs identification and transformation methodologies;
2. Selection of most promising methods through a structured trade-off analysis;
3. Adaptation of selected methods for facilitating their integration into the Systems Engineering process
4. Validation phase: Evaluation of performance through a real-world Earth observation use case.

Collection of relevant methodologies

This initial phase of the research focused on assembling a comprehensive set of existing approaches to user needs collection and transformation. These were sourced from three principal domains: the traditional space sector, the New Space sector, and non-space engineering industries. This broad exploratory scope was necessitated by the relative scarcity of formalized methodologies within the space sector itself, particularly regarding user-centered approaches to requirements engineering. The collection effort was conducted using three main resources: academic literature, industry publications, grey literature online resources, and interviews.

The interviews conducted with industry stakeholders led to the identification of user needs collection and transformation methods not currently described in scientific literature. Once identified, these methodologies were reconstructed based on detailed accounts provided by the interviewed professionals. The reconstruction process involved eliciting a high-level overview of each method, obtaining a step-by-step description of internal workflows, identifying typical inputs and outputs, and, where possible, reviewing internal documentation shared by the interviewees.

Selection of methodology

The second phase of this research sought to evaluate the potential of the identified user needs collection and transformation methodologies for design process improvement and integration into Systems Engineering. Specifically, this phase attempted to select methodologies for further development, through a trade-off.

Prior to trade-off implementation, two methodology selection criteria were applied: 1) applicability to space mission development and 2) potential to provide end-to-end coverage of the user needs process (from initial user engagement through to the formulation of technical requirements). This filtering process resulted in a shortlist of six methodologies, from 32 identified, deemed suitable for inclusion in the trade-off exercise.

Given the nature of the evaluation criteria of the trade-off, which were largely qualitative, a conventional quantitative or purely analytical trade-off method was deemed unsuitable. Most relevant criteria for this study are descriptive, context-dependent, or reliant on practitioner expertise, and as such cannot be meaningfully captured through numerical or deterministic criteria. Only a minority of criteria (such as the number of process steps or the typical number of stakeholders involved) could be considered quantitative in nature.

This evaluation of the methodologies was executed in the form of a trade-off exercise involving multiple internal and external subject-matter experts. Involving professionals with practical expertise in Systems Engineering and Earth observation ensured that the evaluation would be conducted by those who are most likely to use or be affected by these methods in real-world mission design contexts. This approach was considered the most viable means of obtaining reproducible and low-bias results.

To perform the trade-off, a panel of eleven experts was assembled. These experts were selected to ensure a balanced representation of backgrounds and experience levels across Systems Engineering and Earth observation domains. The panel included:

- Two senior Earth observation engineers, (defined as having more than seven years of professional experience in the field).
- Three senior Systems Engineers, (defined as having more than seven years of professional experience in the field).
- Three mid-career Systems Engineers, (defined as having between two and seven years of professional experience in the field).
- Three junior Systems Engineers (defined as having less than two years of professional experience in the field).

Each expert was asked to independently evaluate the six methodologies using a predefined set of evaluation criteria.

The evaluation employed 20 criteria, grouped into six thematic categories, as follows and detailed in Figure 1:

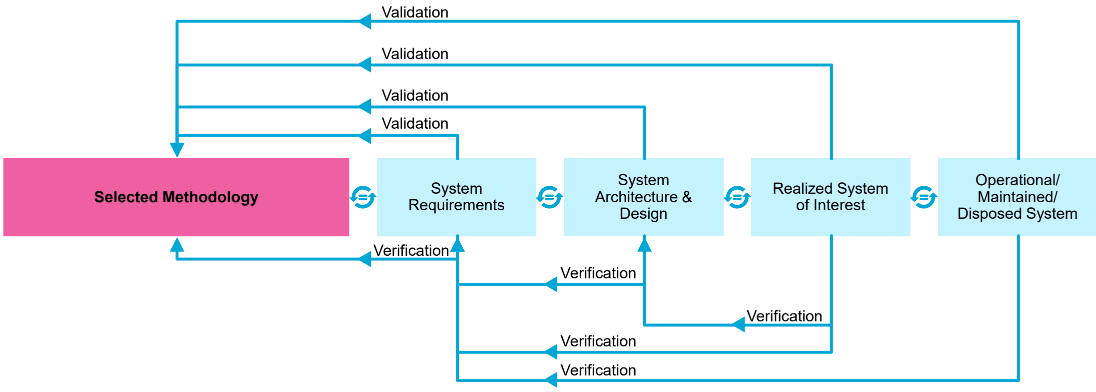

Figure 1. Methodology Integration into Systems Engineering Processes

- Methodology Characteristics
- Systems Engineering Compatibility
- Stakeholder and User Interaction
- Effort and Resource Requirements
- Methodology Framework
- Flexibility and Adaptability

Figure 2. Evaluation Criteria Thematic Categories

Each criterion was rated on a five-point Likert scale. Of the twenty evaluation criteria, eleven were directly scored by the expert panel. The remaining nine criteria (**Figure 2** grey text format) were either inherently quantitative or more suitably assessed through literature review and document analysis. For all criteria to be assessed by the panel of experts, a standardized description and scoring guideline was provided to ensure consistent grading. In cases where an expert indicated prior experience using a particular methodology, their scores were weighted by a factor of 1.5 to reflect the added value of first-hand experience. All individual criteria within each thematic category were weighted equally when calculating the overall category score. The best-scoring methodologies were advanced to the next research phase, which focused on adapting them for integration into Systems Engineering.

Methodology Adaptation

The selected user needs collection and transformation methodologies were adapted to enable their integration into the Systems Engineering framework as defined by INCOSE [4]. Specifically, the adaptations focused on aligning each methodology with the early stages of the INCOSE lifecycle, replacing the conventional steps of Stakeholder Real-World Expectations and Stakeholder Needs and Requirements with equivalent processes from the selected methodologies. The goal of this integration is to ensure that the outputs of the adapted methods are sufficiently structured and detailed to serve directly as inputs to the System Requirements phase of the Systems Engineering process (**Figure 1**).

Methodology Validation

Given the qualitative nature of the trade-off analysis conducted in the previous phase, it is essential that the selected methodologies undergo empirical validation to confirm both their practical applicability and their capacity to enhance the integration of user needs into mission design. To enable a meaningful and consistent validation process, a single use case was selected and applied to both of the shortlisted methodologies. This approach ensured that the performance of each methodology could be directly compared under equivalent conditions. The selected use case was defined in advance and included a clearly specified user and a mission context relevant to Earth observation. The validation exercise was structured to test whether the methodologies were capable of producing a set of coherent and technically relevant mission requirements. In particular, the objective was to determine whether each methodology could be used to derive four key mission design parameters for Earth observation missions based on user input: Spatial resolution, Temporal resolution, Spectral resolution and Radiometric resolution.

Use Case Description

The use case selected to support the evaluation of the proposed methodologies originates from a European Earth observation company engaged in the monitoring of Posidonia Oceanica meadows in the Mediterranean Sea. This work supports Measurement, Reporting, and Verification (MRV) activities related to blue carbon accounting [18] [19] [20].

The validation exercise conducted in this research is based on this specific operational context. The domain expert in seagrass and blue carbon, together with colleagues from the same organization, served as the primary users for both methodology applications.

To reflect a realistic application context for New Space companies, the validation activities were designed assuming a baseline level of Earth observation knowledge equivalent to that of a recent graduate in Earth observation sciences. This was done to ensure that the methodologies could be considered applicable not only in academic or research institutions, but also by engineering-centric New Space organizations that may lack deep domain expertise but require reliable frameworks for user needs integration.

3. RESULTS

The literature review and interviews resulted in the identification of thirty-two distinct methodologies and best practices related to the collection and transformation of user needs into mission and system requirements. These methods differ widely in scope, maturity, and formalization. Some represent highly structured frameworks, featuring clearly defined steps and measurable evaluation metrics, and are well-documented in peer-reviewed publications and professional standards. Others are more conceptual or ad hoc in nature, often lacking detailed guidance but offering flexible, principle-based approaches that can be adapted to different contexts. The identified methodologies were classified under User Identification and Engagement, Needs Collection, Needs Transformation and Conceptual types of methodologies.

Following the collection phase, selection criteria were applied to reduce the number of candidate methodologies to a manageable subset for detailed evaluation through an expert trade-off. Applying these "Space Applicability" and "End-to-End Coverage" criteria (as detailed in methodology section) resulted in the selection of six methodologies for inclusion in the trade-off exercise.

Newly Developed Methodologies

In addition to those retrieved from academic and professional literature, three methodologies that had not previously been documented in published sources were developed through interviews. These include Iterative Prototyping, Tender-Based Needs Solicitation and User Community Conferences. Each was developed and documented based on descriptions of current practices provided by the professionals interviewed. While informal in origin, these approaches were found to represent practices that were repeatedly applied with consistent structures and recognizable patterns of use across multiple organizations.

Iterative prototyping begins with mapping the solution space as a branching set of possible options that could address the problem. These branches are then filtered down, not only by the constraints and preferences expressed by the user, but also by the limits imposed by technical, economic, or contextual "realities." From there, the first prototype, commonly quick and low-cost, serves as a starting point to test assumptions. The process then relies on cycles of building, showing, and adapting. In each round, users are asked to interact with the prototype and provide feedback on what works, what doesn't, and what could be improved. Sometimes this involves showing a single evolving prototype to capture detailed input, while other times multiple improved versions are presented side by side so that users can choose the better option. In both cases, the feedback loops and resulting adjustments ensure that each iteration moves closer to a solution that fits user needs.

