# MATERIAL TRANSITION UNCERTAINTY IN AEROSPACE TEST CAMPAIGNS

## VISUALIZING SOURCES AND IMPACT, AND PROPOSING MANAGEMENT STRATEGIES


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# Material Transition Uncertainty in Aerospace Test Campaigns: Visualizing Sources and Impact, and Proposing Management Strategies

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# Abstract

Innovation has been a key characteristic in the aerospace industry. Launch Vehicles, in comparison, have largely stayed the same over the years; this is changing with the emergence of New Space and the commercialization of space. Competition forces innovation, which leads to companies trying out new materials and propellants that will give them the edge, but such transitions are tied to uncertainty.

This research investigates how material transitions create and amplify uncertainty in megaprojects, focusing on two aerospace test campaigns. The study addresses how uncertainties arise, how they differ between technical and organizational domains, what strategies are used to mitigate them and how a framework can be developed to strengthen procurement and supply chain management in predevelopment.

The study is based on two case studies within ArianeGroup, supported by 12 expert interviews, project documents and a focus group. The Material Transition Map was developed as a tool to visualize interview data and analyze cascading uncertainty across technical and organizational dimensions. The findings show that while technical uncertainty is actively managed through structured modelling and testing processes, organizational uncertainty, especially in supply chains, is more difficult to control. Material transitions trigger cascading effects that link technical changes to procurement delays, supplier challenges and schedule risks. Reliance on heritage plays a dual role in mitigating and amplifying these effects.

Theoretically, the research connects project studies with transition studies, showcasing how material transitions trigger megaproject uncertainty. Empirically, it provides insights into aerospace test campaigns, a sector rarely examined in management literature. Practically, it delivers the Material Transition Map and the Predevelopment Supply Chain Framework, a tailored strategy, validated with practitioners, to support uncertainty management.

# Contents

**Abbreviations**

| | |
|---|---|
| ESA | European Space Agency |
| EU | European Union |
| GEO | Geostationary Orbit |
| GHe | Gaseous Helium |
| LEO | Low Earth Orbit |
| $LH_2$ | Liquid Hydrogen |
| LOX | Liquid Oxygen |
| MLP | Multi Level Perspective |
| MTB | Mobile Test Bench |
| PHOEBUS | Prototype for a Highly Optimized Black Upper Stage |
| SNM | Strategic Niche Management |
| TC | Test Campaign |
| TRL | Technology Readiness Level |
| ULA | United Launch Alliance |

# Introduction

In the aerospace sector, the successful delivery of launch vehicles and space systems depends on long development cycles, complex engineering and high levels of investment. These projects fall under the category of megaprojects, large-scale, high-risk undertakings that require the coordination of numerous stakeholders across multiple domains (Flyvbjerg, 2014). Increasingly, these megaprojects must also respond to broader industry transitions, such as shifts in propellant mixes, manufacturing processes or structural material technology.

Progress in launch vehicle technology, throughout the years, has been largely incremental, with only modest gains in materials, manufacturing and control systems. Despite cost reductions achieved recently by reusability, major breakthroughs in propulsion remain limited, and true economic access to space has yet to be achieved (Aglietti, 2020). However, the rise of private aerospace companies is disrupting traditional space programs by introducing innovative technologies and business models, prompting established industry players to adapt to stay competitive (European Space Policy Institute, 2017). As a result, technological transitions, driven by market competition, are expected to occur more frequently.

Ariane 6 is the flagship launch vehicle of ArianeGroup, developed as the next-generation successor to the widely successful Ariane 5, which completed 117 launches with a 95.7% success rate (Wikipedia contributors, 2025). Unlike a static end product, Ariane 6 is designed as a dynamic platform, continuously evolving through iterative upgrades over its operational lifetime. The two test campaigns examined in this research, focused on a new upper stage type and a new propellant, are part of this ongoing evolution. These R&D efforts explore new materials and configurations that aim to enhance performance, reduce costs and ensure the launcher remains competitive in a rapidly shifting space sector. In this context, innovation is not a one-time milestone but an embedded, continuous process within the Ariane 6 program.

This is why material transition uncertainty must be explored more closely, especially within the context of long-term, high-investment aerospace megaprojects like Ariane 6. As the vehicle undergoes iterative upgrades, the integration of new materials introduces not only technical challenges but also organizational and supply chain uncertainty. This uncertainty can cascade across different project layers, affecting schedules, budgets and risk management practices. Understanding how such transitions generate or amplify uncertainty is essential for developing more adaptive planning and governance approaches, allowing large-scale programs to remain both resilient and competitive in an increasingly innovation-driven market.

Recent work by Winch et al. (2023) emphasizes the need for a deeper understanding of how projects can be structured and managed to support broader systemic transitions. They call for greater integration between project studies and transition/innovation studies, two academic communities that have remained largely siloed despite their overlapping concerns. This research responds to that call by examining material and technological transitions within an aerospace megaproject, providing empirical insights into how uncertainty unfolds in such contexts.

In particular, project scholars have suggested that portfolio and programme perspectives offer promising conceptual tools to analyze the role of projects in large-scale transitions (Winch et al., 2023). This lens is well-suited to the Ariane 6 case as it can be understood as a program composed of multiple subprojects, including the test campaigns studied here, that collectively drive transformation in launcher capabilities and materials.

To explore these dynamics, this research draws on qualitative data collected from experts involved in the two test campaigns. Through semi-structured interviews, the study captures firsthand insights into how material transition uncertainty is experienced and managed within the project. Thematic analysis and clustering is used to identify how uncertainty is generated and concentrated. These findings are then visualized to illustrate the material transition process impact and mitigation. Based on this analysis, the study proposes a framework aimed at improving how one aspect of transition uncertainty is evaluated and managed in complex, evolving project environments.

## Test campaigns of ArianeGroup involved in the study

Ariane 6 is a dynamic and evolving project that is expected to undergo continual changes and modifications throughout its operational lifetime to improve performance and enhance cost efficiency.

A central component of this development process is the execution of Test Campaigns (TCs). These campaigns are, essentially, R&D projects and serve as opportunities to study and validate new materials, systems, configurations and launcher components. The insights gained from these tests contribute directly to the refinement and enhancement of Ariane 6, ensuring its competitiveness and reliability. Additionally, they also contribute to the development of future launchers beyond Ariane 6 or other projects.

In the context of this research, the TCs are an excellent opportunity to study transition uncertainty as they provide real-world data on how new technologies perform under varying conditions and interact with existing systems and processes. This makes them ideal case studies for understanding the technical and organizational challenges that arise when integrating new materials or systems into complex aerospace platforms. By examining these transitions in a controlled but operationally realistic context, the source of uncertainties can potentially be identified, how they are managed by specialists and what strategies are most effective in mitigating risk. Ultimately, this will provide insights not only current launcher development but also future innovation pathways.

The renders shown in Figures 1 and 2, showing the test benches, were sourced from internal ArianeGroup documentation (ArianeGroup, personal communication, June 3, 2025). As these materials are not publicly available, they are used here with permission for academic purposes only.

*Mobile Test Bench*

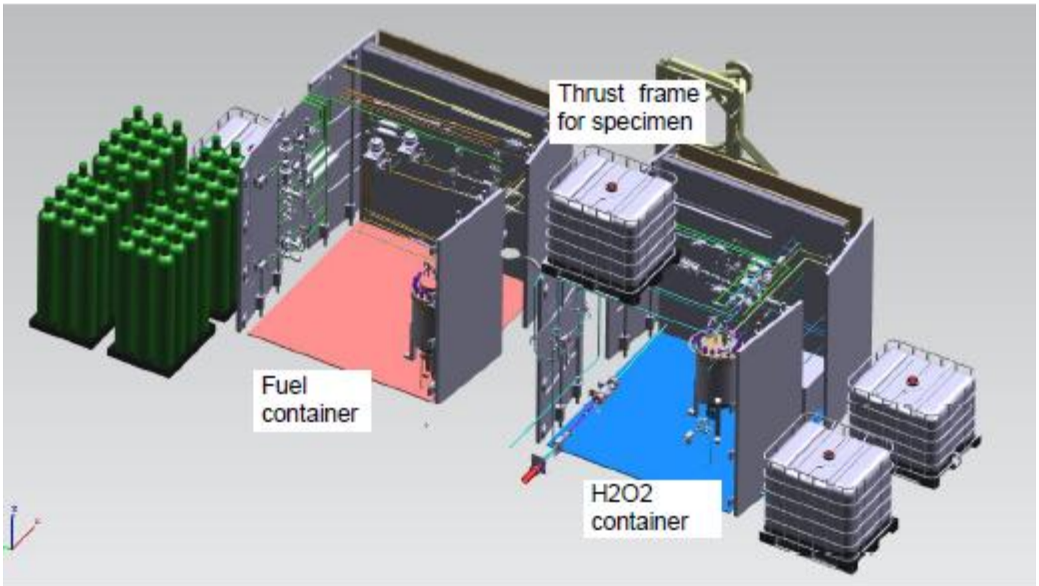
The MTB emerged from a request of ESA to study combinations of propellants, using Hydrogen Peroxide ($H_2O_2$) as oxidizer, a green propellant.

The MTB is a configuration (Figure 1) in which two tanks, one containing fuel and the other containing oxidizer, located in two separate containers, are connected to an engine mount. This way hot fire tests may be conducted. These are ground-based trials where a rocket engine is fired with real propellants to validate performance, integration and safety. During engine operation, fuel and oxidizer combust in a chamber, creating high-pressure hot gases that accelerate through a de Laval nozzle. As the gases expand and speed up, they generate thrust by pushing against the chamber and nozzle walls, following Newton's third law (Halchak et al., 2018). Additionally, the MTB has other components like a series of $GN_2$ bundles for tank pressurization and purging, the process of flushing a system with an inert gas to remove reactive, flammable or toxic substances.

Another novelty of MTB is that in contrast to conventional propulsion test benches, which are normally stationary, is a modular and mobile design. It can be disassembled and transported to another location based on test needs. While this mobility could itself be considered a transition, this research will primarily focus on the shift to green propellants. As discussed in Chapter 3, the choice of propellant has major impact on rocket design, which in turn influences component compatibility, procurement, supply chains etc.

**Figure 1**

*The Mobile Test Bench setup (simple render). Reprinted from internal ArianeGroup documentation (App. D, Table D1), used with permission (2022).*




The engineering team for MTB is based at the ArianeGroup facility in Ottobrunn, Germany, where they lead the design work. The setup of MTB is a joint effort, with teams from both Ottobrunn and Trauen handling different aspects of the project. At the time of this research, the project was in its final preparation phase, with initial tests starting in May 2025.

Studying MTB in the context of transition uncertainty is beneficial because the test campaign has already progressed beyond the design phase and into implementation. This allows for a clear observation of which uncertainties were considered during the conception and design stages, in relation to the adoption of a new propellant, as well as those that emerged during the construction of the test bench and the testing phase itself.

Additionally, MTB provides insight into how the different teams involved in different components, respond to unforeseen challenges during implementation. This should highlight team dynamics, problem-solving approaches and how evolving conditions are managed under real test constraints.

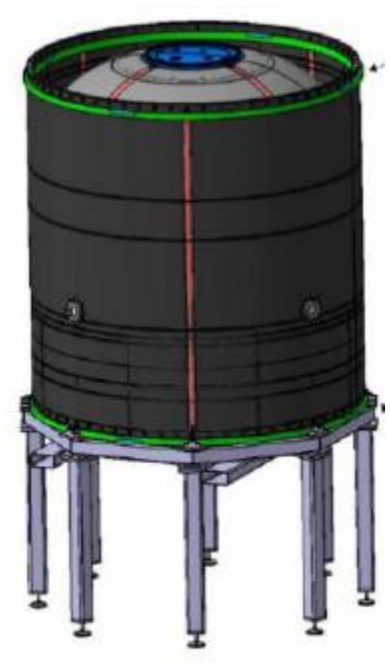
*Prototype for a Highly OptimizEd Black Upper Stage (PHOEBUS)*

PHOEBUS is a carbon composite upper stage demonstrator developed by ArianeGroup. The project aim is to prove that carbon fibre can replace metal in cryogenic tanks, significantly reducing weight and improving payload capacity. This work supports the development of the future ICARUS upper stage and advances cryogenic composite technology for more competitive and sustainable launch systems (ArianeGroup, 2022).

The objective of the test campaign is to design, deliver and test an integrated ground demonstrator for upper stage technologies consisting of a scaled LH2 tank, near full scale LOX tank, a tank connector structure between the $LH_2$ and LOX tanks, filling and draining lines and pressurisation lines.

**Figure 2**

*The PHOEBUS test article (simple render). Reprinted from internal ArianeGroup documentation (App. D, Table D1), used with permission (2024).*



The test campaign does not include engine tests so unlike MTB, hot fire tests are not to take place. Instead, during testing the full tank cycles will be included:

- Conditioning: Prepares the tank by cooling it down to cryogenic temperatures to prevent thermal shocks during propellant loading.
- Filling: Involves loading the tank with propellant, ensuring it reaches the required levels under controlled conditions.

- Topping-up: Adjusts the propellant level to compensate for any losses due to boil-off or thermal contraction, ensuring optimal fill levels.
- Pressurization: Introduces an inert gas (like helium) into the tank's ullage space to maintain the necessary pressure for propellant feed to the engine.
- Draining: Empties the tank of any remaining propellant post-operation or during maintenance, ensuring safety and readiness for subsequent use.

The pressure cycle test involves repeatedly pressurizing a tank to its designated pressure level, maintaining that pressure to inspect for leaks and assess structural integrity and then depressurizing. Such cycles are essential for verifying that the tank can withstand operational stresses without failure.

The engineering team behind PHOEBUS is based in Bremen, where the development and manufacture of the upper stage of the Ariane launchers is taking place. PHOEBUS is currently in the engineering phase, with setup and testing expected to start during late summer/early fall 2025.

The study of PHOEBUS aligns with the goals of this research because it involves a major material shift in the manufacturing of ArianeGroup’s upper stages, moving from metal to carbon composite structures. This transition is expected to affect the entire architecture of the upper stage — including structural integrity, thermal insulation, interfaces with other systems, and manufacturing workflows. Studying PHOEBUS provides valuable insights into how such technological transitions introduce uncertainty, both in design and implementation, and how these challenges are managed across teams and phases.

## Main Research Question and Sub-questions

The main goal of this research is to study material transition uncertainty, how it originates and cascades, its impact on the technical and organizational levels and mitigation efforts. Finally, a framework is created to help manage uncertainty, based on the findings of this research, as such the focus of the framework was not set from the get-go. Later in the research it was decided to target the framework on procurement and supply chain in predevelopment. The main research question is:

***“How do transitions create or amplify uncertainty in megaprojects?”***

The main research question has been broken down into sub questions to help guide the research process.

1. How do technical and organizational uncertainties arise, and how do they differ?
2. How do different types of niche innovations, specifically contribute to uncertainty and affect the overall transition process?
3. What strategies do organizations use to manage material transition uncertainty?
4. How can a framework be developed, based on the findings of the research, to strategically tackle procurement/supply chain issues in predevelopment?

## Overview of Research Methodology

A brief overview of the methodology is given here, which will be further explained in the “Methodology” chapter. To address the research questions and scope down the research, it was necessary to narrow the focus from the beginning, as material transition uncertainty is an inherently broad and complex topic, too difficult to fully address within the scope of this project. The topic also lacked a ready-to-use framework, meaning the research design, thematic structure and analysis had to be developed from scratch. The process began with scoping interviews to reduce the research focus, followed by an in-depth literature review to establish the theoretical foundation for material transitions in launch vehicle subsystems. Insights from these stages informed the development of thematic areas, which guided the design and execution of semi-structured interviews. The collected data were then thematically coded and analyzed using ATLAS.ti, culminating in the creation of the *Material Transition Map* to visually integrate findings.

This structured narrowing allowed for a manageable and targeted investigation while still capturing the interconnected nature of these domains. The research questions, some slightly altered from the initial research proposal, were answered referencing the Material Transition Map, as illustrated in Figure 3.

**Figure 3**

*Overview of the Research Methodology*

# Literature Review

## Part 1: Why Transitions Occur – Theoretical Perspectives and Mechanisms

In the context of this research, it is essential to define and analyze the underlying theoretical concepts that characterize technological transitions and link them to the specific challenges faced in every industry. These include, Transitions Management (TM), which focuses on guiding complex, long-term change processes; Strategic Niche Management (SNM), which explores how protected spaces support the development and scaling of innovations; and the Multi-Level Perspective (MLP), which provides a framework for understanding how interactions between niche innovations, existing regimes and broader socio-technical landscapes drive transitions. By applying these concepts, the research will offer deeper insights into the technological shifts within the aerospace sector, with a focus on the Ariane 6 megaproject. This approach will help link the uncertainties and management challenges that emerge in large-scale transitions.

### Multi-Level Perspective

In the multi-level perspective, transitions are understood as shifts from one sociotechnical regime to another. A sociotechnical regime consists of shared cognitive routines within an engineering community, shaping the progression of technological developments (Geels & Schot, 2007). MLP suggests that transitions occur through the interplay between the sociotechnical regime, landscape and technological niches (Geels & Schot, 2007). The sociotechnical regime is destabilized due to niche innovations, internal tensions within the regime, broader landscape trends exerting pressure (such as climate, economic, cultural, and demographic shifts), and external influences from other systems, regimes, or niches (Papadonikolaki et al., 2023).

Megaprojects, such as space launchers development projects act as controlled spaces where innovation starts and spreads outward (Papadonikolaki et al., 2023), driven by market competition and the pursuit of cost reduction and efficiency increase. This means that there is a need to observe both how small innovations influence big industries (niche-to-regime) and how big industries shape new developments (regime-to-niche) (Papadonikolaki et al., 2023). Unlike typical innovations that evolve through trial and error, megaprojects must be carefully planned and agreed upon in advance, leaving little room for failure (Papadonikolaki et al., 2023).

*Niche, Regime and Landscape Levels in the Aerospace sector*

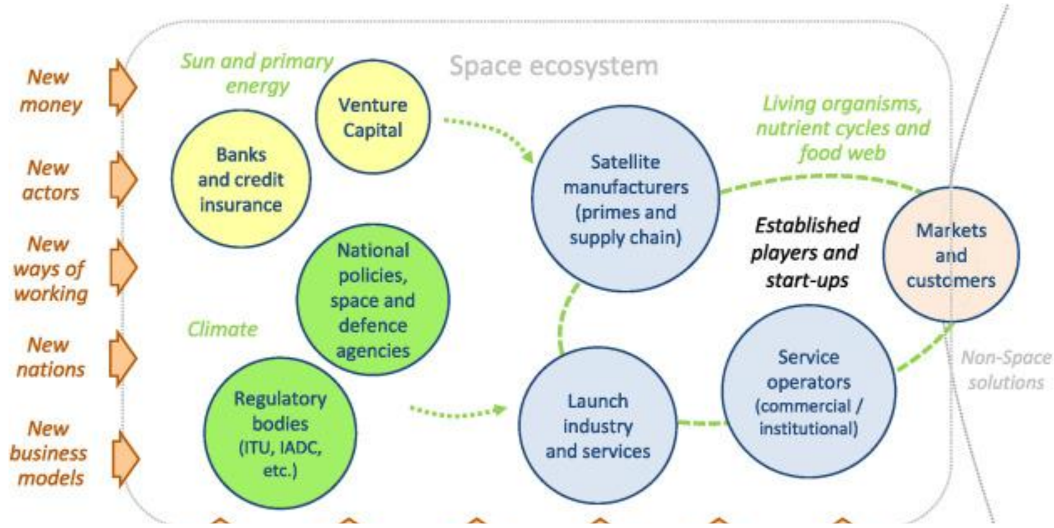
In recent years, there have been developments in the landscape level, driven by policy makers. In the U.S., New Space emerged as a response to post-Cold War challenges, with the government fostering a private space sector through funding, regulations, and outsourcing transport services (Denis et al., 2020). This led to the rise of niche players, SpaceX, Blue Origin and Virgin Galactic. NASA shifted its focus to deep space exploration, while private companies drove commercial innovation. In Europe, the rise of U.S. industrial competition pushed the European Space Agency (ESA) to restructure, granting more responsibility to industry, which gave birth to ArianeGroup in its present form. The EU expanded its space policy, launching Galileo for navigation and Copernicus for Earth monitoring, shifting from public-sector support to economic and private-sector growth (Denis et al., 2020).

The emergence of a new paradigm in space has challenged traditional aerospace methods and business models, as entrepreneurial private sector players adopt more agile strategies and leverage the latest commercial off-the-shelf technologies (Denis et al., 2020). Apart from space communications, most space activities are tied to government projects with long timelines. New players assume there is fresh opportunity in commercial space ventures e.g. the telecom sector is seeing massive LEO constellations for global internet and small GEO platforms for both commercial and military use (Denis et al., 2020). The emergence of new companies poses challenges for established industry players, like ArianeGroup, Lockheed Martin, Northrop Grumman etc, who must adjust their strategies to remain competitive in this evolving landscape (European Space Policy Institute, 2017).

Additionally, neighbouring regimes can influence transitions. One example is the Copernicus Programme, led by the EU with partners like the ESA, which demonstrates how innovation in the space regime can influence other societal regimes such as agriculture and environmental management (and vice versa). Through its Sentinel satellites, Copernicus enables land monitoring services that support land use planning, agriculture, forestry and climate change adaptation. Originally designed for Earth observation, this space-based infrastructure now plays a crucial role in helping sectors manage natural resources more sustainably and respond more effectively to environmental challenges (Jutz & Milagro-Pérez, 2020). Another non-aerospace yet relatable example is provided by Stiles (2020), who uses the post-Covid shift in office work to show how advances in computing technology enabled flexible work arrangements, illustrating how changes in one regime can drive transitions in another.

**Figure *4***

*The Space Ecosystem*




Adapted from Denis et al., 2020

Figure 4, above, illustrates the evolving space ecosystem. The orange arrows symbolize external forces that feed into the ecosystem e.g. new actors (niche players), new technology, new regulation. All of these can kickstart transitions. The green bubbles symbolize the landscape that was described earlier. At the landscape level, policymakers such as the European Union and the European Space Agency play a crucial role in shaping industry by introducing new policies, regulations, and funding mechanisms. These actions influence the sociotechnical regime (blue bubbles), of which aerospace companies are a part. The diagram also emphasizes the growing role of commercial markets and customers, demonstrating how private sector involvement is reshaping the space industry, shifting it from a government-driven sector to a more commercially dynamic and competitive environment.

*Transition Pathways*

This concept by Geels et al. (2016), expands on the MLP by laying out four ways in which socio-technical transitions can unfold. First, technological substitution occurs when a disruptive niche-innovation is ready to take over, as landscape pressures destabilize the existing regime. Second, transformation happens when external pressures push existing regime actors to make gradual changes. Third, reconfiguration involves the integration of compatible niche innovations into the regime, leading to broader structural changes over time. Lastly, de-alignment and re-alignment describes a scenario where intense landscape pressure causes the current regime to break down, followed by a period of instability during which one of several emerging innovations eventually forms the basis of a new regime

Generally, the transitions in the scope of this research follow the transformation pathway. Some examples, of both technical and managerial nature, include:

- Europe (technical): the new upper stage ICARUS for Ariane 6, that ArianeGroup is planning, is constructed using carbon composites instead of metal, resulting in reduced costs and weight. This design enhances payload capacity and enhances the company's competitive advantage (ArianeGroup, 2022).
- Europe (management): ArianeGroup launched a subsidiary, MaiaSpace which utilizes flexible, startup-style operation. By leveraging ArianeGroup's expertise and reusable technologies, MaiaSpace aims to provide competitive launch services for small satellites, addressing the growing market for precise and cost-effective orbital solutions. This approach aligns with the European vision for a future family of eco-responsible, reusable launchers, demonstrating a gradual shift within the established space regime (JEC, 2022).
- US (technical): The engines and boosters (of SLS) are derived from space shuttle main propulsion. In fact, early SLS missions used spare engines and booster hardware from the Space Shuttle Program. The upper stage for Exploration Mission EM-1 derived from the existing Delta launcher Second Stage (Askins and Robinson, 2016).
- US (management): NASA plans to award a sole-source contract to Deep Space Transport, a Boeing–Northrop Grumman joint venture, to produce and launch up to 10 SLS rockets starting with Artemis V in 2029. By changing its contracting strategy, shifting from managing multiple separate contracts to a single services contract they aim to cut the current $2.5 billion per launch cost by half through efficiency improvements and broader use of the SLS, aiming to sustain the Artemis program long-term (NASA Office of Inspector General, 2023).

