Supplier engagement in early stage technology development

a case of liquid hydrogen equipment development at a major aircraft manufacturer

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April 2024

Abstract

Challenges of supplier engagement in early stage technology development in the context of hydrogen propulsion equipment development for aircraft are uncovered. The challenges are viewed from the perspective of the engineering team members within the Liquid Hydrogen storage and distribution department in Airbus' ZEROe project. A qualitative action research approach is taken to gain an in-depth understanding of the context and the stakeholders' perspectives. Through interviews, observational studies, and document analysis, a code base is developed and analysed.

At the highest abstraction level, the analysis finds that uncertainty around hydrogen technologies for aviation drives the supplier engagement challenges. When requirements, specifications, deliverables, and development timelines are uncertain, suppliers are in many cases unable to engage. Concretely, the technological uncertainty leads the engineers to be overly cautious in the development of their equipment's requirements. Over-caution leads to very challenging or impossible requirements which overload suppliers, especially non-aerospace suppliers. This ultimately leads to unsuccessful engagement, limiting the learning potential. Consequently, the lack of learning fuels the uncertainty in a perpetual positive feedback loop (see Figure 1).

Figure 1: Uncertainty feeds unsuccessful engagements

This research proposes two roadmaps detailing behavioural change through a 'mindset shift' of the internal stakeholders to break the uncertainty-fueled cycle mentioned above. The roadmaps link the ZEROe developments until 2030 with the value proposition to suppliers, assets and processes, and the development deliverables. Additionally, the research findings are implemented in the communication materials the engineers use during the Request For Technical Information (RFTI) phase towards suppliers. Through using lessons learned from earlier engagements, the requested RFTI process deliverables are tailored. By building up the technical complexity and load throughout the development, suppliers are less overwhelmed at the start, improving the chances of successful engagements.

Preface

As I sit here writing this preface, I am filled with a mix of excitement and gratitude. This thesis research has challenged me in many ways and has offered me opportunities that I could not have anticipated. From dreaming about research methods to sticking my head in an aircraft's fuel tank, I have experienced it all.

First and foremost, I would like to express my gratitude to the Chair of my thesis committee, Prof. mr. dr. ir. Sicco Santema. When I first proposed my thesis topic to Sicco, he was immediately enthusiastic and helped me set it up. Although this was not easy due to many confidentiality challenges, we managed to make it work. His guidance, professionalism, and engagement during the thesis process was excellent and much appreciated, also from the company's side.

I would also like to thank my mentor, Dr. Euiyoung Kim. Euiyoung supported me on a bi-weekly basis throughout the research process. Thanks to his sharp eye and ability to package feedback effectively, I felt very supported throughout the project. By referring me to relevant academic work, connecting me with peers working on similar projects, and being my sparring partner, I learned a lot.

Dr. Peter Lucas was the hydrogen expert associated with this thesis project. I would like to thank him for the interesting exchanges we had on everything related to hydrogen. By connecting me with industry professionals, I was able to gather data for this project which offered valuable insights in how supplier engagement takes place in other similar contexts.

Lastly, I want to thank my company supervisor Robert Kösch. Robert supported me on a weekly basis during this project and helped me navigate through the complex stakeholder network. Thanks to his and his team's welcoming nature, I felt right at home from the start. This allowed me to freely collect the necessary data which enabled me to conduct thorough research.

Before diving into the research, I leave the reader with a quote. I suggest reading it once before reading the thesis work, and once after again.

> *"Exploration is a state of mind. If we want to innovate and achieve impossible goals, we have to understand that the only obstacle to succeed is our own way of thinking; it's the accumulation of beliefs and habits that keep us prisoner of old certitudes." - Bertrand Piccard*

Jan-Willem van Zwieten
April 11th, 2024

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List of acronyms and abbreviations

CDR = Critical Design Review
CEO = Chief Executive Officer
CFD = Computational Fluid Dynamics
CG = Centre of Gravity
COTS = Commercial Off The Shelf (equipment)
CRA = Cooperation & Research Agreement
DMU = Digital Mock-Up
DAL = Design Assurance Level
DRL = Data Requirement List
EIS = Entry Into Service
ESI = Early Supplier Involvement
H2 = Hydrogen
HLPTS = High Level Product Technical Specification
IATA = International Air Transport Association
iCPS = Integrated Creative Problem Solving
IP = Intellectual Property
IPCC = Intergovernmental Panel for Climate Change
IoT = Internet of Things
ISSM = Internal Supplier Selection Meetings
JDP = Joint Definition Phase
LH2 = Liquid hydrogen
MLI = Multi-layer insulation
MWS = Meetings With Suppliers
NDA = Non-Disclosure Agreement
NPD = New Product Development
NPSH = Net Positive Suction Head
OEM = Original Equipment Manufacturer
SE = Supplier Engagement
SES = Supplier Equipment Specification
SoW = Statement of Work
SRM = Supplier Relationship Management
PDR = Preliminary Design Review
PR = Aircraft General Plan Review
PTS = Product Technical Specification
RDA = Research & Development Agreement
RCP = Requirements Convergence Phase
RFP = Request For Proposal
RFTI = Request For Technical Information
R&D = Research & Development
R&T = Research & Technology
SAF = Sustainable Aviation Fuel
S/R = Safety & Reliability
TOM = Team and Organisational Meetings
TRL = Technology Readiness Level
TRM = Technical review meetings

Introduction

Especially in the last decade, temperature records are being shattered almost yearly. All over the world, extreme weather events in the form of draughts, storms, and flooding, are occurring more and more often. At the time of writing, we are experiencing the tenth consecutive month of record-breaking warmth (Copernicus, 2024). According to the Intergovernmental Panel for Climate Change (IPCC), strong and sustained reductions in emissions of carbon dioxide and other greenhouse gases would limit climate change (Calvin, 2023). For this to happen we have to reduce and ultimately stop the use of fossil fuels. We will have to find sustainable alternatives for our energy needs.

Driven by 'flygskam', changing regulations, and worries about its licence to operate, the aviation industry is pushed to change its ways away from fossil fuels. The aviation industry is known to have emissions that are 'hard to abate', meaning that there are no easy alternative sustainable energy sources. Aircraft require enormous amounts of energy to propel themselves (and their passengers) through the air. On top of that, there is the special constraint for aircraft that the energy carriers must be low in mass and volume per unit of energy. When looking for fuel alternatives, it means that aircraft manufacturers are limited to energy carriers with very high energy densities. Figure 2 plots the volumetric energy density against the mass energy density of several energy carriers that could be considered for aircraft propulsion (adapted from Gangoli Rao, 2015).

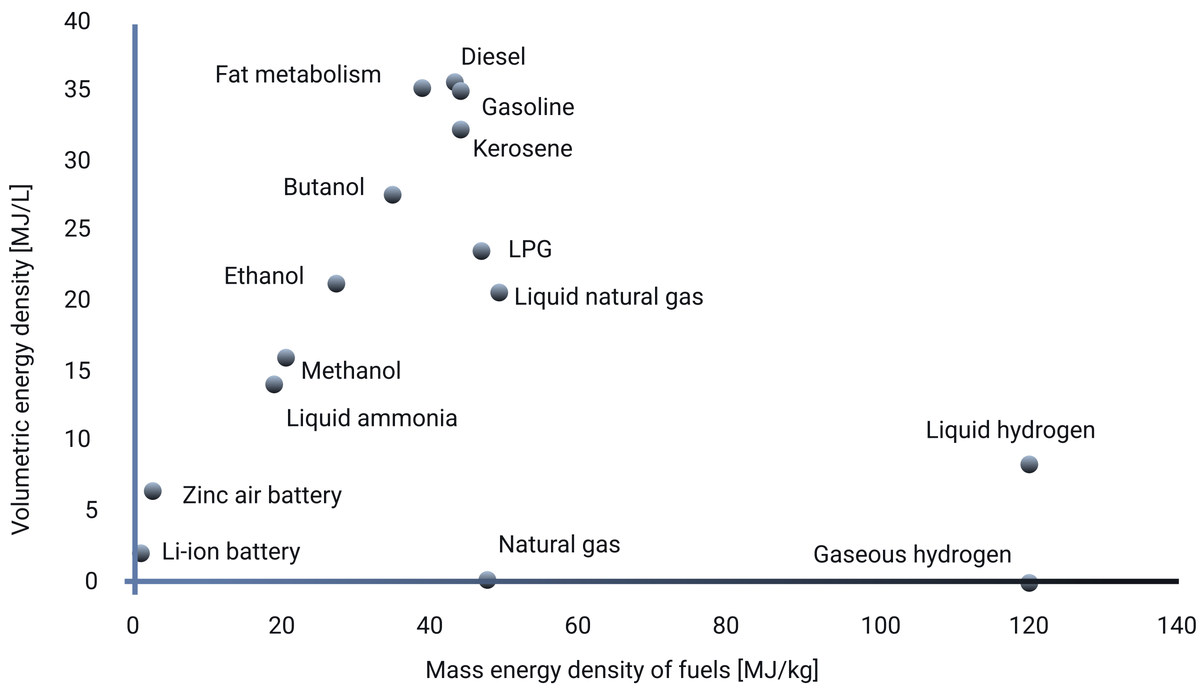


Figure 2: Volumetric and mass energy densities of common energy carriers (Gangoli Rao, 2015).

As can be seen in Figure 2, kerosene has a relatively high energy density per unit of volume and mass. Ideally, we would find an alternative energy carrier with similar or better characteristics and no carbon emissions when consumed. There are Sustainable Aviation Fuels (SAF) which are practically kerosene produced from renewable sources such as biomass (e.g. used cooking oils). As the carbon in these 'net zero' fuels has its origin in a renewable source, the CO_2 balance in the atmosphere does not change when emitted (Ng et al. 2021). The benefit is that this type of fuel can be 'dropped in' to existing aircraft enabling net zero carbon emission aviation without having to design new aircraft propulsion systems. The drawback is that these fuels still produce non-CO_2 emissions such as soot, NO_x, SO_x and H_2O. Nothing comes quite close to kerosene when looking at energy carriers with no/low carbon emissions. However, there is one outlier in the far right corner of Figure 2: hydrogen. In its liquid (cryogenic) form, it is about three times lighter than kerosene. It is also four times more voluminous. Could sustainably produced liquid hydrogen be used as a fuel for sustainable aviation? Theoretically speaking, hydrogen could power commercial aircraft. Technically speaking, there are many challenges.

As was demonstrated by Figure 2, there are practically no other options than hydrogen if we want to fly commercially without emitting any carbon dioxide. While it is not an easy feat, there are initiatives trying to develop hydrogen propulsion technologies for aircraft. One such initiative is ZEROe, a project run by the European aerospace company Airbus. This research uses ZEROe as a context and aims to shed light on just a tiny part of the sustainable aviation puzzle as a whole.

In the last part of this introductory section, the core problem and the goals of this research are discussed. Following the Introduction, the Background section details relevant background information to contextualise this research and its approach. Then, a brief Literature review is given exploring propulsion technology innovation, hydrogen as a fuel for aircraft, and the existing work on supplier engagement in early stage technology development. After that, the Research approach chapter explains the approach to the research of the exploratory phase. The Results chapter then details the findings from the exploratory phase. The report subsequently transitions into the identification phase where the challenges are identified among the findings. This is what the Discussion chapter elaborates on. The next chapter, Design phase, takes the identified challenges from the previous phase and formulates a design challenge from them. It also presents several design outcomes. The Conclusion then concludes on these thesis' research and findings. In the Reflection chapter, I reflect on the research process and the design outcomes.The second to last chapter is Recommendations which summarises the most important findings into recommendations for Airbus. Lastly, the chapter Limitations & Further research highlights the research's limitations and avenues for future academic inquiry.

Core problem

Developing a new commercial airliner aircraft type is a major challenge. Aircraft program development timelines last for many years if not decades. For instance, the development of the Airbus A380 started in the early nineties while the first aircraft entered into service in 2007. Two of the world's most popular aircraft types, the Boeing 737 and Airbus A320 are designs that originated from the 1960s and 1980s respectively and are still operating and selling today (Airbus, n.d.)(Amir & Weiss, 2024). A clean sheet commercial aircraft design requires enormous amounts of resources to complete. Among other aspects, it requires enormous amounts of resources to complete. Among other aspects, it requires stable (public) funding, know-how, and reliable supply chain partners throughout the aircraft development program. This thesis focuses on the last of these three topics, the supplier engagement.

As this thesis is undertaken at Airbus ZEROe, it focuses on the supplier engagement aspects within this project. The internal stakeholders of the project have stated at the start of this project that Airbus is facing challenges in engaging suppliers effectively in the development of equipment and systems for its new hydrogen aircraft. One of the explanations given is the lack of a competent hydrogen-aviation supplier landscape. However, there are more challenges. What these challenges are and what drives them is currently unclear and forms the core problem for this thesis. Hence, I am to uncover these supplier engagement challenges and highlight the drivers that must be resolved in order to successfully develop equipment for commercial hydrogen-powered passenger aircraft.

Research goals

As mentioned, the research for this master thesis on “supplier engagement in early stage technology development” is undertaken at Airbus and specifically within the Liquid Hydrogen Tank systems teams of the ZEROe project. The goal of this research is to uncover the drivers of supplier engagement in early stage technology development in the context of hydrogen propulsion technology development for aircraft and to implement the findings in a design intervention to improve the engagement. To that end, the ZEROe project is taken as a case study as the technology being developed in this project is in early stages and is reliant on extensive buyer-supplier interactions for the development. Within ZEROe, the Tank systems teams offer a context to test design interventions. I am integrated in the research context as an action researcher.

To approach this research in a structured way, it is divided into three phases:

1. Exploratory phase
   a. Goal: understand what the status quo of supplier engagement is within the context of Airbus ZEROe
   b. Main research question: *What are the stakeholder perspectives on supplier engagement within the ZEROe project?*
2. Identification phase
   a. Goal: identify the challenges around supplier engagement in the context of the Tank systems teams
   b. Main research question: *What challenges do the stakeholders face in engaging in joint early stage hydrogen propulsion technology development for aircraft?*
3. Design phase
   a. Goal: design an intervention or carry out deeper analysis around an identified challenge and test/deploy it within the ZEROe Tank systems teams context.

Background

To contextualise the research approach and later on its findings, some background information on the aviation industry and Airbus is relevant. This section details what makes aeronautics different from other industries. It also details the Airbus and ZEROe organisations, the projects within the organisations, the stakeholders involved, and the design challenge at hand.

Aeronautics

What sets the context of this thesis apart is that it is set in the very risk-averse aeronautics industry. There are good reasons for this risk aversion. Similar to the nuclear and chemical industries, companies active in aeronautics cannot afford to create unreliable and unsafe products (Grabaskas, 2022). Any abnormal events during operations can lead to reputational damage and major financial losses for the companies involved. A recent example of this is the door plug debacle plaguing the Boeing 737-900ER aircraft. Defects on supplier delivered equipment caused a door plug to malfunction during flight. This resulted in a grounding of the fleet for extended periods of time (Federal Aviation Administration [FAA], 2024) and huge public backlash. It is no surprise that the highest priority within new product development at aircraft OEMs is safety, especially when it comes to supplier equipment. This also explains why the aeronautics industry is slow at implementing radically new technologies. Risks are preferably avoided rather than managed (Cummings, 2020). This begs the question if the aeronautics industry is capable of radical propulsion technology innovation while keeping the safety standards as high as they have been in the recent past. This is a major challenge in developing novel hydrogen propulsion technology for aircraft at Airbus.

Airbus & ZEROe

With over 130,000 employees, Airbus is one of the world's largest aircraft manufacturers. The company's history goes back to the 1960s when the German and French governments pushed for aircraft development that would make aviation accessible to the masses. Throughout the years, Airbus has established itself as a leader in the aeronautics industry and has a strong business in the defence and space industries. More recently, the corporation has made it its mission to create sustainable aviation for the masses which is reflected in its motto: We pioneer sustainable aerospace for a safe and united world (Airbus, n.d.). In 2020, before the International Air Transport Association (IATA) announced the industry's pledge to become net-zero by 2050 (IATA, 2021), Airbus announced ZEROe, its project to develop the world's first hydrogen-powered commercial aircraft. Such an aircraft would not emit any carbon dioxide into the atmosphere during operation. The ZEROe pre-programme aims to mature all technologies needed to bring a serial production-ready hydrogen-powered passenger aircraft into service by 2035.