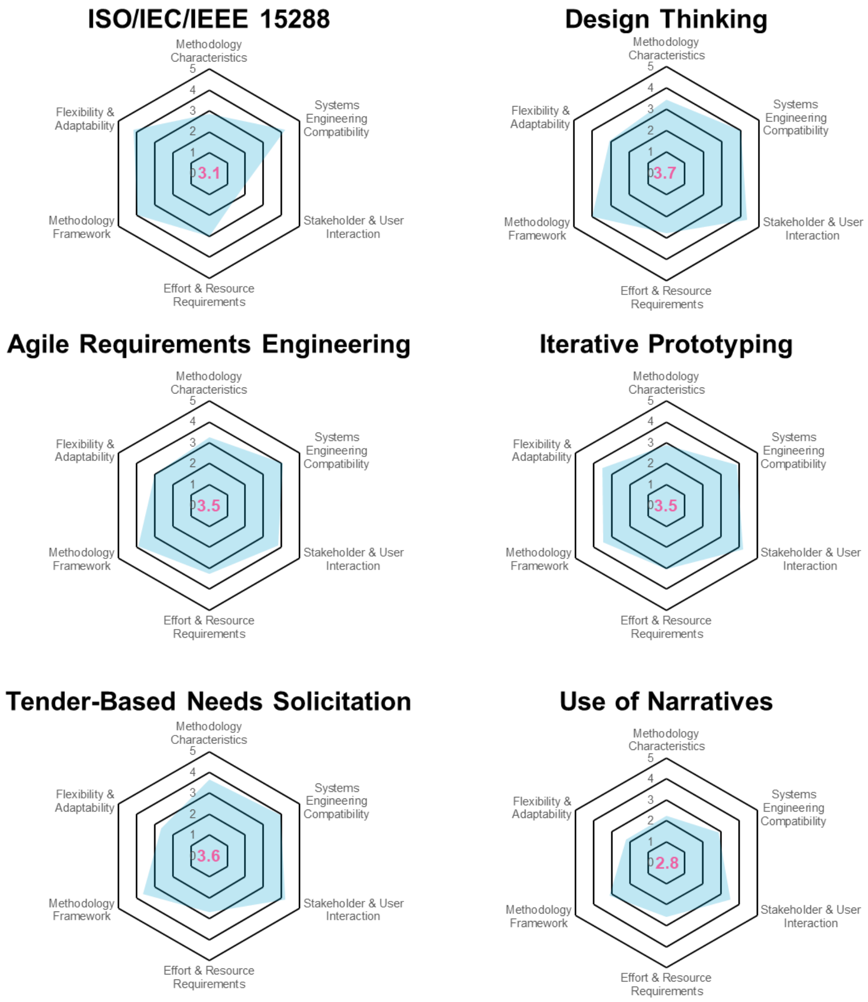

Figure 3. Scoring Spider Graph for Methodology Trade-Off

The Tender-Based Needs Solicitation methodology uses incentive-based tenders to elicit stakeholder input for product development. External actors, including end-users, industry, and researchers, submit either high-level needs or detailed system requirements, depending on the tender scope. Requirements can directly inform the design process, while needs are internally translated into requirements. Submissions are evaluated on feasibility, impact, and alignment with objectives.

The User Community Conferences methodology involves engaging with specific user groups by attending their technical or business conferences to identify needs that could be addressed through Earth observation. This approach has been adopted by multiple New Space companies as an informal, exploratory means of capturing user insights and stimulating innovation through combined sales and technology engagement. Compared to more structured methodologies, this methodology is the least formally defined and relies on direct engagement. Instead of soliciting requirements through formal processes, company representatives observe discussions, interact with participants, and identify challenges articulated within the community, often uncovering opportunities where conventional practices could be replaced or complemented by Earth observation-based solutions. These observations are then analyzed and transformed into potential Earth observation applications, allowing companies to align innovation with emerging, community-driven needs.

The final set of six shortlisted methodologies comprises Systems Engineering (as formalized in ISO/IEC/IEEE 15288 [16]), Design Thinking [21], Tender-Based Needs Solicitation, Agile Requirements Engineering [22] [23], Iterative Prototyping, and Use of Narratives [24].

Methodology Trade-off Results

Eleven experts rated the shortlisted methodologies based on eleven criteria, grouped in six thematic categories. For each evaluation category, a composite score was calculated based on the scoring values of the respective criteria (Figure 3). The average scores ranged from 2.8 to 3.7 (with standard deviations ranging from ±0.83 to ±1.32) across all evaluation groups. Despite the observed variability, attributed to the limited number of participants and the five-point discrete scoring system, a number of consistent patterns emerged for the various evaluation categories. A particularly notable result concerns the Stakeholder and User Interaction category. Systems Engineering, as traditionally practiced, received the lowest scores in this area. Experts consistently assessed it as offering limited interaction with users and stakeholders throughout the early design process. This result is especially significant, as this category directly reflects the key goal of the research: the improvement of integration of user needs into mission design. In contrast, all other methodologies evaluated in the trade-off received scores at least 1.7 points higher in this category, strongly supporting the hypothesis that the current Systems Engineering approach, while rigorous, is insufficiently user centric.

Conversely, Systems Engineering received higher ratings in the Flexibility and Adaptability category, particularly under the criterion of "Standardization." In this context, flexibility was evaluated in terms of repeatability and transferability across projects, rather than adaptability to evolving market conditions or user needs. Other methodologies, while offering greater inclusivity and adaptability, were generally seen as less standardized and, therefore, potentially more difficult to implement consistently across projects.

Another key finding was that the "Use of Narratives" methodology was found by multiple experts to lack space applicability and end-to-end coverage, and it scored lowest across nearly all categories, indicating that despite the methodology passing the pre-trade-off selection process, it is not suitable for collecting and transforming user needs in the space domain.

A comparative analysis (**Figure 3**) reveals that three methodologies (Design Thinking, Tender-Based Needs Solicitation, and Agile Requirements Engineering) showed similar patterns of performance relative to Systems Engineering. Each outperformed Systems Engineering in Stakeholder and User Interaction and methodology Characteristics but scored lower in flexibility and adaptability, particularly due to weaker standardization. In contrast, Iterative Prototyping exhibited a distinctly different pattern. While it performed comparatively worse in the Methodology Characteristics category, it achieved higher scores in Flexibility and Adaptability. This divergence suggests that an integrated approach, one that combines the methodological characteristics (e.g. complexity, number of steps and maturity) of methods like Design Thinking or Agile Requirements Engineering with the flexibility and potential for process formalization offered by Iterative Prototyping, may offer promising results. Based on these findings, Iterative Prototyping was selected as one of the two methodologies to undergo further adaptation and validation. Among the remaining three top-performing methods, Design Thinking was chosen as the second candidate. This decision was informed not only by its overall trade-off performance, which surpassed that of Tender-Based Needs Solicitation and Agile Requirements Engineering, but also by its maturity, widespread recognition, and demonstrated versatility across domains.

These two selected methodologies were then adapted to enable their integration into the Systems Engineering framework as defined by INCOSE [4]. Specifically, the adaptations focused on aligning each methodology with the early stages of the INCOSE lifecycle, replacing the conventional steps of "Stakeholder Real-World Expectations" and "Stakeholder Needs and Requirements" with equivalent processes from the selected methodologies. During the adaptations of the methodologies specific emphasis was placed on ensuring compatibility with verification and validation processes and on improving the traceability and quality of the resulting system requirements. Importantly, the adaptations were kept limited in scope to preserve the original purpose of each methodology with the ultimate goal to make them suitable for integration into Systems Engineering while also maintaining their key strengths, such as user focus and iterative development.

Validation Phase: Iterative Prototyping

The validation exercise was conducted using a real-world use case involving the design of an Earth observation mission focused on mapping

Posidonia Oceanica fields for blue carbon monitoring. The goal of the validation phase was to determine whether each methodology could support the derivation of core mission requirements, including spatial, spectral, temporal, and radiometric resolution. This validation activity was performed for both the Iterative Prototyping and the Design Thinking methodology.

For Iterative Prototyping, the validation process began with a structured interview in which the user articulated the initial problem statement, expressed needs, mission goals, and functional objectives. Based on this input, a solution space was constructed using solution trees that linked high-level user input to system design parameters. This initial mapping revealed that the application required optical imaging in RGB and NIR bands, with a spatial resolution between 30 cm and 10 m, and a temporal resolution not exceeding six years.

Following this, five prototyping rounds were conducted, each building upon user feedback and technical assumptions. Table I presents the specifications developed over the course of these rounds. The prototype in round 3 was developed through spectral analysis of in-situ data collected through a marine spectral mapping project.

Table 1. Iterative Prototyping Methodology Validation Prototyping Rounds

Round	Parameter Tested	Prototype Parameters
1.A	Spatial Resolution	0.3m / 10m / 30m
1.B	Spectral Resolution (Blue)	443nm / 490nm
1.C	Spectral Resolution (Red)	665nm / 705nm / 740nm
1.D	Temporal Resolution (@ 10m)	6 years / 1 year
2.A	Spatial Resolution	0.5m / 2m / 3m
2.B	Temporal Resolution (@ 0.5m)	1 year
3	Spectral Resolution	Processing Algorithm

Various prototypes were presented during the feedback sessions with the users (exemplary prototype in Figure 4). The prototype itself was also provided to the user for further investigation when requested.

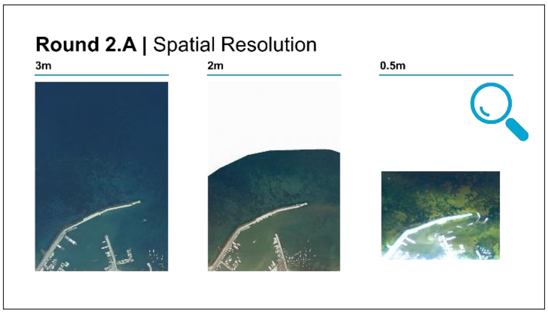

Figure 4. Example Iterative Prototyping Iteration Presentation

The resulting mission requirements derived from this process were as presented in **Table 2**.

The concept of methodological uncertainty used in the table does not refer to uncertainty in a numerical or statistical sense, but rather to the variability range introduced by the methodology itself, calculated by taking the extremes of options available when applying the methodology.

Table 2. Iterative Prototyping Methodology Validation Results

Resolution	Value	Uncertainty
Temporal Resolution	365 days	90 days
Spatial Resolution	3 m	1 m
Spectral Resolution	Inconclusive	N/A
Radiometric Resolution	Inconclusive	N/A
Spectral sampling:		
Blue Band	*400-500 nm*	*50 nm*
Green Band	*500-600 nm*	*100 nm*
Red Band	*630-680 nm*	*70 nm*
NIR Band	*770-900 nm*	*50 nm*

As shown in **Table 2**, Iterative Prototyping is able to produce high-level mission requirements for spatial and temporal resolution within three prototyping rounds. However, for spectral and radiometric resolution, the methodology was unable to converge on definitive values. For this validation use case considered here, this indicates that while Iterative Prototyping appears effective in deriving user-driven requirements for dimensions that are easily perceivable and comparable by stakeholders, it seems less suited to parameters such as spectral and radiometric resolution, where domain-specific expertise and technical benchmarking are indispensable.

Validation Phase: Design Thinking

For the evaluation of the Design Thinking methodology, the standard process structure was employed, consisting of four stages: empathize, define, ideate, and prototype. For the validation exercise, the prototype phase was omitted due to time constraints and infeasibility of creating space mission prototypes. The absence of this phase limits the methodology's end-to-end assessment.