One could argue that SpaceX's reusable rockets (like Falcon 9) are a potential or early-stage substitution, but only if other actors fully pivot to reuse. So far, regime actors, like ArianeGroup in Europe and Northrop Grumman and ULA in the US have partially or not at all switched to reusable systems, reinforcing the transformation pathway as dominant.

**Strategic Niche Management**

Strategic Niche Management (SNM) refers to the process of creating, developing, and gradually dismantling testbeds or demonstration projects for emerging technologies and concepts. The goal is to gain insights into the viability and sustainability of these innovations while accelerating their adoption and diffusion in the broader market (Hoogma et al., 2005). The two pre-development test campaigns taking place in AG Trauen in 2025 are an example of such demonstration projects as will be explained later.

Innovation experiments often fail due to technological barriers, policy issues, market underdevelopment and resistance to change, creating a "lock-in" that favors incremental innovations over more radical transformations. These factors are interrelated and reinforce each other, undermining progress (Hoogma et al., 2005). The technological niche is the protected space within which innovations pick momentum and consist of demonstration projects, initiatives and studies on the advantages and disadvantages (Hoogma et al., 2005). If successful, a technological niche can evolve into a market niche, as users begin to recognize the innovation's value. Over time, this can lead to the emergence of a new regime or integration into the existing one (Kamp & Vanheule, 2015). In Europe, demonstrator projects progress through the ESA's Technology Readiness Levels (TRLs), which are a standardized scale from 1 to 9 used to assess the maturity of a new technology, with TRL 1 being basic research and TRL 9 being flight-proven (ESA, n.d).

*Experiment to niche*

After selecting a concept, the experiment must be carefully designed, balancing openness for learning with control for guidance. Key factors include network setup, user involvement, protection measures, and long-term resilience against competing innovations and technological shifts (Kamp & Vanheule, 2015; Hoogma et al., 2005).

Implementing an experiment is challenging, requiring a balance between protection and adaptability in real-world conditions. Barriers can be technical, economic, or social, from lacking infrastructure to market competition and institutional resistance. The goal is to learn from these challenges, refining the technology, social practices, and expectations while improving communication with stakeholders (Hoogma et al., 2005).

As an experiment nears completion, the focus shifts to scaling it into a niche by linking similar projects or expanding its scope. Large experiments may anticipate scaling, but most require adjustments in organization, location, and stakeholders (Hoogma et al., 2005). For successful niche upscaling, a strong, well-connected network with shared, realistic expectations is essential. Beyond raising awareness, delivering high-quality products with reliable after-sales service is crucial. Effective actors and the integration of lessons learned into practical solutions also play a key role (Kamp & Vanheule, 2015). Even in early stages, experiments should consider potential follow-up, though specifics depend on outcomes (Hoogma et al., 2005).

While some actors continue experimenting to refine and enhance the technology within a technological niche, others swiftly transition to commercialization within a market niche (Kamp & Vanheule, 2015). But the latter is a complicated task.

For example, the early adoption of composites in commercial aviation illustrates the complexities of scaling from niche to regime. As Slayton and Spinardi (2015) explain, moving from secondary to primary structures like wings faced barriers including high costs, labor intensity, and safety concerns. Even with progress in automation and testing, full-scale integration (e.g., the Boeing 787 Dreamliner) required further radical innovation and risk mitigation.

In contrast, Van der Laak et al. (2007) show how Solar Oil Systems (SOS) successfully scaled biofuel innovations through effective expectation shaping, network expansion, and multidimensional learning. Drawing on German examples, SOS mobilized diverse stakeholders—farmers, researchers, and users—while addressing practical challenges such as warranty conflicts and fuel odor.

**Transition Management**

Transition management (TM) initially emerged as a governance and policy approach (Loorbach, 2009) before evolving into a policy framework aimed at guiding long-term societal change and promoting sustainable development (Loorbach & Raak, 2006). This management concept incorporates several elements of modern governance, such as network management, interactive decision-making, inclusivity, a multi-level perspective, and continuous social learning. Multiple stakeholders, including governments, organizations, businesses, research institutions, and intermediaries, are involved (Loorbach 2009; Loorbach & Raak, 2006).

The TM model integrates bottom-up initiatives by connecting different levels of governance and encouraging self-organization through interaction between the different entities and iterative cycles of learning and action (Loorbach & Raak, 2006). Transitions, in a broader sense, are structural transformations within societal subsystems such as energy, housing, transportation, agriculture, and healthcare (Geels, 2002). While this study focuses specifically on technological transitions, it is important to clarify that the concept of transitions extends far beyond technology, including shifts across various sectors.

Transition Management is based on several conceptual starting points. These will be laid down next and examined in the context of this research using examples from both aerospace and construction industries.

*1) Considering all levels in a complex system*

In complex systems, all levels must be taken into account, as changes in one area can create unintended effects elsewhere (Loorbach & Raak, 2006).

For example, the ESA pushes towards the adoption of less toxic, more environmentally friendly propellants. One of the goals of MTB, one of the two aforementioned test campaigns taking place in AG Trauen, is to test Hydrogen Peroxide ($H_2O_2$) as an alternative to toxic Hydrazine derivatives. In the Multi-Level Perspective from Geels (2002), this constitutes a change in the landscape initiated by the policy maker, ESA, and by extension the European Union, which alters the existing regime. This happens because, as explained in the next chapter, the selection of a propellant combination for a liquid rocket stage is crucial, as it directly influences the launch vehicle's size, weight, performance and overall cost (Halchak, Cannon, & Brown, 2018).

*2) Management actions are constrained by system behavior*

The effectiveness of management strategies depends on how the system itself behaves, meaning a rigid, predefined process is not viable (Loorbach & Raak, 2006).

*Macro-level example*

Reusable rockets represent a new goal with distinct project and business management principles, as the systems themselves differ from expendable launch vehicles. As Wertz (2000) explains, the business models for these two types of rockets vary. Expendable launch vehicles remain a more cost-effective solution than reusable ones unless launch rates are high, making cost models obsolete. Although reusability eliminates the need to build a new vehicle for each flight, expendables benefit from lower ongoing costs, simpler operations, and easier technology upgrades. Reusable rockets face high upfront costs, more complex development, and strict reliability demands, making them economically unviable at the current launch rates of most companies. Transitioning to reusable, means that hitherto business models are rendered obsolete.

*Micro-level example*

The specific engine cycle configuration, the system that moves propellant from the tank to the engine of a rocket, is selected to optimize the overall engine design, considering factors like cost, complexity, weight, and performance. It also considers the technological constraints of the engine, such as material limits for operating stress and temperature (Halchak et al., 2018). This aspect is technical, but procuring and testing the materials falls within the management domain due to the involvement of stakeholders, supply chain coordination and resource allocation.

*3) The need for flexible objectives*

Given the constant evolution of complex systems, fixed goals are impractical, and objectives should remain adaptable (Loorbach & Raak, 2006).

Megaproject goals often evolve due to stakeholder engagement, societal expectations, and political pressures (Bourne et al., 2023). For example, the goals of the Markbygden wind farm evolved significantly over time due to technological advancements and regulatory requirements. Initially, standard wind turbines were 80 meters tall, but by the later stages, technology allowed for turbines over 240 meters. The project's goals had to remain flexible to accommodate these changes. Government permits also played a crucial role, with two types of approvals—one allowing flexibility in turbine specifications and another imposing fixed constraint (Bourne et al., 2023).

*4) Intervening at critical turning points*

The most effective moments for intervention occur at critical turning points, where crises can create opportunities for transformation (Loorbach & Raak, 2006).

This point refers to opportunity management, a fundamental concept of project management. The Tampere-Ranta Tunnel project, in Sweden, actively integrates opportunity management within its risk management framework. By maintaining an updated opportunity list every 1–2 weeks, the project continuously identifies and implements innovative solutions, such as optimized tunnel levelling, a lighter-weight bridge and improved work integration. During the development phase, 76 opportunities were identified, with 39 approved and implemented. Through the target pricing process, an additional €3.8 million in opportunities were uncovered, primarily related to procurement, design and operational efficiencies (Afshari et al., 2025).

*5) The risk of stagnation in overly stable systems*

Excessive stability can hinder progress and prevent necessary transformations (Loorbach & Raak, 2006).

While stability can bring predictability and efficiency, it may also hinder innovation. In aerospace, long-standing reliance on proven systems can discourage the adoption of alternative materials or methods, even when external pressures, such as market competition, demand adaptation.

*6) Creating space for new ideas*

Emerging ideas need room to develop before they can effectively challenge the existing system (Loorbach & Raak, 2006).

New concepts need protected environments to develop before they can challenge established systems. This aligns with what Hoogma et al. (2005) describe in SNM. In aerospace, test campaigns like PHOEBUS and MTB offer such spaces to experiment with novel propellants and technologies. These controlled settings help manage risk and promote gradual integration of innovations into mainstream operations.

To sum up, TM involves a multi-domain approach, recognizing that big changes require input from various fields, policies, and perspectives. It follows a multi-temporal strategy, balancing long-term vision with short-term actions. A multi-actor network approach acknowledges that no single group controls change, requiring collaboration. The multi-level approach ensures strategies bridge different levels. Effective transitions involve deepening (developing ideas in safe spaces), broadening (testing in different contexts), and scaling up (expanding successful solutions). Social learning is crucial, as people and groups must learn from each other (Loorbach & Raak, 2006).

In the Transition Management framework, four types of governance activities are identified, each playing a crucial role in transitions: strategic, tactical, operational, and reflexive. Two of these are directly visible through the scope this research. Strategic activities involve vision development, strategic discussions, long-term goal formulation, collective goal and norm setting, and long-term anticipation (Loorbach, 2009). A key example in this study is the push by the ESA (the governing authority) to adopt "green" propellants, which are less harmful to the environment and less corrosive. At the operational level, transition management includes high-risk, innovative experiments aimed at broadening, deepening, and scaling up change (Loorbach, 2009). ArianeGroup's test campaigns fit this definition as steps toward broader adoption of new technologies.

## Part 2: The Impact of Material and Propellant Transitions on Launch Vehicle Systems and the Generation of Uncertainty

Material selection for launch vehicle systems is inherently subject to technical uncertainty due to the extreme conditions experienced during launch and the wide range of configurations tested over time. The literature review will concentrate on the scope and specific requirements of the two test campaigns conducted at AG Trauen. For PHOEBUS, the focus will be on propellant tanks and the use of composite materials, as the goal of this test campaign is to introduce a new FRP upper stage for Ariane 6. For MTB, the emphasis will be on how the choice of propellants influences various aspects of rocket engine design, with a focus here on turbopumps and especially how different propellants interact with engine materials and affect performance across different engine types as one of the goals of this test campaigns is to test hydrogen peroxide as a green propellant replacement for hydrazines and NTO.

While the primary emphasis is on technical aspects, the broader takeaway concerns the systemic nature of these transitions. Both test campaigns illustrate how changes in one component, whether material or propellant, can cascade through a complex system with tightly coupled subsystems. This interdependence introduces layers of uncertainty, not only technically but also in terms of integration, scheduling and supply chain impact. Such complexity is not unique to aerospace; similar dynamics are observed in sectors like construction and energy, where innovation often involves managing systemic interrelations rather than isolated improvements.

*General context - Structural material characteristics*

In aerospace applications, particularly for launch vehicles (LVs), the selection of materials is decided by several key characteristics that determine their suitability for the demanding operational environment. According to Henson and Jone (2018), these include:

1. material strength, based on any applicable failure criteria
2. material stiffness, as quantified by the elastic modulus or moduli
3. mass density
4. nature of the failure modes (gradual or sudden)
5. ability to tolerate small-scale damage
6. mechanical and chemical compatibility with nearby materials

Additionally, materials used in launch vehicles must maintain favorable properties under extreme environmental conditions, including very high and low temperatures, as well as exposure to humid, corrosive, or other degrading environments. Many launch vehicles utilize cryogenic propellants, which require materials to perform well at very low temperatures. Similarly, high-temperature properties are also critical, especially due to the aerodynamic heating experienced during the high-speed atmospheric phase of the trajectory (Henson and Jone, 2018).

For composite materials, which are generally anisotropic (i.e., their properties vary depending on direction), more extensive and often costly testing may be required to fully characterize their behavior. Unlike metals, composite properties are not as readily available, making the selection and validation process more complex for these materials (Henson and Jone, 2018).

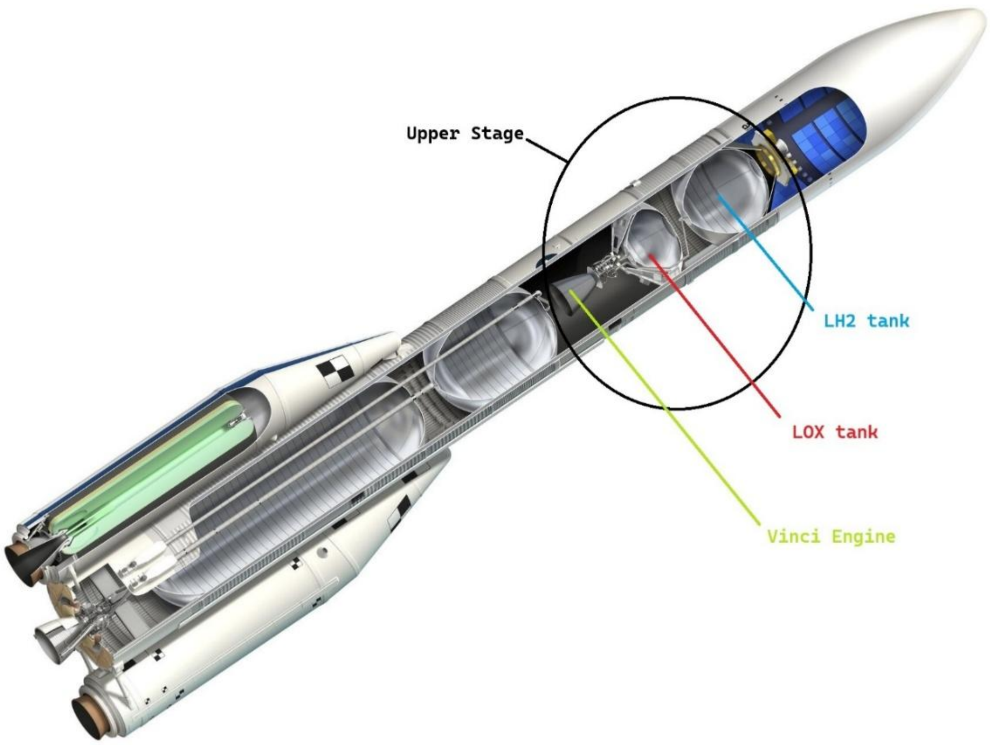
**Propellant tanks**

An expendable launch vehicle is essentially a stack of fuel and oxidizer tanks, with engines at the base and a payload on top. The interior of Ariane 6 is shown in Figure 5 below. The engines, mounted at the aft end, push through a reinforced structure. Tanks are linked by thin-walled skirts or intertanks, and entire stages are joined by cylindrical interstages or adapters (Henson and Jone, 2018).

Unlike stationary pressure vessels, propellant tanks in launch vehicles are subjected to large and highly variable primary flight loads. These loads arise from the dynamic forces experienced during the launch, flight, and potential re-entry phases. As a result, propellant tanks must be designed to withstand not only the operational pressure but also the loading conditions that occur throughout the mission (Henson and Jone, 2018).

**Figure 5**

*Ariane 6 Upper Stage Interior*




Adapted from ESA, Ducros D., 2024

To meet the demanding performance requirements while also addressing the need for mass reduction, propellant tanks are constructed using lightweight materials. This has led to the development of three primary types of propellant tank constructions (Henson and Jone, 2018):

- Stable Metal Tanks: Commonly constructed from 2000-series aluminum alloys or, more recently, aluminum-lithium (Al-Li) alloys. These materials provide both high strength and low weight, with Al-Li alloys offering improved performance characteristics.
- Steel Balloon Tanks: These tanks use steel, which offers high strength but typically at a higher weight than other materials. The design is often optimized to handle high-pressure environments and is sometimes used in specialized applications.
- Composite Tanks: Composites offer significant advantages over metals in certain areas. They provide superior resistance to fatigue and flaw propagation. The fibrous microstructure of composite materials tends to blunt and stop microscopic flaws, which enhances their durability under cyclic loading. However, it is important to note that accumulated fatigue damage in composites can lead to increased permeation of propellant, which may affect performance over time.

An important safety criterion in the design of pressure vessels, including propellant tanks, is the Leak-Before-Burst (LBB) criterion. This criterion ensures that a pressure vessel will develop a leak rather than suffer a catastrophic rupture. By allowing the vessel to leak at a controlled rate, the LBB criterion enhances safety by providing time for mitigation before a complete failure occurs. This approach reduces the risks of explosive failures and helps optimize system design by reducing costs (Henson and Jone, 2018).

LBB verification involves rigorous testing and analysis to confirm that the vessel can sustain its operating pressure even if it develops a through-wall flaw. This ensures that the vessel will not fail catastrophically, even under extreme conditions. Its should be noted that for tank tests, a single article test has limited value unless it reveals a hidden flaw in a critical area. (Henson and Jone, 2018).

This design requirement represents the first clear example of uncertainty introduced by a material transition: when adopting new composite materials for propellant tanks, the process predicting crack behavior, damage tolerance, and overall structural changes compared to traditional metallic tanks due to the different behavior of the material.

*Composite tanks*

Composite materials typically have two distinct components: a reinforcement material and a matrix phase. The reinforcement provides strength and rigidity, while the matrix binds the reinforcement together and helps transfer loads between the fibers, ensuring structural integrity (Daraci, 2023).

These materials offer several advantages, making them suitable for a wide variety of applications in the aerospace industry. According to Daraci (2023) the main benefits, in this related to propellant tanks are:

- Heat and fire resistance, which allows them to perform well in high-temperature environments.
- Vibration damping, contributing to improved comfort and structural performance.
- Resistance to corrosion, enhancing durability in harsh environments.
- Resistance to chemical effects, which supports their use in chemically aggressive settings.

Despite these strengths, composite materials also present certain disadvantages (Daraci, 2023) in the same context of the propellant tanks:

- They have temperature limitations, beyond which their mechanical properties may degrade.
- The presence of air particles or voids within their structure can significantly reduce fatigue resistance.
- There is no universally accepted quality standard, leading to variability in performance and manufacturing consistency.
- Damage detection is challenging, especially for internal defects (Daraci, 2023), it is difficult to control the geometric imperfections that are so damaging to buckling resistance (Henson and Jone, 2018).
- Upscaling, from laboratory scale to production scale, introduces difficulties as described in the example of the X-30 Single-Stage-To-Orbit program in the 1980s. This aimed to utilize composite liquid hydrogen tanks but faced major scaling challenges. Although the composites used showed strong resistance to microcracking in lab tests, the required curing conditions couldn't be replicated at production scale, revealing unforeseen technical hurdles (Henson and Jone, 2018).

Furthermore, a phenomenon that is known in composite tanks is cryopumping. Cryopumping is the process where gas condenses in a void, lowering the pressure and drawing in more gas, which also condenses. When reheated, this trapped gas can rapidly expand and vent, potentially causing damage. In polymeric foam insulation on launch vehicles, this can happen as the insulation cools from contact with cryogenic propellants, then heats up during ascent. If liquid air trapped in the foam vaporizes too quickly and cannot vent gradually, it can rupture the insulation (Henson and Jone, 2018).

**Turbopumps**

Turbopumps feed propellant from the tanks to the engine. They are essential when rocket engine demands surpass what pressurized feed systems can handle, using high-energy gases to drive turbines that power fuel pumps. Their purpose is to deliver the necessary flow and pressure efficiently, in a lightweight and compact design, while ensuring structural reliability throughout the mission (Halchak et al., 2018).

Turbopumps can be designed as either reusable or expendable. Reusable units are intended for multiple missions, requiring longer hardware lifespans, with high-wear components being replaceable and only basic cleaning and inspection necessary for major parts. Expendable turbopumps are designed for a single mission with a minimum number of starts. The materials used, particularly in the turbine end, depend heavily on the chemical composition, pressure, temperature, and flow rate of the drive gas, as these factors influence how the media interact with metallic and non-metallic components (Halchak et al., 2018).

The pump end, which handles the liquid fuel or oxidizer, often operates at cryogenic temperatures—especially with propellants like liquid hydrogen or oxygen. These low temperatures tend to make chemicals less reactive, reducing the risk of material damage. However, high-pressure liquid oxygen introduces significant hazards due to the risk of ignition and fire, requiring the use of materials that are highly oxygen compatible. The density of the propellant also affects pump performance; less dense propellants like hydrogen require greater effort to achieve target pressure and flow rates. In such cases, multiple stages of impellers, separated by diffusers or crossovers, are typically used before the fluid exits the pump at the required conditions (Halchak et al., 2018).

The turbine end is driven by hot gases that spin the turbine to power the pump. Temperatures here can vary significantly but are often high depending on engine design. These gases may be chemically reactive, necessitating the use of materials that can withstand both thermal and chemical stress. If the hot gases come from a gas generator and are hydrogen-rich (e.g., using $LH_2$), materials must resist hydrogen embrittlement, often through special coatings. Conversely, oxidizer-rich gases can pose a risk of catastrophic ignition, particularly at high temperatures and pressures, and in the presence of solid particles, making careful material selection critical (Halchak et al., 2018).

This description should give an idea on how complex these systems are and the cascading effect of a potential change.

**Propellants**

Liquid propellants are composed of a fuel and an oxidizer, each stored separately in liquid form and mixed in the combustion chamber to produce thrust. They allow for precise thrust control and can be shut down or restarted as needed during flight. These propellants are generally divided into two categories: monopropellants and bipropellants. Monopropellants contain both the fuel and oxidizer components within a single chemical compound—examples include hydrogen peroxide ($H_2O_2$) and hydrazine ($N_2H_4$). In contrast, bipropellants involve two separate liquids, a fuel and an oxidizer, which are mixed in the combustion chamber to initiate an exothermic reaction. A common example is the combination of liquid hydrogen and liquid oxygen (Mert, 2023). A more detailed description of the propellants used by ArianeGroup is given in Appendix B.

*Propellant Selection Criteria*

The following criteria illustrate how a change in propellant selection directly influences the design of the test article and the configuration of the test stand. Each propellant brings unique chemical and physical characteristics that affect system architecture, safety measures and operational procedures. As a result, shifts in propellant choice will introduce complexity across materials, storage, feeding systems and ignition methods, contributing to uncertainty in both development and testing phases.

According to Forbes & Van Splinter (2003) considerations for propellant selection include:

1. Chemical Energy: High performance depends on maximizing flame temperature and gas output per unit of reactants, with low exhaust molecular weight enhancing efficiency.
2. Liquid Range: Propellants must meet environmental temperature requirements; cryogenics need special storage and handling due to high vapor pressure.
3. Stability: Long-term chemical stability is essential, avoiding decomposition, gas build-up, or container degradation—even under shock or compression.
4. Reactivity: Propellants should minimize corrosion, seal damage, and contamination; safe, efficient combustion with manageable handling needs is key.

5. Density: Higher density allows for smaller tanks and improved mass fraction, while low thermal expansion helps performance across temperature ranges.
6. Viscosity: Lower viscosity minimizes pressure losses and enables lighter, more efficient pressurization and pump systems.
7. Ignition: Hypergolic or monopropellant systems ensure reliable, restartable ignition without separate ignition systems.
8. Logistics: Total cost includes not just fuel price but also storage, handling, transport, and infrastructure considerations.

*The Hydrogen Peroxide transition*

High-Test Peroxide (HTP) at 98% concentration is a dense, non-toxic oxidizer suitable for low to medium thrust propulsion. As a monopropellant, it yields ~186 s Isp, but in bipropellant systems with fuels like ethanol, it can exceed 325 s Isp and ~2750 K combustion temperatures, offering a green alternative to traditional propellants (Nosseir et al., 2021).

Hydrogen peroxide ($H_2O_2$) once played a major role in aerospace propulsion but was later replaced by toxic hydrazine-based propellants for historical and performance reasons (Wei et al., 2025). Recently, the European Chemicals Agency (ECHA), under the REACH regulation, has listed hydrazine as a Substance of Very High Concern (SVHC), initiating a process that could potentially ban its use in Europe. Hydrazine and similar toxic propellants not only pose safety risks but also increase handling and transportation costs. In contrast, green propellants offer commercial advantages by reducing costs tied to storage, handling, and infrastructure, while also simplifying ground operations (Nosseir et al., 2021).

This growing emphasis on environmental protection and personnel safety is reviving interest in $H_2O_2$ as a green, non-toxic, storable propellant. Companies such as Skyrora (UK) and Dawn Aerospace (New Zealand) are actively developing $H_2O_2$-based engines for spacecraft propulsion, with a rising demand for higher-thrust $H_2O_2$ systems to meet growing commercial space needs (Wei et al., 2025).