Stakeholders

This section highlights the stakeholders involved in the supplier engagement at Airbus ZEROe. It covers high level internal organisational maps of Airbus, the ZEROe organisation, and the Tank systems teams. Following that, an external stakeholder map displays the relations of suppliers to the organisation.

Internal organisational map

Airbus has three main divisions: Commercial, Helicopters, and Defence & Space. While the other two speak for themselves, Commercial holds all of the business around Airbus' commercial passenger aircraft programs such as the A350, A320, etc. Throughout all of these divisions, there are Research & Technology (R&T) activities. Within R&T, new promising technologies are explored, developed, and matured before being handed over to the respective product divisions. Up until February 2024, the ZEROe project was an R&T project, meaning that it was not officially part of any of the aforementioned three divisions. Figure 3 depicts the organisational structure.

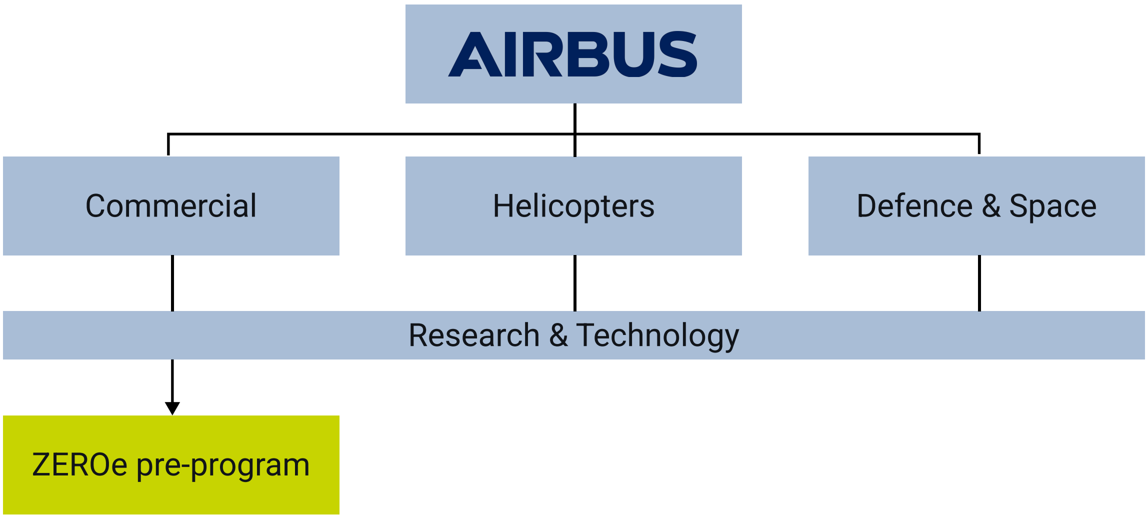


Figure 3: Airbus' general organisational chart including ZEROe's position before March 2024.

However, since March 2024, the ZEROe pre-programme has been incorporated into the Commercial division (see Figure 4). Although it might not seem like it, this is a significant organisational change. In R&T projects, there is quite some organisational freedom in how projects are conducted. As the activities vary widely from exploring aerodynamic improvements to designing new communication systems, the development processes are looser than in Commercial. Safety and quality are of the highest importance within Commercial and this comes with many processes and guidelines to almost every aspect of the business. Although ZEROe is not an aircraft programme yet, the developments will start following the conventional aircraft development processes that are standard in the Commercial division.

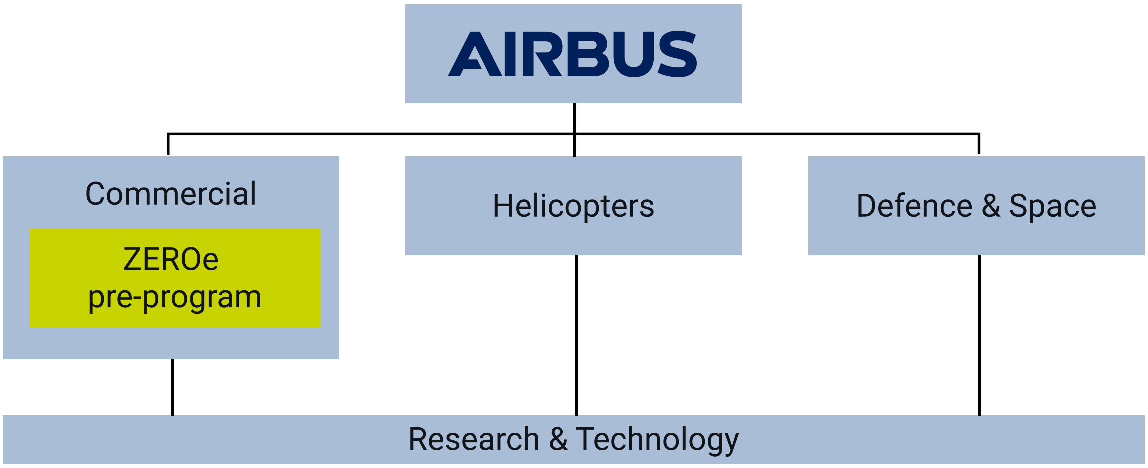


Figure 4: The ZEROe pre-programme was incorporated into the commercial division in March 2024.

Taking a look at the ZEROe organisation itself, there are eight departments working on various aspects of the grand hydrogen aviation challenge (see Figure 5). What sets ZEROe apart from conventional aircraft development is that many aspects outside of the scope of the aircraft itself have to be taken into account. For example, the Ecosystem department develops the partnerships needed worldwide to create a hydrogen 'ecosystem' at airports. Without a stable supply of green hydrogen at the airport, no airline will be able to fly the aircraft. Hence, Airbus has a stake in developing such infrastructure through partnerships.

The department that is of interest to this thesis research is "LH_2 storage & distribution". Within this department, the storage systems and hydrogen distribution systems are developed that feed the 'consumers', either a hydrogen combustion engine or a fuel-cell-based electric engine. These engine systems are being designed in their respective departments. It is important to note that not all systems and equipment are designed and built in-house. There is a distinction between the 'make' and 'buy' strategy. For the fuel cell system, the developments are on the 'make' strategy. Airbus has entered into a joint venture with ElringKlinger, an automotive fuel cell manufacturer to jointly create a fuel cell system for aircraft applications from scratch (Airbus, n.d.). For the combustion engine, the developments are on a 'buy' strategy. CFM International, an aeroengine OEM, is developing the hydrogen combustion engine for the ZEROe demonstrator aircraft (Airbus, n.d.). Figure 5 also shows three pictures of the demonstrators and the products that ZEROe is aiming to develop. The departments in the organisation work interchangeably on each of these sub-projects.

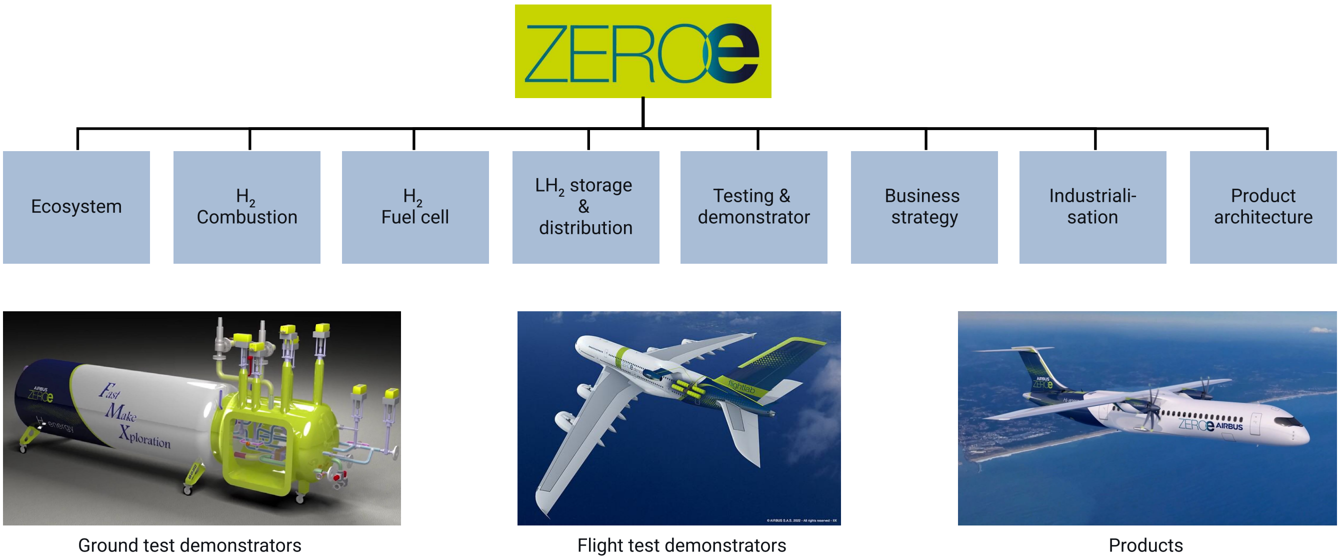


Figure 5: ZEROe organisational chart including the distinction between the demonstrators and the product as referred to in the department names.

To understand the relevant stakeholders within the context of this research, we have to take a closer look at the organisation within the LH_2 storage & distribution department. In it, and next to several other sub-departments, there are the 'Tank systems' teams. As an action researcher, I am positioned amidst the engineers working in the Tank systems teams. These teams are headed by a project manager and supported by partnerships and procurement officers. These stakeholders are all part of the ZEROe organisation and spend all their time working on the project. Additionally, the ZEROe stakeholders are supported by others within Airbus who are not only involved in ZEROe. See Figure 6 for a map of the internal stakeholders.

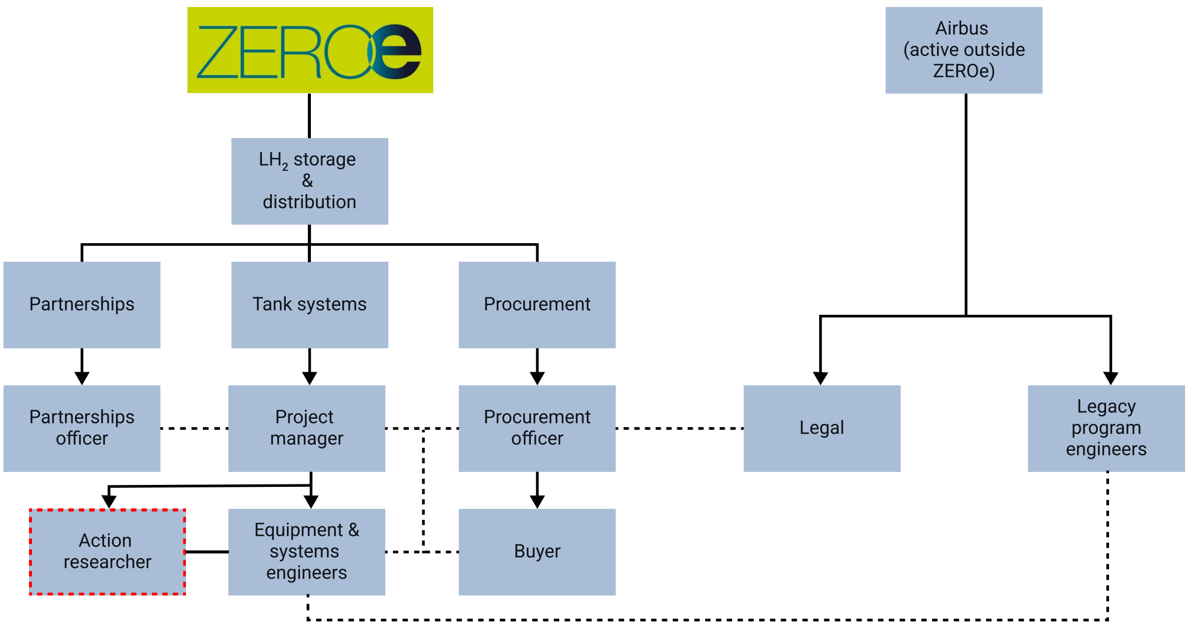


Figure 6: Internal stakeholder map around the ZEROe Tank systems teams.

External stakeholders

Airbus has many external stakeholders and the same is true for ZEROe. Think of governments, the general public, customers, competitors, and of course suppliers. This thesis focuses on the engagement with one group of stakeholders, namely suppliers. Figure 7 shows a map of the interaction links between suppliers and Airbus in general. This is a map of supplier engagement within a development phase which differs only slightly from the 'serial' phase when an aircraft program (e.g. A320, A350) is up and running and aircraft are being delivered. The focus of this thesis is on the development phase as this is where early technology development happens. In the development phase, the project manager is responsible for the engineering side of the engagement while the procurement officer is responsible for the commercial side of it. The lines of communication are defined between the project manager and the procurement officer (Airbus, 2023).

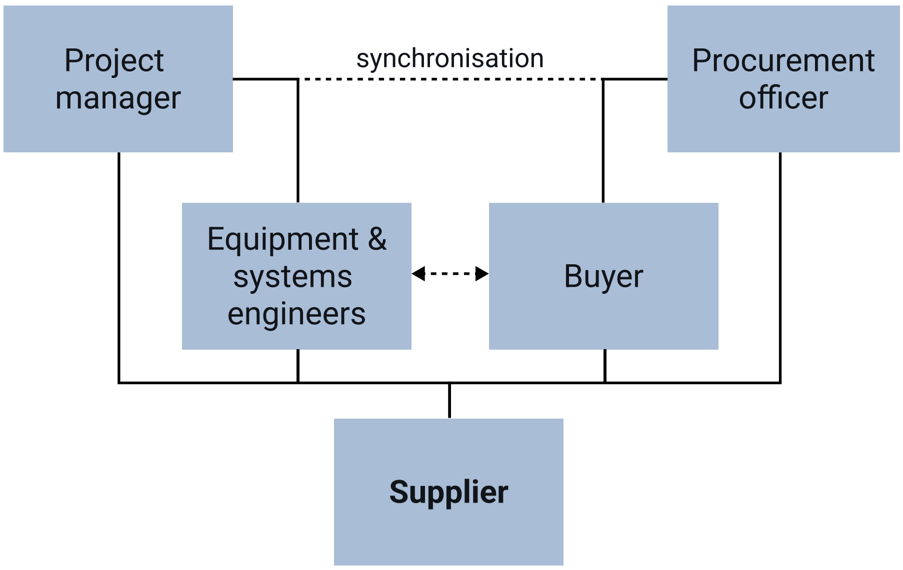


Figure 7: Map of the interaction links between a supplier and ZEROe (Airbus, 2023).

Usually, during the early phases of equipment development, the communication such as document exchanges, NDA signings, and detailing of the statement of work is handled by procurement. The engineers communicate with the buyer and the procurement officers which companies/suppliers they want to contact to potentially collaborate with. The procurement officer or buyer then reaches out to these companies and sets up (kick-off) meetings. When eventually a supplier is selected for the development phase, the communication shifts towards the engineering side where the supplier's engineering teams interact with the Airbus engineering teams to jointly create the equipment/system's designs and specifications. See Figure 8 for a simplified traditional development process from initial supplier contact to the start of manufacturing.