The Design Thinking session followed a structured three-hour format. The workshop began with a user group introduction, allowing participants to share their background and explain their engagement with the Earth observation problem at hand. This was followed by the "Empathize Phase", during which participants collaboratively mapped their experiences, frustrations, and expectations regarding the monitoring of Posidonia Oceanica fields. Differently colored Post-it ® notes were used to track inputs and maintain traceability to specific users.

Once the "Empathy Map" was completed, the workshop transitioned to the "Define Phase". Here, the group synthesized insights from the empathy phase and formulated need statements for each user. Next, participants entered the ideate phase in which participants generated ideas for solutions to the user-defined problems. These ideas were clustered into two distinct concepts. Participants were divided into two smaller groups to elaborate on each concept. At the end of the session, the concepts were presented to the wider group.

In total, five participants took part in the session: the researcher leading the study, an Earth observation engineer, a domain expert on Posidonia Oceanica, an expert in EU environmental projects, and an end-user engaged with Posidonia for commercial applications.

The Design Thinking process produced two distinct concepts:

1. POSISAT – A satellite Earth observation mission dedicated to monitoring Posidonia fields from space.
2. PDG – A drone-based monitoring concept focused on assessing the health and spatial distribution of Posidonia through aerial campaigns.

The concept-cards indicating the key results per concept are as shown in **Figure 5** and **Figure 6**. These concept cards have been copied, cleaned, and anonymized while retaining the original inputs.

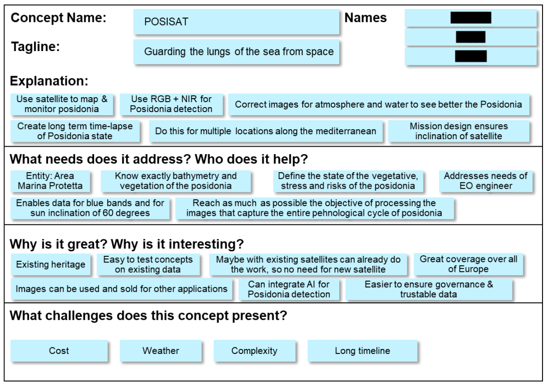

Figure 5. Design Thinking Concept 1: POSISAT

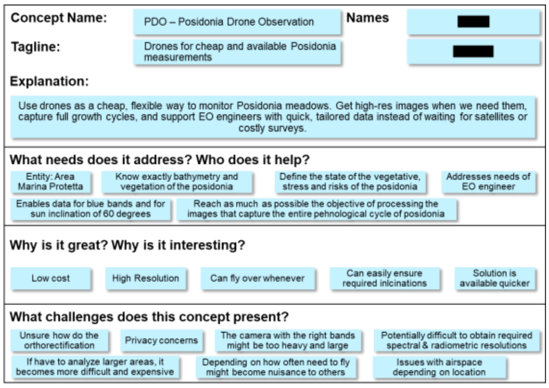

Figure 6. Design Thinking Concept 2: PDO

The Design Thinking methodology validation effort did not result in clearly defined system or mission requirements. While the workshop provided valuable qualitative insights into the user needs and fostered stakeholder engagement, it did not generate outputs that could be directly translated into actionable engineering requirements. Based on this validation use case, the methodology appears effective for eliciting user needs, but less suited for directly translating those needs into mission or system requirements.

4. Methodological Limitations and Strengths

This study explored novel methodologies for user needs collection and transformation. By exploring the differences in approaches between New Space and traditional space organizations it aimed to bridge the gap between these methodologies and to identify best practices that could enhance the overall process of requirements generation. Integrating these methods into Systems Engineering could enable traditional space organizations to better align their missions with the evolving needs of Earth observation users and enhance their responsiveness to the rapidly changing demands of a commercialized space market. Such improved methodologies would provide New Space organizations with a more structured approach for incorporating user needs into their processes. The applied approach supports integration into traditional environments and provides a starting point for new entrants unfamiliar with established processes. Ultimately, this research intends to pave the way for a better understanding of how user-centric, flexible processes can be incorporated into established systems engineering practices.

Iterative Prototyping

In response to the central research question, Iterative Prototyping shows clear potential to improve the integration of user needs into the early phases of Earth observation mission design. Its main strength lies in enabling continuous validation, iterative feedback, and progressive refinement of high-level mission requirements. While only suited to early-stage design, the methodology offers a user-centric alternative to traditional Systems Engineering in the early phases. However, it is less effective for deriving detailed technical or subsystem-level requirements, does not integrate seamlessly with Model-Based Systems Engineering (MBSE), and requires further formalization for broader adoption. Still, as a complementary front-end tool for stakeholder engagement and mission requirement definition, Iterative Prototyping represents a promising way forward.

Further evaluation of the validation of the Iterative Prototyping methodology revealed several limitations. Firstly, the methodology is unable to generate meaningful requirements for spectral and radiometric resolution. This limitation is thought to arise because users are generally unable to distinguish spectral bands beyond the visible range. While they can intuitively assess parameters such as spatial or temporal resolution, spectral and radiometric resolution require specialized knowledge of sensor physics and the interpretation of spectral signatures. Current practice in the field relies on determining the spectral signature of the target subject, a process that demands technical expertise and is not feasible for standard users to replicate [25]. In the simple use case considered here, this limitation was manageable; however, in more complex scenarios, it would be unrealistic to expect non-expert users to provide reliable input on spectral or radiometric requirements. This indicates that Iterative Prototyping should be complemented by established analytical techniques when addressing spectral and radiometric requirements, or any other requirement types for which non-Earth observation specialist users cannot directly perceive the effects in the resulting data products.

Second, achieving meaningful results with this method proved highly dependent on the availability of well-prepared data. The data preparation stage was labor-intensive, assumption-sensitive, and required substantial technical expertise, consuming much of the overall effort. The prototyping workshops themselves were also more time-consuming than expected, particularly early on when user needs were unclear. A key challenge was the absence of a standardized process for eliciting and structuring user needs during solution space identification, which created inefficiency and risk of misinterpretation.

User engagement posed another limitation. Without strong facilitation, feedback was often superficial (e.g., binary yes/no responses), limiting its usefulness. The method also lacks built-in mechanisms for documentation and traceability, requiring additional effort from the facilitator.

Despite these challenges, several benefits emerged. The user viewed the methodology as novel and appreciated its role in refining “wants” into actual needs. For example, an initial request for 0.3m resolution imagery was revised down to 3m after prototype evaluations demonstrated that the coarser resolution was sufficient for the intended use case. Iterative feedback also fostered stronger ownership and engagement, while providing continuous validation checkpoints. Compared to traditional Systems Engineering, which often defers validation until late in the process, this represents a significant improvement in user-centricity and traceability.

Design Thinking

Design Thinking, as applied in this research, demonstrated strong value in the early phases of user engagement. Its structured yet flexible approach enabled participants to articulate needs that might otherwise remain implicit, while also fostering creativity and openness to unconventional solutions. The methodology proved particularly effective in uncovering latent user requirements, reframing vague “wants” into clearer “needs”, and stimulating dialogue among diverse stakeholders. By emphasizing empathy and collaborative exploration, Design Thinking provided a user-centric lens that enriched the understanding of the problem space.

Nonetheless, the Design Thinking methodology, as applied in this research, was unable to generate mission-level requirements from the identified user needs. This indicates a key weakness of the methodology in its current form: it does not provide mechanisms to traceably derive technical system requirements from user input. Even if the full prototyping phase had been conducted, this limitation would largely remain. In Design Thinking, prototyping is typically focused on the prototype of the system itself rather than the output it is intended to deliver (e.g. a prototype of a satellite is the expected output rather than a prototype of a data product) [21]. As such, the transformation of that prototype into concrete data product requirements would still require expert interpretation. Hence, the methodology alone does not support a direct, traceable pathway from user insight to technical specification.

Another methodological constraint is the reliance on technical expertise during workshops. An Earth observation engineer is essential to translate qualitative inputs into viable mission requirements, as shown when a drone-based monitoring concept, without critical system parameters (such as spectral requirements), was generated. This dependence may pose challenges for New Space companies focused on space hardware production, which often lack in-house Earth observation expertise or resources to involve specialists early in design.

The Ideate phase further highlighted limitations. Many concepts generated were either unrelated to space-based solutions or technically infeasible. Moreover, participants struggled to propose innovative Earth observation mission architectures, which may suggest that innovation in this domain often takes place at the technological and data-processing levels rather than in high-level mission design, where substantial expert support is typically required.

Finally, this validation focused on a single, well-defined use case. Scaling Design Thinking to broader Earth observation programs with multiple themes and customers would demand far greater time, resources, and coordination. In such contexts, reaching consensus on shared needs and viable design paths may exceed the practical limits of the methodology in its current form.

Overall, Design Thinking was shown to bring value to user engagement and problem framing, but its direct application in Systems Engineering remains limited without further adaptation. In particular, the absence of requirement-level outputs, the lack of traceability, and the potential divergence from space-specific solutions restrict its utility in current mission design workflows. Future work should investigate hybrid frameworks that combine Design Thinking with methods capable of systematic transformation and integration into the engineering lifecycle.

Methodology Merging

The results of this study's validation effort suggest that Iterative Prototyping is able to refine user needs and transform these into some mission-level requirements but struggles in effectively capturing all user insights. Design Thinking, in its standard form, is not able to generate system or mission requirements that can be directly used in Systems Engineering processes. However, it is effective in capturing early user insights, uncovering needs, and fostering creative exploration. Design Thinking can serve as an effective front-end tool for user need collection, particularly when integrated with more structured methodology that is able to refine these needs and transform them into requirements. The study's analysis revealed distinctive strengths of each methodology. Benefiting from the complementary strengths, the broader recommendation is to combine both methodologies, Iterative Prototyping and Design Thinking, for improved user needs integration into early phase mission design. Design Thinking may be best employed as a precursor to Iterative Prototyping. In this sequence, Design Thinking would serve to define the problem space and generate candidate concepts, while Iterative Prototyping would guide the user through the refinement of those concepts into validated, engineering-ready requirements.

Building on the complementary strengths of both methodologies, future work could best evaluate this combined approach in an extended validation exercise that also compares its outputs against those of a conventional Systems Engineering baseline.