In general, the HPAS (High Performance Alternative Solvents) class of green monopropellants offers the lowest performance among its category; however, it stands out for its hypergolic ignition with fuels like ethanol, propyne, and ionic liquids. This characteristic makes HPAS propellants promising for in-space propulsion and the development of green hypergolic ionic liquids (HILs) for bipropellant systems. Although many green monopropellants, including HPAS, may not match traditional propellants in performance, their favorable thermochemical and physical properties, along with their high-thrust impulsive capabilities, make them well-suited for a range of applications such as deep space missions, small satellite manoeuvring, and upper-stage operations in launch vehicles (Nosseir et al., 2021). A comparison is shown in Table 1.

*Challenges in Material Supply Chains*

While the focus thus far has been primarily technical, the impact of propellant choice on the supply chain is also implied in Table 1. Availability varies by country, and even where a propellant is accessible, identifying qualified suppliers capable of delivering the required volumes and managing the substance under the stringent conditions of a test campaign is a major challenge.

**Table 1**

*Comparison of popular hypergolic propellants.*

| Propellant | Pros | Cons |
|---|---|---|
| **Hydrazine ($N2H4$)** | • High Isp<br>• Well-known technology (High TRL)<br>• Simple system design | • Toxic (GHS 2)<br>• Extra cost for handling (strict safety measures) |
| **Hydrogen Peroxide** | • High maturity<br>• High performance in bipropellant mode<br>• Can be used as an oxidizer in bipropellant and pure as monopropellant (multi-mode)<br>• Hypergolic ignition<br>• Cheap, commercially available | • Not compatible with Titanium<br>• Low performance in monopropellant mode<br>• Careful handling required<br>• Significant self-decomposition rate |
| **NOx compounds (NTO)** | • Self-pressurization properties<br>• Good storability & stability<br>• Low toxicity | • Extremely high chamber temperature<br>• Low density |

Blondel-Canepari et al. (2021)

The Aerospace Manufacturing Sector (AMS) is highly concentrated, both geographically, especially in certain EU countries, and in terms of the small number of dominant companies. Major employment centers include the United Kingdom, France, Germany, Italy, Spain, Poland, and Sweden. Its supply chains are characterized by a mix of small firms producing low-cost components and larger companies manufacturing high-value parts or complex assemblies (Ruiz-Benitez et al., 2017).

Material selection is inherently tied to supply chain management and its consequent issues, such as high lead times. A short introduction should be made here as this topic is highly relevant.

The complexity of aerospace supply chains stems from several intrinsic characteristics of the industry. As outlined by Wooten and Tang (2018), products intended for space operations are typically highly complex, technology-intensive, and produced in low volumes. These factors inherently lead to high costs, longer production cycles and a reduced focus on mass production efficiencies. Consequently, supply chains in the space sector are often less responsive and flexible compared to other industries, with long lead times becoming a persistent structural challenge.

Recent global events (Meier & Pinto, 2024) have further exacerbated these supply chain vulnerabilities. According to Magness (2024), the surge in commercial aerospace production following the COVID-19 pandemic has significantly increased the demand for key raw materials such as titanium and aluminum alloys. Compounding this issue, the ongoing conflict between Russia and Ukraine has disrupted the supply chain of critical materials, on a global level. Both countries are also vital sources of titanium and aluminum alloys used in aerospace applications. These geopolitical disruptions have led to material shortages and additional instability in the aerospace value chain, further extending lead times and creating procurement challenges for ongoing and future projects.

Taking all these factors into account, it is apparent that introducing new materials can significantly exacerbate existing supply chain challenges. With already long lead times, low production volumes, and fragile supplier networks, even minor changes in material specifications can disrupt procurement schedules and heighten the risk of delays. While this issue was not apparent at the beginning of the research, it emerged clearly during the interview phase.

# Methodology

The methodology for this research was developed to address the multifaceted nature of uncertainty stemming from material transitions in aerospace systems. Material transitions inherently impact a wide range of domains, from component integration and performance to supply chain management, risk assessment and project governance. At the start of the research project, the researcher considered the option to narrow the focus to a specific domain, such as upscaling cost increase or supply chain delays. However, doing so would have risked introducing bias by prioritizing one dimension of the transition over others.

Given that the primary objective of this study is to explore how uncertainty is generated during material transitions, it was essential to develop a structure that could accommodate a broad perspective. Rather than ranking or isolating individual impacts, the methodology was designed to consider multiple dimensions, e.g. the cascading effect, upscaling challenge, supply chain and risk management practices. This aligns with one of the goals of the research which is to evaluate where uncertainty will be concentrated in case of material transition.

However, adopting this broader research scope would introduce a new challenge during the literature review phase. A wide approach risks losing focus if not properly scoped; something not acceptable in a 6-month project. To mitigate this, the first step was to conduct informal, scoping interviews with three individuals involved in the two ongoing test campaigns: PHOEBUS and MTB. These scoping interviews helped identify the most relevant uncertainty areas and acted as a point of reference for the literature review.

After the literature review phase, information gathered as well as insights from the scoping discussions were synthesized to define key areas of interest. These areas became the starting point for the formulation of the interview questions used in the primary data collection phase.

A semi-structured interview format was adopted to allow participants to speak freely while ensuring coverage of core themes. The interviews were transcribed, anonymized and sensitive content was redacted. The resulting data was analyzed using qualitative analysis software (ATLAS.ti), which allowed for systematic identification, coding and organization of relevant excerpts across interviews. Quotes were grouped into codes aligned with themes, such as cascading effect, lead times, risk management plans and upscaling.

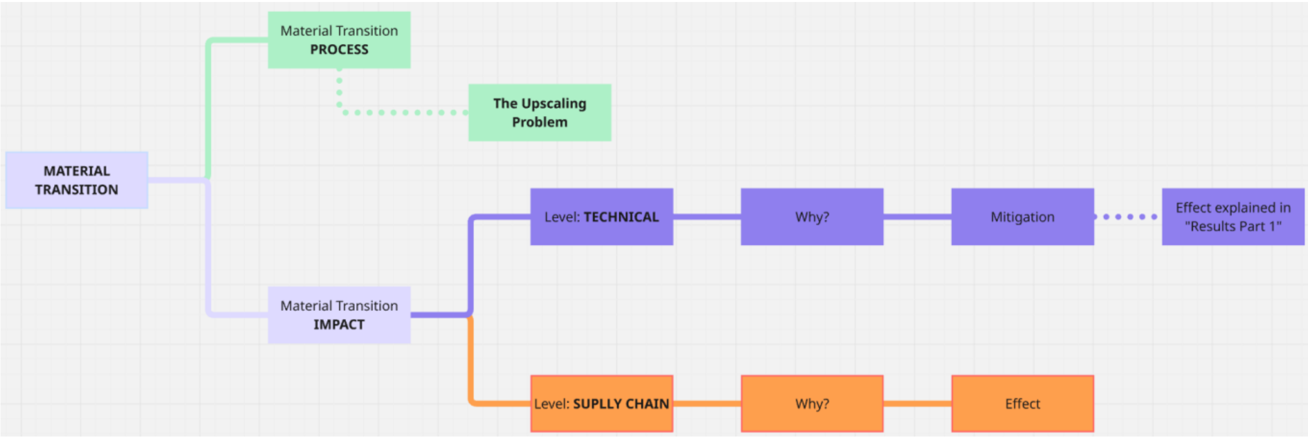
From this structured analysis, the *Material Transition Map* was developed. This map visualizes the transition process and the associated impact domains, serving as an *analytical framework for interpreting the findings*. It captures how uncertainty emerges and ripples across different levels of the system, illustrating the interplay between technical, organizational and external factors. An overview of the Map is given in Figure 6. The two main branches include the Material Transition Process, where the Upscaling Problem is explained, and the Material Transition Impact, which is split into Technical and Supply chain. The causes of uncertainty, its effect and mitigation measures are showcased there.

Having synthesized the Results of the research, based on the Material Transition Map, a framework for managing predevelopment supply chain uncertainty was created. The three

Proposals included were validated, in the last step of the Methodology, by a focus group of 4 ArianeGroup experts, who confirmed the issues addressed, viability of application steps and value of projected benefits.

**Figure 6**

*Overview of the Material Transition Map*



## Step 1: Scoping Interviews with Test Campaign staff

Before conducting Part 2 of the literature review, which aimed to showcase the complexity and interconnectivity of launch vehicle components and therefore the effects of a potential transition, the researcher held informal discussions with individuals directly involved in the test campaigns. These conversations were held with one participant from Bremen involved in PHOEBUS, one from Ottobrunn working on MTB and one from Trauen who is engaged in both test campaigns. The discussions focused on the sources of uncertainty related to the specific material or system transitions in each TC, the participants' roles within the projects and a brief overview of the current status and anticipated short-term challenges for each test campaign. Details of the meetings can be found in App. D, Table D2.

The information (Tables 2 and 3) was not used as empirical data but served as a compass to guide the direction of the research. The aim was to gain early insights into the scope of work, the current status of each test campaign, anticipated next steps and the types of uncertainty encountered. Given the complexity of space launch systems, these discussions were instrumental in narrowing the research scope to specific components within the test campaigns, allowing for a more precise exploration of how uncertainty is generated.

*Key takeaways from Scoping Interviews*

**Table 2**

*PHOEBUS takeaways*

| Topic | Description |
|---|---|
| **1. Material Standards** | Existing material standards only apply down to 77 K (-196°C), while the testing environment for $LH_2$ storage operates around 20 K (-253°C). No established standards exist at these lower ranges, creating uncertainty regarding material behavior. |
| **2. Testing Infrastructure** | Only a few laboratories worldwide can conduct testing in cryogenic temperatures, resulting in high costs, complexity and availability constraints. |
| **3. Supply Chain Challenges** | CFRP supply chain issues were mentioned, primarily due to the involvement of multiple manufacturing companies. |

| | |
|---|---|
| **4. Transportation and Storage** | Staff highlighted that transporting CFRP elements requires continuous refrigeration, as exposure to ambient temperatures could compromise material integrity. This constraint complicates logistics and reduces usable timeframes. |
| **5. Propellant Supply** | The procurement of LOX, $LH_2$, and GHe is made more difficult without long-term supply contracts, as suppliers tend to prioritize clients with predictable and continuous demand profiles. |

**Table 3**

*MTB takeaways*

| Topic | Description |
|---|---|
| **1. Transition to $H_2O_2$** | Switching from traditional propellants (NTO and hydrazines) to $H_2O_2$ introduces significant technical risks. Staff emphasized the lock-in effect from decades of hydrazine use, creating an organizational inertia that complicates change |
| **2. Safety and Performance Risks** | There is no internal experience base with $H_2O_2$, making combustion behavior, ignition reliability, and material compatibility major areas of uncertainty. Extensive testing will be necessary to validate these parameters. |
| **3. Material Redundancy** | Staff mentioned the need for material redundancy to manage the risk of catastrophic failures, which are not uncommon during early engine testing phases. |

| | |
|---|---|
| **4. Project Phase Complexity** | The next phase of testing will include a full engine setup (as opposed to the current combustion chamber demonstrator). New contractors and suppliers will join mid-project, raising system integration and compatibility concerns due to the increased complexity. |

## Step 2: Combining literature review takeaways and project insights

After completing the literature review, the next step involved synthesizing its key points with the Scoping Interview findings from Step 1, namely, the informal discussions and early project understanding. This process aimed to identify recurring patterns, themes and areas of uncertainty that were relevant both in theory and in the context of the two test campaigns.

This step helped refine the research focus by aligning academic theory with observations. It also set the stage for more structured data collection in the next phase, where empirical evidence would be gathered to explore these emerging themes in greater depth.

In the context of aerospace projects such as PHOEBUS and MTB, transition uncertainty manifests in multiple, interconnected ways. These include technical, organizational, and supply chain challenges that emerge when introducing new materials, technologies, or configurations. The following dimensions were identified as particularly relevant in shaping the structure of the interview phase of this research:

*1. Lead Times as Transition Amplifiers*

Long lead times for materials and propellants are a persistent constraint in aerospace testing. This raises a research dilemma: should they be treated as fixed conditions or should transitions be evaluated based on how they amplify or complicate these delays? For example, in the PHOEBUS test campaign, switching from metallic tanks to CFRP introduces more demanding storage and handling requirements, thereby exacerbating lead-time risks. Understanding how transitions interact with these system limitations provides a clearer picture of real-world implementation challenges.

*2. Mini Transitions Triggered by a Major One*

CFRP is a clear technical transition, but its adoption does not take place in a vaccum. It should be explored if it triggers a cascade of “mini transitions” throughout the ecosystem: new tooling, retrofitting of test stands, the need for different sensors and new handling procedures. This domino effect can increase complexity. A key hypothesis of this research is that one of the greatest risks in managing transitions is underestimating the full scope of their ripple effects.

*3. Upscaling from Lab to Real-World Testing*

Another challenge is the gap between lab-scale results and full-scale system performance. This issue of upscaling raises a methodological dilemma: should teams invest in high-precision lab work before upscaling, even if that lacks environmental realism? Or should they move rapidly to full-scale testing, accepting the increased risk of failure in favor of faster learning? This strategic trade-off between caution and momentum is central to evaluating transition approaches.

*4. Safety Planning in the Context of New Technologies*

When new propellants or materials are introduced, a key organizational question is whether existing safety frameworks are adapted or whether new plans are drafted from scratch. The interview questions will also aim to uncover how risk management plans are formulated, whether through precedent, regulatory input or external consultation, and how knowledge gaps are mitigated (e.g., via simulation, cross-sector analysis or third-party reviews).

*5. Quality Assurance Under Unfamiliar Conditions*

The switch to newer materials such as CFRP also complicates quality assurance. Unlike metals, composites often require specialized storage (e.g., cold chain logistics) and subtle production controls that are harder to verify externally. The risk is that quality issues may only become evident during late testing or operational use, making early detection and mitigation more difficult and more critical.

*6. Integration and Knowledge Transfer in Multi-Phase Projects*

Projects like PHOEBUS and MTB span multiple phases and often involve new actors or contractors joining at different stages. In such scenarios, the absence of standardized interfaces or clear knowledge transfer mechanisms can lead to integration challenges. This is a concern in any large project, but the risk is magnified when a technological transition is underway. Not only must new team members adapt to unfamiliar configurations, but suppliers and subcontractors may be forced to modify their own processes and products, sometimes without adequate support.

## Step 3: Interview Phase

**Drafting the Interview Questions**

Following the key theme composition of Step 2, the next step in the methodology involved designing the interview questions. The objective was to gather firsthand insights from individuals directly involved in the test campaigns, both from technical and managerial perspectives. These interviews served to validate theoretical insights, uncover practical sources of uncertainty and better understand how material and propellant transitions are managed in complex aerospace systems.

The interview questions were semi-structured and organized around four topics that emerged from Steps 1 and 2:

1. *Experience with Transitions*

Questions explored past experience with technological transitions, their cascading effects across systems and the extent to which individuals had encountered similar challenges before.

2. *Technical Uncertainty*

These questions addressed issues such as upscaling from small scale tests to full systems, and uncertainty surrounding new material properties, integration and performance under extreme conditions.

*3. Supply Chain & Interfaces*

This theme focused on practical concerns like lead times, supplier availability, and knowledge transfer across partner organizations.

*4. Risk & Safety Adaptation*

Here, participants were asked about how uncertainty and technical risks were managed, including processes for safety validation, contingency planning and compliance with institutional requirements.

To capture both technical and strategic perspectives, some questions were tailored into technical and managerial versions depending on the interviewee's role. Each interview concluded with an open-ended question inviting final remarks, additional reflections, or insights not covered in the structured sections.

The complete list of interview questions is provided in Appendix A.

**Interviews**

A total of 12 interviews were conducted between May and June, with a second shorter round in July. All participants are full-time employees of ArianeGroup, representing three sites: Trauen, Bremen and Ottobrunn. The selected interviewees (Table 4) brought diverse expertise from across several interconnected projects, including:

- The two test campaigns conducted at Trauen: MTB and PHOEBUS
- The development and future operationalization of Ariane 6
- Future launcher development

**Table 4**

*List of interviewees who participated in the research*

| Number | Role | Project | Date of Interview | Location |
|---|---|---|---|---|
| 1 | Systems Engineer | Ariane 6 | 8/5 | Bremen |
| 2 | Test Engineer | MTB | 12/5 | Trauen |
| 3 | Systems Engineer | Ariane 6 | 8/5 | Bremen |
| 4 | Test Engineer | PHOEBUS | 19/5 | Trauen |
| 5 | Test Engineer | MTB / PHOEBUS | 12/5 | Trauen |
| 6 | Test Engineer | PHOEBUS | 20/5 | Trauen |

| | | | | |
|---|---|---|---|---|
| 7 | Project Manager | PHOEBUS | 22/5 | Online |
| 8 | Project Manager | MTB | 21/5 | Online |
| 9 | Test Engineer | MTB / PHOEBUS | 30/5 | Trauen |
| 10 | Project Manager | MTB / PHOEBUS / Ariane 5 (past) | 8/7 | Online |
| 11 | Project Manager | MTB / PHOEBUS / Ariane 5 (past) | 10/7 | Online |
| 12 | Test Engineer | MTB | 11/7 | Online |

This composition ensured a balance of perspectives from both technical and managerial roles, as well as from different phases of (pre)development and testing.

The interviews provided rich insights that reinforced the four thematic areas previously identified. The data collected demonstrated strong thematic saturation, indicating that the range of perspectives captured was sufficient to represent the relevant insights and recurring themes within the scope of this research. The interviews not only validated the previously defined themes but also deepened the understanding of how transition uncertainty emerges and is managed in practice.

*Sample Size Justification*

The number of interviews conducted for this study was guided by both the research focus and principles of qualitative sampling. *Qualitative Data Analysis* by Miles et al. (2014), and specifically the section *"Sampling: Bounding the Collection of Data"* (pp. 46–47) was particularly relevant and helpful in grounding the rationale for the chosen sample size.

First, as the authors explain, “sampling involves decisions not only about which people to observe and/or interview but also about settings, events, and social processes” (Miles et al, 2014, p.46). In alignment with this, the sample was deliberately limited to individuals directly involved in the two full-scale test campaigns under investigation and Arinae 6, the megaproject. This choice was aimed at preserving the case-specific relevance and consistency of the findings. Otherwise, including participants from unrelated projects would have introduced settings and experiences not applicable to the research context, thereby potentially distorting the conclusions.

Moreover, the authors emphasize that “the prime concern is with the conditions under which the construct or theory operates, not with the generalization of the findings to other settings” (Miles et al, 2014, p.46). Following this logic, the study prioritized conceptual relevance over statistical representativeness. The sample provided a full range of relevant perspectives across various roles and areas of expertise. By the 12th interview, no significantly new themes were emerging, only variation in emphasis depending on each interviewee’s expertise, indicating that thematic saturation had been reached.

Finally, with respect to the number of interviews, Miles et al. (2014) acknowledge the complexity of qualitative cases and warn against very large samples: “With high complexity, a study with more than 10 cases or so can become unwieldy... the price is usually thinner data” (p.47). They go on to suggest that even five richly researched cases can suffice for in-depth, multiple-case study research. Given that this study involved 12 in-depth interviews with individuals closely involved in the projects and explored multiple themes across a complex technical and organizational setting, the resulting data set is both rich and detailed. In this context, increasing the number of interviews to include more “peripheral” stakeholders would have risked compromising depth, without necessarily enhancing insight.

*Personal Data Protection*

In accordance with ethical research standards, the researcher obtained the appropriate approval from the Human Research Ethics Committee (HREC) prior to conducting interviews. All interviews were voluntary and conducted with informed consent. To ensure participant privacy, all data has been anonymized and no identifying information is disclosed in the report. Interview responses are presented thematically and used solely for academic analysis.

## Step 4: Data Analysis

Data analysis was conducted using ATLAS.ti, an interview analysis software. All interview transcripts were anonymized and select lines containing sensitive or project-confidential information were redacted to maintain participant and organizational confidentiality.

The data was organized using a set of codes. These included:

- Cascading Effect
- Cascading Effect Expected?
- Company Culture
- Lead Times
- Lead Times Expected?
- Material Property Data
- Risk Management Plan
- Supply Chain
- Type of Transition & Uncertainty
- Upscaling
- When Does Uncertainty Become Apparent?

Using the Quotation Manager feature in ATLAS.ti, coded segments were systematically extracted and analyzed one code at a time to identify recurring patterns, divergences, themes and relevance to the research questions.

Table 5 illustrates the takeaway extraction process using eight representative examples. The green column presents the actual interview quotes, with minor clarifications added in brackets where necessary for context. The blue column displays the corresponding *ATLAS.ti* code assigned to each quote during the interview transcript analysis. The light grey column summarizes the key *takeaway* derived from each quote and finally the dark grey column shows how many times this theme was mentioned; these takeaways are directly used in the Material Transition Map, with the quotes serving as supporting evidence.

The output of this analysis led to the development of the Material Transition Map, as each takeaway of the light grey column corresponds to one element of the Map. The entire process, from interview notes to the creation of the Material Transition Map is summarized in Figure 7.