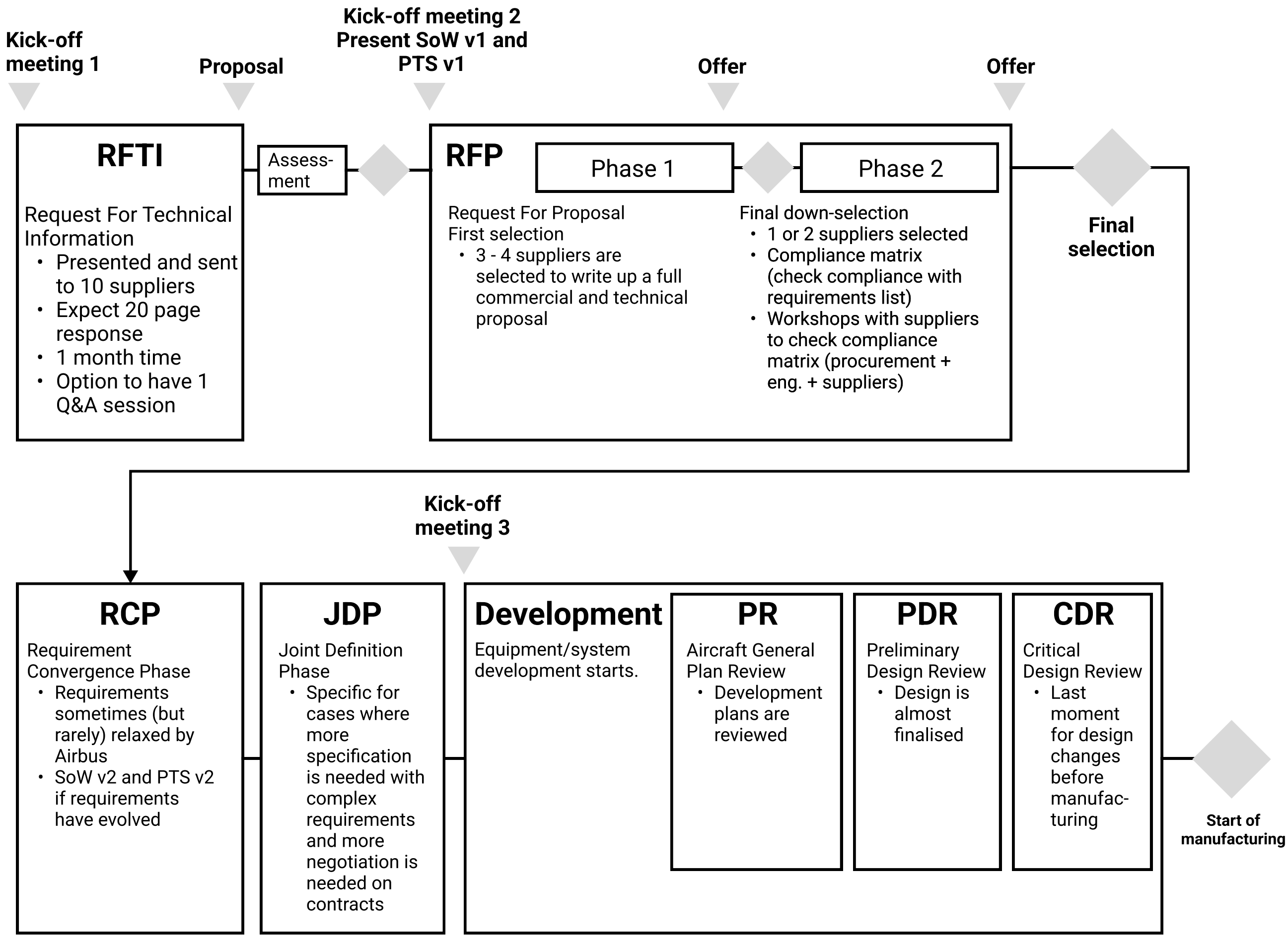


Figure 8: Equipment development process from initial supplier selection to the start of manufacturing (adapted from Airbus, 2023).

This (simplified) process is a frequently occurring development process for equipment development at Airbus and ZEROe. Although almost all developments start with an RFTI, there are variants of this process where the RFP phase is replaced for more collaborative forms where Collaborative Research Agreements or Research & Design Agreements are formalised. Nonetheless, the RFP is the dominant form of development after the RFTI and provides enough context for this research.

Literature review

This section provides a general overview of the literature related to the context of this thesis. As the Exploratory and Identification phases of this thesis will narrow down the specific challenges faced by the stakeholders, it is important to have a general understanding of the relevant literature. This literature review dives into the history of propulsion technology in aeronautics, discusses hydrogen technologies in aviation and its major challenges, and contextualises ‘supplier engagement in early stage technology development’.

Propulsion technology innovation in aeronautics

This research project is set in the aeronautical context, a context that is characterised by a rich history of technological development. To put the developments of hydrogen propulsion technologies into perspective, it is worth exploring the history of technological innovation in aeronautics. Technological innovation in aeronautics covers a wide range of different components, systems, technologies, and designs. Current examples range anywhere from new bio-based materials for interior cabin panels (Lufthansa Technik, n.d.)(Bcomp, 2023) to laser satellite communications enabling high-speed data transmission (Airbus, 2023) to folding wing tips improving aerodynamic performance (EASA, 2018)(Boeing, 2020). For the sake of this research which is focused on hydrogen propulsion technology development, this section will only cover the general technological developments in aircraft propulsion technologies.

Aircraft propulsion all started with a 12-horsepower reciprocating intermittent combustion engine on the famous ‘The Flyer’ by the Wright brothers. Broadly speaking, this type of engine powered all aircraft until the late 1930s and operated on gasoline (Farokhi, 2014). The 1930s also brought about the invention of the gas turbine engine which was still powered by gasoline and would only be adopted widely decades later. Interestingly, in 1937, one of the first inventors of air breathing gas turbine engines, the German physicist Von Ohain, powered his turbojet engine with hydrogen for its first tests (Smithsonian’s National Air and Space Museum, n.d.). Due to combustor developmental challenges, hydrogen was soon after replaced with liquid fuels such as aviation gasoline (Edwards, 2002, p.1). Throughout the years, there were many advancements in the design of the engines, the fuel storage & distribution systems and in the fuels themselves, striving for evermore longlasting propulsive power. With regards to the fuel storage systems, early aircraft had flexible fuel tanks. Around the 1950s, when aircraft structures became more stiff, integral tanks were introduced which were sealed cavities in the wings and other parts of the structure which is still common today. Since fuel is used up in operation, the centre of gravity (CG) of the aircraft shifts depending on the location of the tanks. In modern aircraft, a fuel transfer system transfers fuel from one tank to the other to optimise the CG location and the stability of the aircraft (Goraj, 2016). When it comes to fuel, the Wright brothers used relatively low octane gasoline. By the time of the second World War, aircraft were almost exclusively powered by high octane aviation gasoline. After World War II, the use of high octane aviation gasoline kept rising until the adoption of gas turbine jet engines in commercial airliners (Ogston, 1981). These aircraft started using kerosene as a fuel due to its lower freezing point (Edwards, 2002) which eventually led to the phasing out of the piston engine-propeller combination in large airliners.

Today, most commercial aircraft use turbofan jet engines powered by Jet A1 kerosene. These engines have evolved over the years to have high by-pass ratios increasing their propulsive efficiency and hence fuel efficiency (Rolls Royce plc, 1996). The by-pass ratio is the ratio between the mass flow rate of air going around the engine's core versus the mass flow rate of air going through it (Hall, 2021). Enabling a high by-pass ratio in turbofan engines has been one of the key technological innovations in commercial aviation. Between 1970 and 2019, it has enabled an average fuel burn reduction of 40% on new aircraft (Zheng & Rutherford, 2020).

As Murman et al. (2000) put it, the aeronautics industry has transitioned into the "specific phase" of innovation since the 1990s where dominant designs for aircraft and their components dictate product evolutions. Figure 9 adapted from Utterback (1996) shows product innovation and the accompanying process innovation needed to create commercially successful products. If the aeronautics industry wants to live up to upcoming regulatory and societal pressure to decarbonise, it will have to break out of the incremental developments in propulsion technology that it has been used to for decades. The industry has realised this (Hoelzen, 2022) and many players have now committed to developing these new technologies. It seems that we are at the start of a transition from the aforementioned specific phase back into a fluid product development phase for propulsion technology. Contrary to the specific phase, this fluid phase is characterised by new definitions of basic product features and many new companies entering the field (Murman et al., 2000).

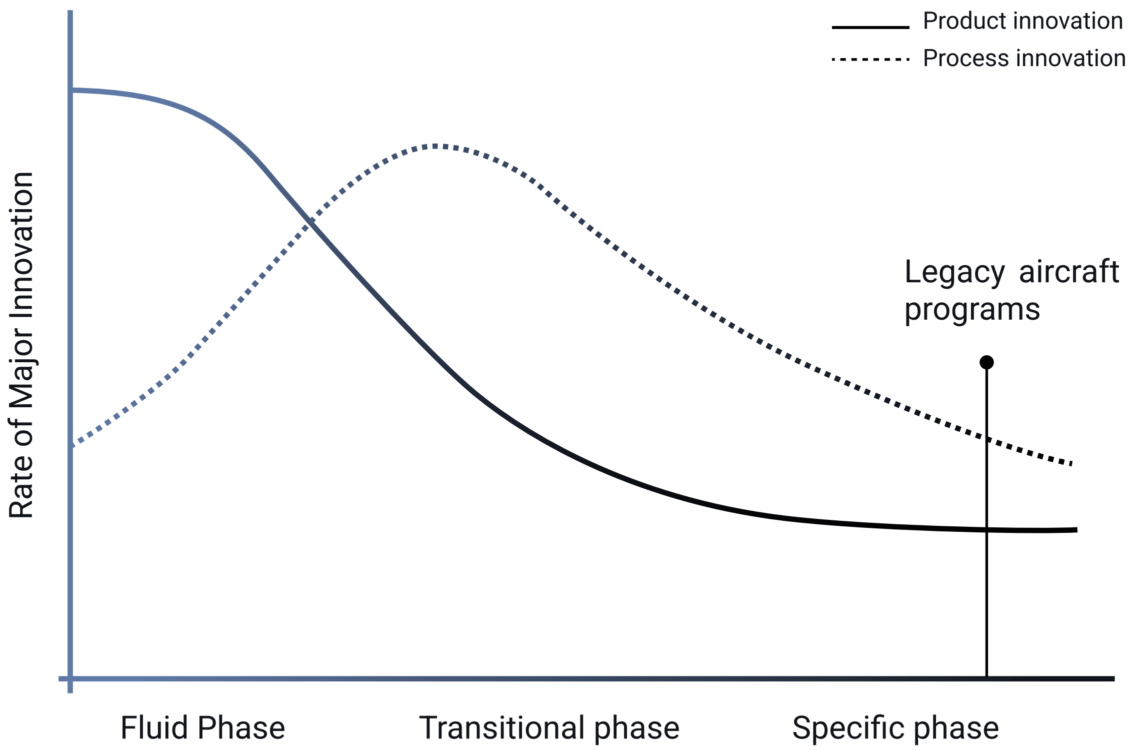


Figure 9: Adaptation of Utterback's (1996) model of product and process innovation.

Hydrogen in aviation: a radical innovation?

Regardless of what one characterises as incremental or radical innovation, it is clear to see the fundamental similarities between the fuels used by the Wright brothers and the fuel we use today. Low octane gasoline (Ogston, 1981) has been switched out for Jet A1 kerosene but fundamentally, these are very similar hydrocarbon-based fuels distilled from the same crude oil source. With regards to the storage and distribution systems, there have certainly been developments, mainly with regards to the safety and reliability of the fuel supply to the engine(s) (Langton et al., 2009, p.10). However, since the fuel has more or less remained the same, the developments have been incremental. When looking at the engines, more or less the same parallel can be drawn. The four cylinder engine used on 'The Flyer' and the state-of-the-art high by-pass turbofan engine powering most of the world's commercial aircraft today are both based on the same principle of converting potential energy released in the explosive expansion of a compressed gas into useful work (Gibbert & Scranton, 2009).

Norman & Verganti (2014) propose that radical innovation is "a change of frame: 'doing what we did not do before'" whereas incremental innovation constitutes "improvements within a given frame of solutions: 'doing better than we already do'". With the above brief history of propulsion technology in mind, it is safe to say that three main components of an aircraft's propulsion system (fuel, fuel storage & distribution, and powerplant) have undergone mostly incremental changes over the 121-year history of powered aviation. The 'frame' that Norman & Verganti (2014) propose can in this case be the type of fuel being used: a liquid hydrocarbon-based fuel. Replacing this fuel for a different energy source would radically change the entire propulsion system. However, as was mentioned earlier, hydrogen has already been tested in aero engines in the 1930s. Back then, it was dropped due to combustor challenges for a more manageable liquid fuel such as gasoline or kerosene. Although hydrogen is not completely new to aviation, there have not been major developments in hydrogen propulsion technology up until the recent past. Introducing hydrogen on a commercial jet today would require a re-designed combustion engine and a "completely new" fuel system through "dedicated technology development" (Haglind et al., 2006). The "re-design" part becomes clean-sheet design when considering the fuel cell - electric motor combination.

For this research, it is important to keep in mind that hydrogen propulsion technology development for use in commercial aircraft is something that has never been done before. Considering the history of the propulsion technologies in aviation, it is hard to overstate the significance of a shift to green hydrogen propulsion after 121 years of hydrocarbon-based propulsion systems.

Major challenges

To illustrate the challenge of developing propulsion equipment for (liquid) hydrogen-powered commercial aircraft, this section details some of the major technical hurdles.

Firstly, let us consider the hydrogen molecule. As Figure 2 demonstrated, it is the liquid form that we should consider as an energy carrier on board an aircraft. However, the gaseous phase also plays a role in the fuel system. Figure 10 shows the key physical characteristics of hydrogen in a phase diagram.

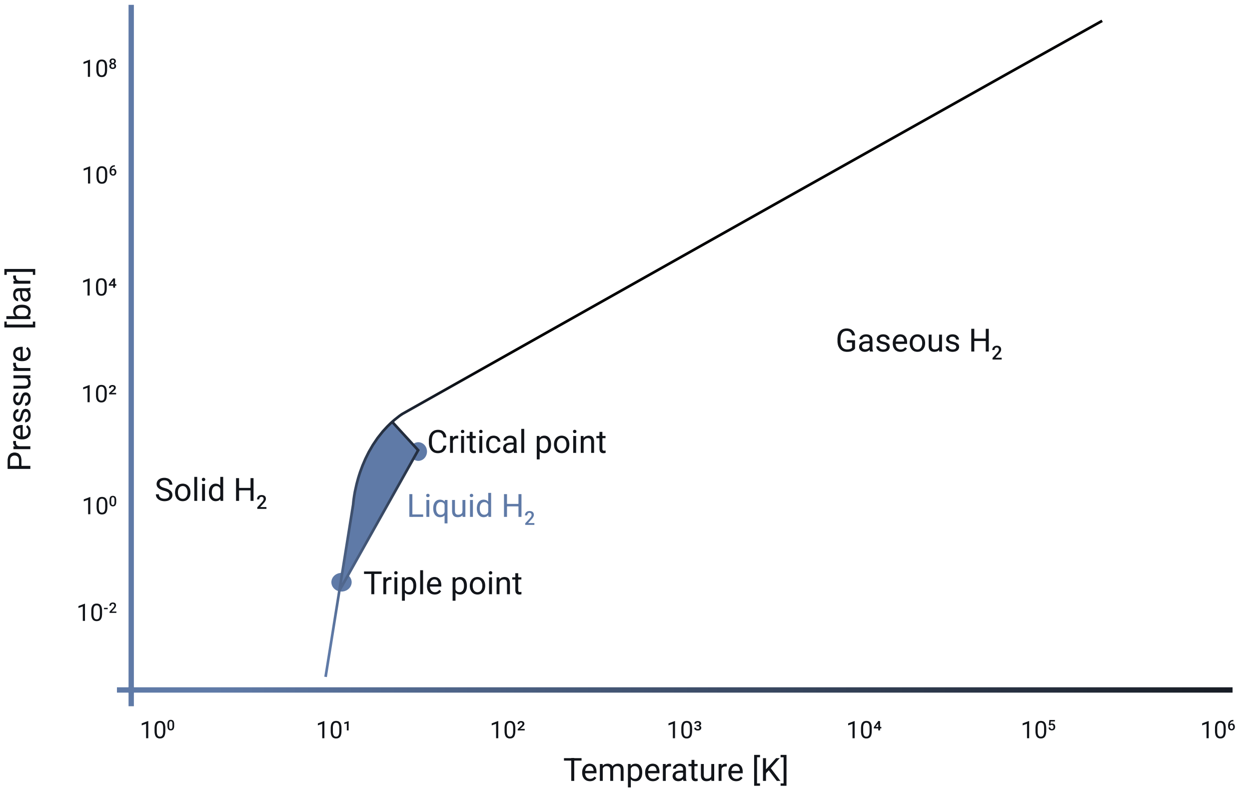


Figure 10: Phase diagram of hydrogen (adapted from Züttel, 2004)

With a normal boiling point at about 20K (-253°C), hydrogen must be stored at cryogenic conditions to keep it in the liquid phase. To ensure extended storage times, cryogenic tanks are used. These tanks aim to limit the heat ingress by having insulating features such Multi-layer insulation (MLI) and a vacuum layer between the inner and outer tank wall. These storage requirements present the first challenge of using hydrogen compared to kerosene as a fuel on-board aircraft. As mentioned in the previous section, kerosene can be stored in specially lined cavities in the wings and belly of an aircraft. This is not the case for hydrogen. As cryogenic tanks have to be optimised to prevent heat ingress, the outer surface area to volume ratio of the storage solution should be kept to a minimum. Spherical shapes are best at doing so. However, these shapes are in conflict with the available space (and its geometry) on the aircraft. The wings are too thin to hold large spherical tanks and placing them within the fuselage reduces the seating/cargo capacity. Therefore, finding an optimal storage geometry and location combined with efficient overall aircraft design is a major technical challenge on aircraft level.