5. CONCLUSIONS

This research set out to address the methodological gap between traditional Systems Engineering and the user-centered design approaches increasingly adopted in the New

Space sector. Specifically, it aimed to investigate how user needs collection and transformation methods and practices identified in and outside of the New Space sector can be integrated into the Systems Engineering framework used by the traditional space industry to improve the integration of user needs into mission designs.

A structured methodology was employed to identify 32 relevant methods, followed by a trade-off analysis that shortlisted six for further evaluation. Of these, Iterative Prototyping and Design Thinking emerged as the most promising candidates. Both were adapted to align with Systems Engineering practices and validated through application to a real-world Earth observation use case focused on Posidonia monitoring.

The results from this study suggest that user-centered methodologies, such as Iterative Prototyping and Design Thinking, can enhance the front-end phases of Systems Engineering by improving user engagement, enabling early validation, and fostering iterative refinement of user needs. For the Posidonia monitoring use case, the Iterative Prototyping methodology, in particular, showed strong potential for supporting continuous user feedback and convergence on certain mission-level requirements, although it struggled to produce spectral and radiometric requirements. The Design Thinking methodology, in the context of this research and validation use case, was unable to produce system level requirements based on user inputs. However, it was effective at collecting user needs, problem framing and stakeholder involvement but lacked mechanisms for (traceably) deriving system-level requirements, especially in complex technical domains.

Both methods have the ability to be integrated into Systems Engineering workflows through minor adaptations. However, the research indicates that while user-centered methodologies offer valuable enhancements to traditional Systems Engineering, they are not standalone solutions. Rather, when carefully integrated and technically supported, they function best as complementary tools.

In conclusion, the study demonstrated that the use of novel methods, such as Iterative Prototyping and Design Thinking, applied in the early phases of the conceptual design process improves user engagement and promotes the elicitation of user needs. The study's trade-off analysis indicates that Iterative Prototyping also facilitates the derivation of mission requirements directly driven by user needs.

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3 Conclusions and recommendations

This chapter summarizes the findings of the research presented in Chapter 2 and addresses the main research question and the six sub-research questions formulated in Chapter 1. The research set out to investigate how user needs collection and transformation methods, identified from within and outside the New Space sector, can be integrated into the systems engineering framework used by the traditional space industry to improve the incorporation of user needs into mission designs. The conclusions drawn here are based on the results of the literature review, expert interviews, trade-off analysis, and validation exercises detailed in Chapter 2.

3.1 Conclusions

The results of the work performed in this research demonstrate that user-centred methodologies can be integrated into the front-end phases of the INCOSE Systems Engineering lifecycle by replacing the conventional Stakeholder Real-World Expectations and Stakeholder Needs and Requirements steps with equivalent processes from the selected methodologies. Out of the six shortlisted methodologies that were evaluated in this research, Iterative Prototyping and Design Thinking emerge as most promising. Both methods show indications of improvement of early-stage user engagement and needs elicitation relative to traditional systems engineering practice. Iterative Prototyping, in particular, supports continuous feedback loops, iterative refinement, and the derivation of mission-level requirements directly driven by user input, while maintaining validation and verification traceability within the systems engineering framework. Design Thinking contributes effectively to problem framing and stakeholder engagement but does not provide a traceable pathway to technical specifications and mission requirements in its current form.

In addressing the main research question: "*how user needs collection and transformation methods identified in and outside of the New Space sector can be integrated into the systems engineering framework to improve the incorporation of user needs into mission designs*", this research finds that integration is achievable through targeted replacement of the front-end process steps of the INCOSE lifecycle with user-centred methodologies, provided their outputs are structured to maintain requirements traceability. Of the methods evaluated, Iterative Prototyping offers the most direct path to this integration, enabling the derivation of spatial and temporal mission requirements from user input within a traceable, iterative framework. Design Thinking complements this by improving the quality and completeness of user need elicitation in the preceding phase. Together, these methods address the identified deficiency of traditional systems engineering in engaging users during conceptual design, offering a structured yet user-driven alternative to conventional front-end practices. Whether this integration constitutes a true improvement over traditional systems engineering practice is indicated, but not yet proven, by the trade-off analysis. Expert scoring favoured the proposed methodologies over conventional systems engineering in user engagement and needs incorporation, yet empirical confirmation through a controlled comparative use case remains necessary to substantiate this conclusion.

Sub-question 1: *What widely adopted methods for user needs collection and transformation are used by New Space organizations?*
The research found that very few formalised methodologies for user needs collection and transformation exist within New Space organizations. The practices identified through interviews are largely informal and organisation-specific, and include direct and frequent user engagement meetings, attendance at user community conferences to identify emerging needs, and iterative prototyping to refine solutions through successive user feedback cycles. Three of these practices were sufficiently structured and consistently applied across multiple organisations to warrant documentation as novel methodologies: Iterative Prototyping, Tender-Based Needs Solicitation, and User Community Conferences. The absence of standardised, documented methodologies in this domain represents a gap that this research has partially addressed.

Sub-question 2: *Which New Space organizations have successfully validated their Earth observation satellite services against the initially collected user needs, and what methods were used in this validation process?*
No evidence was found of New Space organizations conducting extensive formal validation of their Earth observation satellite services against initially collected user needs. Interviews with industry practitioners revealed that market acceptance, most notably, the willingness of customers to pay for a service, is commonly treated as a proxy for validation. This was cited by three interviewed parties as the primary indicator of whether user needs had been adequately addressed. While pragmatic, this approach does not constitute systematic validation and reflects a broader absence of structured verification and validation practices in the New Space sector's front-end processes.

Sub-question 3: *What methods can be used to evaluate the effectiveness of user needs collection and transformation processes for Earth observation missions, and what criteria or metrics support this evaluation?*
No established methods for evaluating the effectiveness of user needs collection and transformation processes specific to Earth observation missions were identified in the literature. In response to this gap, this research developed an evaluation framework comprising 20 criteria grouped into six thematic categories: Methodology Characteristics, Systems Engineering Compatibility, Stakeholder and User Interaction, Effort and Resource Requirements, Methodology Framework, and Flexibility and Adaptability, assessed through a structured expert trade-off. The practical effectiveness of the two selected methodologies was subsequently evaluated through their ability to derive four key mission design parameters: spatial, temporal, spectral, and radiometric resolution, applied to a real-world Earth observation use case focused on seagrass monitoring.

Sub-question 4: *To what extent have the user needs collection methods used by New Space organizations in the past ten years been effective in identifying the needs for operational Earth observation satellites?*
No peer-reviewed studies were identified that formally evaluate the effectiveness of user needs collection methods employed by New Space organizations over the past decade. The relative youth, and inherently long timescales of the sector and the proprietary nature of commercial practices make such assessment difficult. Nonetheless, the growing commercial success and market influence of New Space organisations in the Earth observation domain suggest that their user engagement practices have been sufficiently effective to drive adoption and shape the broader industry. A formal, comparative assessment of their effectiveness remains an open research question.

Sub-question 5: *To what extent are the user needs transformation methods used by New Space organizations in the past ten years effective in converting user needs into system requirements for operational Earth observation satellites?*
Even less information is available on the effectiveness of user needs transformation practices in the New Space sector than on collection practices. Transformation processes are rarely documented or disclosed publicly, making systematic evaluation infeasible at this time. The interviews conducted in this research suggest that the transformation of user needs into system requirements in New Space organisations is largely informal, undocumented, and dependent on individual expertise rather than structured methodology. This represents a significant gap and underlines the relevance of the methodological contributions of this research.

Sub-question 6: *In what way can the proposed methodology be integrated into the requirements generation processes of (Model-Based) Systems Engineering?*
The selected methodologies were adapted to align with the early stages of the INCOSE systems engineering lifecycle, specifically replacing the Stakeholder Real-World Expectations and Stakeholder Needs and Requirements process steps. The adaptations were deliberately limited in scope to preserve the original strengths of each methodology (particularly their user-centric focus and iterative character) while ensuring that their outputs are sufficiently structured to serve as direct inputs to the System Requirements phase. Particular attention was paid to re-establishing the verification and validation traceability links associated with the replaced process steps, ensuring consistency with the broader systems engineering framework. Integration with Model-Based Systems Engineering remains limited in the current form of both methodologies and is identified as a priority for future development.

Together, the findings of the six sub-research questions substantiate the answer to the main research question. The identification, evaluation, adaptation, and validation of methodologies sourced from within and outside the New Space sector demonstrate that user needs collection and transformation methods can be incorporated into the systems engineering framework by replacing its front-end processes with user-centred equivalents, provided that the outputs of the latter are structured so as to preserve requirements traceability. Among the methodologies assessed, Iterative Prototyping provides the most direct and traceable pathway from user input to mission-level requirements, whereas Design Thinking enhances the preceding elicitation phase. These results address the main research question and contribute to a more systematic incorporation of user needs into the conceptual design of Earth observation missions.

3.2 Recommendations for future work

Prior to this research, mission requirements generation in space systems engineering remained predominantly stakeholder-centric, with limited attention paid to end users as distinct contributors to the requirements generation process and with continuous user-driven validation largely absent from established frameworks. The methods adopted within the New Space sector, although recognised as more user-driven, were not systematically documented and could not be directly mapped to the methodologies described in the existing body of literature or integrated into the systems engineering framework. The present work addresses these gaps on three levels. First, it provides a structured review of methodologies for improved user needs collection and transformation, identified from both academic literature and current industry practice, in order to determine which approaches are best suited to improving user need elicitation and the generation of mission requirements. Second, it formalises a set of previously undocumented New Space practices identified through expert interviews, rendering them open to systematic comparison and assessment. Third, it proposes a combined application of selected methodologies (Iterative Prototyping and Design Thinking) at the front end of the systems engineering process, intended to strengthen user needs incorporation in the derivation of mission-level requirements. The contribution of this research is therefore best understood as a conceptual advance over the current state of the art, providing a foundation upon which subsequent work can build. The directions for future work outlined in the remainder of this chapter follow directly from this positioning, identifying both the limitations to be addressed and the developments required to translate the present contribution into a fully validated component of systems engineering practice.

The most fundamental limitation of this research is the absence of a direct comparative validation between the proposed methodologies and the conventional systems engineering process applied to the same use case. Such a comparison, which lies outside the scope and timeframe of the present work, would be required to empirically substantiate the claim of improvement. In its absence, the trade-off results reflect expert judgement of likely improvement rather than demonstrated evidence. The principal recommendation arising from this limitation is therefore the application of the conventional systems engineering process to the same Posidonia Oceanica monitoring use case, with a subsequent direct comparison of the resulting requirements against those produced by Iterative Prototyping and Design Thinking, in terms of both quality and degree of user need incorporation. Such a study would provide the empirical grounding currently absent from this work and would constitute a decisive test of the claim that the proposed methodologies improve upon conventional practice.