**Figure 7**

*Process for Deriving Material Transition Map Nodes from Interview Data*

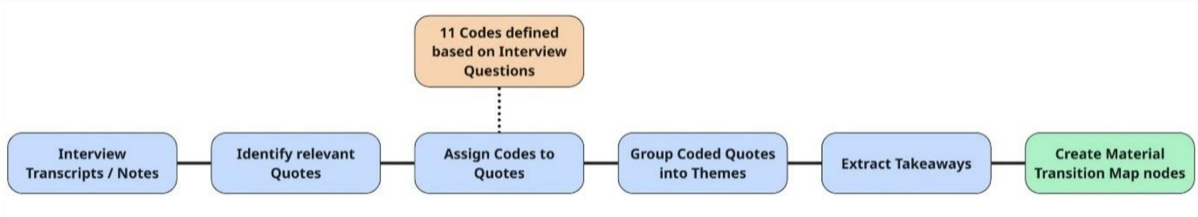


**Table 5**

*The quantitative data analysis process in this research was conducted using dedicated software. In some cases, the wording of interview quotes was slightly refined, without changing the original meaning, to improve clarity.*

| Quote → | Code → | Takeaway | No. of Interviewees mentioning it |
|---|---|---|---|
| *Phoebus: utilized FRP experience from past TCs* | Material Property Data | **Reliance on Heritage** | **12 out of 12** |
| *The problem with MTB is that H2O2, the oxidizer, is very reactive with most materials commonly used. This is not the case with Hydrazines, the heritage propellant. This means that the architecture must be reconfigured as the tank, pipes, valves, must be made from compatible materials.* | Type of Transition | | |
| *The TRL is of less importance. What matters most of all is experience with the material, propellant etc* | Type of Transition | | |
| *This is the disadvantage of heritage. When it does not exist, people get nervous* | Risk Management Plan | | |
| *We rely of course on heritage data; For FRP we took advice from Airbus who is familiar with the material. We chose to hire people with FRP experience* | Risk Management Plan | | |
| *Established risk management process Updated every two months, based on existing projects Dynamic process "Cannot cover everything"* | Risk Management Plan | | |

| | | | |
|---|---|---|---|
| *With material transitions, the ESA itself relies on heritage, prior to developing new components and innovation and conducting testing they explore past experience (example from main client)* | Type of Transition | | |
| *You need to consider how to place and support the test article in the test field* | Upscaling | **Cost of test bench increases as Level increases** | **9 out of 12** |
| *If you change the diameter (of a tank) from 1 m to 2 m its fine. If you go to 10m, then something change in the setup are required.* | Upscaling | | |
| *Because you use 10 times more $LH_2$ per run, the heat radiation increases as well, and your safety area increases.* | Upscaling / Risk Management Plan | | |
| *We are low on suppliers' priority list... We did this (procurement change to increase order volume)* | Supply Chain / Lead times | **Low on suppliers' priority list** | **8 out of 12** (all interviewees in managerial roles mentioned this) |
| *We are not a money-making customer* | Supply Chain / Lead times | | |
| *There is no redundancy of suppliers of critical components, and they prioritize companies with the largest deliveries* | Supply Chain / Lead times | | |

| | | | |
|---|---|---|---|
| *Small quantity orders are not prioritized; there is not high interest from suppliers because they don t make as much money* | Supply Chain | | |
| *For some other materials there is no redundancy in suppliers. There are very few that can manufacture them or even only one company (in the US for example). Not of lot of suppliers exist anyway* | Supply Chain / Lead times | **No redundancy in suppliers** | **8 out of 12** (all interviewees in managerial roles mentioned this**)** |
| *So single source is never a good thing. Not a good thing in skills or suppliers. If one supplier can't deliver, for what reason, you're into trouble and the thing is, changing to a different supplier it's once again a change of process.* | Supply Chain / Lead times | | |
| *We have very basic material data, like properties at room temperature. We don't have any failure criteria which makes design difficult* | Material Property Data | **Lack of Material Property Data** | **10 out of 12** |
| *Information that we get, maybe that's not very accurate and we need to perform tests.* | Material Property Data | | |
| *You can get guaranteed minimum values for new materials (e.g., strength, conductivity, thermal resistance) from suppliers and then you have two options: you can trust them you can run your own tests to verify.* | Material Property Data | | |

| | | | |
|---|---|---|---|
| *Standards exist though quality may vary because it depends on other things as well* | Material Property Data | | |
| *They fall from the sky. The supplier calls you and says, "We are not ready, we need another three months", and there is absolutely nothing we can do about it* | Lead Times expected? | **Supply chain Impact expected / Long Lead Times** | **10 out of 12**<br><br>(the rest explicitly stated that supply chain is not their domain) |
| *In a project you don't think about a connector lead times you think about the tanks and the liquids (so lead times for small components may be overlooked)* | Lead Times expected? | | |
| *Lead times are sometimes predictable and are often taken into account during planning, but there are also unexpected delays or sudden price increases due to bottlenecks or accessibility* | Lead Times expected? | | |
| *We have a long lead item key point where we try to define all the items which have lead time of more than six months.* | Lead Times expected? | | |
| *One distinction in Test Campaigns is that it's not immediately clear which parts are critical and sometimes non-critical items can become critical without notice due to supplier's internal changes or unforeseen events (a supplier's factory burned down in Germany)* | Lead Times/ Lead times expected? | | |

| | | | |
|---|---|---|---|
| *In projects like MTB this is problematic because catastrophic failures do happen and there can be no spares for everything especially expensive items.* | Lead Times | | |
| *Between the engineof A5 and A6 only small changes were made in the design geometry, elements were removed. All that to reduce production cost, weight etc. All this will have a functional impact* | Cascading Effect | **Cascading effect / Impact on existing system** | **12 out of 12** |
| *If you changed, for example, a valve which is put into multiple system elements. Then the change may be a Horror Story because you have multiple fluidic systems impacted…* | Cascading Effect | | |
| *Absolutely, specific change or requirement that was recognized later in the implementation phase had an impact on the final planning and design.* | Cascading Effect | | |
| *A new system can be designed cleanly from scratch, but adapting a new system into an existing architecture often causes more problems. It can have ripple effects, requiring changes in many connected systems,* | Cascading Effect | | |

<table>
<tr><td>The impact of propellant choice was not expected in components, not “in touch” with it but that belonged to the test bench. Propellant could leak out and cause exothermal chain reaction that could lead to catastrophic failure</td><td>Cascading Effect</td><td></td><td></td></tr>
<tr><td>If we scale up these tests and now, we want to use tonnes of hydrazine. Then we must make sure that we have the allowance from the authority to do such tests (extra time and cost)</td><td>Upscaling</td><td rowspan="3">Extra cost and time of Upscaling</td><td rowspan="3">12 out of 12<br><br>(Implied from everyone due to its multifaceted nature)</td></tr>
<tr><td>Scaling and the problems associated with it are often overlooked or recognized too late. For example, that there are no production machines in this size or the return on investment is greatly reduced by the increase in size due to new initial purchases for production machines or additional work steps.</td><td>Upscaling / Transition Impact expected?</td></tr>
<tr><td>We have to handle, let's say, 10 kilograms of hydrogen per second, 10 times higher than what your flare stack is designed for. Is it still possible to use your flare stack or do we have to use a larger flare stack. (existing infrastructure or equipment not adequate)</td><td>Upscaling</td></tr>
</table>

| | | | |
|---|---|---|---|
| *Often, (the suppliers) have to invest in new equipment and tools, which the company has to at least in part, pay for. Sometimes they must develop these tools and machinery when they don't exist, or the required component has not been manufactured before* | Upscaling | | |

**Visualizing the Data – The Material Transition Map, a new Analytical Tool**

The Material Transition Map, shown in Appendix C, Figure C1, was developed directly from the coded interview data. It features two main branches, the Material Transition Process and the Material Transition Impact.

*Material Transition Process*

The first branch of the Map highlights the different levels involved in a transition process (App. C, Figure C2). On the Lab Level, or small scale, material samples are tested in isolation, to define their properties. These can include everything from simple tensile strength tests to tests to chemistry tests.

The second tier, the Breadboard Level, involves tests with at least some interfaces and different components. These can include vibration testing of structural components or valve tests with basic piping setups. These tests begin to reveal interaction effects and potential integration issues.

Finally, the Application Level involves near or full-scale complex systems with full mechanical and electrical interfaces. These Application-Level tests are high-stakes undertakings, often spanning multiple years and involving extensive coordination across engineering teams and contractors. Both MTB and PHOEBUS fall into this category.

In line with the ESA Technology Readiness Level (TRL) framework referenced earlier in the SNM literature, reaching TRL 9, the threshold for flight qualification, requires successful full-scale system validation. In other words, transitions cannot be completed without advancing through the entire material transition process, culminating in these complex, large-scale tests.

And there lies the Upscaling Problem (App. C, Figure C3), the significant challenges that arise when transitioning from small-scale laboratory testing to full-scale application-level testing. There are a few reasons behind this.

First, costs and time increase substantially at each higher level of integration. For example:

1. Safety requirements become more stringent when larger quantities of propellant are involved, necessitating additional safety systems and compliance procedures.

2. At the application level, the test setup must often replicate the complete system under realistic operating conditions. This means reproducing not just the material but the entire subsystem it interacts with, further driving up cost and complexity.
3. Test bench infrastructure for full-scale systems, such as that required for PHOEBUS, can be technically challenging to design and construct, especially when dealing with novel materials or propellants.
4. Regulatory and logistical requirements escalate, such as obtaining special permits for the storage and handling of large volumes of propellant or hazardous substances.

To illustrate this further, consider the first objective of the MTB test campaign: testing both a demonstrator engine and the overall test setup. The MTB infrastructure consists of two shipping containers, one for handling fuel and one for oxidizer, connected to an engine mount. However, this setup is supported by a larger and more complex system. It includes a pressurization system for feeding propellant to the engine, a purging system to safely remove residual fuel post-test and an external measurement system. This system features a network of sensors distributed across the setup; all connected to a centralized control unit responsible for data acquisition and system oversight. This example highlights how, even for a relatively contained demonstrator test, full-scale testing requires replicating not only the primary components but also all critical support systems, driving up both cost and complexity.

Secondly, interviewees noted that the impact of upscaling is often overlooked in early-stage planning. The number of intermediate test stages is frequently underestimated, leading to optimistic assumptions about time and resource requirements.

Assessing the impact of upscaling is inherently difficult. The transition path cannot always rely on existing heritage, especially when dealing with new materials or configurations. This introduces a layer of uncertainty that makes planning and budgeting for transitions more complex and prone to errors.

*Material Transition Impact*

*Technical*

The Technical Impact branch of the Material Transition Map (App. C, Figures C4, C5) focuses on the effects that material or propellant changes have at the system level. Interviewees generally agreed that some level of impact is expected when transitioning to new materials or propellants. However, the magnitude of this impact is largely dependent on whether the change is introduced within a new system or integrated into an existing one.

When material or propellant changes occur within a new system, the impact is often less severe. This is primarily due to the greater design freedom, which allows engineering teams to better navigate around uncertainty. Moreover, industry practices strongly favor building on existing systems and knowledge. ArianeGroup, like all other aerospace companies, actively seeks to reuse proven components, architectures or even subsystems when developing new projects. This strategy, here mentioned as “reliance on heritage”, is intended to reduce technical risk, development time and cost.

A notable example of this approach is the development of Ariane 6, which is not a completely novel design but an evolution of Ariane 5. By updating rather than reinventing the launcher architecture, ArianeGroup was able to capitalize on past experience. This reliance on heritage is a recurring theme throughout the interviews and plays a central role in managing uncertainty during material transitions. It will be further explored in later sections of the report.

In an existing system, the impact is usually significant. There are two reasons for that, (1) a lack of new material property data and (2) the uncertain interaction between the new addition and the existing system.

To mitigate the data gap, teams rely on a combination of simulations and data acquisition, including:

- Direct material testing (though often costly, particularly for cryogenics)

  *Example: Hire a lab to run material tests*

- Using data from third parties

  *Example: Existing research from other parties e.g., research institutes*

- Depending on guaranteed minimum values provided by suppliers, though these are not always available or comprehensive.

  *Example: Suppliers will typically give minimum strength values*

This uncertainty in data availability requires the application of safety margins, adjusted depending on the confidence in the data. For example, when less data is available, larger safety margins are used, often requiring conservative assumptions and resulting in heavier or more durable systems. Then the focus is on the balance between safety and cost.

For example, if a test day requires approximately 10 m³ of propellant for two to three engine runs, engineers will size the tank to hold more than that baseline amount. This additional capacity accounts for boil-off losses, system losses and operational safety margins. However, in the case of cryogenic propellants, tank construction is particularly expensive due to material requirements (insulation) and additional safety measures required. As a result, the safety margin cannot be excessively high. Engineers must therefore find a careful balance between functionality, safety and cost, ensuring sufficient propellant availability without oversizing the system beyond what is economically or technically feasible.

To assess the interaction between new materials or components and existing systems, ArianeGroup usually establishes a multidisciplinary task force during a transition phase. This group brings together experts from various technical domains, such as propulsion, materials science, safety and systems engineering, to collectively evaluate the potential impact of the change. The goal is to capture the full scope of possible effects across all interfaces.

However, one important challenge in this approach is resource availability. Certain disciplines, particularly highly specialized ones, are often low on availability, because these experts are already assigned to ongoing projects or other test campaigns.

An advantage ArianeGroup possesses in this context is its systems engineers, many of whom have experience with legacy platforms like Ariane 5 and, of course, Ariane 6. These engineers play a central role in analyzing integration risks, given their knowledge of system architectures and of previous transitions. Their experience enables them to anticipate issues not immediately evident from component-level data alone.

To support the analysis, simulations are done to estimate how the new material or subsystem might behave in conjunction with existing components. In this case too, both the systems engineers and the task force rely heavily on heritage knowledge, lessons learned from previous programs and platforms, to guide assumptions, narrow uncertainties and propose mitigation strategies.

*Supply Chain*

On the supply chain level (App. C, Figure C6), transitions involving new materials or technologies tend to cause considerable disruption, and while issues are generally expected, unforeseen problems are a recurring issue. The impact is often significant and can ripple through the entire project. One of the main reasons is that many components, such as the FRP tanks developed for PHOEBUS, are being manufactured for the first time. This novelty introduces a level of uncertainty even from the supplier's side, making lead times difficult to estimate accurately in the early stages of procurement.

In addition, the highly specialized nature of space launcher systems means that material and component requirements are extremely high. ArianeGroup, like other players in the aerospace industry, sets very high standards to ensure system reliability and safety. However, these requirements drastically reduce the pool of suitable suppliers. Not many companies possess the technical capability, appropriate certifications, or the willingness to assume the financial and logistical risk involved. Compounding this is the fact that production volumes in space projects are relatively low, which limits profitability for suppliers. As a result, ArianeGroup often finds itself low on the priority list, especially when competing with high-volume industries such as the German automotive sector.

The combination of high requirements, low supplier redundancy and limited supplier motivation leads to long and often unpredictable lead times. While six months may be considered a typical delivery time, examples in this research reached up to two years. In some cases even, a firm timeline could not be established at all. These delays have serious consequences, as they can cause project downtime—halting progress and tying up resources while awaiting the delivery of critical components.

Another issue is that as explained, risk for complex innovative items can spill over to the supplier. This, amplified by ESA's tendency to award only fixed price contracts, even for pre-development projects, can lead to supplier defaulting. This will inevitably require negotiating the deal, which will derail the project timeline.

*What was not included in the Map*

While constructing the Material Transition Map, it was not feasible to include every single piece of information derived from the interviews, setting aside the necessary thematic saturation. Therefore, some elements were deliberately excluded. These omissions were primarily due to either their highly specialized or sensitive nature or because they were not directly related to the processes of material transitions.

This decision was made to better streamline the research which already had a broad scope from the beginning. Including peripheral information would have risked overcomplicating the Map without adding to the research questions.

That said, it is important to note that although certain pieces of information were not directly integrated into the Map, they are used in Part 2 of Results, where a practical framework is proposed to consolidate and capitalize on the insights gained through this study.

Some examples of excluded content include:

- Levels of supplier integration that, while relevant to the broader organizational context, fall outside the scope of material transitions.
- Project-specific operational issues that are confidential or not publicly disclosed.
- Detailed numerical data such as specific item costs or delivery times, which were deemed to be very specific and not essential to the thematic mapping of material transition processes.

By maintaining this balance, the research preserves both depth and confidentiality while still ensuring that key takeaways from the data are effectively utilized in the overall analysis.

## Focus group for validating the Predevelopment Supply Chain Framework

From the Results of this research and to answer the fourth research question "How can a framework be developed, based on the findings of the research, to strategically tackle procurement/supply chain issues in predevelopment?", a strategy composed of three proposals was created, to address the issues related to supply chain and procurement showcased on the Material Transition Map.

The focus group was designed as a validation step, testing whether proposals formulated in the framework were perceived as relevant, feasible and beneficial by the people involved in the test campaigns.

*Sampling Criteria*

Participants were selected based on their role and their involvement in project management activities related to test campaigns. The same people also participated in the Interviews ensuring that they had firsthand knowledge of the challenges and uncertainties described in the Material Transition Map. In total, 4 participants took part whose profiles are shown in Table 6**.** Three of the participants are also involved in serial production activities at ArianeGroup. They were specifically chosen because a Proposal of the Framework includes combining parts of Test Campaign and production procurement, so their insights would be very useful.

**Table 6**

*The profiles of the focus group participants*

| Number | Role | Project |
|---|---|---|
| 1 | Project Manager | PHOEBUS, MTB, Serial Production |
| 2 | Project Manager | PHOEBUS, MTB, Serial Production |
| 3 | Project Manager | MTB |
| 4 | Project Manager | PHOEBUS, Serial Production |

*Design*

The focus group was conducted online because participants were located in different facilities. The session followed a structured *talk–ask–talk* approach. For each of the three proposals within the framework, the researcher introduced the targeted issue, explained the proposed mitigation and application steps and showed the expected benefits, and invited discussion through three short sessions:

1. short discussion on problem recognition and solution viability
2. validation and prioritization of benefits
3. positioning of the proposal on an impact-versus-feasibility grid.

This design encouraged prioritization, by allowing the group to assess trade-offs across proposals.

The duration of the focus group was around 1 hour.

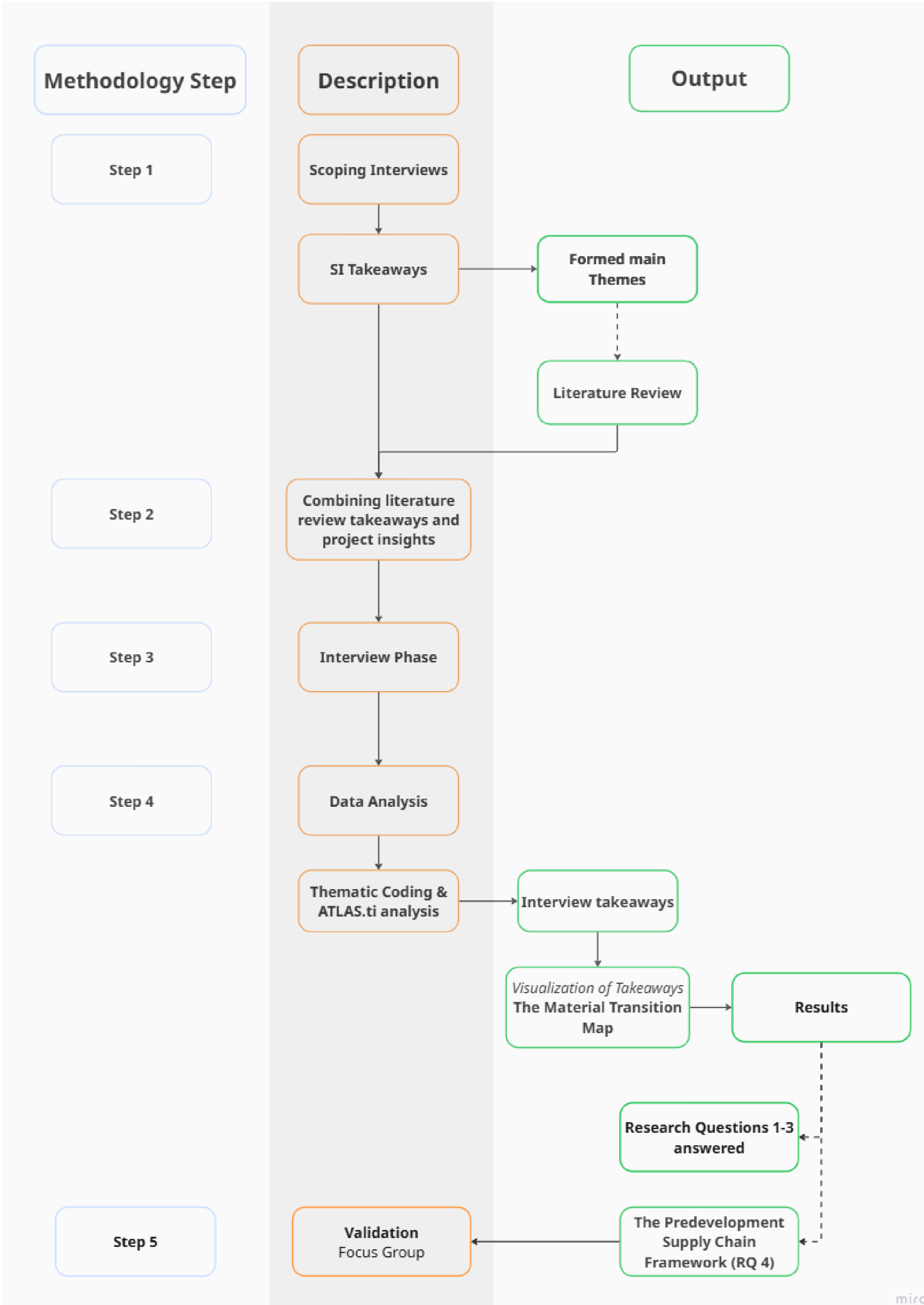
*Data Collection and Analysis.*

The session was transcribed through the respective function on MS word, with additional notes taken during the discussion. This was viable due to the short duration of the focus group. Analysis was conducted, focusing on three dimensions: (1) validation of whether the problems and issues identified in earlier stages of the research were recognized by participants, (2) evaluation of the perceived feasibility and applicability of the proposed measures and (3) assessment of the benefits of the proposals. The results of this focus group will be shown in the Discussion chapter, in the answer of the fourth research question, the framework.

A recap of the entire Methodology, is shown in Figure 8, showing steps 1-4 that lead to the visualization of the interview data in the Material Transition Map, the formation of the Predevelopment Supply Chain Framework from the Map and its final validation through the focus group.

**Figure 8**

*Overview of the Methodology Steps and their Outputs. From the Scoping Interviews to the Interviews to the validation of the Predevelopment Supply Chain Framework*



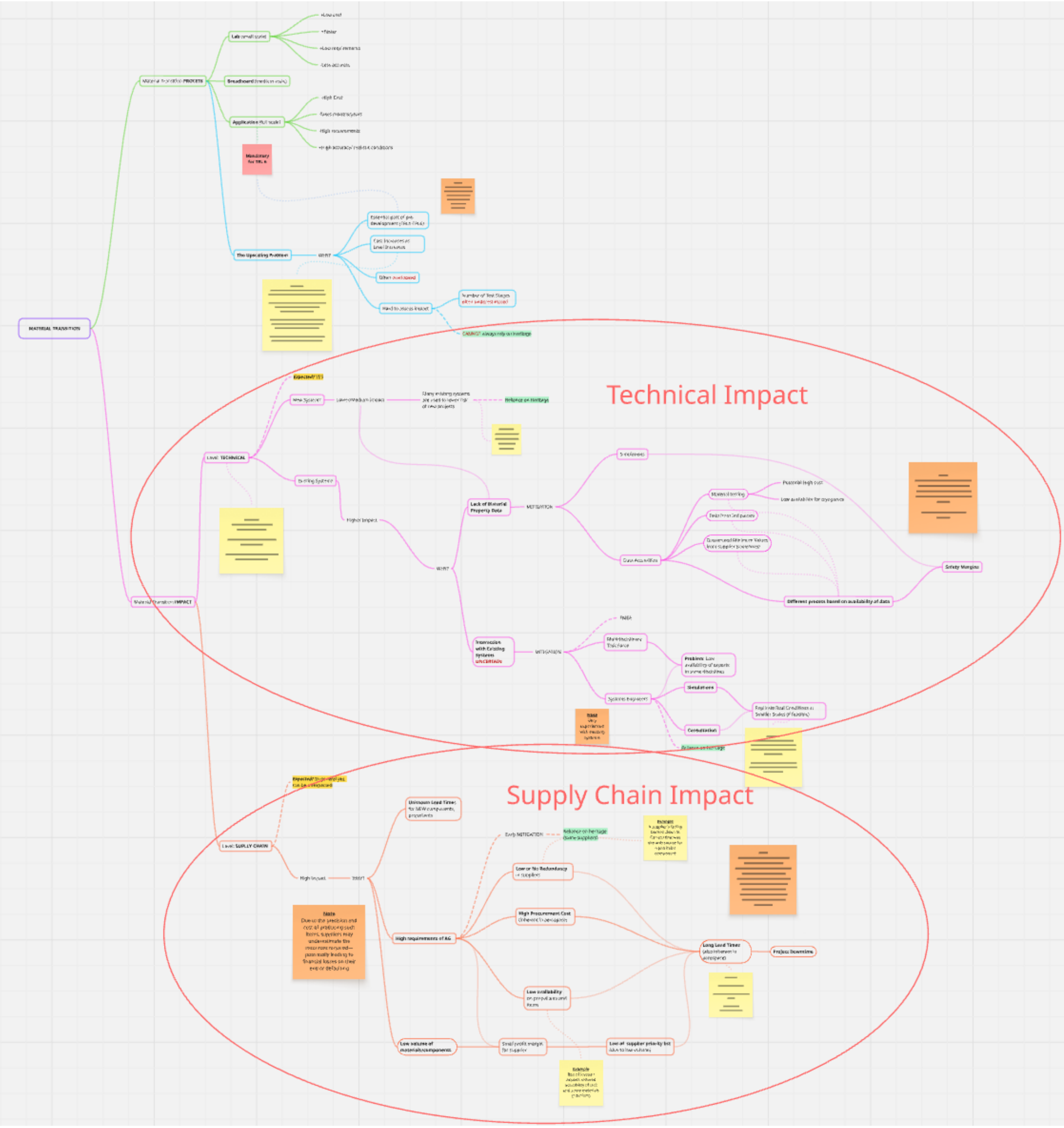
# Results

## Part 1: Key Takeaways of the Material Transition Map

### 1) Technical vs Supply Chain Impact Comparison

**Figure 9**

*The Technical and Supply Chain Impact branches compared in the first takeaway*



First the two main branches of the Material Transition Map, Technical Impact and Supply Chain Impact (Figure 9), will be compared.

Technical uncertainty is inherent to change. Launch vehicles are highly complex systems, composed of tightly interconnected subsystems where a modification in one area can have ripple effects throughout the entire design. As one interviewee explained, *“material changes can cause major uncertainty, especially when the material is widely used in critical, safety-related components that are deeply integrated into the system. Because these components can’t be easily isolated, a change in material affects a large portion of the system and requires rigorous validation”* (Interviewee 4). This perspective was brought up by several others, who emphasized how interconnectivity and cascading effects make transitions particularly difficult to control (Interviewees 4, 5, 6, 12). To manage such challenges, the company relies heavily on simulations and analyses designed and run by experts, processes that were described in detail by Interviewees 3, 4, and 7. In cases of material transitions, this complexity intensifies due to unknown interactions or material performance deviations under extreme conditions, which are typically addressed by applying conservative safety factors.

Supply chain challenges are amplified by material change. Even under stable conditions, the aerospace supply chain is vulnerable due to limited or, sometimes, even a single source for critical components (Interviewees 1, 4, 5, 7). Interviewee 4 recalled delays after a Canadian facility, the only global producer of a specific aerospace component, was heavily damaged by fire. Delays and disruptions can also emerge unexpectedly even with established suppliers; Interviewee 9, for example, recounted how a German supplier’s factory fire suddenly made a previously non-critical item a bottleneck for the project.