Besides the geometry and location of the tank, the weight budget for the storage solution offers an arguably bigger challenge and is more specific to equipment development. As kerosene 'tanks' are lined cavities in the aircraft, the tank gravimetric efficiency of the fuel system is very high. In other words, the added weight of the components needed to contain the fuel on board is relatively low compared to the fuel weight. This is very different for the cryogenic tanks used to contain hydrogen on board. Due to the double walled vacuum insulated architectures that are deemed adequate for aviation use, there is a lot of additional weight added to the aircraft just to contain the hydrogen. Although literature holds varying estimates, currently, a ratio between weight of hydrogen and weight of tank plus hydrogen of about 0.45 seems realistic (Huete et al, 2021). Huete et al. (2021) argue that future improvements could push this figure over 0.70. Therefore, it remains a major technical challenge to keep the weight of the equipment at a minimum.

Zooming in on the transport of hydrogen from the storage towards the consumers (combustion engines or fuel cells), there are many more challenges. Figure 11 shows four simple architectures of a hydrogen fuel system based on Mangold (2021) to illustrate the major components required in such a system.

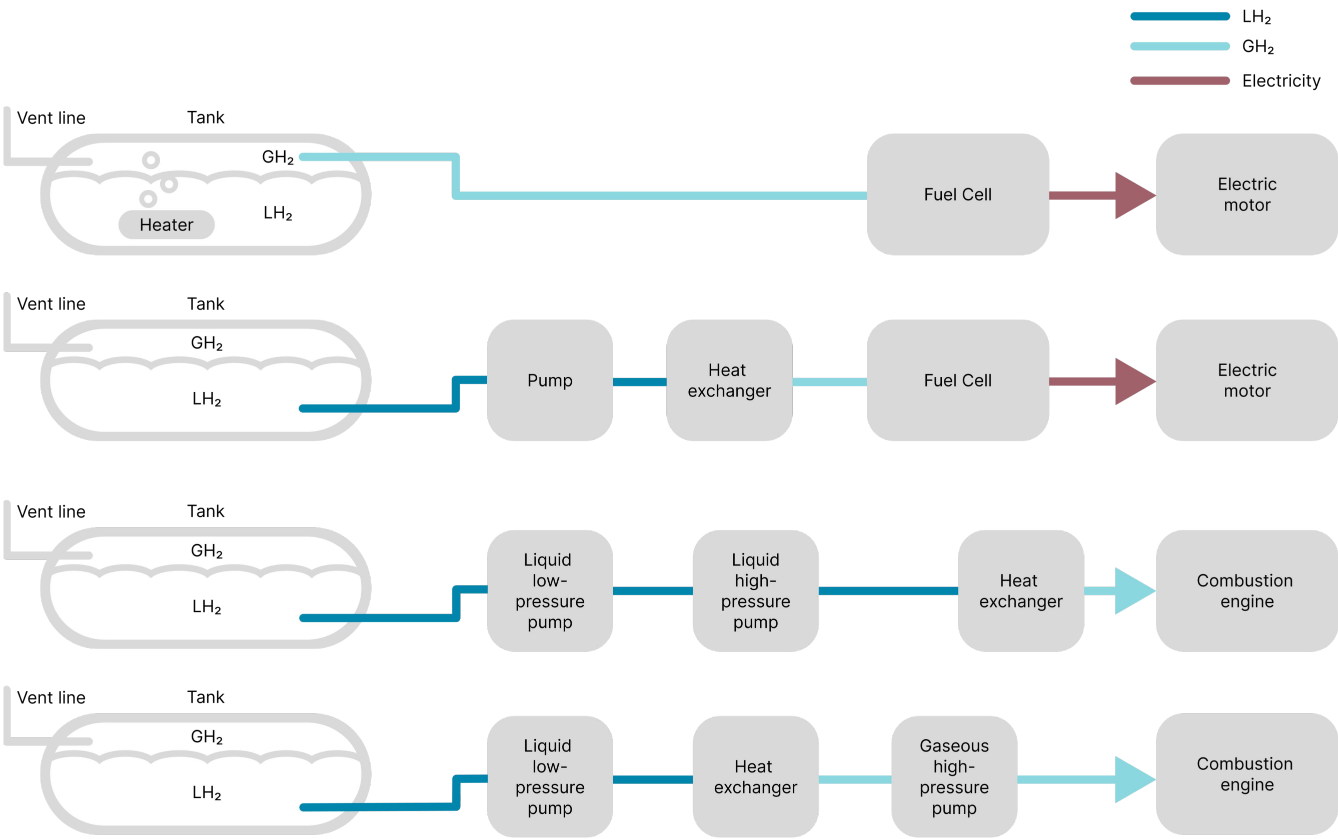


Figure 11: Four simplified fuel system architectures (adapted from Mangold, 2021)

As can be seen from Figure 11, three out of four architectures feature hydrogen flows in both liquid and gaseous phases. Only the first architecture on the top of the figure features a pressure-fed gaseous hydrogen flow induced by a heater in the tank. Nonetheless, all four architectures require the hydrogen to be thoroughly conditioned before it enters the consumer. Within the industry, there is no consensus yet on which architecture is optimal for aircraft use. The trade-off depends on empirical data from to-be-developed equipment and on the overall aircraft architecture including the desired flight envelope.

In the bottom three architectures, the conditioning requires pumps and heat exchangers. Although there are many technical challenges in each equipment, I will highlight one hydrogen-specific challenge for the pumps which has ramifications for the rest of the system. The attentive reader might have noticed that across each pump, the phase of hydrogen does not change in the flow. Due to the risk of cavitation, the flow of hydrogen must remain in a constant phase, either liquid or gaseous. Cavitation occurs in pumps when the phase suddenly changes from liquid to gas within the pump. This causes vibrations and damage to the components and the performance of the pump becomes unreliable (Mangold, 2021). To avoid cavitation, the Net Positive Suction Head (NPSH), must be kept above a critical level. In simple terms, NPSH is the pressure experienced by the liquid at the entrance of the pump (Blackhurst & Harker, 2001). It is a function of the liquid hydrogen's temperature and it can vary throughout the flight phases of the aircraft through different levels of heat ingress from the environment. The flight condition is what sets it apart from an industrial system which can be placed in a closed environment with an unlimited weight budget. Therefore, for an aircraft application, the temperature of the liquid hydrogen must be strictly and precisely controlled through every component in the system. This means having high levels of insulation in the tank, valves, and pipes while also being able to control the pressure and mass flow throughout the system. This increases the weight of the system and/or lowers the total mass of fuel that can be taken on board, in turn lowering its commercial competitiveness with conventional aircraft.

Another option would be to use a pump that can operate with saturated liquid hydrogen. Saturated liquid hydrogen is a state in which any decrease in pressure would cause it to start boiling. Although this property might be beneficial for the performance of the whole system, these types of pumps are still to be developed (Mangold, 2021). The challenge lies in the development costs of such a system and are inherent to cryogenic hydrogen equipment. Performing tests to validate prototypes requires the use of test facilities that can supply cryogenic fluids (preferably hydrogen). Facilities that can do this with the required safety standards needed to validate aircraft requirements are currently scarce and therefore costly to use. It highlights the challenge and the low maturity of the technology. It will require extensive cooperation between partners across industries to bring the development costs down.

Supplier engagement in early stage technology development

To understand the scope of this thesis, let us briefly explore the literature on the title's terms, as well as relevant adjacent terms.

One of the most covered topics in supply chain management literature is Early Supplier Involvement (ESI). ESI refers to the vertical cooperation between a manufacturer and its suppliers in the early phases of product development (Mikkola & Skjøtt-Larsen, 2003). As Bidault et al. (1998) suggest, this involvement usually happens in the concept design phase of New Product Development (NPD). McIvor & Humphreys (2004) name several advantages of incorporating EIS into a firm's development practice such as the increased body of available information and expertise regarding new technologies. On top of that, they argue that it can reduce development times by improving communication and information sharing. The authors also mention several disadvantages of ESI such as possible ineffectiveness in environments undergoing significant changes or environments with high degrees of technological uncertainty. In these cases, ESI can lead to delays in the product development process (Primo & Amundson, 2002).

In new product design, Supplier Engagement (SE) is defined by Yepeng et al. (2022) as "the extent to which suppliers are engaged in the product design activities of a manufacturing firm by providing knowledge resources or directly engaging in decision-making, including providing design ideas, undertaking component and system design, etc." The authors also argue that SE is different from other supplier collaboration forms since SE requires more from suppliers than merely external transactions. In SE, suppliers cross the organisational boundaries to participate jointly in the innovation activities of the manufacturing firm. In the context of sustainable developments, SE is defined by Awan et al. (2019) as “the commitment, collaboration, and exchange of reciprocal information with buyers to achieve compliance with resources and priorities.” Achieving compliance seems to be a joint effort in this case. Tidy et al. (2016) argue that Supplier Engagement is the corporate practice term for Supplier Relationship Management (SRM) which is used more in academic literature. The authors argue that trust and communication are the key characteristics of successful SE/SRM while mistrust and poor communication are at the roots of failing supplier relationships.

It is clear that there are many different terms describing ways in which firms interact with suppliers to create new technologies, designs, systems, and products. Yet, each of these terms have slight nuances that are relevant to their respective contexts. In comparing Early Supplier Involvement with Supplier Engagement, it becomes clear that the former is a term that is relevant to New Product Development in general whereas the latter seems to be specifically relevant to new product design. This subtle difference is important for this research as in New Product Development, the degree of collaboration between the firm and the suppliers is not defined. It can range from very intensive to merely transactional depending on the innovativeness of the product. Highly innovative new products require more intensive collaborations and vice versa for less innovative new products (Olson et al., 1995). In new product design, buyer-supplier relationships are of a joint nature where the supplier actively engages in the innovation activities of the buyer (Yepeng et al., 2022). Since this thesis is set in a corporate project environment with high technological uncertainty and complexity, equipment/systems with varying innovativeness, and joint component and system design, the term Supplier Engagement is chosen over other related terms. It also best describes the way in which the buying firm (Airbus) collaborates with suppliers in the ZEROe project to create new technologies and products.

With this background in mind, we have a proper high level understanding of the context in which this research is set. What is left now is to gain a more in-depth understanding of the supplier engagement context within the Tank systems teams of ZEROe. The next chapter details the research methods used to explore this context.

Research approach

The goal of the research approach is threefold and matches the three phases of this research:
1. to **explore** and understand the supplier engagement landscape,
2. to **identify** the challenges in the context,
3. and to provide a grounded foundation to build **design solutions** on.

As the context of supplier engagement within the ZEROe project is complex, holds many stakeholders, and can not be completely quantified, I chose a qualitative research approach. To gain this understanding, the information must be rich and in-depth which fits qualitative analysis well. Through this approach, I hope to gain an in-depth understanding of the phenomena relating to the problems that the stakeholders face (Blessing & Chakrabarti, 2009).

Stakeholders identification

In the exploratory phase of this research, my goal is to understand what the status quo of supplier engagement is within Airbus ZEROe through gaining an understanding of the context and the perspectives of the stakeholders involved in the development of the tank systems. I identified several direct stakeholders that could offer insights to understand the aforementioned supplier engagement context:

1. **Engineers** within the Airbus ZEROe Tank systems teams. These are the people I am in closest contact with as I am also in their teams. They interact with suppliers mostly on topics related to technical product requirements, specifications, technical drawings, and testing.
2. **Engineers** within Airbus. These people are Airbus employees but not necessarily working only on the ZEROe projects. They are also involved in engineering teams related to other projects within Airbus such as ‘legacy’ aircraft programs.
3. **Project, Program & Domain managers** within Airbus ZEROe. These are people coordinating the work between the engineering teams and they are responsible for the planning and budgeting of the projects. They interact with suppliers mostly on topics related to planning but they are often also involved in budgeting and contractual discussions.
4. **Top managers** within Airbus ZEROe. These people are responsible for the ZEROe project as a whole and report directly to the Airbus Group top management. Issues relating to suppliers that are outside the control of the engineers and project, program, and domain managers are tackled by these managers.
5. **Procurement and partnerships officers** within Airbus. These are people who negotiate the contracts with suppliers and partners, organise the communication between engineers and suppliers, and make sure that the legal aspects and risks are managed on the Airbus side.
6. **‘Legacy’ aircraft engineers** who transitioned to ZEROe within Airbus. These people have experience in the ‘legacy’ aircraft development programs such as the development of the A350 or A321XLR aircraft and have now joined the ZEROe pre-programme full-time. They have interacted with suppliers in a different aircraft development program prior to ZEROe.
7. **Suppliers** are external parties Airbus interacts with and buys products or services from. These companies range from large Tier 1 aviation suppliers to smaller companies with specific expertise in the hydrogen domain.

I carried out observational studies during meetings with (and between) the different stakeholders. In total, I distinguish four types of these observational studies: Team and organisational meetings, Meetings with suppliers, Technical review meetings, and Internal supplier selection meetings. The interactions during those moments were not only rich in conversational (textual) data but also in latent context-dependent data which were important to understand the meaning of the spoken words.

Additionally, I carried out interviews with internal and external stakeholders. Descriptions of both the observational studies and the interviews can be found in Table 1 which discusses the stakeholders involved, the data capturing methods and their accompanying rationales. The stakeholder numbers correspond to the above numbered list.

Table 1: Observational studies and interview descriptions.

Observational study / Interviews	**Stakeholders involved**	**Data capturing method**	**Rationale for method**
Interviews (one-on-one semi-structured)	1, 3, 5, 6, 7	Audio (and video) recordings	To be able to capture the full answers to my questions. To help deduce the latent information in for example sarcastic or ironic comments.
Team and organisational meetings	1, 3	Hand-written notes in a notebook and/or typed notes (with screenshots) in Google Docs.	To capture quickly and discreetly what people were saying and doing. Direct quotes from participants could be written down. Capturing the full interaction with for example audio or video recording would be too intrusive.
Meetings with suppliers	1, 2, 3, 5, 6, 7	Typed notes and taking screenshots of presentation slides in Google Docs.	As it was not appropriate to ask for the meetings to be audio or video recorded, typing notes with screenshots of the slides was the next best option. It allowed for capturing the interactions and adding the visual material that was presented in line with the text.
Technical review meetings	1, 2, 3, 4	Typed notes in Google Docs. Screenshots were taken of presentation slides which were shared with the participants prior to or after the meetings and presented live during the session.	As it was not appropriate to ask for the meetings to be audio or video recorded, typing notes with screenshots of the slides was the next best option. It allowed for capturing the interactions and adding the visual material that was presented in line with the text. Oftentimes, not the whole meeting would be relevant to this research. Therefore, audio/video recording would be over-capturing.
Internal supplier selection meetings	1, 2, 3, 4, 5, 6	Typed notes in Google Docs. Screenshots were taken of	As it was not appropriate to ask for the meetings to be audio or video recorded, typing notes with screenshots of the slides

		presentation slides which were shared with the participants prior to or after the meetings and presented live during the session.	was the next best option. It allowed for capturing the interactions and adding the visual material that was presented in line with the text. Oftentimes, not the whole meeting would be relevant to this research. Therefore, audio/video recording would be over-capturing.

Interview participants

In total, I interviewed ten people who were either stakeholders or external professionals who might have relevant information related to the topic. Table 2 contains more information on these interviewees.

Next to the direct stakeholders mentioned above, I interviewed an external industry professional who had no stake in Airbus or ZEROe. This interviewee was selected for their outside perspective and due to their position as a product owner in an energy distribution company. In their role, they work with many international suppliers on creating complex IoT products related to energy distribution to households in The Netherlands. They could offer an independent perspective on a similar set of challenges that the ZEROe teams are currently facing thanks to similarities between the two industries. As the developments at the energy company are driven by the energy transition, they have potentially overcome challenges with their suppliers that Airbus is currently facing in the transition to sustainable fuels.

Table 2: Descriptions and counts of the interviewees.