A second set of limitations concerns the methodology of the trade-off exercise itself. The expert panel comprised eleven participants, a sample size that limits statistical robustness and generalisability, and that introduces a non-negligible dependence on the individual professional experience of the participants. The use of Likert-scale scoring further introduces an inherent degree of subjectivity, and several evaluation criteria (notably Inclusivity and Adaptability) were defined at a level of abstraction that may have permitted divergent interpretations across experts. A potential bias of the panel toward more contemporary methodologies, such as Design Thinking, cannot be excluded. To address these limitations, future work is recommended along two lines: a substantial expansion of the expert panel, including practitioners representing a more diverse cross-section of methodological traditions, and a refinement of the evaluation criteria.

A third consideration relates to the scope of the validation exercise, which was conducted on a single Earth observation use case (Posidonia Oceanica monitoring). While this naturally bounds the extent to which the findings can be claimed to generalise across mission types, thematic domains, and user types, no factor specific to the present use case was identified that would preclude the replication of these results for comparable Earth observation applications. The derivation of spectral and radiometric requirements directly from user input was, however, found to lie beyond the reach of user-driven prototyping alone, and for this use case continued to rely on expert judgement. Future work is therefore recommended to extend the application of the proposed methodologies to a wider set of Earth observation domains, including missions involving multiple user groups or broader thematic scope, in order to confirm and further substantiate their generalisability, as well as to investigate structured approaches for the derivation of spectral and radiometric requirements from user input.

Notwithstanding the limitations identified above, the methodologies proposed in this work offer a coherent and traceable pathway toward stronger user needs incorporation in the conceptual design of Earth observation missions. Further opportunities arise from the sequential combination of Design Thinking and Iterative Prototyping as a unified front-end methodology. Together with the recommendations outlined above, these directions provide a clear path toward strengthening and validating the methodologies proposed in this work for use in Earth observation mission design.

Appendix A: Overview Identified Methodologies

This appendix presents an overview of the methodologies identified through the literature review and industry expert interviews conducted in this research.

Two distinct literature studies were carried out over the course of the project. The first examined the current state of the art in systems engineering as practised within the traditional space and New Space sectors, with particular attention to how user needs are taken into account and subsequently transformed into mission requirements. This first review was concerned with the framework itself and with the limitations associated with it. Its results are presented in Chapter 1 of this report and in the introduction of the journal paper included as Chapter 2. The second literature study was directed at the identification of methodologies capable of addressing those limitations, focusing on approaches for the collection and transformation of user needs, drawn from the New Space sector, the traditional space industry, and from domains outside the space industry. The methodologies presented in the table below result from this second study, together with the practices identified through the industry expert interviews.

From an initial collection of 75 methodologies, 32 were deemed sufficiently relevant to the research scope to warrant further consideration, based on a preliminary applicability assessment. These 32 methodologies are listed in the table below. From this set, the Space Applicability and End-to-End Coverage selection criteria described in Chapter 2 were subsequently applied to identify the six methodologies shortlisted for inclusion in the expert trade-off exercise, which are highlighted in blue.

Beyond the methodologies retrieved from the literature, the industry expert interviews revealed a number of practices that were consistently applied across organisations but could not be traced to any previously published source. Three such practices (Iterative Prototyping, Tender-Based Needs Solicitation, and User Community Conference) were encountered repeatedly during the interviews, yet no corresponding methodology could be identified in the academic or professional literature to which they could be mapped. During those interviews, practitioners described recurring practices that were applied with consistent structures across multiple organisations, yet could not be mapped to any methodology previously documented in published sources. As a result, it was not possible to assign an existing name or reference to these approaches. Instead, they were newly defined and formalised within this research, based on the descriptions provided by the professionals consulted, in order to make them available for systematic assessment alongside the literature-derived methodologies.

Table 3 - Overview of the Identified Methodologies

Name	Source
ISO/IEC/IEEE 15288	[16]
Co-Creation (for NPD)	[26]
Value-Driven Design	[27]
Best-for-project perspective (Project Front-End)	[28], [29]

Design Thinking	[30] [31] [21]
Iterative Prototyping	Newly Defined
Simplified NPD	[32]
Tender-Based Needs Solicitation	Newly Defined
Agile Requirements Engineering	[22], [23], [33], [34]
Use of Narratives	[24]
Co-Working Spaces/Living Labs	[21]
Service & Customer Experiences	[35], [36]
Governance-Based S/H Engagement	[28]
Value-Based Stakeholder Engagement	[28]
Dynamism-Based Stakeholder Engagement	[28]
Open Innovation Platforms	[37], [38]
Ideas of Value Workshops	[39], [40]
Text-Mining & Idea Screening	[41], [42]
User Involvement Strategy	[43]
Embedded Lead Users	[44], [45], [46], [47]
Company Culture Improvement	[37]
User Engagement through Integration	[48]
Online Platforms	[49]
User Community Conferences	Newly Defined
Early Phase Involvement NPD	[50], [51]
Tradespace	[52]
AR Technology for Reviews	[53]
Performance Indicators for Success	[5], [54], [55]
Qualitative Data	[56]
Decentralized Decision Making	[57]
Requirements Representation	[58]
Knowledge-Driven Functional-Oriented Requirements Elicitation	[59]
Business Process Modelling	[60]

Appendix B: Methodology Trade-Off Description Sheets

This appendix presents the methodology description sheets used during the expert trade-off exercise. Each sheet was provided to all eleven experts prior to scoring and was designed to ensure a consistent and bias-minimised basis for evaluation. To reduce potential framing effects arising from author-drafted descriptions, the methodology descriptions were generated using a large language model (LLM), specifically OpenAI's ChatGPT (GPT-4). The primary source documents for each methodology were uploaded directly to the model, which was then prompted using a standardised instruction to produce a neutral, structured description of each methodology. The same prompt was applied uniformly in an attempt to ensure consistency in tone, depth, and framing, while preserving the information from the original source, which is quoted in the sheet. The use of an LLM for this purpose was considered methodologically preferable to author-drafted descriptions, as it reduces the risk of unconscious bias in the presentation of methodologies the author had already evaluated. All generated descriptions were subsequently reviewed by the author for factual accuracy and verified against the original source material. No content was accepted that could not be substantiated by the primary source.

Experts were instructed to evaluate each methodology independently against the predefined criteria, without reference to or comparison with other methodologies. Scoring was conducted on a five-point Likert scale, where 1 indicates the methodology does not meet the criterion and 5 indicates full compliance. Evaluations were performed individually, without knowledge of other experts' scores. Where clarification on a methodology was requested, the original source was cited to preserve neutrality. Figure 7 presents the standardised evaluation sheet provided to each participant, on which scores and additional remarks per methodology could be recorded.

Each description sheet presents an overview of the methodology, including a process description, its heritage in the space and systems engineering domains, and the primary source from which the methodology was derived. The sheets for the six shortlisted methodologies are presented in Figure 7 through Figure 13.