Introducing a new material, such as fiber-reinforced polymers (FRP) for upper-stage tanks or new propellants such as $H_2O_2$, adds a new layer of uncertainty, particularly because suppliers often lack prior experience with the associated manufacturing or qualification processes. Several interviewees (3, 6, 9) noted that predevelopment projects frequently demand extra investments in tooling, machinery and equipment, that suppliers may be unwilling or unable to make, even when funded in a big part. These issues, compounded by other vulnerabilities captured in the Supply Chain Impact branch of the Map, often translate into longer lead times, higher costs, high supplier bargaining power and even the risk of supplier defaulting.

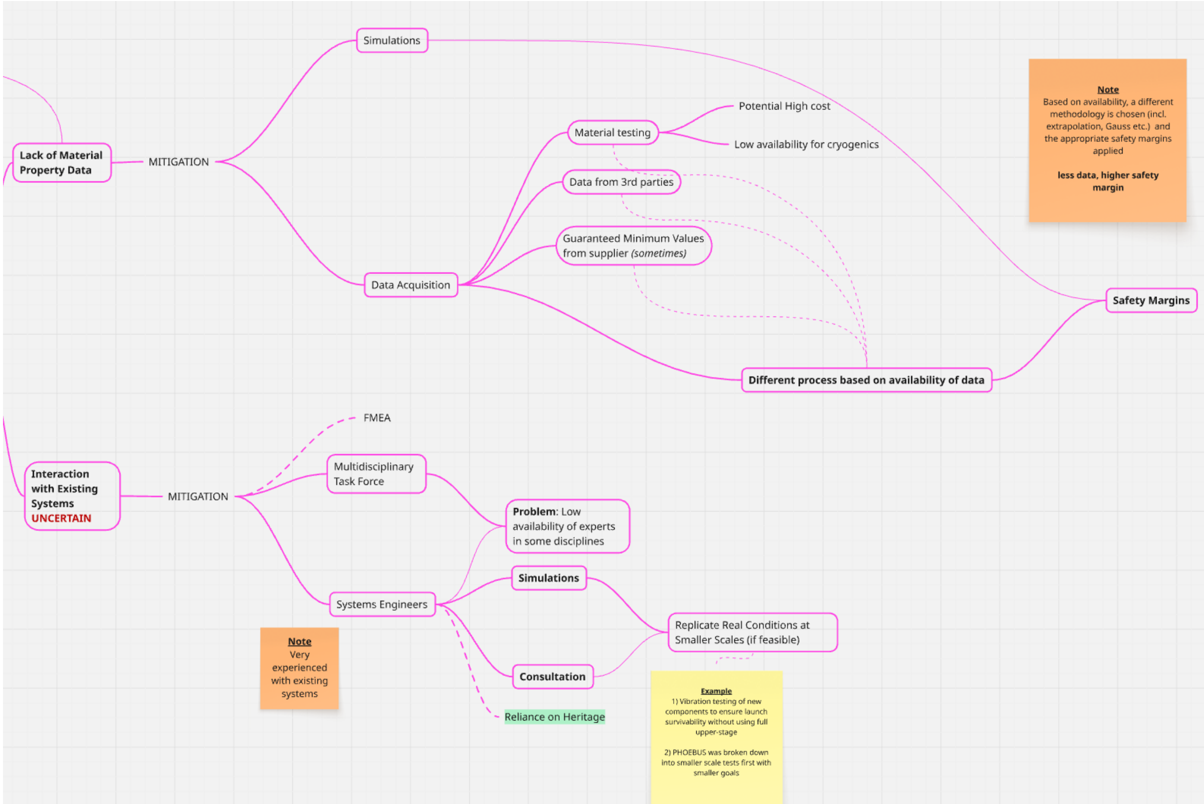
Therefore, during a material transition, technical uncertainty tends to be internal; it arises from the introduction of new technologies or materials within the engineering and design process. In contrast, supply chain uncertainty is largely external, as it depends on the readiness, capabilities and responsiveness of third-party suppliers. While the company has established mechanisms to anticipate and mitigate internal technical risks, it remains significantly exposed to external supply chain disruptions.

This imbalance reveals a critical insight: organizational uncertainty, particularly when it stems from external dependencies, is far less manageable than operational or technical uncertainty, even in the case of aerospace components where technical complexity is inherently high. Mitigating these external risks requires not only improved supplier management strategies but also coordination beyond the immediate boundaries of a single project.

## 2) Navigating Uncertainty: Organizational Practices and Perceptions

**Figure 10**

*Detail of the technical impact mitigation part of the Material Transition Map*




In addressing the question of how managers and engineers within the aerospace industry perceive and navigate uncertainties arising from technological transitions, particularly in the context of the Ariane launcher megaproject, the research reveals a structured and multi-layered approach to uncertainty mitigation.

Technical uncertainty is recognized as an inherent part of innovation and material transition. Interviewees described a well-developed process designed to handle this type of uncertainty, particularly in relation to new materials or configurations. This process is structured around the progressive gathering of data and risk reduction through staged testing and modelling As one engineer explained, *"We start with models and validate them with sample tests; then intermediate demonstrators are built and tested, the models are validated again, and only then are they used to predict and design the full-scale demonstrator"* (Interviewee 3). Models often rely on extrapolations, statistical assumptions (such as Gaussian distributions), and conservative safety factors to compensate for gaps in empirical evidence (Interviewees 4, 7).

Once a baseline understanding is established, lab-scale testing on small samples refines the models further and helps decrease safety factors. As one participant explained, the safety factors have to do with fundamental design questions, *"For example: how much GHe to put in the system for pressurization? Same for LH2 propellant"*, and are decided through this iterative process (Interviewee 1). Breadboard testing, which involves linking multiple components, follows to explore component interaction or component-system interaction (e.g. vibration tests, Interviewee 4). Each step in this validation chain progressively narrows margins of uncertainty and increases confidence before full-scale development proceeds (Interviewees 7, 8).

To estimate impact on existing systems, the company relies on internal resources, particularly systems engineers and multidisciplinary task forces (Interviewees 4,8). These teams provide a holistic view of the transition's technical impact, ensuring there are no systems, mechanical, electrical, structural, etc., treated in isolation. This integrated approach allows for better forecasting of cascading effects and ensures that mitigation strategies are better aligned.

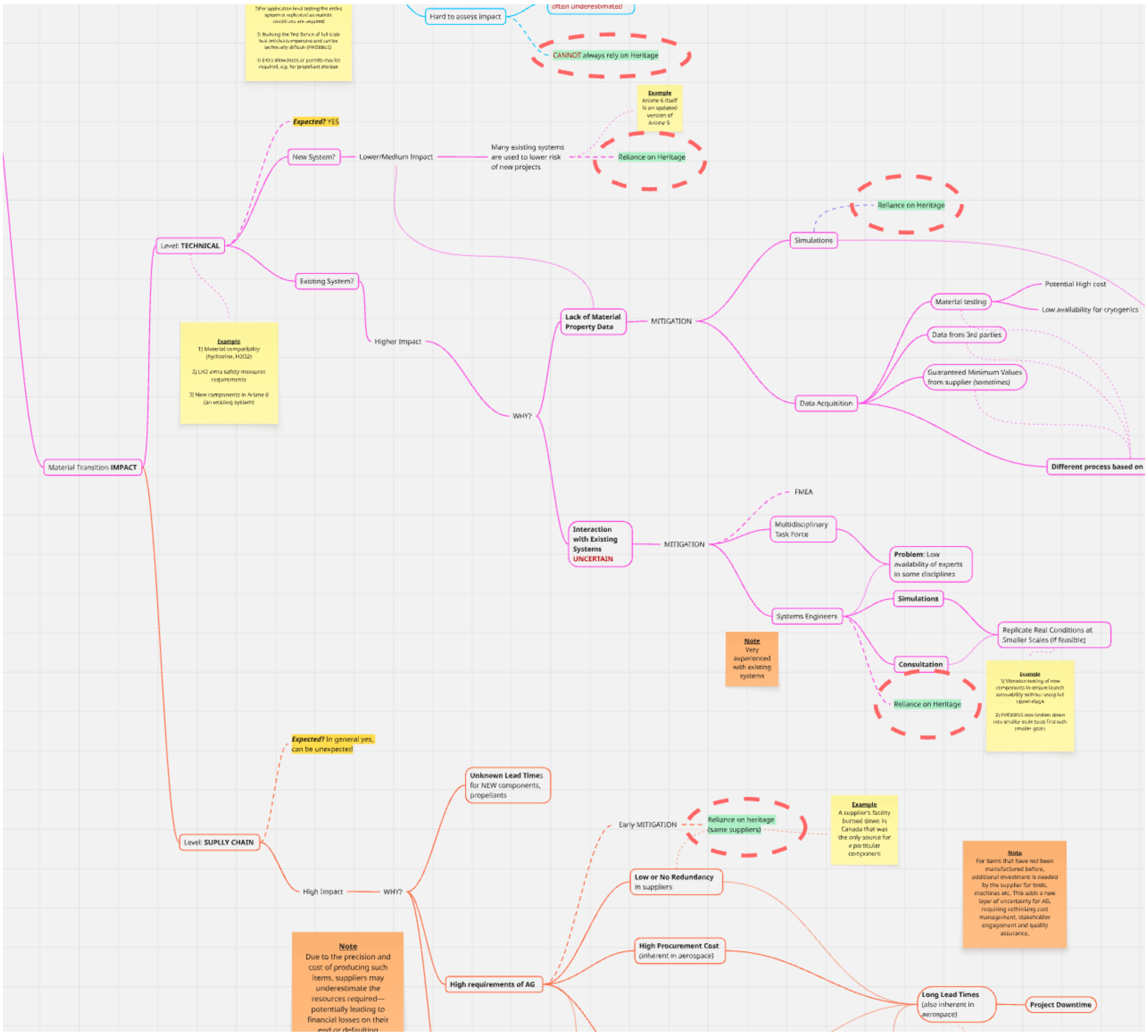
Reliance on heritage also plays a central role in mitigating technical uncertainty. When possible, previous test campaign results, legacy designs and flight-proven materials are used as reference points. This accelerates development but is also a derisking method by counterbalancing innovation with validated practices. This will be explored further next, in part (3).

While technical or operational uncertainty is actively managed through structured internal processes, organizational uncertainty, particularly related to supply chains, is far more challenging. Delays, high cost and low willingness from suppliers (especially when new expertise is required) are common problems. While processes for handling technical uncertainty are streamlined and well-established, equivalent processes for supply chain challenges were not observed. Instead, pragmatic but fragmented practices were used. For instance, one interviewee emphasized the importance of planning long-lead and high-risk items well in advance to allow for time buffers (Interviewee 9). Yet, in practice, it was observed (App. D, Table D2) that even some critical components were procured on an ad hoc basis and no centralized procurement strategy tailored to the needs of predevelopment projects was identified.

### 3) Reliance on Heritage

**Figure 11**

*Points in the Map where reliance on heritage emerged as a mitigation measure*




Reliance on heritage emerged as a recurring theme across all expert interviews and is reflected in every branch of the Material Transition Map. Heritage is drawn upon at multiple levels: to assess the impact of new components on existing systems, to evaluate the properties of new materials using established models and simulations, and even in procurement, where the company often prefers to continue working with known suppliers. For instance, one project manager explained, *"For the PHOEBUS FRP tanks, we got help from Airbus (the mother company), which has experience with this material"* (Interviewee 7). This illustrates how industry-wide heritage, not only internal company experience, serves as a valuable reference point.

While familiar suppliers are often preferred, new technologies sometimes require choosing entirely new partners, which compounds supply chain risks (Interviewee 8). Every interviewee emphasized, in different ways, the value of experience from previous test campaigns: familiar systems and materials create a sense of security and predictability, functioning as an important derisking mechanism. Conversely, the absence of heritage was associated with discomfort. As one participant joked, engineers and project managers become *"nervous"* in the absence of heritage data (Interviewee 4). Another highlighted the inertia created by heritage, noting, *"People say, 'we've done it like this for so long—why change it now?'"* (Interviewee 5).

These insights suggest that reliance on heritage is not only a strategy on the operational level but also an organizational one. It shapes how uncertainty is perceived, mitigated and at times resisted. One example from Interviewee 9 underlined this dynamic: *"We use an established risk process, built on heritage and updated every two months, based on existing projects."* Such practices reinforce stability and predictability but can, potentially, also create barriers to change by anchoring decision-making to familiar models.

This strong dependence on heritage highlights the need to critically assess its role in material transitions. While heritage provides an essential safety net, it can also amplify risks by discouraging exploration of new solutions or suppliers. In the Discussion, the advantages and disadvantages of this approach will be explored through relevant literature, offering a broader perspective on how heritage both stabilizes but also contains pitfalls for large-scale innovation projects.

**4) The Cascading Effect observed, Linking two branches of the Material Transition Map**

It would be interesting to explain the mechanism behind cascading uncertainty generation as was observed in the two test campaigns. The most common understanding of the Cascading Effect is how one change in a complex system leads to other necessary reconfigurations to accommodate for this change. This was one of the main themes of the interviews. The general consensus was that though the Cascading Effect is expected and its impact can be predicted and mitigated there were various examples given by the interviewees, where that was not the case. In MTB, where $H_2O_2$ replaced hydrazine derivatives, modifications were made to prevent peroxide decomposition, like using the appropriate metal alloys for the tank, pipes and valves; however, unanticipated leaks allow $H_2O_2$ to enter aluminium capillary sensors, normally isolated from oxidizer, triggering reactions and possible catastrophic failure through pressure buildup (as explained by Interviewee 12).

Additionally, in some cases, design changes trigger predictable follow-up modifications, but the main challenge is in reassessing the resulting functional behavior, which may differ from initial predictions. For instance, when transitioning from the Vulcain engine to the Vulcain 2.1 on Ariane 6, the design modifications were planned and accounted for, but the resulting changes in engine characteristics, such as combustion behaviour, internal pressure and thermal loads, had to be re-evaluated after implementation (Interviewee 8).

But by studying the interview findings and observing the Material Transition Map, a different interpretation of the Cascading Effect can be drawn. It can be understood from the two previous examples that one way or another, the Cascading Effect increases the overall technical uncertainty. As seen in the Map, the greater the uncertainty the greater the need to use higher safety margins; designing components to withstand higher loads or greater thermal stresses or designing tanks to store more propellant. While such margins improve reliability, they also tend to increase mass and potentially complexity and manufacturing requirements, which in turn raise costs and extend development schedules.

Exactly how this relation works would be very interesting to explore as the overall cost and schedule of a project is directly influenced, but this require a deep quantitative analysis that is beyond the scope of this research.

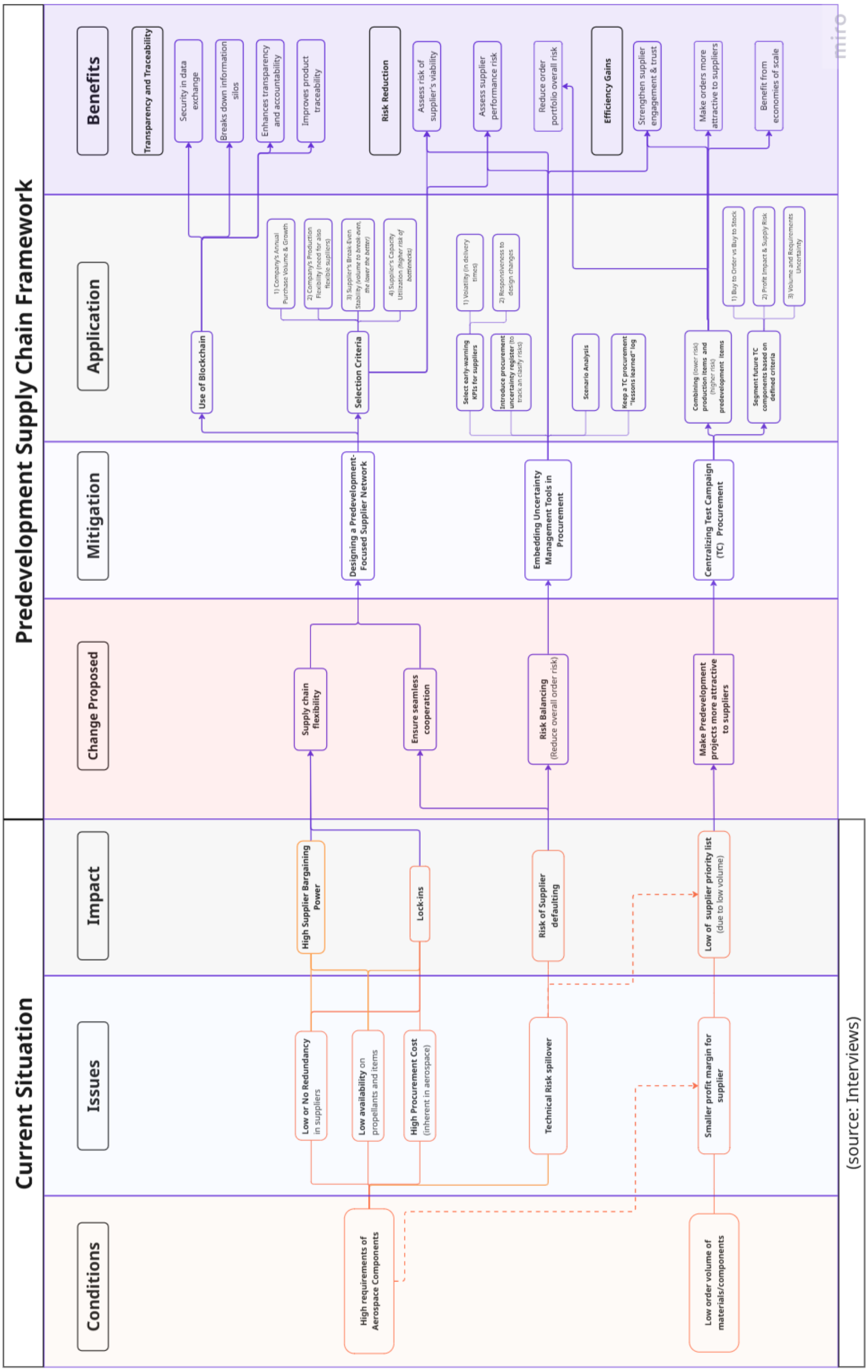
But what is clear is that these design adjustments can then disrupt procurement in several ways. First, they reduce the already limited number of suppliers capable of meeting aerospace-grade requirements. Second, more complex or larger components may require new suppliers or the development of specialized manufacturing processes. As Interviewee 3 noted, *"No production machines exist in this size, or the return on investment is greatly reduced by the increase in size due to new initial purchases for production machines or additional work steps."* Similarly, Interviewee 8 highlighted that suppliers often must invest in entirely new tools or machinery sometimes for the first time and the company frequently bears part of this cost. Third, when components are sourced from highly specialized vendors with limited production capacity, lead times inevitably lengthen, especially since most of these parts cannot be mass-produced.

As a result, technical uncertainty in material performance can ripple across design, testing, supply chain and ultimately project schedule and cost. This cascading nature of risk in megaprojects shows how small technical unknowns can escalate into broader organizational challenges. The Cascading Effect thus, as explained here, directly links the Technical Impact and Supply Chain Impact branches of the Material Transition Map, highlighting the systemic complexity of material transitions.

## Part 2: Framework for handling Supply Chain & Procurement uncertainty in Predevelopment (up to TRL6 full-scale test projects)

**Figure 12**

*Overview of the Predevelopment Supply Chain Framework*



The Predevelopment Supply Chain Framework (diagram shown in Figure 12 above) is derived directly from the Material Transition Map. The nodes in the first three columns, describing the “Current Situation,” are taken from the Supply Chain branch of the Map. These outline the Conditions affecting Test Campaign procurement, the Issues they generate and the resulting Impacts on the Test Campaigns themselves. The remaining four columns in Figure (A) form the core of the Predevelopment Supply Chain Framework. It begins with the Changes Proposed to mitigate or offset the identified impacts. The Mitigation column then highlights the strategic-level measures proposed to deliver these changes, while the Application column details how these measures can be implemented, again with a focus on the strategic level. A more detailed analysis of the Application column will later demonstrate how strategic-level actions can be translated into operational practices. Finally, the Benefits of the proposed framework are summarized under three categories: Transparency and Traceability, Risk Reduction and Efficiency Gains.

This structure ensures a clear narrative flow, linking the observed conditions to strategic intervention and measurable benefits. By doing so, the framework maintains a high-level, strategic focus suitable for predevelopment, while leaving space  for the company to adapt and refine the measures at operational and tactical levels where specific data and resources are needed.

*Conditions*

As explained earlier, in the Material Transition Map, Test Campaign procurement is characterized by a combination of very high component requirements and low order volumes. Full-scale TCs aim to simulate realistic launch conditions as closely as possible, which means the temperature, pressure and dynamic loads present are extreme. In addition, unlike launch vehicles themselves, which are one-use, the test benches and test articles must withstand multiple test runs. This can include multiple pressure cycles for propellant tanks or hot fire tests for engine setups. Therefore, the materials and components used must be of exceptionally high quality to avoid wear, tear or catastrophic failures that could set back the project by weeks or even months.

At the same time, because TCs are one-off projects that are dismantled after testing ends, the overall procurement volumes remain low, especially compared to serial production activities such as the Ariane 6 upper stage assembly line in Bremen or the submarine rescue system (RESUS) in Trauen.

*Issues*

These two conditions inevitably create several issues for TC projects. First, the high component requirements mean that only a limited number of suppliers can provide them and even those suppliers often have low availability because they must serve multiple companies. Earlier in the results, for example, a Canadian manufacturer was mentioned that supplied the same component to all major aircraft manufacturers. By market logic, limited supply drives up procurement costs, which is already a major challenge in the aerospace industry.

Furthermore, for critical items such as the FRP tanks of PHOEBUS, which are custom-made and innovative for each test campaign, the high requirements mean that the technological risk inevitably spills over to the supplier. Because these components involve new or unproven processes, suppliers may misjudge the time, cost, or complexity required to deliver them, which can lead to delays, cost overruns, or quality issues. Finally, this technological risk, combined with the low order volume, means that suppliers potentially face lower profit margins compared to streamlined, lower-risk production items.

*Impact*

The issues identified in TC procurement translate directly into strategic-level impact for the company. First, the combination of low or no redundancy in suppliers and low availability of propellants and other critical items leads to high supplier bargaining power. In practice, this means that suppliers can dictate pricing and delivery conditions, leaving the company with little leverage to negotiate.

In addition, the combination of low supplier redundancy, limited availability and high procurement costs often results in lock-in situations, where the company becomes dependent on a single supplier or a very narrow supplier base. These lock-ins reduce flexibility and increase vulnerability to both cost escalation and delays of critical items.

The issue of technical risk spillover, particularly for innovative or custom-made components such as the FRP tanks of PHOEBUS, creates a risk of supplier defaulting. This happened in PHOEBUS as Interviewees 7 and 11 mentioned, the supplier responsible for making the tanks asked for renegotiation of the contract terms because the final deliverable proved to be more complex and expensive than had been estimated at first. Suppliers, faced with the burden of developing and delivering highly complex components under uncertainty, may struggle to meet deadlines, specifications or budgets, potentially stalling the entire campaign.

Finally, the combination of technological risk spillover and smaller profit margins for suppliers places the company low on the supplier's priority list. For suppliers, higher-volume or lower-risk clients represent a more attractive business case, leaving test campaign projects vulnerable to delays. This concern was explicitly raised by interviewees 4, 7, 8, and 12. For example, in the case of the FRP tanks for PHOEBUS, ArianeGroup had to compete with the established clients of the FRP manufacturer, such as major German car manufacturers, who place large, stable orders and therefore secure higher priority.