Interviewee	**Count**	**Description**
Tank systems engineers	4	Tank systems engineers are involved in the ZEROe project full-time and create the requirements for the systems that are produced by the suppliers. They interact with suppliers through procurement officers and with project managers.
Partnerships officer	1	The partnerships officer is involved in ZEROe full-time and handles strategic topics around which partners to work together with. They interact with procurement, engineers and project managers.
Procurement officer	1	The procurement officer is involved in ZEROe full-time and handles the communication between engineering and the suppliers in the early phases of the development projects. They are responsible for the legal and commercial aspects and interact with the project managers, the partnerships officers, and the suppliers.
Project manager	1	The project manager is involved in ZEROe full-time and manages the engineering developments of the tank systems engineering teams. They interact with the

		engineers, procurement officers, and partnerships officers.
Fuel cells engineer	1	The fuel cells engineer is involved full-time with ZEROe and creates the requirements for the fuel cell systems and equipment that are produced by the suppliers. They interact with their own procurement officers, project managers, and suppliers and have little overlap with the Tank systems teams.
UpNext engineer	1	The UpNext engineer is not involved in ZEROe directly but works on projects related to hydrogen in Airbus UpNext, an project incubator outside of the Airbus organisation. They interact sporadically with ZEROe engineers and staff.
External professional	1	The external professional works for an energy distribution company as a product owner. They have nothing to do with Airbus nor ZEROe and bring in a full outsider perspective on related supplier engagement issues.

Data gathering

The observational studies were captured and processed as accurately as possible in text. In many of the interactions, material (documents) was shared between the participants (and me) such as slide decks, visuals, charts, timelines, minutes of meetings, and whiteboard drawings. When possible, this material was added to the document in which I kept notes as part of the context of the interactions. Having the material used in a session/meeting in one document made it easier to analyse as references made by the participants to visual material could be included (see Figure 12).

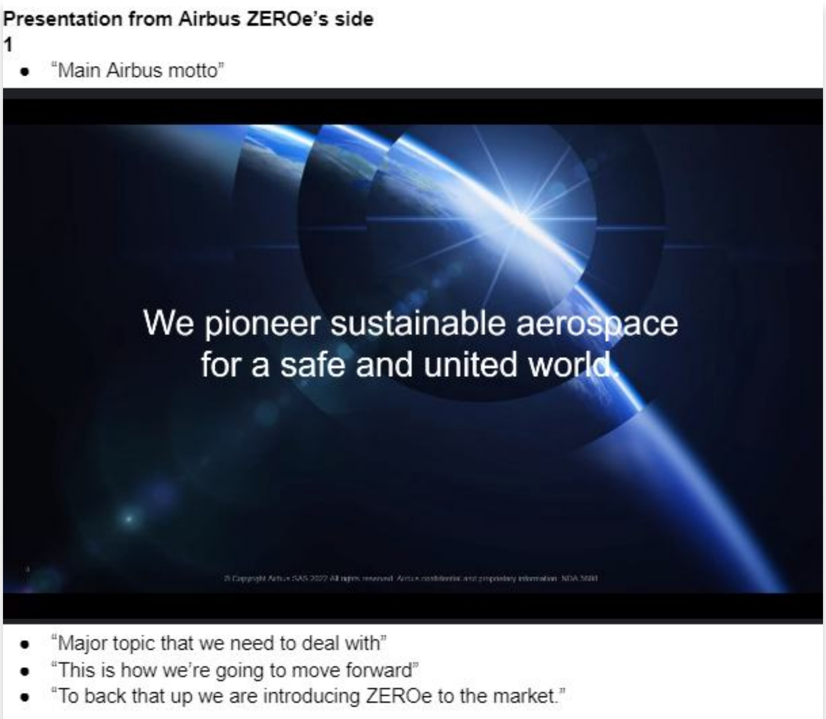


Figure 12: Excerpt from meeting notes from a meeting with a supplier.

Additionally, other material used by the stakeholders such as *Statements of Work, Product Technical Specifications, Requests For Technical Information, supplier proposals*, and *minutes of meetings* were skimmed. I used the information contained in these documents to contextualise the data collected in the observational studies. These materials were then used to inform the questions in the semi-structured interviews and to consequently inform the quest for additional information (in documents or future interactions) (Bowen, 2009). Figure 13 shows the iterative process of data gathering and analysis.

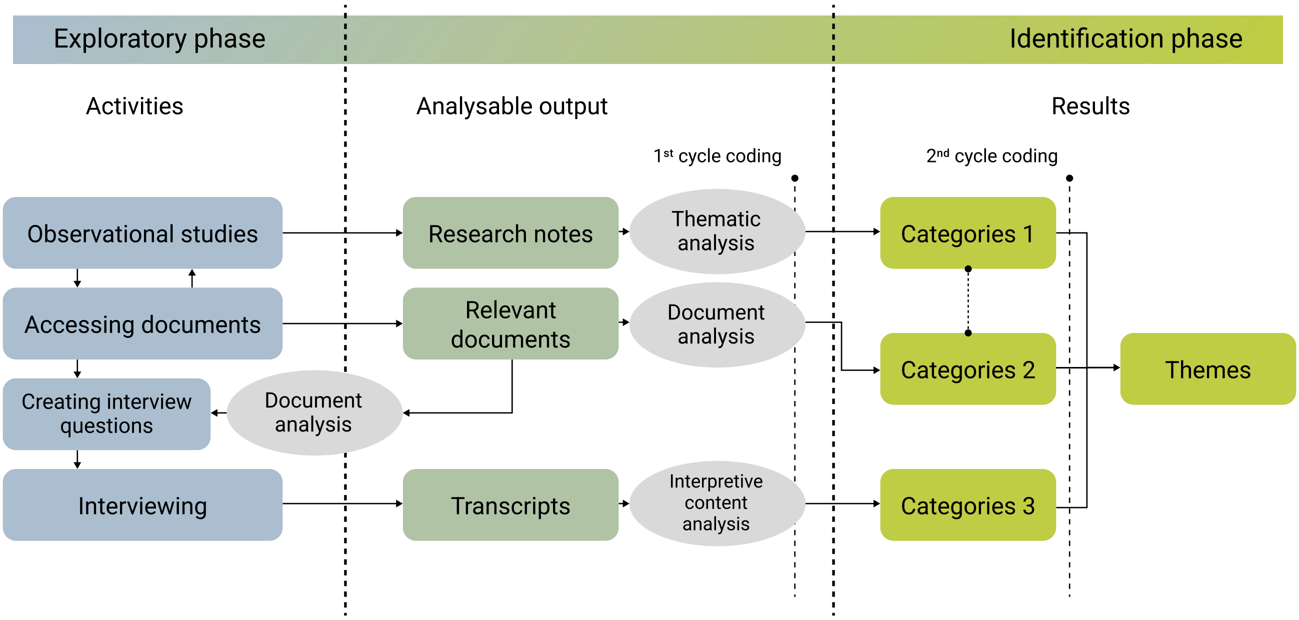


Figure 13: Iterative process of data gathering and data analysis in the exploratory and identification phases.

Data analysis

The data gathering and analysis processes were done in an intertwined fashion where one would inform the other. However, the coding activities on the interview transcripts and the field notes from the observational studies were done in an ordered fashion:

First cycle coding
1. Interview transcripts (interpretations)
2. Meetings with suppliers field notes (MWS)
3. Team and organisational meetings field notes (TOM)
4. Technical review meetings field notes (TRM)
5. Internal supplier selection meetings field notes (ISSM)

The rationale for this order was as follows. Interview transcripts contain in-depth information on what individuals say which could be different from what they do in interactions with suppliers. I felt that it was important to have that contrast next to each other. Therefore, these notes were analysed one after the other. The last type of observational study that was analysed was the internal supplier selection meetings field notes. These were analysed last as this is the newest information and background knowledge is needed to understand and follow the supplier selection process. The notes from team and organisational meetings and technical review meetings were analysed third and fourth respectively in no specific order.

Three interview transcripts (from the external industry professional, a Tank systems team engineer and a partnerships officer) were conducted during the analysis of the technical review meetings notes due to time constraints. These transcripts were interpreted for the first cycle after the completion of the analysis on the field notes.

Preparing the raw data

In order to properly analyse the data, a data layout was chosen and the field notes were structured accordingly before the first cycle of coding. For the interview transcripts, the data were separated in paragraph answers per question (see Figure 14). The interpretations were then made per question and written down in a separate document.

For the observational studies, the notes were separated by numbered headings in bold describing the topic that was being discussed (see Figure 15). These numbered headings were placed in the texts whenever the topic of discussion seemed to change to something else (Saldaña, 2021). When sub-topics were being discussed, numbered subheadings were added. The activity of adding the headings to the notes also served as a way to read the notes again and let them sink in before the first cycle of coding. The first cycle codes were written down in the code base next to their accompanying heading number in a spreadsheet with the corresponding document code. For example, the notes from the second Team and Organisational observational study would be tagged TOM2.

First cycle codes

Once all of the interview transcripts and observational study notes were processed and structured, the first cycle coding was carried out. Below, you will find a description of how this was carried out including examples with excerpts of the interactions.

Interview transcripts

For the interview transcripts, I used interpretive content analysis. This method is appropriate for summarising large data sets while inductively deducing the participants’ feelings, intentions, and thoughts (Drisko & Maschi, 2016). As the interview transcripts were lengthy passages of text (over 50,000 words in 10 interviews), it was important to use a method that summarises data effectively while retaining its meaning. An example of the first cycle coding interpretation for interview transcripts is given below in Figure 14.

Interviewer:
And then (2.6) when was the most rewarding moment that you can recall?

Engineer 1:
Ehm, actually it was with just before, also in June, with Supplier 1 during a meeting when we finally managed to eh, define the next steps, and be ready to contract. Ehm… but however, two months later it was frustrating…

Interviewer:
It's very interesting that that can be with the same supplier then, ehm

Engineer 1:
Yes indeed, indeed

Interviewer:
These highs and lows in experiences.

Engineer 1:
Yes, yes, yeah. Probably linked to the emotions that we feel working with Supplier 1, when there were a lot of twists and turns.

→

2.6
Most rewarding moment with the same supplier as the most frustrating. Most rewarding moment was when the next steps were finally defined. There were "a lot of twists and turns", an emotional rollercoaster.

→

2.6
1. "a lot of twists and turns"
2. Emotional rollercoaster

Figure 14: From left to right: Excerpt from an interview with an engineering team member, interpretation of the answer and discussion, and the resulting codes (Interview Engineer 1).

If follow-up questions were asked or discussion ensued, I included the passages in the section of the main question. Usually the probing questions were follow-ups of the main question so they were closely related to each other and therefore it seemed natural to code it together.

One interview was carried out in Dutch with an external industry professional as the company they work for is based in the Netherlands and has Dutch as the main language. I decided it would be best to transcribe the full interview in Dutch to keep the words matching what the interviewee said. The interpretations of the transcript were done in English without intermediate (automatic) translation. I interpreted the Dutch text and wrote down my interpretation in English.

Meetings with suppliers field notes

The field notes of the Meetings with suppliers were usually notes of dialogues between Airbus and the suppliers. The notes were analysed using initial coding as this enables me to remain open to all directions for further research (Charmaz, 2006, p. 46).

Most often, the meetings would start with a presentation from one of the parties after which a discussion followed. As this is a social interaction that flowed naturally between the stakeholders, the field notes were recorded in dialogue form with my observations and transcribed quotes from the attendees. After the meetings, the notes would be split into different sections based on my insight whenever the topic in the discussion seemed to change (Saldaña, 2021, p. 17). See an example below in Figure 15.

2.1 Discussing the amount of work

- Supplier 1:
  - It is a fair number of requirements
  - We need to evaluate how much time it is going to take w.r.t. The requirements
  - We need to evaluate how much time we need to allocate
  - This will mean that we will need to extend our offer
  - "We don't know how much time it is going to take." That's why we need to allocate more time.
  - We are disappointed that we are not able to start.
  - We don't want this pressure from above [Airbus] that says "You need to go fast otherwise we will not pay."
  - We have info on the position of the SOW
- Procurement officer 3:
  - Airbus expects that within the time of the RSA, for the activity D1.2.1, that a certain amount of requirements must be reviewed during the period of time.
  - Does Supplier 1 need more time to be able to commit to those activities? Or is it ok?

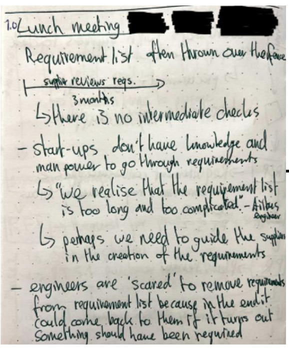
2.1 Codes

1. Too many requirements
2. Uncertainty around how much time the work will take
3. Commercial offer will be extended
4. Disappointed about delay of the project start
5. Don't want pressure from 'above' (Airbus)
6. More time needed to be able to commit?

Figure 15: Excerpt from a meeting with a supplier and the associated first cycle codes on the right (MWS1).

Team and organisational meetings field notes

For the Team and organisational meetings field notes, I made both written and typed notes. Similarly to the notes of the Meetings with suppliers, it was often a discussion between different stakeholders which I recorded in dialogue form next to the stakeholders' (anonymised) names. Therefore it was also analysed using initial coding. See an example below in Figure 16.



1.0 Lunch meeting with Engineer 4, Engineer 1, and Project Manager 2

Requirement list is often thrown over the fence

- There is no intermediate checks

Start-ups don't have knowledge and man power to go through requirements

- "We realise that the requirement list is too long and too complicated"
- Perhaps we need to guide the suppliers in the creation of the requirements

Engineers are 'scared to remove requirements from requirement list because in the end it could come back to them if it turns out something should have been required.

1.0

1. requirement list often thrown over the fence
2. no intermediate checks
3. startups don't have resources to go through requirements
4. engineers realise that requirements lists are too long and complicated
5. idea to guide suppliers during creation of the requirements
6. engineers "scared" to remove requirements

Figure 16: Written Team and organisational meetings (TOM2) field notes (left) typed out (middle) and the first cycle codes (right).

Technical review meetings field notes

The technical review meetings were often conducted in an online 'forum' with engineers from different departments in the project and company. In these meetings, Airbus engineers review technical information produced by the suppliers to understand the proposed equipment and assess the feasibility and viability of the proposals. The notes from these meetings are structured in the same way as the previous two types of notes. Therefore it was also analysed using initial coding. See an example below in Figure 17.

2.0 Take over responsibility

Proc:

- Quite challenging for Supplier 5, no experience in commercial aircraft program, not really aware which work they really have to do, "I think they will struggle" with everything we want of them, also for sub-tier (C15) might be challenging, idk
- I wonder if we can take some of the responsibility over from them, DOA
- Do you see a chance to take over the responsibility quality?

Quality:

- It's possible… *hesitant*
- Issues that have come up with this project, nobody has a hydrogen test facility

Proc:

- For all of us it's new

Quality:

- It would be beneficial to us to help them with anything they do with C15

Proc:

- Think about a strategy on how it could work out in the future

→

2.1 Codes

1. supplier not aware which work they have to do
2. "I think they will struggle"
3. take some responsibility from supplier
4. general issue that nobody has hydrogen test facilities
5. beneficial to us to help supplier test with tier 2

Figure 17: Excerpt from a technical review meeting and the associated first cycle codes on the right (TRM2).

Internal supplier selection meetings field notes

The field notes of the Internal supplier selection meetings were analysed in a similar fashion to the other types of notes mentioned above. Hence, they were also analysed using initial coding. In these meetings, engineers together with procurement officers present to experts and procurement managers their analyses of the suppliers' proposals. The goal of these meetings is to down-select which suppliers to continue with into the next phase. See an example below in Figure 18.