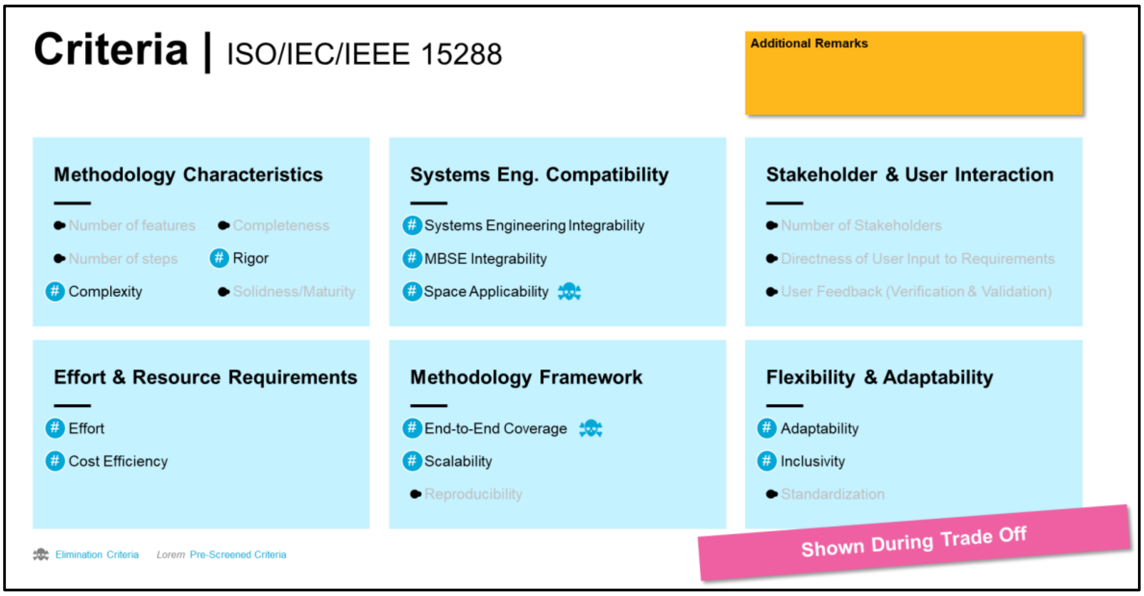

Figure 7 - Methodology Trade-Off Scoring Sheet

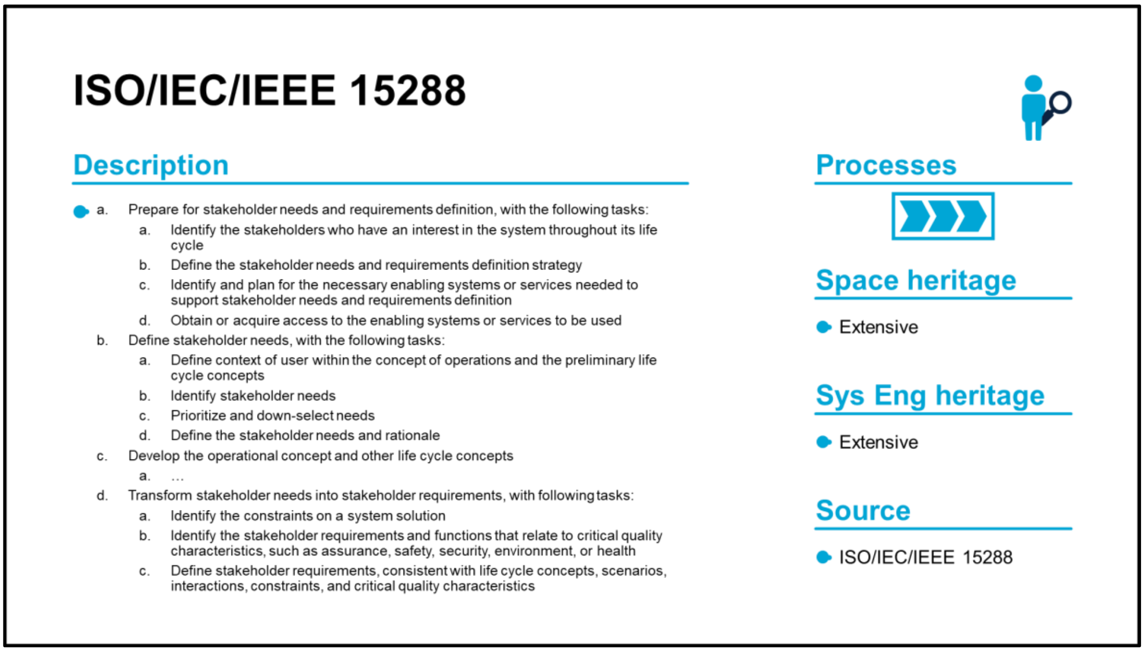

Figure 8 - Methodology Trade-Off Description Sheet ISO/IEC/IEEE 15288

Design Thinking

Description

- The Design Thinking methodology is an iterative and creative process that integrates analysis, experimentation, and user feedback to address complex challenges and generate innovative solutions. It emphasizes collaboration, rapid prototyping, and continuous iteration to align designs with user needs.

  The process begins with identifying a problem or challenge and assembling a diverse team to bring varied perspectives. Stakeholders, users, and beneficiaries are interviewed to deeply understand their needs and experiences, this is often done in the form of interactive workshops or interviews. Insights from these workshops and interviews are analyzed and synthesized to refine the problem statement.

  The transition from needs to system requirements occurs through iterative synthesis based on the problem statement, where insights from user interactions and sacrificial prototyping guide the definition of functional and operational requirements. Instead of a fixed, document-driven approach, the methodology enables emergent requirements based on evolving user feedback, ensuring that the final design remains aligned with actual user needs

Processes

Space heritage

- Moderate

Sys Eng heritage

- Moderate

Source

- McGowan

Figure 9 - Methodology Trade-Off Description Sheet Design Thinking

Tender-Based Needs Solicitation

Description

- The Tender-Based Needs and Requirements Solicitation methodology involves publishing tenders with a monetary incentive to solicit either user needs or system requirements for a specific technology or satellite. This approach engages a diverse set of external stakeholders—including end-users, industry partners, and researchers—to provide detailed input, ensuring that the development aligns with real-world applications.

  Depending on the tender specifications, participants can submit high-level needs or fully defined requirements. When requirements are provided, they can directly inform the design process, accelerating development. In cases where needs are collected, they are analyzed and transformed into detailed requirements through internal processes. Proposals are evaluated based on their feasibility, impact, and alignment with the tender's objectives.

  By incentivizing external contributions, this methodology accelerates idea generation, ensures diverse input, and drives competitive innovation, ultimately leading to more effective and user-centric technological solutions.

Processes

Space heritage

- Moderate

Sys Eng heritage

- Minimal

Source

- Interviews

Figure 10 - Methodology Trade-Off Description Sheet Tender-Based Needs Solicitation

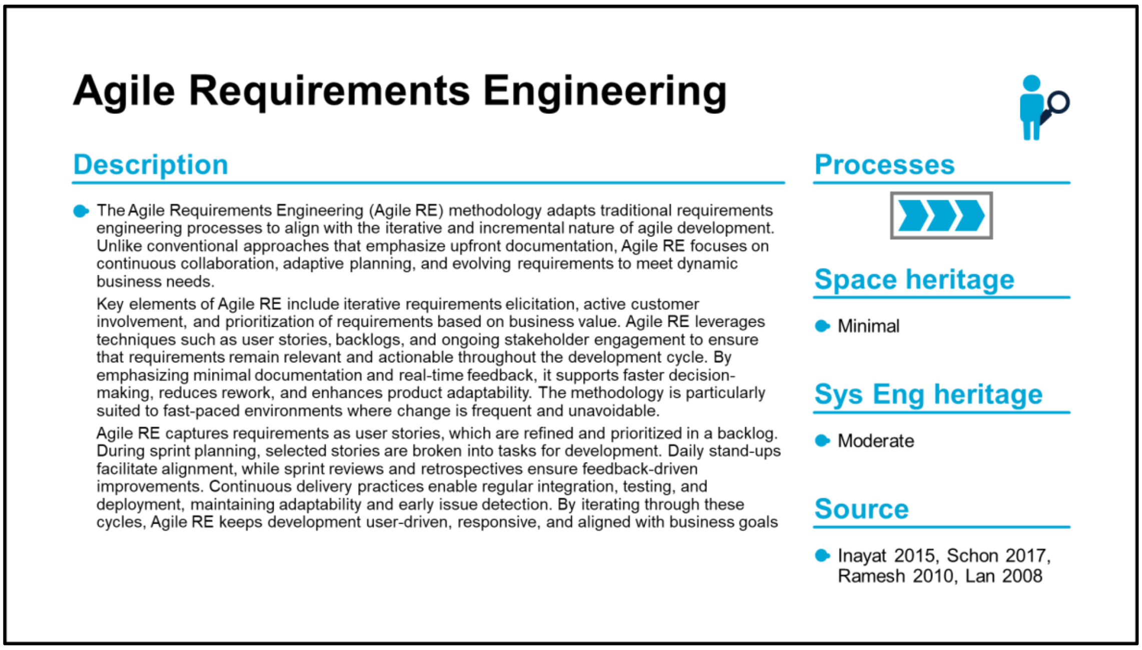

Figure 11 - Methodology Trade-Off Description Sheet Agile Requirements Engineering

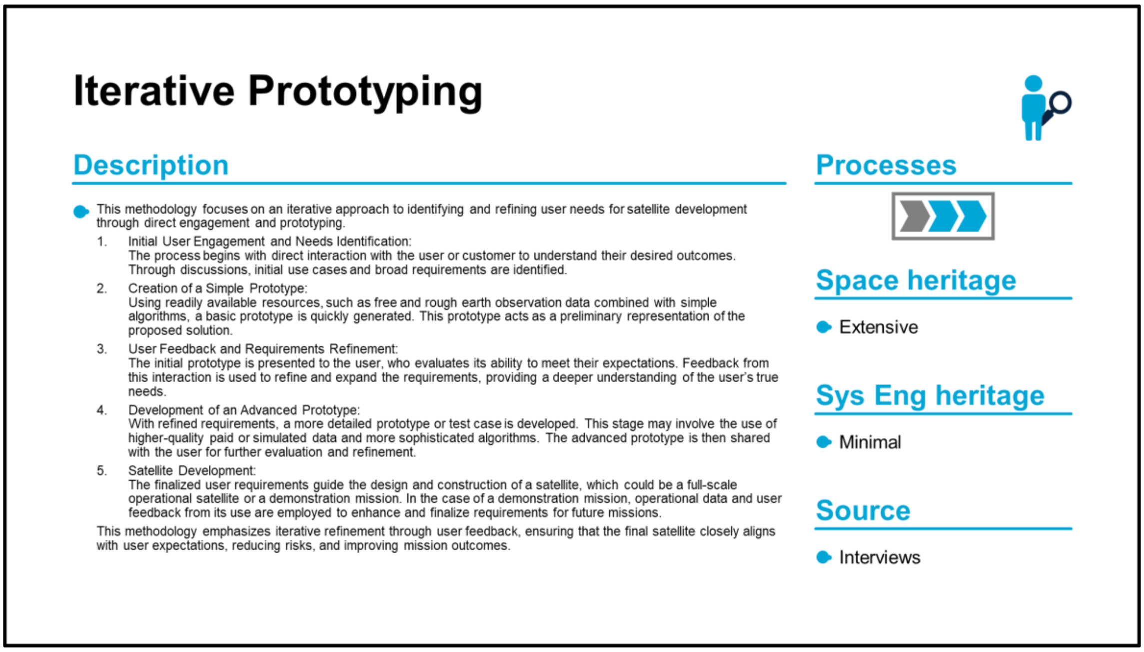

Figure 12 - Methodology Trade-Off Description Sheet Iterative Prototyping

Use of Narratives

Description

- This methodology integrates narrative theory into engineering decision-making processes to improve understanding, training, and stakeholder consensus in complex systems engineering and design contexts. It outlines three primary methods:
  - Understanding Decision-Maker Objectives:
    Narratives are used to capture and convey a decision maker's goals and perspectives. By framing analytical results as narratives aligned with these objectives, engineers can make the analysis more relatable and actionable.
  - Integrating Narratives into Simulations:
    Narratives are embedded within computer simulations to train decision makers. These simulations use engaging and vivid storytelling to immerse users, enhancing their understanding of scenarios and decision-making processes.
  - Creating Consensus Through Shared Narratives:
    Narratives elicited from diverse stakeholders are synthesized into a shared narrative. This approach fosters understanding among parties with differing perspectives, promoting consensus in collaborative decision-making. (Delphi method)

  The application of these methods helps bridge the gap between technical analysis and human understanding. By framing systems analysis in narrative terms, the methodology makes complex engineering issues accessible to diverse stakeholders, ensuring decisions align with user needs and objectives. Further research could explore challenges in implementation, stakeholder alignment, and the empirical effects of narrative integration in decision-making.

Processes

Space heritage

- Minimal

Sys Eng heritage

- Minimal

Source

- MacKenzie 2019

Figure 13 - Methodology Trade-Off Description Sheet Use of Narratives

Appendix C: Trade-Off Criteria

This appendix provides a detailed description of the evaluation criteria used in the expert trade-off exercise. The 20 criteria are organised into six thematic categories, each of which is described below along with a per-criterion breakdown detailing the specific aspect of the methodology being assessed. These descriptions were provided to the expert panel prior to scoring to ensure a consistent and unambiguous basis for evaluation. Criteria assessed directly by the expert panel are indicated as such; the remaining criteria were evaluated through literature review and document analysis, as described in Chapter 2.

Methodology Characteristics
This category encompasses the intrinsic attributes of each methodology, such as completeness, clarity, structure, and procedural rigour. It evaluates how well-defined and systematic a methodology is, including whether it provides clear guidance across the different stages of the user needs process. The category comprises six sub-criteria, of which two are assessed by the expert panel.