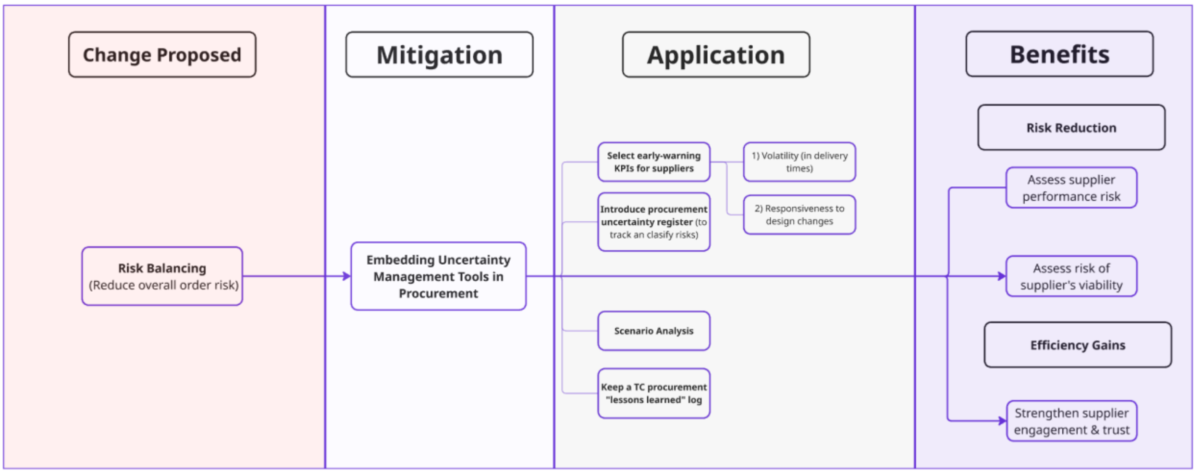
*Change Proposed – Mitigation – Application – Benefits*

So far, a portion of the Material Transition Map has been explained to establish the rationale behind developing this framework. The first three columns of the diagram in Figure 12 *Conditions, Issues,* and *Impact*, and the way they are interconnected have already been discussed. For the remainder of this chapter, the focus will shift to the other side of the framework. Specifically, the *Proposed Changes, Mitigation, Application,* and *Benefits* columns will be explained in a linear manner to highlight the causal links between changes needed, the strategic response introduced and the outcome. This approach allows for a clear demonstration of how the framework addresses each impact systematically, moving from problem recognition to benefits.

*1st Proposal*

**Figure 13**

*Overview of the 1st Proposal*




The first proposed strategy (Figure 13) revolves around the risk balancing in TC procurement. This measure is about estimating and weighing uncertainty that can compromise delivery times or supplier performance, leading to delays of many months.

Risk balancing can be achieved by embedding uncertainty management tools into the procurement process. While it is not entirely clear to what extent such tools are already in place, this research builds on observations and interview data to propose a structured approach.

On the Application, the use of uncertainty management tools can be organized along four main axes:

1. Selection of early-warning KPIs for suppliers. Interview data highlighted that delivery delays are often unpredictable, with one interviewee (2) noting that "they fall from the sky." By defining early-warning indicators, the company could better anticipate disruptions. While the specific KPIs should be determined at the operational level, two examples identified through interviews include:
    - *Volatility in delivery times* (since many types components are procured from the same suppliers across TCs, this is easy to track)
    - *Responsiveness to design changes* (especially relevant for items that are normally procured but whose requirements are modified during development, such as measurement equipment).
2. Procurement uncertainty register**.** A general risk register already exists within the company, but a more targeted tool focused on procurement-specific uncertainties is proposed. This would allow risks to be systematically tracked, categorized and verified across test campaigns.
3. Scenario analysis. At the operational level, this could involve exploring measures such as dual sourcing, flexible contracts or in-house production. As highlighted by Interviewee 1, dual sourcing is often prohibitively expensive; however, it may be justified for certain critical

components and scenario analysis should be done for individual cases not predevelopment in general. While this approach requires additional time and resources, it could prevent delays of three to six months, which were frequently cited during interviews (Interviewees 2, 4, 5, 8, 9,11).

4. Lessons-learned log for TC procurement**.** This is a low-cost, low-effort measure that could deliver high value. A structured record of procurement experiences across different test campaigns and facilities (e.g., Germany and France) would enable cross-checking and sharing of insights. Over time, this would contribute to a stronger institutional memory and more consistent supplier engagement.

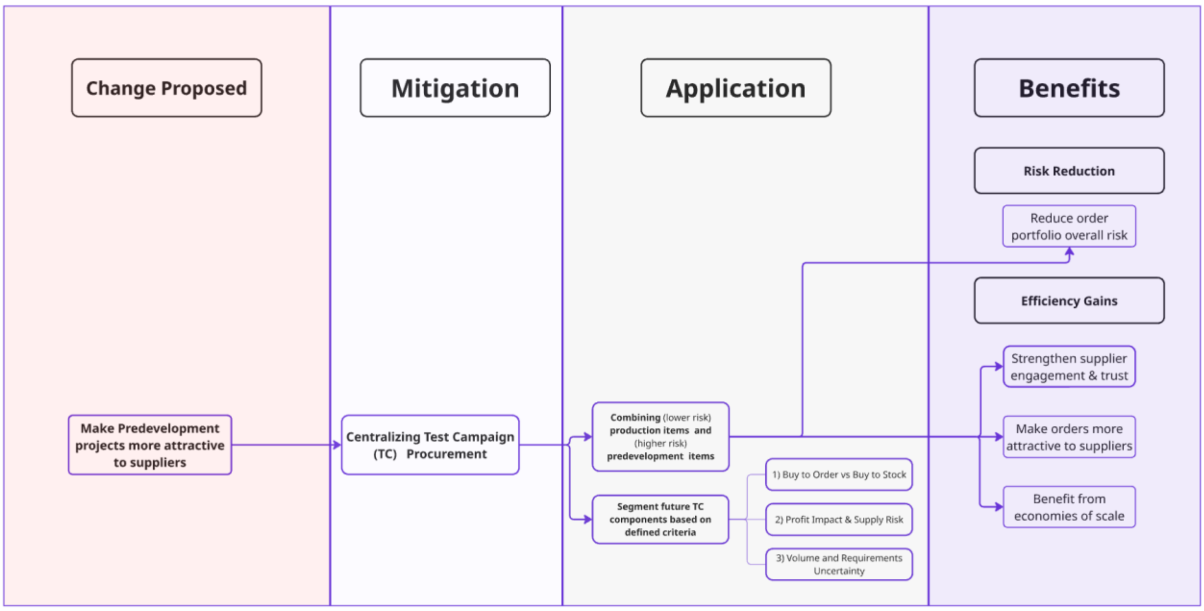
The Benefits of this strategy can be grouped into two main areas:

- Risk reduction: Improved ability to assess supplier performance risk and supplier viability.
- Efficiency gains: Strengthened supplier engagement and trust, as well as greater predictability in procurement outcomes.

*2nd Proposal*

**Figure 14**

*Overview of the 2nd Proposal*




The second Proposal (Figure 14) aims at making predevelopment projects (Test Campaigns, TCs) more attractive to suppliers and strengthening AG's competitiveness in a supply chain currently dominated by large players with stable, high-volume and lower risk orders (such as major aircraft or car manufacturers).

The proposed mitigation measure is to centralize TC procurement, since many critical, high-risk items are currently sourced on an ad hoc basis. By consolidating and strategically managing procurement, AG can create stronger incentives for suppliers while also reducing fragmentation and inefficiency.

The Application of this strategy unfolds across two complementary axes:

1. Combining production items and predevelopment items. Unlike many other European aerospace companies that are relatively small and focused on a single early-stage launch vehicle, AG can leverage its stable production activities (e.g., the Ariane 6 upper stage in Bremen and the RESUS program in Trauen, Germany). By combining these lower-risk production orders with higher-risk predevelopment orders, AG can increase overall order volume and bargaining power, making the TC-related procurement more attractive to suppliers.
2. Segmenting future TC components based on predefined criteria. Another way to increase order volume and improve strategic management is to group and segment future TC components across campaigns wherever feasible. Although final specifications for complex components (e.g., PHOEBUS FRP tanks) may not be fully defined until later stages, early segmentation still creates significant value by highlighting sourcing priorities and identifying potential risks. This component can and should be combined with component 1. More specifically production components should be considered in the following segmentation.

Currently, the only formal classification observed in TCs is that of Long Lead Items (LLIs), which applies mainly to critical components with extended procurement times. The framework proposes a more extensive segmentation approach at the operational level, using three complementary dimensions:

a. Buy to Order vs. Buy to Stock. Following Fletcher et al. (2020), three metrics are critical to determining whether a component should be stocked or purchased only upon order:
    - Customer Lead Time: The time between receipt of an order and the promised delivery date. In TCs, deadlines are often adjusted, as ESA (the main client) tends to be flexible. This creates an environment where delays are somewhat anticipated.
    - Supplier Lead Time: Both contractual and actual, and largely outside AG's control. This is often the main determining factor.
    - Cutoff Time: Defined as Customer Lead Time minus the days required for manufacturing, processing, and delivery. For TCs, this represents the internal planning deadline for completing all preparations (design, procurement, test stand setup) before the campaign begins.

Based on these metrics, acc. to Fletcher et al. (2020):

- If supplier lead time is longer than cutoff time, the component must be stocked.
- If supplier lead time is shorter, the component can be ordered after customer confirmation.

Exceptions include, acc. to Fletcher et al. (2020):

- Expensive parts (e.g., FRP tanks for PHOEBUS) should generally not be stocked, as tying up cash in high-value inventory is risky. It may not even be possible since many such components are custom made and unique.

  - Low-quality or risk-prone parts (e.g., commercial-grade valves) might be stocked despite low cost to avoid late-stage disruptions if a faulty delivery arrives.

b. Profit Impact vs. Supply Risk (Kraljic, 1983). Items should also be categorized along two dimensions:

  - Profit Impact: Volume purchased, share of total procurement costs, influence on quality and business growth.
  - Supply Risk: Material availability, supplier base concentration, competitive demand, potential for in-house production, storage/substitution risks.

This produces four categories, acc to (Kraljic, 1983):

  - Strategic (high profit impact, high supply risk)
  - Bottleneck (low profit impact, high supply risk)
  - Leverage (high profit impact, low supply risk)
  - Noncritical (low profit impact, low supply risk)

c. Volume and Requirements Uncertainty (Van Donk & Van Der Vaart, 2004). In aerospace TCs, overall volume uncertainty is generally low (as campaigns are one-off projects). However, requirements uncertainty can vary significantly. Two key scenarios apply, according to (Van Donk & Van Der Vaart, 2004):

  - Low Volume Uncertainty / Low Requirements Uncertainty. Both demand volume and specifications are predictable. Efficient supply chain practices such as continuous replenishment, Vendor Managed Inventory (VMI) or Kanban systems can be applied. In this category fall standardized fittings or instrumentation consumables that rarely change from campaign to campaign.
  - Low Volume Uncertainty / High Requirements Uncertainty. While demand volume is stable, product specifications vary (e.g., valves with campaign-specific design modifications). In this case, holding inventory is risky since components may quickly become obsolete. Instead, the recommended practice is to reserve supplier capacity (production slots, machine time) in advance.

The Benefits of this strategy can be grouped into two main areas Risk Reduction and Efficiency Gains:

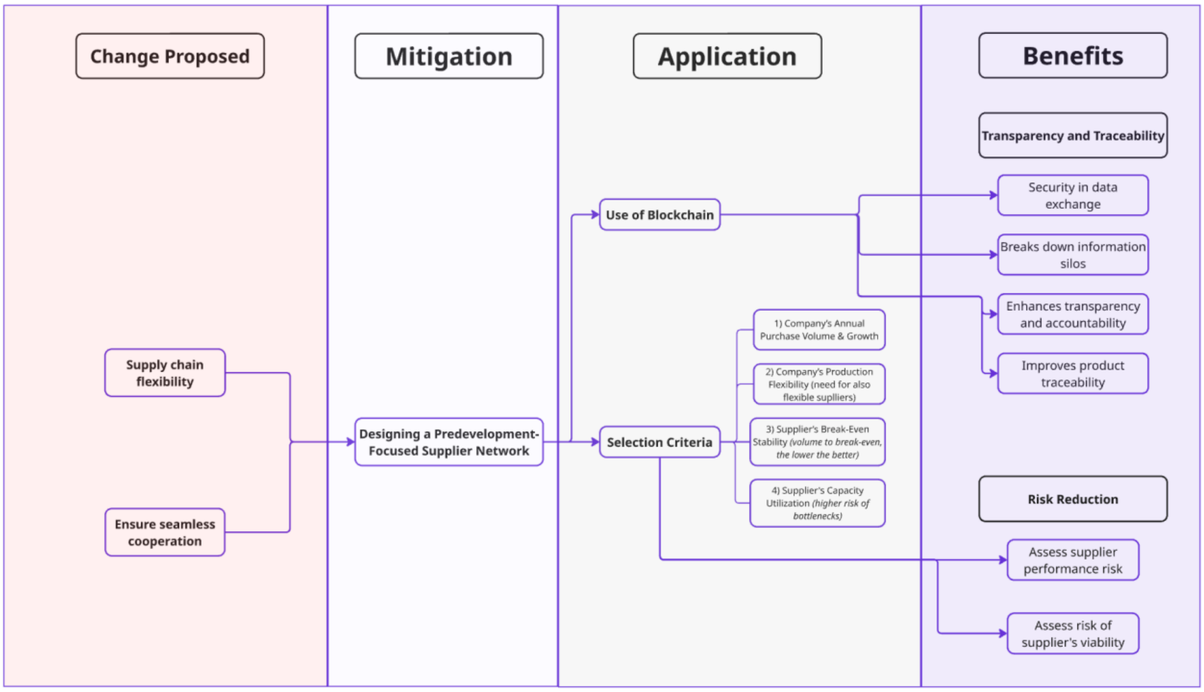
Risk Reduction. By combining production and predevelopment items, AG can reduce the overall risk exposure across its procurement portfolio.

Efficiency Gains. Consolidated orders become more attractive to suppliers, improving cooperation and responsiveness. Economies of scale can be leveraged by grouping orders across campaigns, reducing per-unit costs and strengthening supplier relationships.

*3rd Proposal*

**Figure 15**

*Overview of the 3rd Proposal*




The final Proposal (Figure 15) addresses three major Impacts identified in the current situation: high supplier bargaining power, lock-ins and the risk of supplier defaulting. The key change required is to increase supply chain flexibility and ensure seamless cooperation with suppliers.

The Mitigation strategy centers on designing a predevelopment-focused supplier network, one that better reflects the low-volume, high-requirement nature of aerospace test campaigns. Achieving that, would bring the company much needed flexibility, redundancy and would lower the risk of delays.

The Application, again, unfolds along two complementary elements:

1. Supplier Selection Criteria. To ensure resilience and reduce dependence on vulnerable suppliers, selection criteria can be introduced or refined. Building on Kraljic (1983), four practical dimensions are suggested:

    - *Supplier Capacity Utilization*: Suppliers operating close to full utilization (e.g., 90%) risk bottlenecks, making them unreliable partners for test campaigns with strict timelines.

    - *Supplier Break-Even Stability*: Suppliers that reach financial stability at lower utilization (e.g., 70%) are more robust in negotiations and less likely to default.

    - *Company's Annual Purchase Volume & Growth*: Larger and more stable purchase volumes translate into stronger bargaining power, which can be leveraged in predevelopment.

    - *Company's Production Flexibility*: Suppliers with greater flexibility can better adapt to the fluctuating and uncertain demand patterns typical of predevelopment.

2. Use of Blockchain. To utilize the full potential of a resilient supplier network, digital tools such as blockchain can be integrated. Blockchain enhances the reliability and efficiency of inter-organizational collaboration by providing a shared, secured ledger of transactions and information. Blockchain is a distributed ledger technology that has emerged as a valuable tool for improving security, transparency and trust in complex supply chain environments (Dong et al., 2024). Current supply chains face inefficiencies such as information silos, limited transparency, and poor product traceability, which hinder collaboration, trust and accountability (Lim et al., 2021).

Moving towards this direction, the company has significant Benefits to reap. By building the supplier network according to these selection criteria overall project risk can be reduced, since it becomes easier for the company to:

- Assess supplier performance risk by considering utilization rates, flexibility, and financial stability.
- Assess supplier viability risk by identifying suppliers at risk of default or unable to meet future demands.

Furthermore, as noted by Lim et al. (2021), blockchain can mitigate inefficiencies such as information silos, lack of transparency, and poor product traceability issues highly relevant for test campaigns where delays or quality issues can cause cascading setbacks. Blockchain addresses these issues in the following ways (Lim et al., 2021):

- Breaks down information silos by providing secure, shared access to relevant data for all supply chain participants.
- Enhances transparency and accountability through verifiable records of transactions.
- Improves product traceability by tracking every transaction and movement across the supply chain, allowing full lifecycle visibility.
- Increases security in data exchange and transactional integrity.

# Discussion

This research set out to investigate how material transitions generate and amplify uncertainty in aerospace megaprojects, specifically targeting their effects at both the technical and organizational levels. The main research question guiding the study was: *How do transitions create or amplify uncertainty in megaprojects?* To address this, the research was structured around four subquestions: (1) how technical and organizational uncertainties arise and differ; (2) how niche innovations, such as changes in materials or propellants, contribute to uncertainty and influence the transition process; (3) what strategies organizations employ to manage material transition uncertainty; and (4) how can a framework be developed, based on the finding of the research, to strategically tackle procurement/supply chain issues in predevelopment. While the focus of the framework was not decided at the outset, the analysis of test campaigns revealed that supply chain and procurement in Test Campaigns emerge as vulnerable areas, leading to their selection as the central point of the proposed framework.

## Research Question Findings

*First Research Question: How do technical and organizational uncertainties arise and differ?*

In addressing the first research question, the study examined how and technical and organizational uncertainty arise during material transitions in complex projects, and how they differ. Technical uncertainty was found to originate internally, stemming directly from the transition itself, from the complexity of launch vehicle systems with their tightly interconnected subsystems and from the engineering and design processes that must accommodate such changes. Operational or supply chain uncertainty, by contrast, arises primarily from external factors, such as supplier’s willingness to share risk, the company’s internal capacity to manufacture components and broader market conditions.

Internal technical uncertainty is both expected and, in principle, addressable through simulations, testing and the application of the necessary safety factors. However, the quantification of its impacts remains challenging. For example, interviewees noted that the number of testing stages required is sometimes underestimated, with direct consequences for the time and cost projections of the overall project. Additionally, safety factors tend to increase when uncertainty grows, which, while reducing technical risk, also drives up component costs and makes supply chain requirements stricter further amplifying procurement challenges when dealing with specialized, high-specification aerospace materials and components.

External supply chain uncertainty is inherently more difficult to control because it depends on independent actors with their own constraints and priorities. The factors represented on the supply chain branch of the Material Transition Map illustrate how the search for suitable suppliers can be prolonged, and even when they are found, the perceived high risk and comparatively low profitability of such projects, especially when contrasted with customers who have more streamlined or predictable requirements, can reduce supplier engagement and flexibility. This challenge is compounded by the fact that procurement for pre-development test campaigns operates on a need basis rather than as a steady, repeat order, meaning suppliers cannot rely on sustained demand to justify investments in tooling, qualification, or specialized production capacity.

From a literature perspective, the study found that supply chain uncertainty in this context is difficult to address because most existing research focuses on standardized production processes rather than one-off, engineer-to-order projects with exceptionally high performance and quality requirements. Even the most relevant studies often reduce recommendations to broad strategies such as “build a network of suppliers” or “maintain close communication,” offering limited prescriptive guidelines for the unique dynamics of high-stakes test campaigns. This reveals a notable literature gap: while the technical dimension of uncertainty in aerospace material transitions is relatively well understood and methodologically supported, the supply chain and procurement dimension, especially for tailor-made, high-requirement, project-based components, remains underexplored.

*Second Research Question: How do niche innovations, such as changes in materials or propellants, contribute to uncertainty and influence the transition process?*

Based on the second research question, this research examined how specific types of innovations, particularly in material and propellant choice, generate uncertainty and influence the overall material transition process within launch vehicle development. Drawing from the context of the two selected test campaigns, the study focused on propellant tanks, where the Phoebus project aimed to evaluate fiber-reinforced plastic (FRP) as a structural material, and turbopumps, where the MTB project explored the operational impacts of switching to different propellant types.

These components were chosen because they represent clear examples of how a single change in material or propellant can effectively alter the design of an entire subsystem. For example, FRP tanks differ significantly from their metallic counterparts, not only in terms of weight and manufacturability but also in the way they comply with critical safety criteria, such as the Leak Before Burst. Similarly, change in propellant will heavily influence engine architecture.

The literature review, drawing on both academic studies and reports, particularly from NASA, highlighted challenges of considering FRP as propellant tank material, noting trade-offs between endurance and mass saving and issues such poor damage detectability, upscaling etc. In the case of propellant transitions, the research showed how reactive chemicals impose additional constraints on material compatibility and operational safety.

These patterns were verified later by interview data. In the MTB case, because $N_2O_2$ is so chemically reactive, design considerations extended beyond the immediate propulsion system. It was not enough to alter the material of tank, feed lines, or demonstrator engine, engineers also had to redesign parts of the test stand itself, including replacing certain aluminum sensors that would otherwise react with the oxidizer. Such adjustments would not have been necessary if legacy propellants like hydrazine had been selected. Similarly, in the PHOEBUS campaign, the use of FRP tanks necessitated changes not only to the tanks themselves but also to test bench elements like the structural “mount” for the tanks. Even though the company had previously conducted comparable tests with metal tanks, the FRP transition required additional considerations to ensure structural integrity under cryogenic conditions.

This part set the tone for the entire research. It revealed that material transitions are inherently complex, with changes at the material level often prompting complete redesigns of components or subsystems. The Material Transition Map reflects this complexity, showing the process as multilayered spanning from laboratory tests of individual samples and components to full-scale demonstrations under realistic operational conditions. This finding also clarified why the research is valuable: it demonstrates that managing material transitions is a major challenge in any such project whose implications need to be further studied and understood.

*Third Research Question*

This part of the research explored the strategies used by organizations to manage uncertainty during material transitions in megaprojects, with a focus on the two Test Campaigns. The findings, in the *Technical Impact* branch of the Map, suggest that technical uncertainty management is not an ad hoc activity but rather a structured, multi-layered process that combines data validation with reliance on proven knowledge.

This process of narrowing uncertainty encompasses both the Material Transition Process branch of the Map, progressing from lab-scale experiments to breadboard testing and ultimately to full-scale validation, and the Technical Impact branch. This includes the systematic determination of material properties when these are initially unknown and the crucial step of validating how newly introduced components interact with and impact existing systems, a particularly critical consideration for the Ariane 6 megaproject, which is continuously evolving in design.

Reliance on heritage emerged as a particularly interesting and recurring theme in both interviews and supporting documents. Heritage often assumes stable and capable suppliers but sometimes introducing even a minor modification to a heritage design can disrupt these relationships if suppliers lack the necessary tooling or expertise, as apparently from the interviews and even the focus group, has been the case.

*Advantages*

Heritage is often seen as a practical way to reduce uncertainty in R&D. Reusing proven systems and materials can lower technical risks, compress schedules, and cut costs. There are many examples across the industry. Relying on heritage technologies can offer several benefits. According to Hein (2016):

- Can highly reduce development costs and timelines by reusing proven designs and increasing the likelihood of passing verification and testing phases efficiently.
- Lower programmatic risk, as heritage systems often require smaller cost and mass margins due to their established performance.
- Finally, heritage use can boost confidence in system quality and reliability, since previously validated technologies are generally seen as more dependable than new, untested ones.

This confirms what has been mentioned by the Interviewees combining theory with empirical data.

*Risks and Limitations*

To bring an example of another organization, NASA's Discovery and New Frontiers (D&NF) programs deliberately prioritize mature, high-Technology Readiness Level (TRL) systems to meet the constraints of small- to medium-sized deep space missions (Barley et al., 2010). However, heritage use is not without drawbacks. A component's TRL does not always guarantee compatibility with new mission environments (Barley et al., 2010).

- Assumed compatibility without full analysis: Projects sometimes assume that heritage systems can be reused without thoroughly assessing environmental or systems-level differences. This can result in late design changes, increased costs, and schedule delays (Barley et al., 2010). Moreover, such assumptions can introduce unnecessary system complexity (Newhouse et al., 2010). Small, incremental changes can destabilize overall system architecture, and insufficient updates to testing or integration plans can amplify risk.
    - *Example*: A D&NF mission reused a previously flown instrument for a different planetary environment. The resulting redesign due to higher radiation and updated science models depleted nearly all schedule and cost buffers (Barley et al., 2010).
    - *Example*: Some missions adopted legacy fault management systems that were overly complex for the simpler needs of current missions. The added complexity led to increased testing and operational burdens without additional benefits (Newhouse et al., 2010).
- Claiming heritage prematurely: Some projects cite hardware as heritage even when it has not flown, or not for its full intended operational duration.
    - *Example*: A mission assumed that some heritage instruments were ready for reuse. However, after further analysis, design changes were needed to meet new target requirements, leading to increased costs and a delayed launch (Barley et al., 2010).
- Underestimating integration effort: Even when heritage is valid and appropriate, projects often underestimate the resources required to integrate and qualify it.
    - *Example*: A D&NF project relied on a propulsion system from a prior mission but failed to verify it during early design. Design changes during later phases that the level of heritage was overestimated, contributing to major cost increases and almost cancelling the mission (Barley et al., 2010).