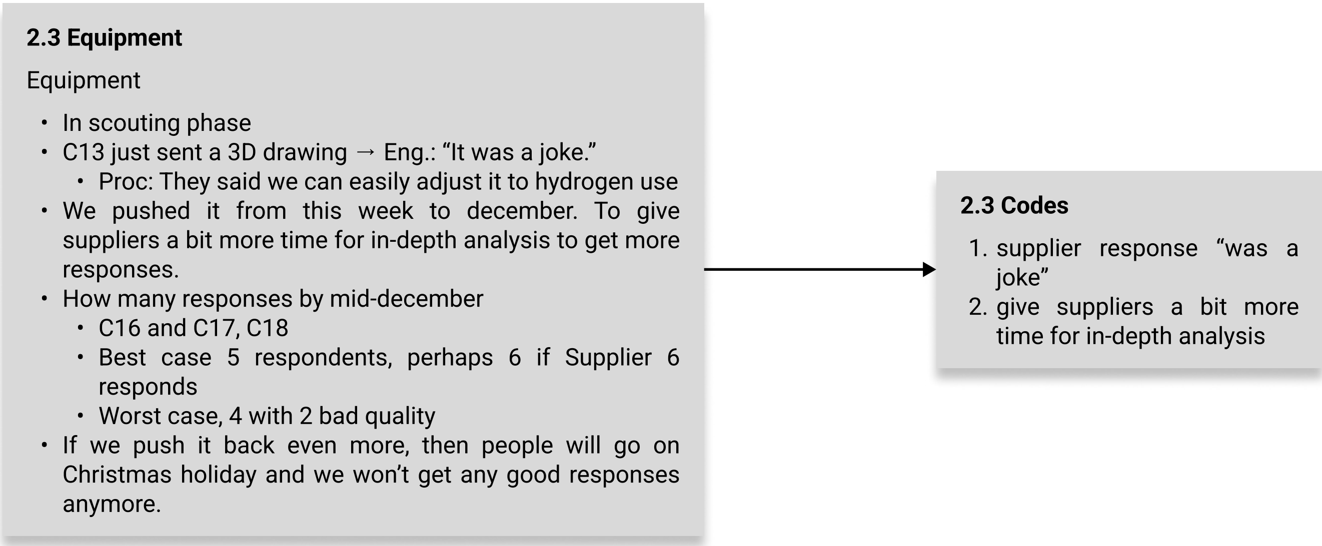


Figure 18: Excerpt from Internal supplier selection meeting notes and the associated codes on the right (ISSM1).

Post first cycle coding

As the interpretative content analysis of the interview transcripts yielded interpretations of the participants’ answers, the data needed to be further summarised and condensed. To do this, I used initial coding (a first cycle method) on the interpretations. As the interpretations included many direct quotes from the interview transcripts and I wanted to remain open to all of them, this method was deemed appropriate. It also aligns with the method used in the first cycle of the other interaction types yielding the same types of codes across the full dataset.

Second cycle

For the second cycle of coding, I followed a focused coding method. As my goal is to uncover overarching categories and eventually themes in the data while not paying attention yet to other properties such as frequency counts, this coding method seems applicable (Saldaña, 2021). As the first cycle coding method was initial coding (which is very open), doing frequency counts would not yield any meaningful results yet as there were too many unique codes. Furthermore, the total code base after the first cycle had about 1314 codes with on average about 37 codes per data instance (observational study or interview). Reviewing all these codes per data instance and clustering them would be hard to do while giving each code from each data instance the same amount of consideration. Therefore, I randomly took three codes from each data instance (see Randomisation method in Appendix A). Data from one of the technology review meetings had just two codes and both were included. This left me with 107 codes to do an initial round of clustering with. With this method, data instances with a larger amount of codes were relatively underrepresented and data instances with a lower amount of codes were relatively overrepresented. As I will go through all of the codes after this initial clustering, I do not believe this will be a problem. This is supported by focused coding where the newly constructed preliminary categories can be compared to the other data (in this case the other codes outside of the random sample). Additional information on the clustering approach can be found in Appendix A under Clustering approach.

Post second cycle coding

During the second cycle of coding, ten broad categories were identified, some with subcategories. Strong links were found between two groups of categories. Other categories were loosely related. As the codes used for the second cycle were just a sample of the complete dataset, information could still be hidden in the dataset which could add to, reinforce, alter, or disprove the categories and links found.

To focus the analysis and converge towards major themes, I went through the dataset and looked for supporting and/or disproving codes for the two groups of categories mentioned above. These results and the results of the second cycle of coding are detailed in the next section.

Results

This section details the results of the second coding cycle and the analysis that happened after it. The goal is to find patterns in the data that might lead to the identification of themes. Additionally, the analysis should point to patterns in the data that are actionable to design for.

Second cycle coding results

The focused coding with the randomly selected codes yielded ten tentative categories in total, some with sub-categories. Table 3 lists the categories and subcategories. The full table with corresponding codes can be found in Appendix B, Table 1. Many codes are positioned in between two categories or even outside of a category during clustering. The codes that seemed to have the least connections to a category were examined further and either placed in a (new) category or were discarded.

Table 3: Preliminary categories and subcategories.

Category name	**Sub-category name**
Responsibility & power	
Seeing opportunity	
Engagement enablers	
Certainty	General
	Technological
	Commercial
Uncertainty	General
	Technological
	Commercial
	Organisational
Interacting	
Process frustrations	

Barriers	Safety focus
	Challenging requirements
	Overly cautious
	Asking for the impossible
Fear-of-missing-out	

Upon shuffling, placing, re-placing the codes, and naming and renaming the (sub-) categories, patterns and links emerged among the preliminary categories. Some categories are closely linked while others seem more distantly related. Figure 19 shows the ten categories and their subcategories mapped. Two groups of categories seem closely linked. Group 1: *Certainty & confidence, Engagement enablers* and *Seeing opportunity* all seemed linked to each other with Interacting. The second group (*Group 2*) is *Uncertainty* and *Barriers* with a small link to *Interacting* through *Fear-of-missing-out*. To illustrate the connections found, the next sections cover these groups.

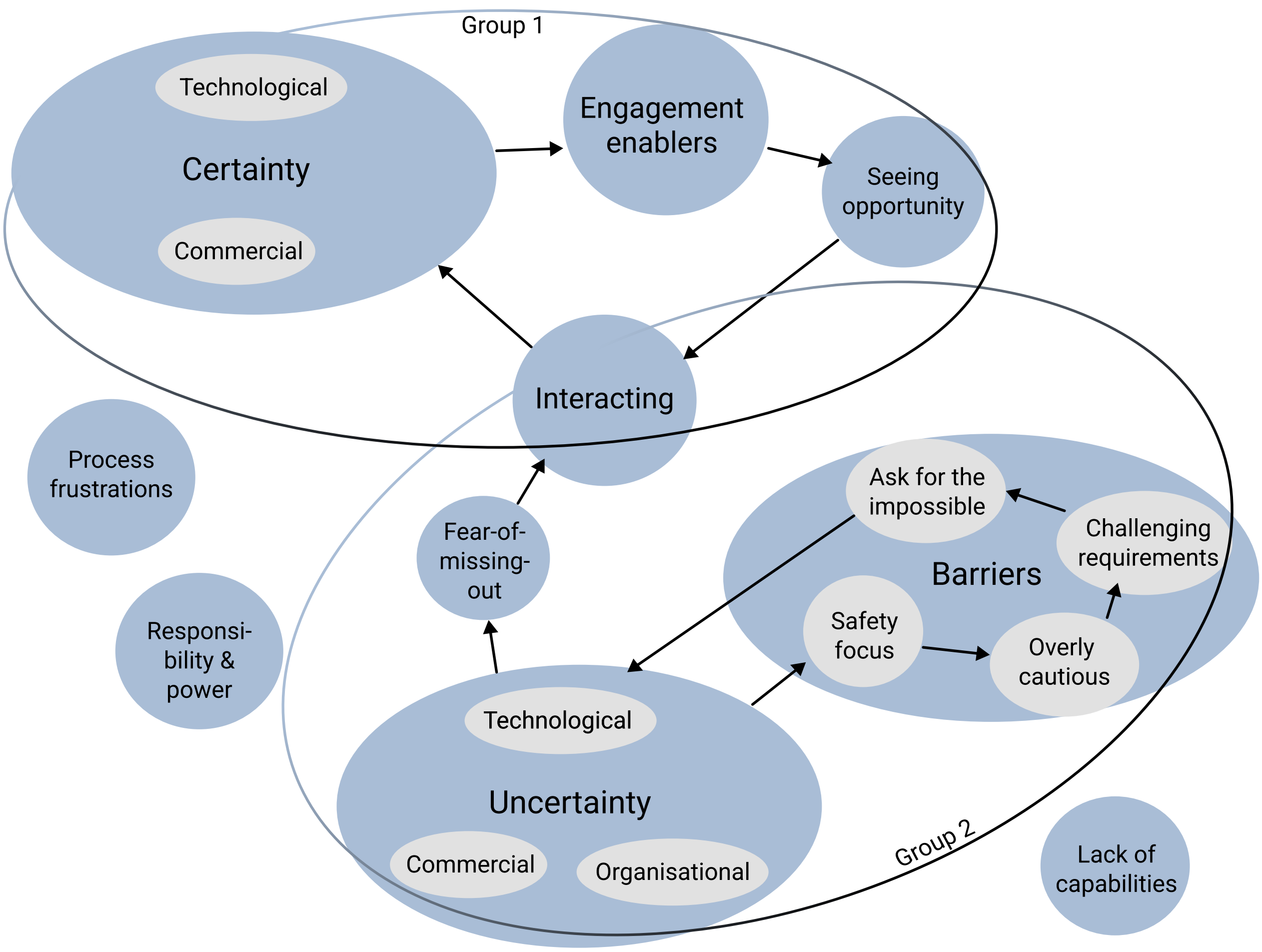


Figure 19: Map of the categories and subcategories with links.

Group 1

In this first group, *Certainty & confidence, Engagement enablers, Interacting* and *Seeing opportunity* were identified as preliminary categories of codes (see Figure 19). Within the category *Certainty & confidence*, codes such as *"very surprised with CFD calculations as it's costly"* were placed. This example code came from an Internal supplier selection meeting where an engineer went through the response of one of the suppliers to Airbus' request for technical information (RFTI). An RFTI can be seen as a pre-tender phase where Airbus is trying to gather information on what potential suppliers are able to produce based on a set of requirements (see Figure 8 in Background). This information is then used to formulate a tender which is sent out to suppliers who can bid. This code came from an instance where a supplier had included computational fluid-dynamics (CFD) calculations in their proposal to validate the design choices of the equipment. The Airbus engineer sending out the RFTI had not asked for such calculations and was positively surprised by them. They gave the engineer more confidence and certainty in the proposal of this supplier as it showed that the supplier was motivated and technically capable to put resources into it.

"Motivation + technical abilities" is a code in the Engagement enablers category that came from an interview with a project manager when asked about their dream scenario when working together with a supplier. They mentioned that suppliers need not only to be motivated for the project but they should also have the technical capabilities to answer Airbus' requests.

When both these conditions are met, usually it is a supplier who understands the potential of the project and wants to be part of the product. The *Seeing opportunity* category holds two codes relating to that.

The Interacting category hosts various codes related to how the interactions take place between Airbus and its suppliers. Some codes are positive, some negative, others describe a process. In this case, the code *"Open and honest discussions"* relates to several codes in the Certainty & confidence category as the discussions with the supplier that provided CFD calculations were more open than with other suppliers. Due to resource constraints, the ZEROe engineer had to take over some of the communication with the supplier from the procurement officers. Thanks to this, the supplier requested an intermediate meeting to clarify questions and to show their progress. It helped the ZEROe engineer assess and give feedback which in the end resulted in a positively surprising and impressive response to the RFTI.

In the example with the supplier providing the impressive RFTI response there was certainty and a positive interaction which enabled both parties to see the opportunity in an engagement. The relations between these categories seem to be a positive feedback loop where if one is positive, it also creates a positive in the other categories. Figure 20 shows the links between the preliminary categories in a diagram.

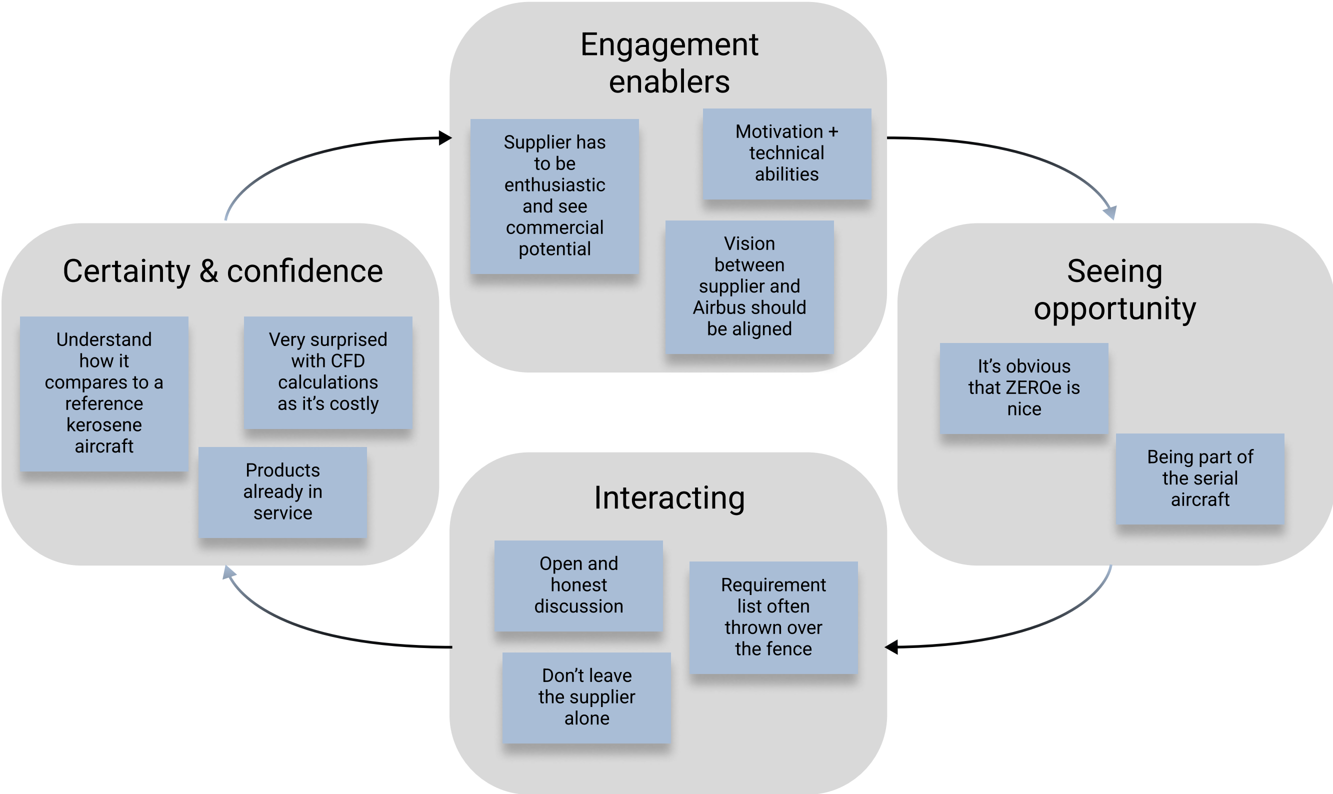


Figure 20: Links between four preliminary categories of codes in Group 1.

Engagement enablers & Interacting

As the interaction example mentioned above showed positive engagement between Airbus and a supplier, it is worth looking for other codes related to *Engagement enablers* and *Interacting* to find actionable items. I went through the codes from the ten interviews as I asked about positive (and negative) experiences in them, and identified 89 codes in total relating to the two aforementioned categories. I compared these codes and found five actionable subcategories. Table 4 shows these actionable subcategories ranked based on the number of codes associated to each subcategory. The full list of codes identified relating to these actionable subcategories can be found in Appendix B, Table 3.

Table 4: Actionable subcategories of codes based on Engagement enablers and Interacting

Category	**Number of codes**	**Exemplar code**
Finding an efficient way of collaborating	46	intermediary meeting very helpful in assessing supplier progress
Defining the right incentives and fit	15	don't force a supplier to engage if they don't want to
Having a clear strategy	13	make sure suppliers know Airbus' plans
Learning with suppliers	10	learn from suppliers with less fit
Defining needs clearly	5	suppliers should understand better the Airbus needs

Group 2

The second group of preliminary categories sees a strong link between *Uncertainty* and *Barriers*. There is again a link with *Interacting* (see Figure 19).

Uncertainty is the category with the highest number of codes in this cycle, 30 out of the 107 randomly selected codes. I identified four subcategories: *General, Technological, Commercial,* and *Organisational*. These last three subcategories relate to Melander & Tell (2014) who identified eponymous types of uncertainty in collaborative new product development.
Within the *Barriers* category, I found four subcategories, namely: *Safety focus, Challenging requirements, Overly cautious,* and *Asking for the impossible*. These subcategories are all linked in a chain starting with *Safety focus*.