Table 4 - Methodology Characteristics Criteria Descriptions

Criterion	Description
Number of Features	The number of distinct aspects or capabilities a methodology offers (e.g., tools, frameworks, adaptability to various scenarios).
Number of Steps	The total number of steps required to execute the methodology.
Completeness	How well the methodology covers all necessary aspects to collect user needs and/or transform them.
Solidness/Maturity	The extent to which the methodology is established, based on the number of peer-reviewed publications, documented case studies, and applications.
Complexity	The level of intricacy involved in understanding and applying the methodology. This criterion is judged by experts.
Rigor	The level of thoroughness, precision and formalism in the methodology. This criterion is judged by experts.

Systems Engineering Compatibility
This category assesses the degree to which each methodology aligns with conventional Systems Engineering practices. Key aspects include the methodology's ability to produce outputs compatible with requirements engineering, its support for traceability, and its potential for integration within established Systems Engineering workflows and toolchains. The category comprises three sub-criteria, all of which are assessed by the expert panel.

Table 5 – Systems Engineering Compatibility Criteria Descriptions

Criterion	Description
Systems Engineering integrability	The ease with which the methodology can integrate into existing Systems Engineering (INCOSE) workflows, including handling iterations and use cases. This criterion is judged by experts.
MBSE integrability	The ease with which the methodology can integrate into Model-Based Systems Engineering processes with minimal changes. This criterion is judged by experts.
Space Applicability	The extent to which a methodology is suitable for the design of space systems. This criterion is judged by experts.

Stakeholder and User Interaction

This category captures the degree and quality of engagement with stakeholders and end-users throughout the methodology's application. It addresses inclusivity, the directness of user input, and the extent to which user perspectives shape the resulting system requirements. The category comprises four sub-criteria, of which one is assessed by the expert panel.

Table 6 – Stakeholder and User Interaction Criteria Descriptions

Criterion	Description
Number of Stakeholders	The number of stakeholders (not solely users) required to implement the methodology effectively.
Directness of User Input to Requirements	How directly user input is translated into requirements, without adaptation of engineers, ranging from user-driven creation to engineer-defined requirements.
User Feedback (Verification & Validation)	The extent to which the methodology incorporates user feedback for verification and validation.
Inclusivity	The degree to which the methodology considers diverse user perspectives.

Effort and Resource Requirements

This category evaluates each methodology in terms of cost-effectiveness, time demand, and required human or technical resources. Methodologies that achieve effective results with reasonable effort and cost are rated more favourably. The category comprises two sub-criteria, both of which are assessed by the expert panel.

Table 7 – Effort and Resource Requirements Criteria Descriptions

Criterion	Description
Effort	The overall time and resources required to implement the methodology.
Cost Efficiency	The extent to which a methodology minimizes costs, considering implementation time, required tools, and organizational efforts.

Methodology Framework

This category considers the overall structure, repeatability, and documentation support provided by each methodology. It examines whether the methodology can be implemented systematically and whether it supports long-term reproducibility and institutional adoption. The category comprises three sub-criteria, of which two are assessed by the expert panel.

Table 8 – Methodology Framework Criteria Descriptions

Criterion	Description
End-to-End Coverage	The extent to which a methodology addresses the full process of user identification, user need collection, and the transformation of needs into requirements.

Scalability	The ability of the methodology to scale across projects of varying sizes and complexities.
Reproducibility	The ease with which the methodology can be replicated in future projects.

Flexibility and Adaptability
This category reflects each methodology's ability to accommodate different contexts, applications, and user profiles. It includes adaptability to new use cases, modularity, and the potential for tailoring without loss of methodological integrity. The category comprises three sub-criteria, of which two are assessed by the expert panel.

Table 9 – Flexibility and Adaptability Criteria Descriptions

Criterion	Description
Adaptability	The flexibility of the methodology to adapt to different Space/Earth observation domains.
Standardization	The extent to which a methodology is or can become a formal standard, ensuring structured and repeatable application.

Appendix D: Trade Off Results

This appendix presents the full trade-off scoring results for each of the six shortlisted methodologies. For each methodology, the individual scores assigned by the eleven experts are presented per criterion, alongside the calculated average score (indicated as AVE) per criterion and per thematic category. The overall average score per methodology is also reported. A subset of criteria, marked in the tables as LT, was not assigned to the expert panel. These criteria correspond to two categories of properties of the methodologies. The first comprises quantitative properties that can be determined directly from the documentation of each methodology, such as the number of process features and steps, the typical number of stakeholders involved, and the directness of user input to requirements. The second comprises properties whose assessment requires a more in-depth study of the methodology than could reasonably be expected of external experts within the scope of the trade-off exercise, such as solidness/maturity, the role of user feedback in verification and validation, and standardisation. In both cases the criteria were assessed by the author through review of the methodology documentation and supporting literature, rather than through expert scoring. This allocation was adopted both to maintain consistency across methodologies and to reserve the expert exercise for criteria that genuinely depend on practitioner experience. As discussed in Chapter 2 of this thesis [14]:

> "*Given the nature of the evaluation criteria of the trade-off, which were largely qualitative, a conventional quantitative or purely analytical trade-off method was deemed unsuitable. Most relevant criteria for this study are descriptive, context-dependent, or reliant on practitioner expertise, and as such cannot be meaningfully captured through numerical or deterministic criteria. Only a minority of criteria (such as the number of process steps or the typical number of stakeholders involved) could be considered quantitative in nature. This evaluation of the methodologies was executed in the form of a trade-off exercise involving multiple internal and external subject-matter experts. Involving professionals with practical expertise in Systems Engineering and Earth observation ensured that the evaluation would be conducted by those who are most likely to use or be affected by these methods in real-world mission design contexts. This approach was considered the most viable means of obtaining reproducible and low-bias results.*"

Table 10 - ISO/IEC/IEEE 15288 Trade-Off Scoring Results

Methodology: **ISO/IEC/IEEE 15288**

Average Score **3.1**

Category	AVE	Criteria	AVE	LT	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Methodology Characteristics	**2.79**	Number of features	**3.0**	3											
		Number of steps	**1.0**	1											
		Complexity	**3.0**		3	4	3	2	3	4	1	2	4	4	3
		Completeness	**2.0**	2											
		Rigor	**2.7**		2	2	4	3	5	2	2	2	4	2	2
		Solidness/Maturity	**5.0**	5											
Systems Engineering Compatibility	**4.12**	Systems Engineering Integrability	**4.2**		5	3	5	4	5	4	3	4	5	4	4
		MBSE Integrability	**3.2**		3	3	4	3	5	3	3	2	3	3	3
		Space Applicability	**5.0**		5	5	5	5	5	5	5	5	5	5	5
Stakeholder & User Interaction	**1.93**	Number of stakeholders	**2.0**	2											
		Directness of User Input to requirements	**1.0**	1											
		User Feedback (Verification & Validation)	**2.0**	2											
		Inclusivity	**2.7**		2	5	2	2	5	2	2	2	3	3	2
Effort & Resource Requirements	**2.77**	Effort	**2.9**		2	4	3	4	3	2	1	3	4	3	3
		Cost Efficiency	**2.6**		3	1	3	3	4	4	2	1	4	2	2
Methodology Framework	**4.00**	End-to-End Coverage	**5.0**		5	5	5	5	5	5	5	5	5	5	5
		Scalability	**4.0**		5	5	4	4	5	4	2	4	4	3	4
		Reproducibility	**3.0**	3											
Flexibility & Adaptability	**4.18**	Adaptability	**3.4**		3	3	1	3	5	3	2	5	4	5	3
		Standardization	**5.0**	5											

Table 11 - Design Thinking Trade-Off Scoring Results

Methodology: **Design Thinking**

Average Score **3.7**

Category	AVE	Criteria	AVE	LT	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Methodology Characteristics	**3.47**	Number of features	**5.0**	5											
		Number of steps	**1.0**	1											
		Complexity	**3.4**		5	2	3	5	4	4	3	1	3	2	4
		Completeness	**4.0**	4											
		Rigor	**3.4**		5	5	4	3	4	3	3	1	3	3	3
		Solidness/Maturity	**4.0**	4											
Systems Engineering Compatibility	**4.01**	Systems Engineering Integrability	**3.5**		3	3	4	3	5	1	3	4	4	4	5
		MBSE Integrability	**3.5**		3	3	5	3	3	1	3	5	4	5	4
		Space Applicability	**5.0**		5	5	5	5	5	5	5	5	5	5	5
Stakeholder & User Interaction	**4.34**	Number of stakeholders	**3.0**	3											
		Directness of User Input to requirements	**5.0**	5											
		User Feedback (Verification & Validation)	**5.0**	5											
		Inclusivity	**4.3**		5	4	5	2	5	4	4	5	5	4	5
Effort & Resource Requirements	**2.79**	Effort	**2.6**		3	1	4	3	3	1	3	4	1	2	4
		Cost Efficiency	**3.0**		3	1	4	3	4	2	3	5	3	2	3
Methodology Framework	**4.24**	End-to-End Coverage	**5.0**		5	5	5	5	5	5	5	5	5	5	5
		Scalability	**3.7**		3	2	5	4	5	2	3	3	5	4	4
		Reproducibility	**4.0**	4											
Flexibility & Adaptability	**3.09**	Adaptability	**4.2**		5	4	5	3	5	4	4	3	5	4	3
		Standardization	**2.0**	2											

Table 12 - Tender-Based Needs Solicitation Trade-Off Scoring Results

Methodology: **Tender-Based Needs Solicitation**

Average Score **3.6**

Category	AVE	Criteria	AVE	LT	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Methodology Characteristics	**3.64**	Number of features	**5.0**	5											
		Number of steps	**5.0**	5											
		Complexity	**3.0**		3	2	4	1	4	3	3	3	5	2	4
		Completeness	**2.0**	2											
		Rigor	**2.8**		5	2	3	3	2	4	2	4	2	1	2
		Solidness/Maturity	**4.0**	4											
Systems Engineering Compatibility	**4.11**	Systems Engineering Integrability	**4.0**		5	3	4	3	4	4	4	5	1	5	5
		MBSE Integrability	**3.3**		3	3	4	2	4	3	3	3	4	5	3
		Space Applicability	**5.0**		5	5	5	5	5	5	5	5	5	5	5
Stakeholder & User Interaction	**4.20**	Number of stakeholders	**5.0**	5											
		Directness of User Input to requirements	**5.0**	5											
		User Feedback (Verification & Validation)	**4.0**	4											
		Inclusivity	**2.8**		1	5	2	3	5	3	2	3	3	2	3
Effort & Resource Requirements	**2.64**	Effort	**2.7**		5	1	3	2	4	2	2	3	2	2	4
		Cost Efficiency	**2.5**		1	2	3	3	1	4	2	3	4	1	4
Methodology Framework	**3.80**	End-to-End Coverage	**5.0**		5	5	5	5	5	5	5	5	5	5	5
		Scalability	**3.4**		3	3	4	4	5	3	3	4	3	2	4
		Reproducibility	**3.0**	3											
Flexibility & Adaptability	**2.64**	Adaptability	**3.3**		3	5	2	3	5	3	3	5	3	4	1
		Standardization	**2.0**	2											