The Mars Observer mission is a well-known example of over-reliance on heritage. According to the NASA Board, the program did not adjust its systems after the mission concept changed significantly. Instead, it relied too heavily on spacecraft components from very different missions. The Board concluded that there was overreliance on the heritage regarding spacecraft hardware, software, and processes. NASA responded by implementing a policy requiring more thorough review of inherited designs and procedures, recognizing that heritage, while valuable, must not be accepted uncritically (Cunningham, 1996).

Overreliance on past performance data is not limited to internal systems. Similar assumptions introduce uncertainty in supply chains. Organizations may expect reliable suppliers to consistently deliver or assume poor-performing suppliers will never improve. However, both supplier capability and market conditions can shift unexpectedly. As Fletcher et al. (2020) argue, relying solely on historical data can lead to mismatches between demand and supply, resulting in excess inventory or critical shortages.

While internal uncertainties could be addressed through these structured processes, supply chain-related uncertainties proved more resistant to control leading to long lead times for critical items. This corroborates the findings from the first research question, where external dependencies were identified as less manageable than internal technical uncertainties. This further underscored the need for developing a more strategic approach to predevelopment procurement, last part of this research.

*Fourth Research Question*

The Predevelopment Procurement Framework represents the final output of this thesis, answering the fourth research question: *How can a framework be developed, based on the finding of the research, to strategically tackle procurement/supply chain issues in predevelopment?* The framework integrates findings from interview data, visualized in the Material Transition Map, and literature into a coherent set of strategic-level interventions.

The framework is directly grounded in the empirical results. The *Conditions–Issues–Impact* chain reflects the first and third research questions: identifying the supply chain & procurement context of test campaigns, the challenges it generates and current mitigation in place. Building on these, the proposed *Changes–Mitigation–Application–Benefits* columns offer a systematic response. In this way, the framework moves toward being prescriptive, showing how specific procurement issues can be offset by targeted strategies.

A key feature of the framework is its focus on the strategic level. Rather than proposing detailed operational measures, which it does only in some application steps, it highlights changes required to reduce uncertainty and improve test campaign procurement on the higher level. This aligns with the nature of test campaigns, which are characterized high requirement and high complexity components and low order volume. At this level, the framework provides guidance that is broad enough to be adapted across different campaigns, while still based in the observed procurement challenges.

Despite this limitation, the framework adds value in two important ways. First, it provides a coherent narrative that links observed supply chain and procurement conditions to actionable strategies, offering a structured approach. Second, by grouping benefits into three categories, transparency, risk reduction, and efficiency gains, it enables project managers to evaluate trade-offs and prioritize actions according to organizational constraints.

**Focus Group Discussion**

As already mentioned in the Methodology, to validate the proposed predevelopment procurement framework, a one-hour online focus group was conducted with four ArianeGroup project managers. The session followed a structured format in which each of the three proposals was presented and then discussed. The aim was not to collect new data, but to test the plausibility, feasibility and usefulness of the framework with experienced professionals. Therefore, this section is kept short and mainly focuses on the takeaways of the focus group.

*Proposal 1: Embedding uncertainty management tools to better estimate and weigh supplier defaulting risk*

All participants confirmed that the problem of unpredictable supplier performance and delays is highly relevant to test campaigns. Examples from PHOEBUS and other recent projects were brought up to illustrate the frequent underestimation of risks at the start of procurement. One participant, unknowingly, linked this to Proposal 3, noting that supplier capacity, a key selection criterion, often drives delays. The mitigation measures were considered valid, particularly the use of scenario analysis and more systematic monitoring of supplier responsiveness to change. However, the participants raised concerns about the management effort required. While participants agreed the measures would bring benefits, they stressed the importance of balancing workload with achievable impact. Overall, the group rated the proposal as high impact but moderate feasibility, reflecting that while the tools are useful, implementation would demand significant number of working hours.

*Proposal 2: Centralizing test campaign procurement, Increasing supply chain competitiveness*

The Participants strongly agreed on the value of the second Proposal. They confirmed that procurement for test campaigns is currently fragmented, with no dedicated team or individual responsible. This disconnect between production procurement and predevelopment activities was illustrated by difficulties in estimating needs for fluid media in earlier campaigns. Participants agreed that centralization would bring clear advantages. The idea of combining production and test campaign orders, particularly for standardized components such as sensors, was seen as feasible and beneficial. Standardization of test components (test bench components, such as sensors, lines etc) was highlighted as an area with good potential. In contrast, more innovative or prototype test articles would be harder to include. The group placed this proposal in the high impact, high feasibility quadrant, outlining strong support and relatively ease to apply.

*Proposal 3: Designing a predevelopment-focused supplier network*

The third proposal also resonated with participants who confirmed that single-source dependencies are a recurring problem, particularly for fluids and other specialized items. A stronger, more spread-out supplier network would therefore be beneficial, though its feasibility depends heavily on the similarity of test campaigns and the nature of the components. Participants pointed out that in practice, political and funding constraints sometimes are the deciding factor in supplier choice, limiting flexibility in building the network. While the idea of breaking down complex components and sourcing sub-parts from multiple suppliers was seen as theoretically viable, it was considered difficult in practice. Despite these issues but highlighting potential benefits, participants rated the proposal as high impact and moderate feasibility.

Across all three proposals, participants validated the core problems identified in the framework and confirmed that the proposed mitigations would address real issues observed in practice. Proposal 2 (centralization of procurement) was considered the most immediately actionable, with both high impact and high feasibility. Proposal 1 (uncertainty management tools) was recognized as important but raised concerns about workload requirements, placing it in high impact but medium feasibility. Proposal 3 (supplier network design) was seen as valuable but constrained by external political factors and again, workload requirements. Overall, the focus group confirmed that the proposed framework reflects real challenges in ArianeGroup's test campaign supply chain & procurement. The validation exercise demonstrated both the potential benefits and the barriers of practical application, providing a clearer picture of how the proposals could be adapted and prioritized for implementation.

**Figure 5**

*The Impact and Feasibility matrix, the participants were asked to put the three Proposals on. The number on each bubble shows the proposal and the color indicates the participant*


## Research Contribution

### Theoretical Contribution

This research makes several important theoretical contributions by bridging project studies and transition studies, two academic communities that have often remained siloed despite their overlapping concerns. As mentioned in the Introduction, Winch et al. (2023) highlight the need to understand how project design and management can allow for wider systemic transitions and urge for better integration of these two domains. This study responds to that call by using aerospace test campaigns as case studies of projects that showcase material transitions, specifically the development of FRP cryogenic tanks in PHOEBUS and the replacement of hydrazine derivatives with hydrogen peroxide ($H_2O_2$) in MTB. These cases serve as steppingstone for advancing theoretical knowledge about how uncertainty arises, cascades and shapes transitions in technologically complex megaprojects.

A first contribution lies in the connection of the three main theoretical concepts of transition studies used here, Multi-Level Perspective, Strategic Niche Management and Transition Management, to the test campaigns. Through MLP, the research illustrates how landscape-level pressures, such as the gradual ban of toxic propellants (incl. hydrazines) by the European Union, translate into regime-level change through the adoption of green propellants like $H_2O_2$. Similarly, the ICARUS composite upper stage, of which PHOEBUS is a part, exemplifies the "transformation pathway" described by Geels (2016), where increasing competition in the launcher sector pressures regimes to adapt incrementally to adapt to competition. In terms of SNM, the study draws a parallel between test campaigns and innovation experiments, as described by Hoogma et al. (2005) and Kamp & Vanheule (2015). However, it adds a new layer by demonstrating that niches in aerospace are never fully protected. Even in these experimental spaces, supply chain constraints, limited supplier availability and capacity and organizational dependencies will inevitably shape experiment outcomes. In Transition Management, the study linked its conceptual starting points by Loorbach & Raak (2006) to examples form the test campaigns and other aerospace projects.

Second, the study contributes by addressing the gap observed in both project and transition literature regarding the management of uncertainty in supply chains characterized by high complexity, high requirements and low volume components. Prescriptive guidance on how organizations can strategically manage such conditions is largely missing in existing literature. This research advances the discussion by proposing a framework for predevelopment procurement and supply chain management that explicitly responds to these characteristics. In doing so, it moves beyond theory to offer a structured approach that alleviates some of the challenges observed in test campaigns.

A third contribution stems from the Material Transition Map. While primarily designed as a practical tool for the purpose of analyzing interview data, the Map also represents a theoretical innovation. It connects technical uncertainties with organizational uncertainties, particularly those relating to supply chain and procurement. By visualizing how uncertainty cascades between domains, a link between technical uncertainty and supply chain uncertainty was made, connecting the need to use of high safety factors to worsening existing supply chain challenges, as analyzed in the Results. This linking of uncertainty domains contributes to project studies by making interdependencies visible, enabling a more systemic approach to risk and uncertainty management.

Finally, this research contributes by highlighting the concept of heritage within transition studies. Heritage is often framed as a stabilizing factor that locks regimes into path dependency. This study demonstrates its dual role: on one hand, heritage reduces uncertainty by providing trusted designs, processes and practices; on the other, it creates inertia and resistance to new approaches and can lead to false assumptions. Recognizing heritage as a dual-edged mechanism adds theoretical nuance to transition theory and provides a more balanced understanding of its influence on uncertainty dynamics.

**Knowledge Contribution**

From an industry and case study perspective, aerospace launch vehicle development represents an underexplored, niche sector, particularly in management-oriented research. While engineering and technical aspects of launcher development have been extensively documented, management topics such as material transition uncertainty remain largely absent from academic literature. With the increasing commercialization of space and the rapid growth of “New Space,” this sector is entering a period of transformation in which such studies are urgently needed.

Even within aerospace, research and development projects, particularly predevelopment test campaigns such as PHOEBUS and MTB, are rarely analyzed in academic studies. No comparable case studies were identified during the literature research phase; existing documentation comes primarily from technical reports by NASA. This thesis therefore provides rare insights into a domain that is both highly complex and highly innovative. By documenting large-scale test campaigns, it extends project studies into a setting that has remained largely inaccessible to researchers due to confidentiality and organizational barriers.

Another distinctive contribution lies in the context of competition. Historically, launcher development was dominated by national monopolies, meaning that material transitions were commenced mainly for technical and scientifical advancement. Today, with private players entering the market, the need to innovate in order to stay competitive makes material transitions a strategically critical issue. This research could be among the first to examine transition uncertainty under these new market conditions, since again during the literature research phase no such articles were found.

From an empirical perspective, the thesis draws on interviews with experts whose experience spans decades, including involvement in the development of Ariane 5. These insights capture both established practices and new challenges, creating a bridge between legacy aerospace approaches and transition dynamics. In doing so, the research generates original empirical data from a sector where access has been typically restricted, offering a rare window into how uncertainty is generated, cascades across levels and is mitigated.

**Practical Contribution**

ArianeGroup operates across several sites in France and Germany, with teams typically focused on their own projects or subprojects related to Ariane 6 production (e.g., engines, upper stages, boosters). The research represents a valuable opportunity to exchange knowledge between facilities. Because it integrates insights from experts based in Trauen (test field), Bremen (upper stage) and Ottobrunn (propulsion, engines), the findings help project managers in one location understand the types of challenges their colleagues face elsewhere. For example, an upper-stage manager in Bremen can learn from propulsion-related uncertainties observed in Ottobrunn and vice versa. This strengthens organizational learning.

The research also highlights the importance of viewing test campaigns not only as standalone projects but as a distinct project type within the company's portfolio. By analyzing uncertainty at the campaign level, it encourages ArianeGroup to group together core elements (such as supplier networks, procurement) and manage them centrally. As the framework illustrates, strategies suh as the three Proposals can be implemented once, centrally and benefit all test campaigns.

One of the key outputs of the research, the Material Transition Map, provides a structured and easy to follow visualization of uncertainty as experienced by the company's experts. Complex knowledge held by engineers and project managers is translated into an easy-to-read tool that makes patterns of technical and organizational uncertainty visible. This provides value as a decision-making tool, as it allows different stakeholders, like engineers and project managers, to engage around the same visual representation and share a common understanding of challenges. By including fragmented, empirical knowledge, essentially its source, the Map can help streamline decision-making. Managers can use it to identify which areas of uncertainty are most critical and which mitigation strategies should be prioritized. For example, the cascading link between technical design changes and supply chain challenges becomes immediately visible.

The Map is also easily expandable. Much like the company's existing risk management tools, it can be updated and built upon as new insights and experience are gained from future test campaigns. It reflects reliance on heritage, a theme that has been analyzed in the research where experience can be integrated into the Map and used as a reference point for future campaigns. This ensures that the Map can evolve into a dynamic tool, adaptable across projects, rather than a static output.

The second practical contribution lies in the Predevelopment Supply Chain Framework, which was deliberately designed at the strategic level. Its benefits are grouped under risk reduction, transparency & traceability and efficiency gains, all of which were validated through a focus group with project managers. This confirmed its practical relevance and alignment with the company's reality.

The framework provides clear managerial guidance. By linking "Changes Required" with "Mitigation, Application and Benefits," it translates strategic insights into structured application. This offers ArianeGroup a structured process from problem recognition to implementation. Importantly, the framework does not prescribe a single solution but provides three complementary proposals, enabling managers to weigh trade-offs between feasibility and impact. Overall, all proposals' feasibility was assessed as at least medium-to-high during the focus group. Concerns centered on the additional working hours required, which are relatively straightforward for ArianeGroup to quantify. The cost–benefit balance also favors implementation: while benefits are harder to measure precisely, the high costs of test campaigns (often tens of millions of euros) mean that even small efficiency gains or risk reductions can generate substantial value.

Finally, the framework provides a replicable structure that could be adapted and used across the European space industry. While the immediate focus is ArianeGroup, the general principles of centralization, supplier engagement and risk reduction could, theoretically be adapted by ESA, or even some commercial New Space companies facing similar challenges.

**Limitations**

This study, while contributing insights into material transition uncertainty in aerospace megaprojects, is subject to some limitations that must be acknowledged. These limitations primarily stem from the company-specific research context, the scope of the Material Transition Map, and the limitations of the proposed framework.

The empirical research was conducted through two test campaigns within a single organization, ArianeGroup. While ArianeGroup is one of the largest and most established aerospace players globally, with substantial legacy, resources and access to Airbus expertise, the majority of contemporary aerospace companies belong to the so-called "New Space" sector. These firms are often startups with leaner structures, limited resources and different approaches to risk management and supplier engagement. As such, the mechanisms identified in this study, such as the uncertainty mitigation strategies or reliance on heritage, may not directly translate to smaller organizations. Also, this research is primarily based on qualitative interviews, which capture rich insights but can also include bias such as the professional background of the interviewees.

While the study includes insights from internal experts within ArianeGroup, it does not capture perspectives from external suppliers, regulatory bodies or customers. Including interviews with third parties, such as the supplier responsible for the FRP tanks of PHOEBUS would have been very useful, since external actors play a decisive role in shaping both technical feasibility and supply chain resilience and these perspectives could have added depth and balance to the findings. From a practical point of view setting up such interviews would be very difficult.

The research reflects a snapshot of practices and perceptions at a specific point in time, during the Ariane 6 and PHOEBUS test campaigns. Aerospace projects evolve over long timeframes and organizational practices may change in response to shifting market conditions, regulatory pressures or technological advances

The Material Transition Map developed in this study provides a handy tool for visualizing uncertainty and its cascading impacts. However, its scope is not exhaustive. By design, the map emphasizes the processes most relevant to the research objectives. This means that several processes, especially within the technical impact branch, were excluded because their contribution to the central research questions was limited. Similarly, the supply chain branch does not include certain processes that are more relevant to serial production than to the test campaigns that formed the empirical base of this study. Consequently, while the Map offers a strong conceptual foundation, it does not represent the full picture of material transition dynamics. In addition, the Map does not quantify transition impact. The relative weight of technical versus organizational uncertainty therefore remains indicative rather than measured, for example lead times of 6 months to 2 years and several month delays are mentioned but are not translated to project cost.

In addition, as already mentioned, the framework for predevelopment procurement presented in this thesis is intentionally designed at the strategic level. Though some elements of operationalizing the framework were proposed, moving fully into operational or tactical levels would require a more quantitative methodology (involving analytical costing) and access to company data that were beyond the scope of this study.

**Future Research Recommendation**

Building on the findings of this study, several proposals for future research can be made. First, further work should focus on procurement and supply chain management in projects characterized by high requirement and low order volume components, to fill the literature gap mentioned already. Unlike serial production where procurement processes are relatively standardized, aerospace test campaigns combine low production volumes with high complexity, creating unique vulnerabilities. Dedicated research in this space could generate frameworks that explicitly account for the interaction between technical and organizational uncertainty, thereby supporting more resilient and predictable pathways for material transitions.

Second, vertical integration deserves closer examination as a strategic response to external supply chain risk. While excluded from the scope of this framework due to its organizational and market-wide implications, future research could analyze the feasibility, risks and benefits of vertical integration for aerospace firms, especially in the EU. Such an assessment would need to address not only the internal capabilities of organizations like ArianeGroup but also the broader European aerospace ecosystem.

Finally, future studies could adopt a comparative approach, examining material transitions in adjacent sectors such as defense, advanced energy systems or other high-complexity engineering fields. These industries often share similar characteristics, strict regulatory environments, low production volumes and dependency on niche suppliers and may therefore offer lessons that can be transferred. By placing aerospace within this context, researchers could develop cross-sector insights into how uncertainty during technological transitions can be more effectively managed.

# Conclusion

This study's goal was to understand the nature of material transition uncertainty in megaprojects, with a focus on its generation, impact and mitigation strategies. Grounded in transition theories, such as the Multi-Level Perspective, Strategic Niche Management and Transition Management, the research first examined the drivers and mechanisms behind material transitions. Using two ongoing Test Campaigns from ArianeGroup, testing a new type of propellant tanks and propellant as case studies, the study showcased the decision-making dynamics of material and propellant selection, highlighting the complex technical, operational and organizational considerations involved. These findings underscored the inherent complexity of material transitions in aerospace engineering.

Through extensive interview data, the Material Transition Map was developed, visually representing how transitions occur, the resulting impacts and the mitigation efforts in place. This mapping process enabled a clear distinction between technical uncertainty, internal to the material transition processes, and organizational (or supply chain) uncertainty, which is largely external and shaped by supplier readiness, market constraints and willingness to share risk. While technical uncertainty can be systematically reduced through testing, simulation and derisking processes, organizational uncertainty remains more challenging to manage due to its dependence on independent actors and external conditions. The analysis also revealed the cascading effect of transitions, that the technical and supply chain aspects, though often addressed separately, are in practice interconnected and should be studied as part of a single, integrated process.

A recurring theme throughout the study was the reliance on heritage, established suppliers, processes and designs, which offers both stability and significant constraints. While heritage reduces risk by drawing on proven methods and components, it can also limit innovation and flexibility, particularly when new materials or processes are required.

In response to the procurement and supply chain challenges identified, the development of the Predevelopment Supply Chain Framework represents the main practical contribution of this research. Building on the Material Transition Map and insights from expert interviews, the framework p the complexity of test campaign procurement into a structured roadmap linking observed conditions to proposed changes, mitigation strategies and measurable benefits. Its three proposals, risk balancing through introducing certain uncertainty management tools, centralization of procurement and the design of a predevelopment supplier network supported by digital tools, offer complementary measures for addressing the uncertainty inherent in material transition. The validation through the focus group confirmed both the relevance of the issues targeted and the practicality of the proposed applications, with feasibility rated as medium-to-high. While cost implications were primarily associated with additional working hours, benefits were recognized as potentially significant, given the scale and cost of test campaigns. In this way, the framework not only advances academic understanding of supply chain management in aerospace predevelopment but also provides ArianeGroup with a practical tool.

Overall, this study contributes to both theory and practice by linking transition theory with practical aerospace engineering realities, by clarifying the dual nature of uncertainty in material transitions and by providing a tailored procurement framework to address the specific needs of one-off, engineer-to-order projects. The findings highlight that effective uncertainty management requires treating technical and supply chain issues as codependent and adopting a strategic approach to supply chain. As the aerospace sector continues to evolve under increasing competition and regulatory pressures, the ability to anticipate and strategically address uncertainty will be critical, for successful individual projects but also for broader systemic transitions.

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# APPENDIX

## APPENDIX A: Interview Questions

**Interview**

The purpose of these interviews is to identify how organizations involved in complex, large-scale technical systems manage uncertainty during instances of technological transition. Your participation will help identify patterns, challenges and strategies in current ArianeGroup test campaigns. You will be asked a series of questions regarding your experience with technological transition, particularly in test campaigns but also concerning Ariane 6 if deemed necessary. These may include questions about uncertainty, decision-making, risk perception and organizational adaptation.

**Questions**

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**Section 1: Experience with Transitions**

1. **General:** Looking at your past and current work with PHOEBUS/MTB — what kind of changes or transitions (materials, suppliers, configurations, etc.) have caused the most uncertainty or issues?

*Follow-up: Did you anticipate these uncertainties, or did they become apparent only during execution?*

**Cascading effect:** In your experience, where there any situations where the initial transition triggered additional changes (modifications to test stands, instruments etc) that were not anticipated at the start?

*Follow up:* Do you think the cascading effect is understood during planning/design or does it become apparent during implementation?

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**Section 2: Technical Uncertainty**

**2a. Upscaling (technical):** When switching to new materials (like CFRP or $H_2O_2$), what has been your experience with lab test results vs. full-scale testing?

*Follow-up: Do you think upscaling issues are properly assessed in the design phase?*

*Follow-up: Would you prefer more lab testing first or more iterative full-scale tests?*

**2b. Upscaling (managerial):** When introducing new materials or propellants, how do you approach the balance between early small-scale testing and full-scale testing? From a planning and resource perspective, which approach tends to be more effective or manageable?

*Follow-up: Have there been cases where unexpected issues appeared only after scaling up? How did that impact timelines or budgets?*

*Follow-up: Do you feel that upscaling risks are given enough attention during early project planning?*

3. **Materials (1):** When it comes to some materials, there are no universally accepted quality standards. How do you handle this when multiple suppliers or subcontractors are involved?

*Follow-up: Do you have internal guidelines for consistency?*

*Follow-up: How do you ensure a new supplier's work matches your requirements?*

**4a. Materials (2) (technical):** In terms of technical uncertainty, especially under extreme cryogenic conditions, how do you deal with the lack of standardized material property data (e.g. CFRP at 20 K)?

*Follow-up: How do you validate that the material will behave as expected (at those temperatures or interact as expected with the setup)?*

**4b. Materials (2) (managerial):** When working with materials in extreme conditions, like cryogenic temperatures, how do you approach the uncertainty that comes with limited data on material behaviour or properties? How does that affect decision-making around design or supplier selection?

*Follow up: What kind of contingencies are put in place when data is incomplete?*

*Follow up: Does this uncertainty influence how you plan resources or testing phases?*

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**Section 3: Supply Chain & Interfaces**

5. Have you experienced issues when new subcontractors join mid-project, especially in projects that span multiple phases like PHOEBUS and MTB?

*Follow-up: How do you ensure technical knowledge is transferred?*

*Follow-up: What happens if new actors are not aligned with previous standards?*

6. **Lead times**: With long lead times for cryogenics, gases, or FRP, how do transitions (e.g. switching materials) affect your procurement strategy or scheduling buffers?

*Follow-up: Are these delays usually expected or disruptive?*

**Section 4: Risk & Safety Adaptation**

7. Safety plan: When adopting a new material or propellant, do you revise the risk management plan from scratch or adapt the existing one?

*Follow-up: Who is involved in that process (internal experts, external advisors, suppliers)?*

8. What do you think is the biggest blind spot in managing risk during these transitions?

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**Closing Question**

Is there anything else you'd like to add, any lessons learned, challenges, or observations about working with new technologies or materials that we haven’t covered, but you think are important when managing transitions in these kinds of projects?

# APPENDIX B: Propellant types and their characteristics

a. **Cryogenic Propellants**

*Liquid Oxygen (LOX)*

LOX is non-toxic, stable, non-corrosive, cost-effective, and widely available. However, LOX must be stored cryogenically, which makes it unsuitable for long-duration space missions (Forbes & Van Splinter, 2003).

Materials used with LOX must tolerate extremely low temperatures and rapid thermal stress. Suitable metals include stainless steels, aluminum alloys, copper alloys and nickel alloys. For non-metallic components, materials like Teflon™, Kel-F™, and low-temperature silicone rubber are commonly used (Forbes & Van Splinter, 2003).

Oxygen itself does not burn but supports combustion. It is hypergolic (ignites without a fire source) with certain substances (e.g., triethylaluminum), but not with typical rocket fuels (Forbes & Van Splinter, 2003).