At any aircraft manufacturer, safety is the highest priority. Unsafe aircraft will not be tolerated by passengers and might cost the company its licence to operate. Therefore, there are many safety protocols in place at Airbus, one of which is around *"sensitive novelties"*. Hydrogen technology is seen as a sensitive novelty as it is not yet well understood (subcategory *Uncertainty*). Hence, there is an additional safety layer (subcategory *Safety focus*) that engineers should take into account when creating their designs compared to the design in legacy aircraft programs. This links to the subcategory *Overly cautious*. Due to the extra safety barriers, engineers add additional safety margins to their designs and they are *"'scared' to remove requirements"*. This leads to *"crazy requirements"* that are transferred down to suppliers and make it very challenging to create the requested equipment. *"Scope was 150% which was overwhelming suppliers"* is a code that illustrates this in the *Asking for the impossible* subcategory where Airbus knew it was demanding too much from the supplier to see how far they would go.

The *Uncertainty* category links to *Barriers* and specifically to the subcategory *Safety focus* as the extra safety measures stem from a general uncertainty about hydrogen aviation at Airbus. Then, through *Asking for the impossible*, Airbus gets more uncertainty back as suppliers have difficulties satisfying the requirements and the demands imposed on them. The code *"different components quoted between supplier offers"* is a testament to this showing that suppliers' proposals differ, making it hard for Airbus to compare apples to apples. Figure 21 highlights the links between *Uncertainty,* and *Barriers* and its subcategories.

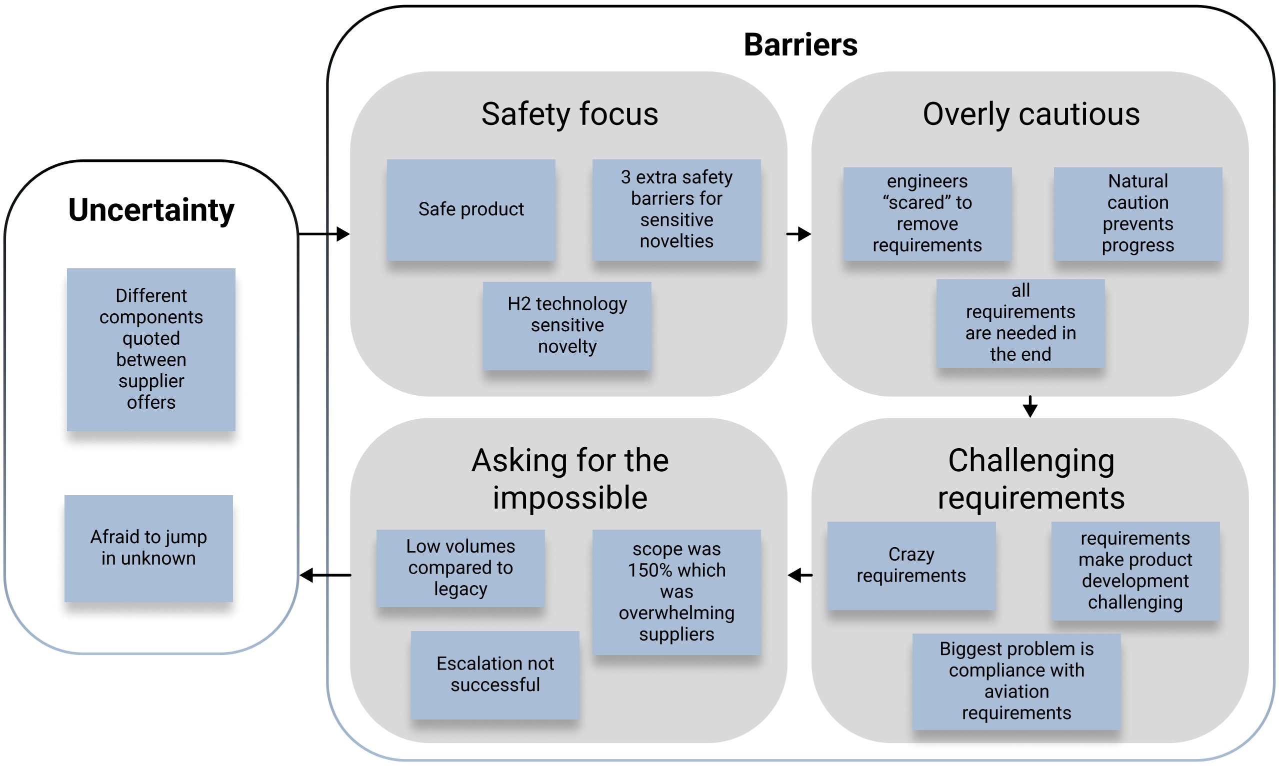


Figure 21: Relations between the categories Barriers and Uncertainty, their subcategories, and a selection of the categorised codes (Group 2).

Link to Interacting

A link between *Uncertainty* and *Interacting* was identified through the category *Fear-of-missing-out* and its single code *"not able to follow in the serial aircraft"* (see Figure 19). This code originated from a Meeting with a supplier where the supplier expressed their concern of not being able to follow the developments on Airbus' side. They were afraid that they would miss something which would lead them to fall behind and not be considered for the serial aircraft. A form of uncertainty was present on the supplier's side which they linked to the way Airbus was interacting with them.

Post second cycle results

After the second cycle of coding, I went through the full dataset of *Meetings with suppliers* codes to find supporting and/or contradicting codes related to *Group 1* and *Group 2*. As *Group 1* showed a successful engagement with a supplier and *Group 2* showed examples of more difficult engagement, I focused my further inquiry into these two groups. Between *Group 1* and *Group 2*, the categories of *Certainty & confidence* and *Uncertainty* seemed to be related but in juxtaposition. I took these two categories and went through the code dataset identifying codes that related to either category.

I identified 71 codes that related to certainty and/or uncertainty. In every meeting with suppliers, there were codes relating to certainty/uncertainty giving a clear indication that this was a recurring theme of discussion within the engagements with suppliers. Following Melander & Tell (2014), I tried sub-categorising these codes into *Technological, Commercial,* and *Organisational* uncertainties to see if any codes would be left that would not fit within either of these categories and to see which subcategory would contain the most.

The *Technological uncertainty* subcategory had the highest number of codes: 35. Which is almost half of all of the identified certainty/uncertainty codes within the Meetings with suppliers interaction type. For *Commercial* and *Organisational* uncertainty, there were less codes, 16 each. Four codes were left uncategorised but all of them mentioned uncertainty in a general manner such as *"margin of uncertainty is high"* and *"uncertainty on every axis"*. Therefore, these were ignored.

In examining the subcategories further, I found several codes that were similar to each other and pointing to recurring topics within the subcategory. Figure 22 shows a tree-diagram with these recurring topics. The full code list related to these topics can be found in Appendix B, Table 2.

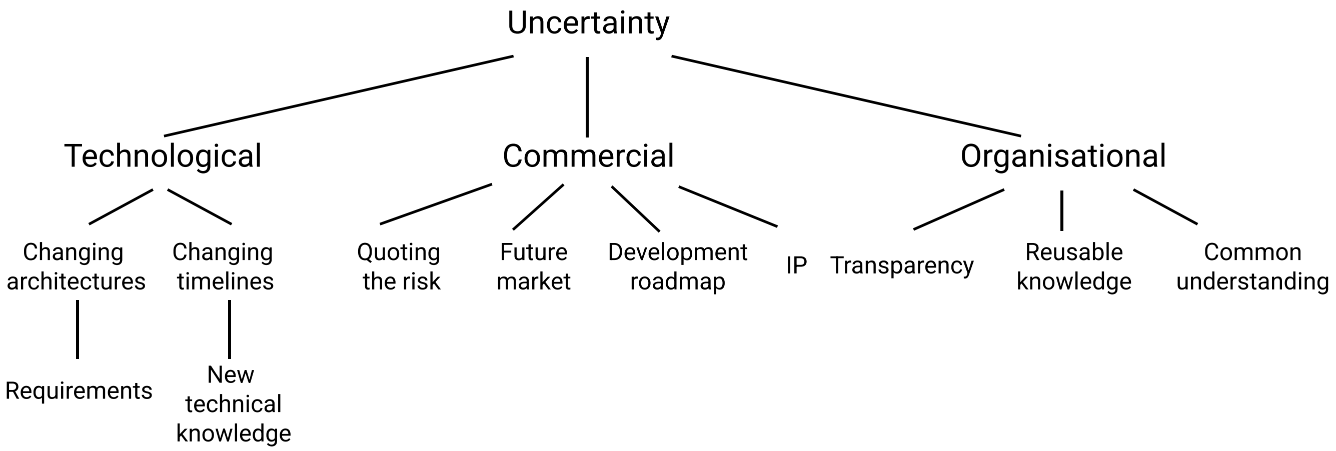


Figure 22: Tree-diagram of the Uncertainty category, its three subcategories and their recurring code topics.

On the Technological side, I identified a link again between *Uncertainty* at the abstract level and the difficulties dealing with Airbus requirements at the concrete level. On the other hand, it was not directly clear from this breakdown that the safety focus (as mentioned above in *Group 2*) is driving these difficulties with requirements. This does not necessarily mean that the safety focus is not a driver but it shows that there are potentially more drivers.

Within the *Organisational uncertainty* subcategory there were many codes relating to interactions between the supplier and Airbus. It supports the links identified earlier between *Interacting* and *Certainty & confidence* in *Group 1* and between *Group 2* and *Interacting* through *Fear-of-missing-out*. The same code from *Fear-of-missing-out* was also categorised under the *Organisational uncertainty* subcategory.

Discussion

This chapter discusses the results from the exploratory phase of this research. It is the transition from the exploratory into the identification phases. From the results, it is clear that the supplier engagement landscape within Airbus and more specifically within ZEROe is broad and complex. There are many different (internal) stakeholders, perspectives, and challenges. This section details the general findings and defines a way forward in the form of three design challenges and two analysis challenges. At the end of this section, a choice is made between these challenges.

General findings

At the highest abstraction level, it is the **uncertainty** surrounding hydrogen technologies for aviation that drives the supplier engagement challenges. There are technological uncertainties regarding the development pathway of new hydrogen equipment such as liquid hydrogen pumps, tanks, valves, etc. There is commercial uncertainty on the demand for hydrogen aircraft, on the prices of the equipment, and on when the development milestones are supposed to be met. And of course, there is organisational uncertainty around how Airbus and its suppliers should organise themselves in order to create the needed technologies.

In comparing *Group 1* and *Group 2*, it became clear that one was highlighting positive engagements with suppliers and the other was highlighting the more difficult engagements. Within the groups there were relations between the categories that reinforced each other in positive feedback loops. Figure 23 gives a schematic overview of these relations and the high level themes that were uncovered in the analysis.

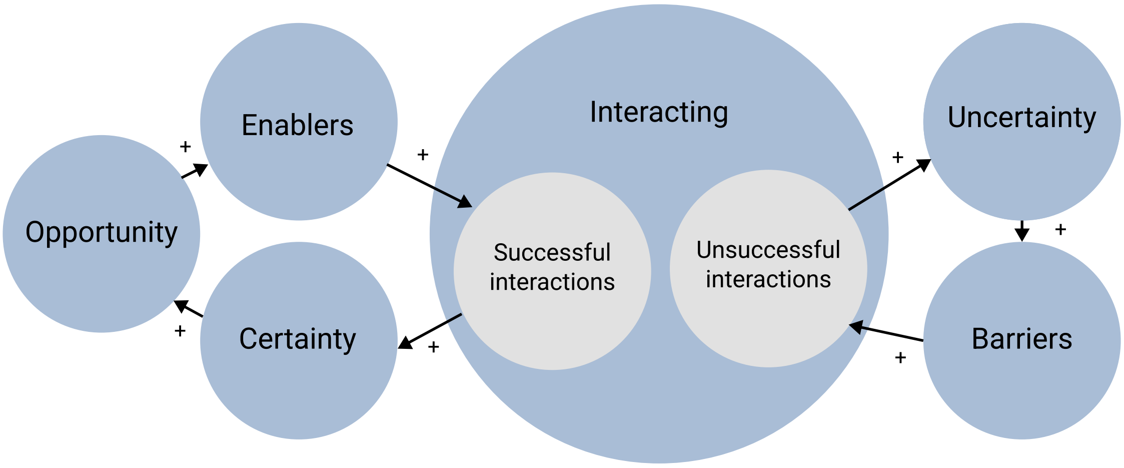


Figure 23: Overview of the main themes and the interactions between them.

These feedback loops are the main high-level finding of this analysis. In *Group 1*, the positive feedback loop leads to positive engagement while in *Group 2* it leads to no or negative engagement. As was found, there were many more instances of the uncertainty driving the negative engagements. It seems as if Airbus is unable to break the positive feedback loop leading to bad engagement in many interactions. However, as was seen with the example in

Group 1, it is possible to break it and create momentum that reinforces itself.

Research questions

The exploratory phase of this research is characterised by trying to understand the context of the supplier engagement within the Tank systems teams of ZEROe. My goal was to understand how the different stakeholders interact currently in supplier engagements. I asked myself the following research question: *What are the stakeholder perspectives on supplier engagement within the ZEROe project?*

Although each of the stakeholders have complex perspectives on the matter of engaging in hydrogen propulsion technology development, I briefly summarised the perspectives per main stakeholder:

1. **Tank systems engineers & project managers**: their main goal is to adhere to the technological roadmap and deliver the required equipment to meet each Technology Readiness Level milestone up until Entry Into Service. Of course, these developments have to remain within budget. Supplier engagement is the way to reach those goals as suppliers develop sub-systems and components, feeding into the complete aircraft architecture.
2. **Procurement officers**: procurement is supposed to get the best offers from suppliers possible with respect to Time, Cost, Quality, and Performance. This is easiest to do when there are many suppliers able to deliver the same equipment. To make sure the IP conditions are favourable for Airbus, procurement officers orchestrate the interactions between the suppliers and the engineers.
3. **Suppliers**: suppliers are willing to engage in R&D activities when the product fits their strategy and product line-up, and when the development costs are clear. Selling products to Airbus could mean high revenues for prolonged periods of time. That is what makes R&D worthwhile for suppliers.

For the identification phase, I asked myself the following research question: *What challenges do the stakeholders face in engaging in joint early stage hydrogen propulsion technology development for aircraft?* Again, I have summarised the main points per stakeholder in the list below:

1. **Tank systems engineers & project managers**: Supplier engagement is mainly difficult for them as they do not feel comfortable with what they are requesting from the suppliers currently. (Top-level) requirements are not fully defined making it difficult to write Statements of Work and Product Technical Specifications which will not constantly change. They feel restricted and bottlenecked by the commercial processes around supplier engagement. There is a need to learn and implement the learnings effectively.
2. **Procurement officers**: Compared to procurement processes in legacy programs, procuring equipment for the Tank systems teams is difficult due to the technological and commercial uncertainties. There are no strong ‘carrots’ or ‘sticks’ that can be used to entice suppliers to engage, leading to slow interactions and a small supplier pool.
3. **Suppliers**: At the start, many suppliers are enthusiastic about ZEROe and want to engage. Once the relationship develops, it becomes clear how uncertain all of the developments are. Suppliers are not able to properly calculate the risks of engaging in developments. Even when the risk is clear, the suppliers are usually required to self-fund most of the development costs, forcing them to raise their commercial offers. This is especially the case for hydrogen propulsion technology development as there is currently no big market with other customers available.

For the design phase, there is no research question. Instead, the goal is to design an intervention around an identified challenge and test/deploy it within the ZEROe Tank systems teams context. The next sections discuss the identified challenges.

Towards a design challenge

The high level findings offer an intuitive view to supplier engagement: the more uncertainty in the to-be-designed equipment/systems, the less successful the interactions with suppliers will be. However, this abstract notion does not offer a concrete avenue for a design solution. For that, we should consider the actionable insights from the research. The identified actionable subcategories of *Group 1* offer an avenue to scope down the design challenge (see section *Engagement enablers & Interacting* in Results). This section covers the three identified actionable subcategories with most codes and highlights the possibilities to improve the supplier engagement through them as design/analysis challenges. Details on the design challenge *Learning with suppliers* and the analysis challenge *Defining needs clearly* can be found in Appendix C.

Design challenge: Finding an efficient way of collaborating

The actionable subcategory of *Finding an efficient way of collaborating* had the most amount of codes related to it compared to the others. Interestingly, the codes from the interview with the external professional had many overlapping points with the codes from the interviews with internal stakeholders. For example, the external professional explained having weekly meetings with suppliers to be able to monitor their development progress as closely as possible (code: *suppliers' progress is monitored weekly*). From an interview with a ZEROe engineer, they expressed the need for more frequent meetings and the need to monitor the progress made (code: *intermediate supplier progress reporting needed*) even during the supplier selection phase (code: *"exchange freely and build knowledge"* in RFTI phase).