Table 13 - Agile Requirements Engineering Trade-Off Scoring Results

Methodology: **Agile Requirements Engineering**

Average Score **3.5**

Category	AVE	Criteria	AVE	LT	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Methodology Characteristics	**3.24**	Number of features	**5.0**	5											
		Number of steps	**1.0**	1											
		Complexity	**3.1**		3	3	3	3	4	3	3	3	2	3	4
		Completeness	**3.0**	3											
		Rigor	**3.3**		3	5	4	3	4	5	3	1	5	2	3
		Solidness/Maturity	**4.0**	4											
Systems Engineering Compatibility	**4.04**	Systems Engineering Integrability	**3.4**		3	3	4	3	5	4	3	2	4	2	5
		MBSE Integrability	**3.7**		3	3	4	2	5	3	3	5	4	4	4
		Space Applicability	**5.0**		5	5	5	5	5	5	5	5	5	5	5
Stakeholder & User Interaction	**3.76**	Number of stakeholders	**3.0**	3											
		Directness of User Input to requirements	**3.0**	3											
		User Feedback (Verification & Validation)	**5.0**	5											
		Inclusivity	**4.0**		5	4	5	2	5	5	4	4	5	3	3
Effort & Resource Requirements	**3.34**	Effort	**3.2**		3	3	3	3	3	2	3	4	2	4	4
		Cost Efficiency	**3.5**		3	1	4	4	3	3	3	4	5	4	4
Methodology Framework	**3.87**	End-to-End Coverage	**5.0**		5	5	5	5	5	5	5	5	5	5	5
		Scalability	**3.6**		3	1	5	3	5	5	3	3	3	3	5
		Reproducibility	**3.0**	3											
Flexibility & Adaptability	**2.89**	Adaptability	**3.8**		5	5	5	3	5	4	3	2	5	3	3
		Standardization	**2.0**	2											

Table 14 - Iterative Prototyping Trade-Off Scoring Results

Methodology: **Iterative Prototyping**

Average Score **3.5**

Category	AVE	Criteria	AVE		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Methodology Characteristics	**2.88**	Number of features	**4.0**	4											
		Number of steps	**1.0**	1											
		Complexity	**3.4**		5	4	3	4	4	4	3	2	3	4	2
		Completeness	**2.0**	2											
		Rigor	**2.9**		1	4	4	3	5	2	2	2	4	3	2
		Solidness/Maturity	**4.0**	4											
Systems Engineering Compatibility	**4.01**	Systems Engineering Integrability	**3.4**		1	3	4	4	5	2	3	4	2	4	5
		MBSE Integrability	**3.6**		3	3	4	4	5	1	3	5	5	4	4
		Space Applicability	**5.0**		5	5	5	5	5	5	5	5	5	5	5
Stakeholder & User Interaction	**4.20**	Number of stakeholders	**5.0**	5											
		Directness of User Input to requirements	**3.0**	3											
		User Feedback (Verification & Validation)	**5.0**	5											
		Inclusivity	**3.8**		5	2	5	3	5	3	3	4	3	3	5
Effort & Resource Requirements	**3.04**	Effort	**3.0**		3	4	2	5	1	5	3	2	2	3	3
		Cost Efficiency	**3.0**		2	5	2	5	1	4	3	1	3	3	4
Methodology Framework	**3.60**	End-to-End Coverage	**5.0**		5	5	5	5	5	5	5	5	5	5	5
		Scalability	**2.8**		3	1	4	3	5	2	2	1	2	3	4
		Reproducibility	**3.0**	3											
Flexibility & Adaptability	**3.54**	Adaptability	**4.1**		5	2	5	2	5	5	4	3	5	4	4
		Standardization	**3.0**	3											

Table 15 - Use of Narratives Trade-Off Scoring Results

Methodology: **Use of Narratives**

Average Score **2.8**

Category	AVE	Criteria	AVE		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Methodology Characteristics	**2.24**	Number of features	**2.0**	2											
		Number of steps	**3.0**	3											
		Complexity	**2.7**		5	4	2	3	2	1	4	4	1	2	0
		Completeness	**2.0**	2											
		Rigor	**2.8**		1	2	4	3	2	3	2	5	1	4	0
		Solidness/Maturity	**1.0**	1											
Systems Engineering Compatibility	**2.88**	Systems Engineering Integrability	**2.8**		5	3	4	3	2	1	2	3	1	4	0
		MBSE Integrability	**2.3**		1	3	4	3	2	1	2	3	1	3	0
		Space Applicability	**3.5**		5	1	5	1	5	5	1	5	1	5	0
Stakeholder & User Interaction	**3.51**	Number of stakeholders	**3.0**	3											
		Directness of User Input to requirements	**3.0**	3											
		User Feedback (Verification & Validation)	**4.0**	4											
		Inclusivity	**4.0**		5	5	4	5	5	3	4	5	2	3	0
Effort & Resource Requirements	**2.57**	Effort	**2.3**		3	3	2	5	1	1	3	2	2	2	0
		Cost Efficiency	**2.8**		5	3	2	3	1	4	3	2	3	2	0
Methodology Framework	**3.06**	End-to-End Coverage	**3.9**		5	5	5	1	5	5	5	5	1	1	0
		Scalability	**3.3**		1	3	4	3	5	4	3	4	1	4	0
		Reproducibility	**2.0**	2											
Flexibility & Adaptability	**2.27**	Adaptability	**3.5**		3	3	4	4	5	4	4	3	1	4	0
		Standardization	**1.0**	1											

Appendix E: Validation Phase Results

This appendix presents the outputs of the validation exercises conducted for both the Iterative Prototyping and Design Thinking methodologies, as described in Chapter 2.

Iterative Prototyping

The final prototype, presented in Figure 14, constitutes the basis from which the user needs and mission requirements were derived. It is the product of seven prototyping iterations conducted across three sessions.

All prototypes were developed in collaboration with Uptoearth GmbH, with their support extending across the full series of iterations. During the final round, Uptoearth GmbH additionally applied a proprietary processing algorithm in an attempt to derive requirements for spectral and radiometric resolution.

The decision to conduct the prototyping work in collaboration with an external partner reflects the scope of this research, which is centred on the systems engineering framework and on the incorporation of user needs into the requirements generation process, rather than on the development of prototyping capabilities as such. The validation phase was intended to verify whether the proposed methodologies could be integrated into the Systems Engineering framework and whether their application leads to a potential improvement in user needs incorporation. To remain focused on this objective and to avoid divergence into the technical development of prototypes themselves, Uptoearth GmbH was engaged to provide the necessary prototyping expertise.

Figure 14 - Iterative Prototyping Final Prototype

Design Thinking

Figure 15 presents the unaltered outputs of the Ideate phase of the Design Thinking workshop, as recorded during the session. These results reflect the direct input of the participating users and have not been modified or interpreted by the author.

Figure 16 presents the concept card developed for the POSISAT concept (a satellite Earth observation mission dedicated to monitoring Posidonia Oceanica fields from space) which represents the most relevant output of the Design Thinking validation exercise in the context of this research, and forms the basis for the validation assessment presented in Chapter 2.

Figure 15 - Design Thinking Ideate Phase Results

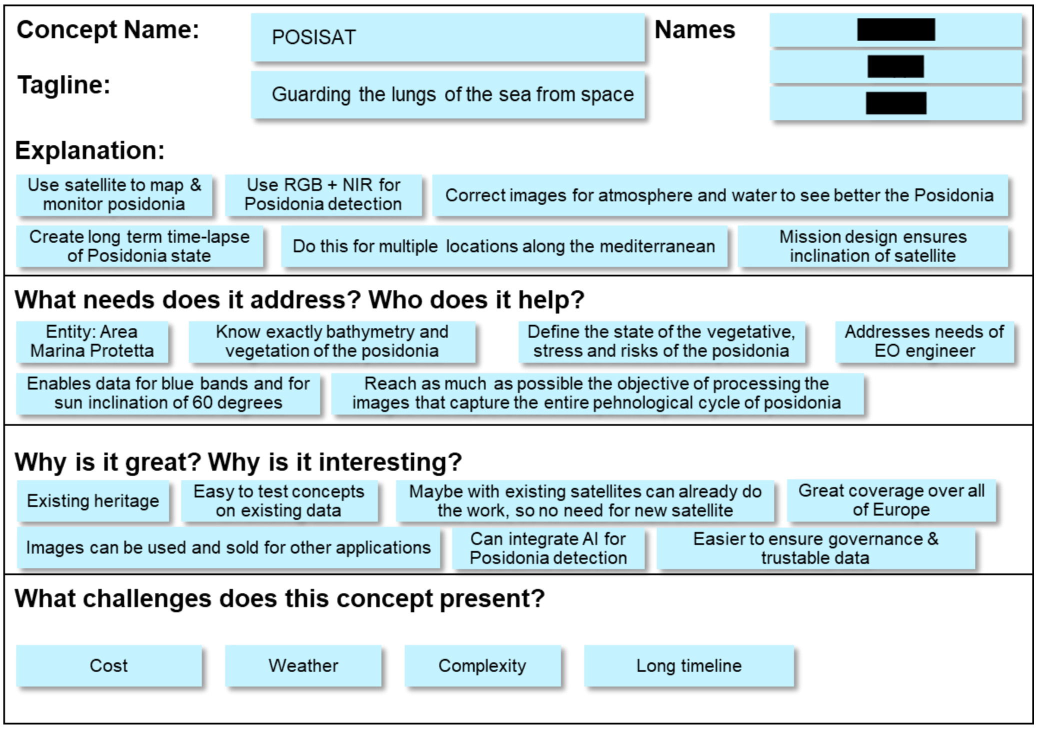

Figure 16 - Design Thinking Concept Results

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