*Liquid Hydrogen ($LH_2$)*

Hydrogen is a non-corrosive cryogenic fuel but can cause hydrogen embrittlement in certain metals, especially at high temperatures. While chemically stable, liquified hydrogen requires specialized storage due to its extremely low boiling point (Forbes & Van Splinter, 2003).

In well-designed tanks, boil-off can be minimized to around 1.5% per day in a 1000-gallon vessel. Suitable materials for $LH_2$ systems must retain strength and flexibility at cryogenic temperatures. These include polyester fibers. Many iron alloys and elastomers become brittle at such low temperatures (Forbes & Van Splinter, 2003).

b. **Storable Propellants**

*Nitrogen Tetroxide / NTO ($N_2O_4$)*

Nitrogen tetroxide is one of the most widely used storable oxidizers in rocket propulsion. It is affordable and produced in large quantities, but its high freezing point limits its versatility. To lower the freezing point and reduce stress corrosion cracking (SCC) in titanium tanks, it is mixed with nitric oxide, commonly used in spacecraft propulsion (Forbes & Van Splinter, 2003).

$N_2O_4$ is also a toxic gas, requiring strict handling and containment procedures (Forbes & Van Splinter, 2003).

*Hydrazines (Hydrazine, MMH, UDMH)*

Hydrazine-based fuels are hypergolic with common storable oxidizers like $N_2O_4$ and MON (a blend of nitrogen tetroxide and nitrogen oxide). Hydrazine is the most reactive of this group and should be handled carefully. While hydrazines are stable to friction and shock, they are thermodynamically unstable and can react in the presence of certain catalysts (Forbes & Van Splinter, 2003).

They are non-corrosive to most metals. Some elastomers and plastics are compatible, though only a limited number (Forbes & Van Splinter, 2003).

Hydrazines are toxic substances; they are also suspected carcinogens (Forbes & Van Splinter, 2003).

*Hydrogen Peroxide ($H_2O_2$)*

Hydrogen peroxide is used as both a monopropellant and an oxidizer. Concentrated $H_2O_2$ (90–98%) is less corrosive, does not emit toxic fumes, and can be catalytically decomposed into hot gas for propulsion (Forbes & Van Splinter, 2003). It is attractive for non-cryogenic storage, its simplicity and lower toxicity (Forbes & Van Splinter, 2003).

Storage requires strict material compatibility, as mentioned in the Interviews (especially 12), the material's effect on peroxide is more critical than peroxide's effect on the material. Common stainless steel is suitable, and decomposition can be kept low with adequate systems. Safety relief systems must be installed to vent oxygen from decomposition (Forbes & Van Splinter, 2003).

In *Hydrogen Peroxide ,* toxicity is not a major concern (Forbes & Van Splinter, 2003).

# APPENDIX C: The Material Transition Map

## Figure C1

*The Material Transition Map*

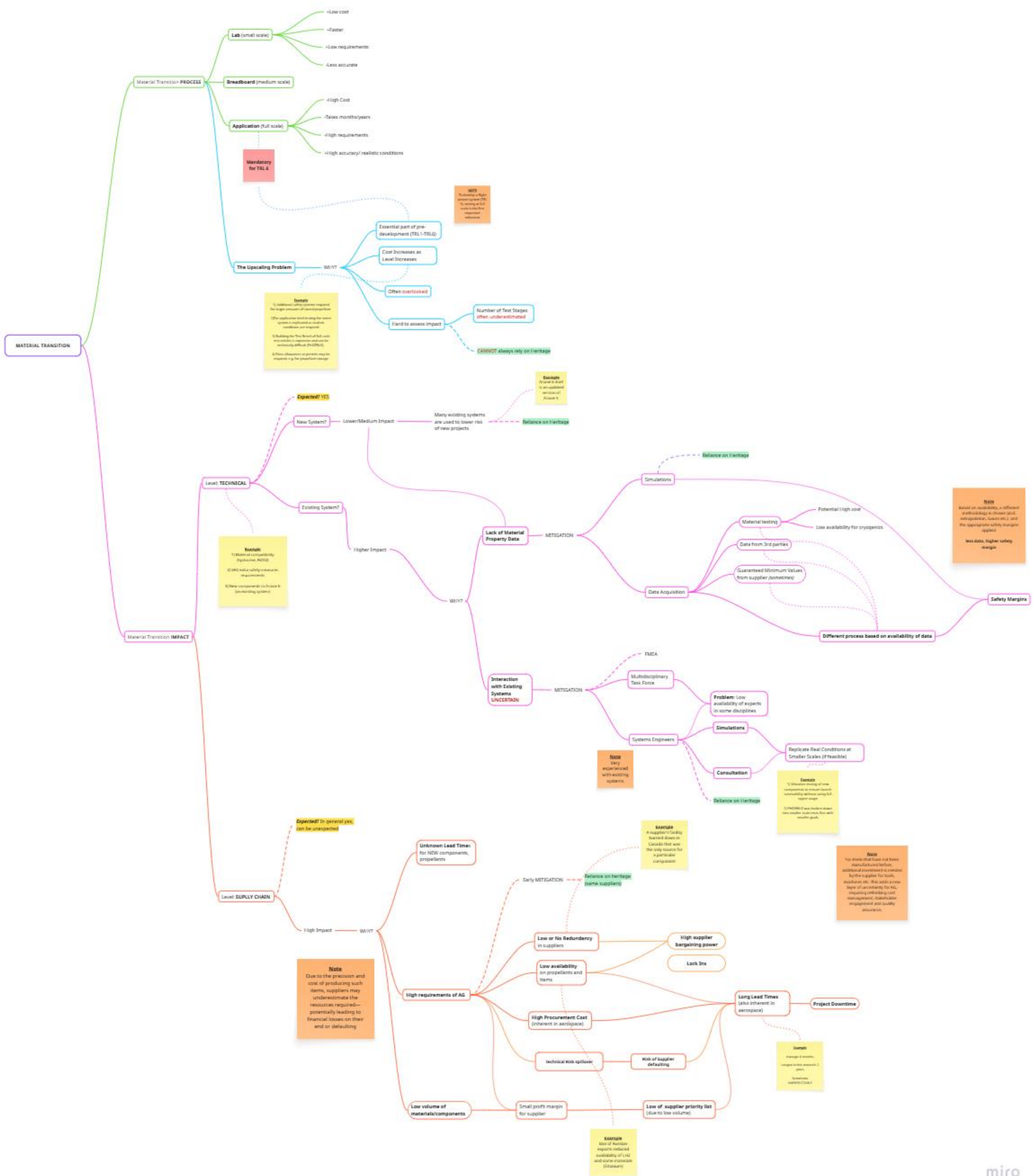


**Figure C2**

*The Material Transition Process*

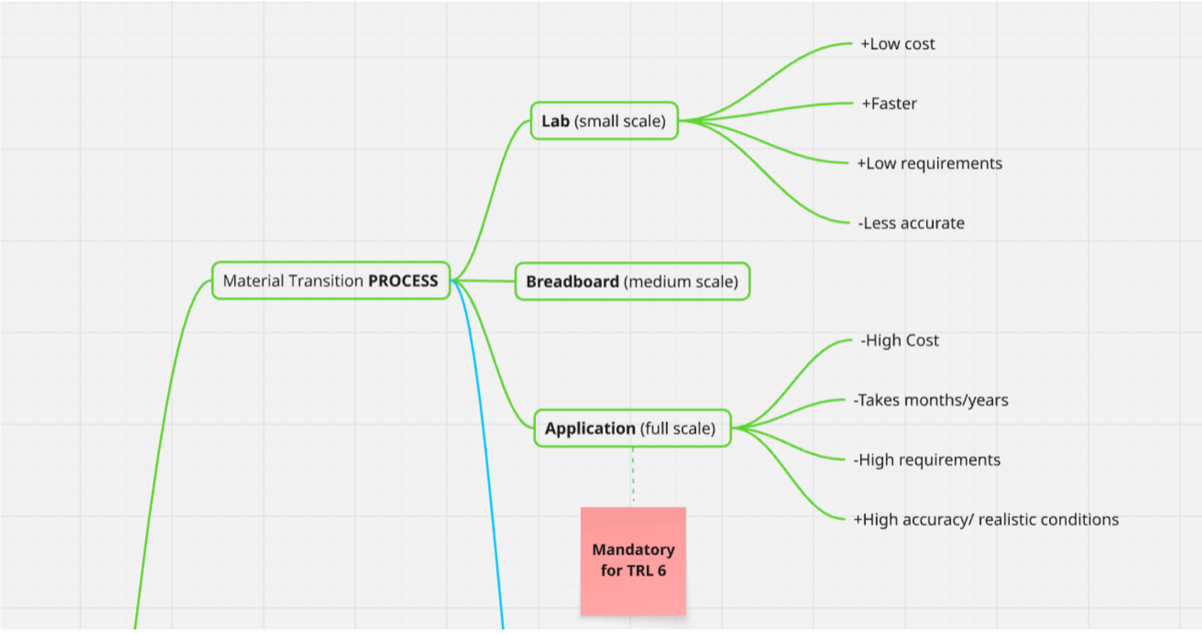



**Figure C3**

*The Upscaling Problem*

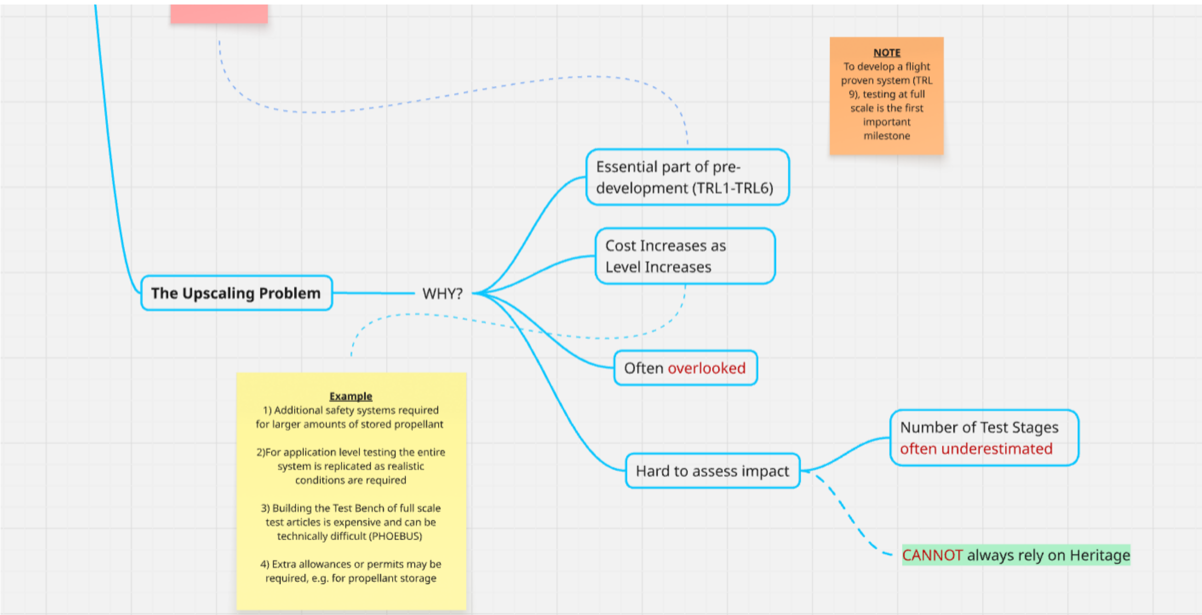
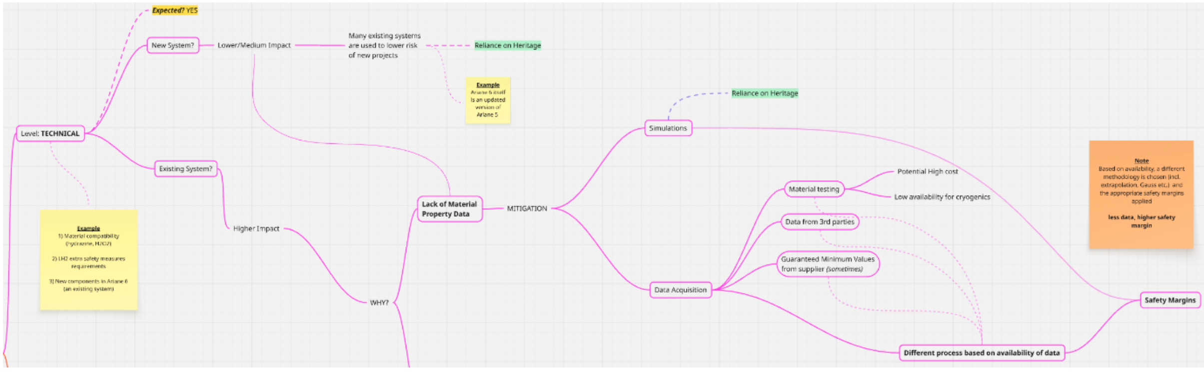


**Figure C4**

*Technical Impact, Source: Lack of Material Property Data*



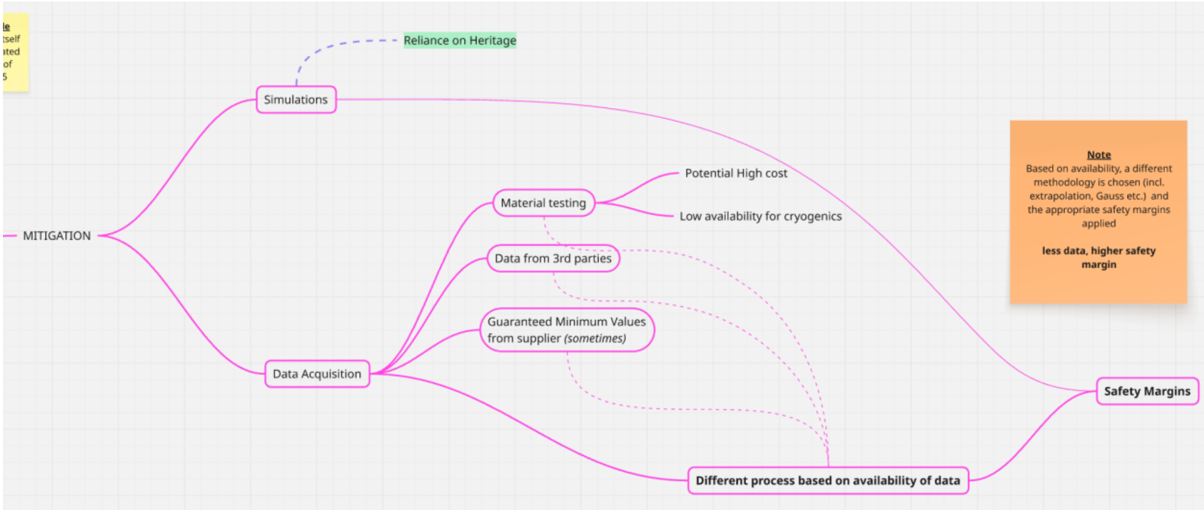



**Figure C5**

*Technical Impact, Source: Uncertainty in interaction with existing systems*

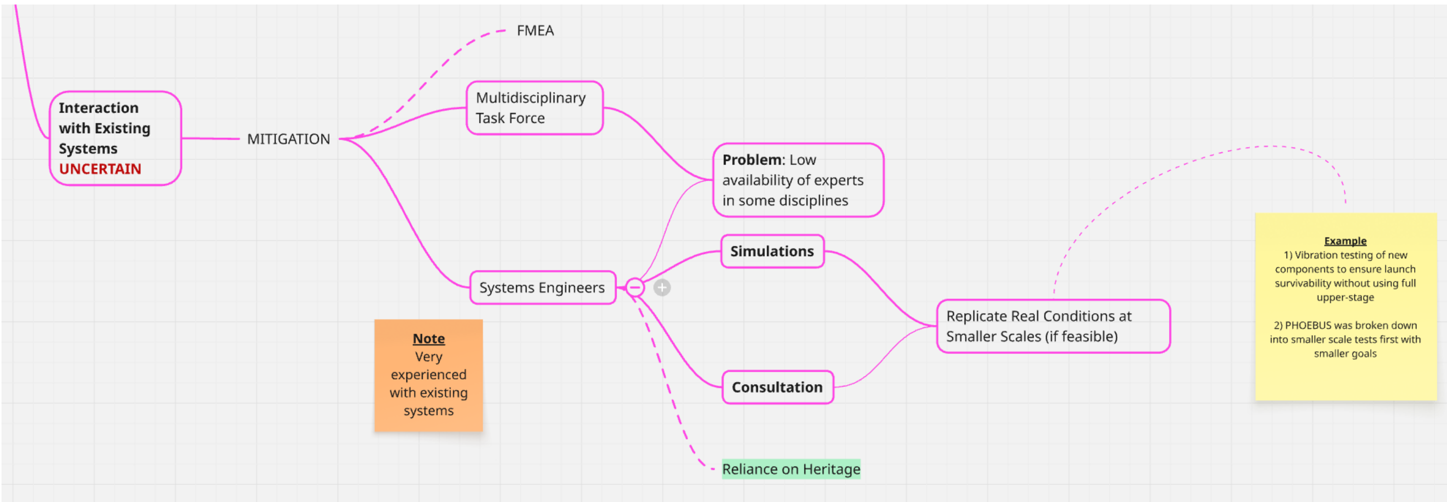
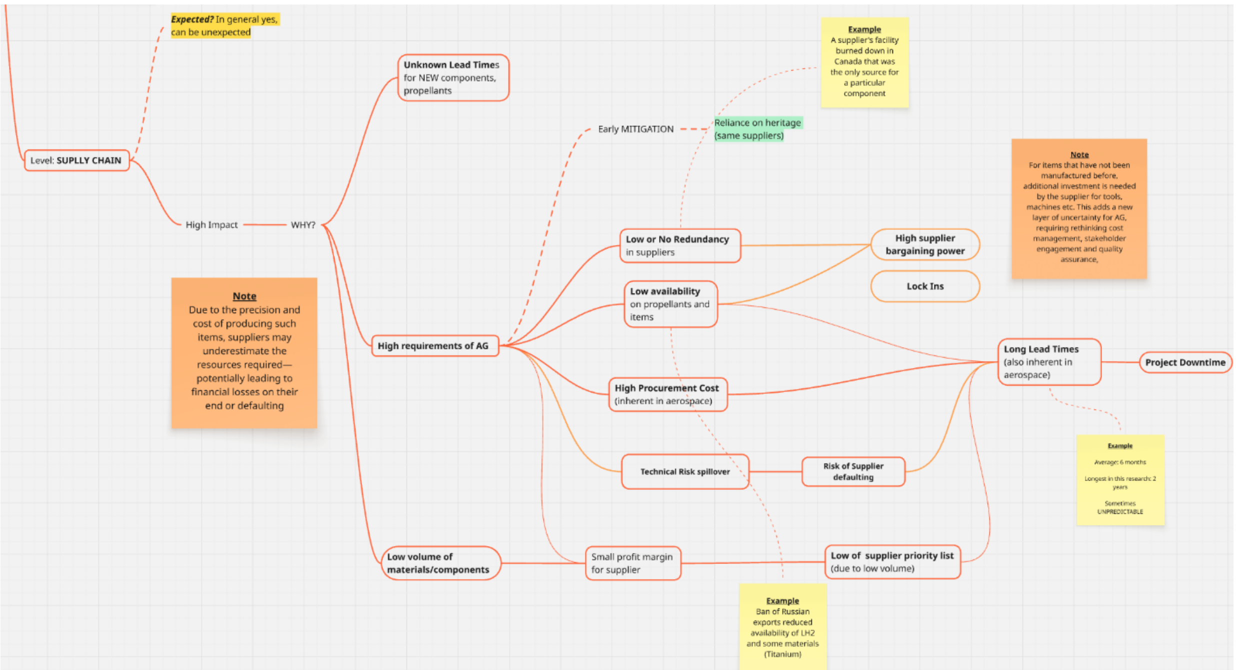
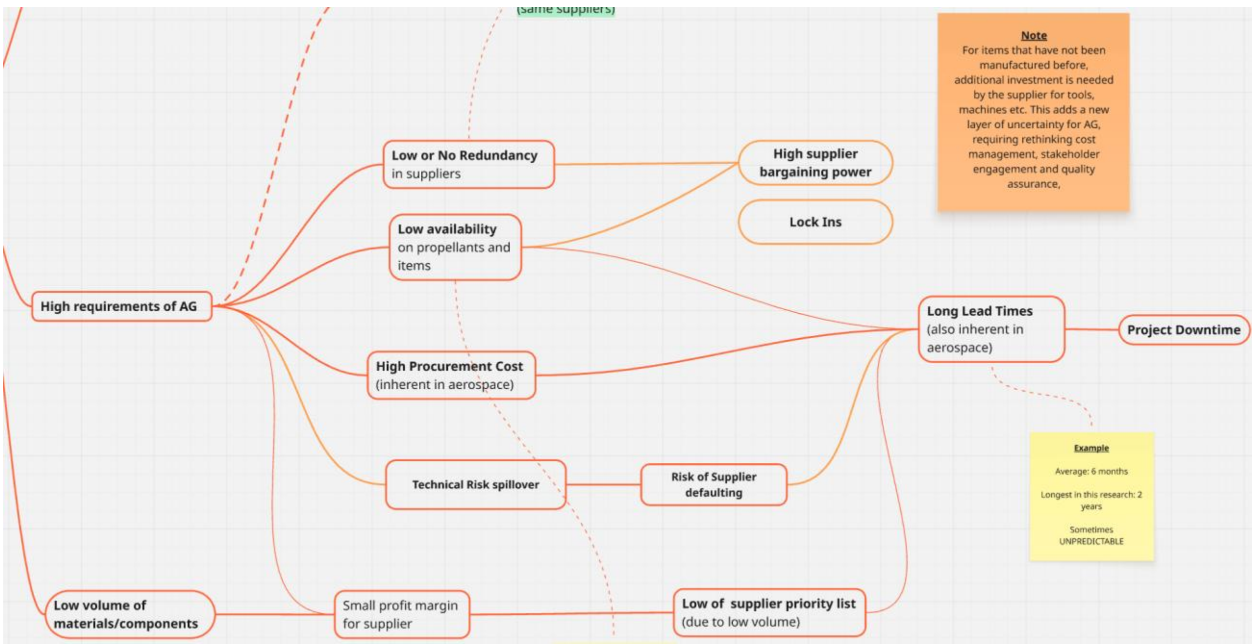


**Figure C6**

*Supply Chain Impact*



# APPENDIX D: List of Meetings and Documents used

**Table D1**

*List of internal ArianeGroup documents used in the research*

| Document Title | Description | Source | Date Accessed | Version | Page numbers | Notes / relevance to study |
|---|---|---|---|---|---|---|
| MTB1 Design Description | Overall design presentation, mechanical, electrical design, specifications for valves, measurement tools etc | Internal | 11/03/2025 | 1st | 93 | Understand the design of MTB, Used MTB render in the Introduction |
| MOBILE TEST BENCH 1 | Presentation of project goals and purpose | Internal | 11/03/2025 | 1st | 6 | Understand project goals |
| PHOEBUS TEST SCENARIOS AT AG TRA | Overall design presentation, test scenarios, technical specifications, WBS, ROM quotation | Internal | 11/03/2025 | 1st | 59 | Understand the design, project goals. Used PHOEBUS render in the Introduction |

**Table D2**

*List of important meetings, including the scoping interviews*

| Meeting Title | Purpose / Agenda | Date | Location | Roles observed | My role (observer / participant) | Key observations | Link to research questions |
|---|---|---|---|---|---|---|---|
| PHOEBUS scoping interview | To learn more about the project, progress, bottlenecks, risks etc. Scope down literature review by focusing on the most crucial sources of uncertainty | March 2025 | AG Trauen | Lead Engineer | Participant | First contact with the issues encountered in the project, realized the technical difficulty and supply chain issues | Set the early parameters for the entire project |
| MTB scoping interview | Same as the PHOEBUS scoping interview, with the difference that this project was in a more advanced stage (the setup of the test stand was already ongoing) | March 2025 | AG Trauen | Lead Engineer | Participant | Same as PHOEBUS | Same as PHOEBUS |
| MTB / PHOEBUS scoping interview from test field manager's POV | To understand the projects from AG Trauen's staff POV, which are responsible for designing the measurement system, supporting elements, help with building the test stand and running the tests | March 2025 | AG Trauen | Project Manager | Participant | Was very important in understanding the WBS and logistics of the projects | Same as PHOEBUS and MTB |
| PHOEBUS tank procurement, RFQ parameters set | Support work for the company | May 2025 | AG Trauen | Project A | Participant | Important for understanding how the parameters laid down on the Material Transition Map (supply chain branch) actually materialize | Important for research question 1, technical vs organizational uncertainty and research question 5, building the framework |