Redesigning the progress monitoring process and the touchpoints with the suppliers could be a fruitful avenue for the engineering teams. As development phases for the equipment are continuously being started, it would be possible to test whether a different way of collaborating would improve the supplier engagement.

Analysis challenge: Defining the right incentives and fit

Within ZEROe, many developments requested from the suppliers are self-funded. This means that the suppliers themselves fund the R&D needed to produce the requested equipment to Airbus. The R&D needed to define the equipment and test its viability and feasibility often spans years and requires multi-million dollar investments. For many companies, this becomes problematic when there is uncertainty about the ability to sell the equipment at scale later on. The reality is that ZEROe is in a pilot phase while Airbus is requesting equipment from suppliers as if it was an aircraft program with committed volumes. In the interview with the external professional, it was clear that during pilots, the energy distribution company pays for the supplier's development costs creating the incentive for them to join. Many ZEROe suppliers do not have this incentive currently as Airbus is unable to finance all of the R&D needed to develop the equipment. Therefore, the challenge is to find other incentives that would motivate companies to self-fund the R&D. On top of that, it would be important to identify the characteristics that define a right fit between a ZEROe supplier and Airbus once they have chosen to commit to self-funding.

This challenge is geared towards deeper analysis of the incentives a company needs to engage with ZEROe and what characterises these companies. This analysis could be relevant in selecting the right suppliers to make sure no time is wasted with suppliers that eventually will not commit (code: part ways without wasting time). There is not yet an opportunity for a concrete design without doing deeper analysis first. This makes it less usable in the short term for the engineering teams.

On the other hand, knowing which suppliers to select, and knowing what incentives to offer them could be valuable information, also for engineering.

Design challenge: Having a clear strategy

Several codes pointed to the need for Airbus to communicate more clearly what its intentions are with regards to the hydrogen technologies that it wants to develop. Across several interviews in the dataset, participants suggest that suppliers are not fully aware of Airbus' plans. Additionally, it is currently unclear how Airbus views the future hydrogen aircraft market. Airbus communicates clearly on the ambition to create hydrogen-powered aircraft but is not naming any prospected market sizes nor are there any customers officially on board yet even though there is interest (Perry, 2023). For suppliers this brings uncertainty. It leaves interpretations about Airbus' commitment open to speculation.

As a design challenge, this topic is not easy to tackle as decisions about strategy and the communications about those decisions are taken at the (ZEROe) top management or even Airbus executive committee (CEO) level. Some decisions that would reduce the uncertainty for the suppliers and ease the engagement are not taken yet. Recommendations that would flow from the design would most likely not be implemented at the engineering level which this project is situated in, reducing its applicability.

On the other hand, it could be valuable to create a stronger link between the uncertainties that the engineers face in their daily work, and the strategic decision making that happens at the higher levels. This is supported by an engineering interviewee's perspective that there is not enough upward feedback within Airbus (code: *stronger feedback stream upwards in Airbus*). Streamlining this process could therefore accelerate the decision making which was identified as being problematic by one of the interviewees (code: *engineers afraid to take risky decisions*).

Choosing a design/analysis challenge

All five challenges explained above relate to important topics of supplier engagement within the ZEROe Tank systems teams. As I have limited time and resources for this thesis, I will choose a focus for the design/analysis challenge.

Between the five challenges, I have to take into account the academic relevance and the relevance for the ZEROe Tank systems engineering teams. These interests are somewhat conflicting as for the academic relevance, I would ideally design/analyse something that is

generalisable. For the relevance to the Tank systems engineering teams, the design/analysis would be most relevant if it is fully tailored to their situation, reducing the generalisability.
With that in mind, the analysis challenges (*Defining needs clearly* and *Defining the right incentives and fit*) are dropped as they depend too much on Airbus' needs in this specific project. Nonetheless, *Defining the right incentives and fit* remains relevant for future research.

With the design challenge *Learning with Suppliers*, the issues around intellectual property might become showstoppers in trying to get Airbus ZEROe to learn from suppliers. As I am not specialised in law, these issues might be hard to find solutions around. Therefore, this design challenge is also dropped.

Between the last two, the design challenge around *Finding an efficient way of collaborating* seems to strike a balance between relevance for the engineering teams (highest number of codes) and the academic relevance. Regarding the latter, there are still question marks around the degree of influence of organisational uncertainty (Yepeng et al., 2022) and technological uncertainty on the involvement of suppliers in new product development (Melander & Tell, 2014, p. 118) (Johnsen, 2009, p. 195). Johnsen (2009) specifically mentions the need to better understand these characteristics between projects with suppliers. This is precisely what can be tested within this design challenge as multiple supplier relationships are ongoing.

Additionally, the *Having a clear strategy* topic touches on an important cause for uncertainty within ZEROe that is felt daily by the Tank systems engineering teams and their stakeholders. During one of the team and organisational meetings, a project manager was explaining the difference between the development streams of the prototypes and the final product to the engineering team. To distinguish between these streams, each development is marked with an identifier. When the project manager referred to these identifiers and their sub-versions, the engineers got confused. There was a misunderstanding on what was a prototype and what would be the actual product. Upon asking about the use of the identifiers, the project manager in question explained to me that this naming is based on development trajectories from legacy aircraft programs. They added that they did not believe that this development strategy/roadmap fully fits the needs of the ZEROe project currently.

To choose an appropriate design challenge between the last two options, the results of the identification phase were discussed with both the university graduation committee and the company's internal stakeholders. I adjusted the challenges slightly after the discussions with the stakeholders. Figure 24 shows the updated challenges in short.

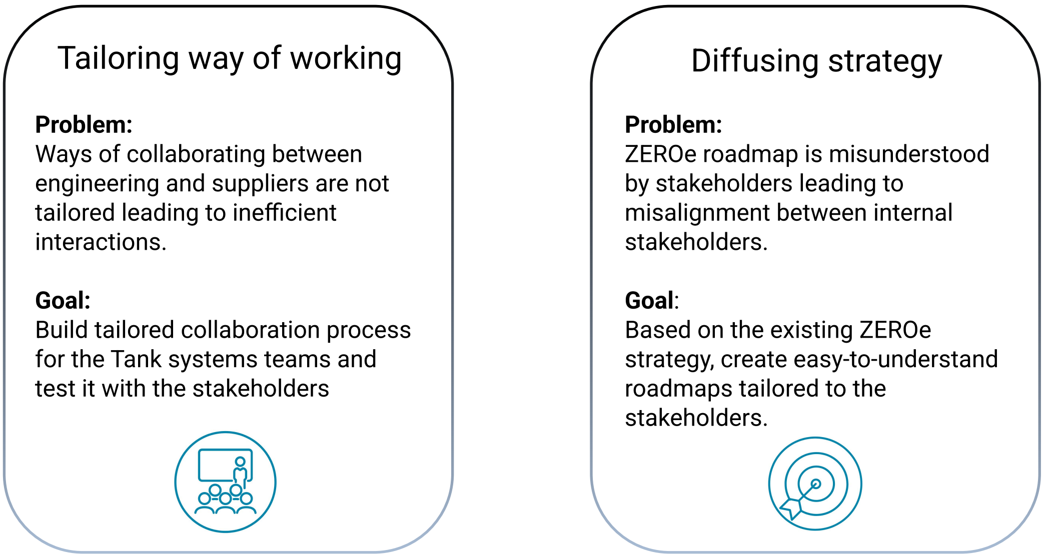


Figure 24: The two considered design challenges.

After combining this feedback with the insights gathered throughout the research phase, I decided to focus on what was initially defined as *'Finding an efficient way of collaborating*' and is now *"Tailoring way of working"*. The exploration and identification phases showed that this topic has a high relevance to the team as it had the most amount of codes related to it. In an interview with an engineer working on drafting their first RFTI (Request For Technical Information), they said:

"Now I get the opportunity to do one of those, an RFTI. Yet I find, as far as I can tell, there is no process, no template, no methods for RFTI. So now I got to yolo my own way through this process which will be directly sent to external suppliers."

So, there is a clear need for more guidance in this process.

The *'Having a clear strategy*' was renamed to *'Diffusing strategy'*. This topic remains relevant and was highlighted by the internal stakeholders to be a driving force in supplier engagement. However, this is not a topic that the engineering teams have direct influence on which makes it less relevant for this thesis. Therefore, it was chosen to drop this challenge.

In the next chapter, the chosen design challenge is taken as a starting point of the design phase.

Design phase

During the exploratory and identification phases, I have provided an overview of the supplier engagement landscape and I have identified the most relevant challenges related to it for the Tank systems engineering teams. In the design phase, I will tackle the *Tailoring way of working* design challenge jointly with the Tank systems team members.

The chapter starts with defining the scope of the design. Then, the approach to tackling the challenge is described and carried out. The Results section details the findings. The form of the deliverables are presented and discussed in the Design form section. Lastly, the design proposals are iterated on and validated in the Validation section.

Scope

The general findings from the identification phase (presented in Figure 23) lead to an abstract view on the influence of (un)certainty on the success of the interactions with suppliers. It is obvious that cases with high levels of uncertainty in the equipment specifications, requirements, and development roadmaps caused barriers that lead to unsuccessful supplier engagements. The design must help reduce this uncertainty through tailoring the way of working in supplier engagements. This section scopes down how the design should concretely reduce the uncertainty.

With the advent of hydrogen-powered aircraft, Airbus is redefining the basic aircraft architecture for hydrogen technologies. On the other hand, Airbus' bread and butter are the legacy aircraft programs based on decades' old aircraft designs. These programs are deep into the specific phase of product development. Established processes make sure that this productivity and quality is reached (Murman et al., 2000). A part of the issues in the supplier engagement that I found can be linked back to the tension between the different product development phases the legacy programs are in versus ZEROe. The development processes used across them is at the core of this.

One of the established processes that Airbus uses in product development is the Request For Technical Information (RFTI). As mentioned in the *Group 1* section of the Results chapter on page X, it is used to explore and develop new technologies together with suppliers. The RFTI is used at Airbus as a sub-part of a so-called 'stage-gate' product development process (Cooper, 2000). Structuring the innovation process in this way is meant to reduce uncertainty along the way of new product development. Tidd and Bessant (2020) mention that this uncertainty is reduced "through a series of problem-solving stages, moving through the phases of scanning and selecting and into implementation - linking market- and technology-related streams along the way." Within the 'scanning and selecting' part of the process at Airbus, multiple RFTIs are conducted with suppliers to select the appropriate solutions to the design challenges defined in the concept phase. Figure 25 shows an outline of the development process Airbus uses for new aircraft program development and includes the RFTI as a sub-process within it.

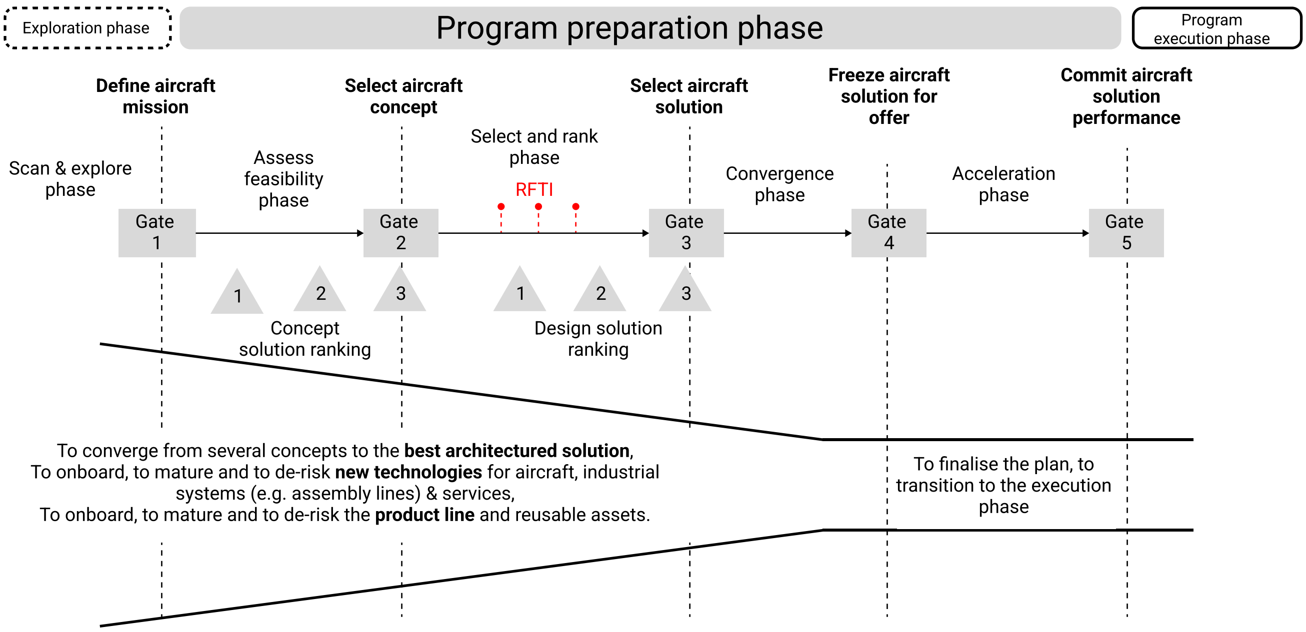


Figure 25: An Airbus specific adaptation of Cooper's (2000) stage-gate product development process combined with Wheelwright's (2011) development funnel (Airbus, n.d.).

This process outline, including the RFTI process, has its origins in the legacy aircraft programs and has been used successfully in the development of new kerosene-powered aircraft for decades. Naturally, this process is now being applied to new hydrogen aircraft developments within ZEROe. Cummings (2020) argues that the "notion of heritage" dictates the choice of one technology over another in innovation. In the context of this project, I believe the "notion of heritage" can also be applied to the processes chosen for a new product's technology development. Processes such as the RFTI have a proven heritage in the legacy programs at Airbus. The process is used to procure safe components and systems with incremental innovation in the propulsion technology of aircraft and has proven to be very successful at doing so. However, when applying it to radically new propulsion technology development, there are clearly limitations.

The Group 1 section in the Results chapter demonstrated that a deviation to the usual RFTI process with one supplier yielded better results than with suppliers with which the process was strictly followed. In their conceptual model linking creativity, supplier engagement, performance, and green innovation, Awan et al. (2019) argue that teams at multinational firms engaged in inter-firm cooperation should have members capable of divergent thinking beyond the acceptable practices of that cooperation. In other words and applied to the context of this project, it implies that the engineers in the Tank systems teams should be able to think beyond the typical processes (= "acceptable practices") used with suppliers. By doing so (and demonstrated in the case in the Group 1 section of the Results chapter), the supplier engagement could potentially be improved. It does beg the question if by doing so, the same levels of safety and reliability will be achieved. The flexibility to deviate from a development process to improve the supplier engagement should not compromise the safety and reliability of the to-be-designed system/equipment. This is a strict requirement for any design solution developed in the following phases.

Therefore, the scope of the design phase is on the tension between the legacy ways of working and the needs of the Tank systems engineers within ZEROe. With that, it dives deeper into the RFTI process and aims to find improvements to it that reduce the uncertainty for both Airbus and its suppliers.

Design challenge: Tailoring way of working

This section discusses the approach taken to tackle the *"Tailoring way of working"* design challenge. It also discusses how the stakeholders are involved in the design process. Some possible outcomes that I expect to deliver at the end of the design process are given.

As the topic of collaboration is wide and the problems the team members identified during the interviews were varied, I deem it important to spend time jointly formulating the problem statement of the design challenge. A clear problem statement enables the team to come up with ideas and concepts that are relevant for me to work out into (a) solution(s). Therefore the design challenge statement is as follows:

Jointly design implementable improvements to collaboration processes between the ZEROe Tank systems engineering teams and their suppliers.

Approach

To create stakeholder ownership over the design, I am facilitating creative sessions in which the team goes through several design diamonds. The goal is to converge to a design solution that is relevant for their context. To achieve this, I am applying techniques from the integrated Creative Problem Solving (iCPS) model (Buijs & Van der Meer, 2013). More specifically, I am using an expanded model and approach that builds on iCPS by Heijne & Van der Meer (2019). Figure 26 shows the approach I am taking which is an adapted version of the triple diamond iCPS process. Instead of going through the solution finding diamond which iCPS prescribes as the third diamond, I work out the ideas and concepts from the idea finding diamond together with the team members in iterative loops spread over multiple sessions. This is more effective as the ideas that are generated in the idea finding phase are very specific to certain use cases for the engineering team members. Hosting a third design diamond with all stakeholders in which a solution is developed in one go would not be enough to work out the solution to a sufficient degree.

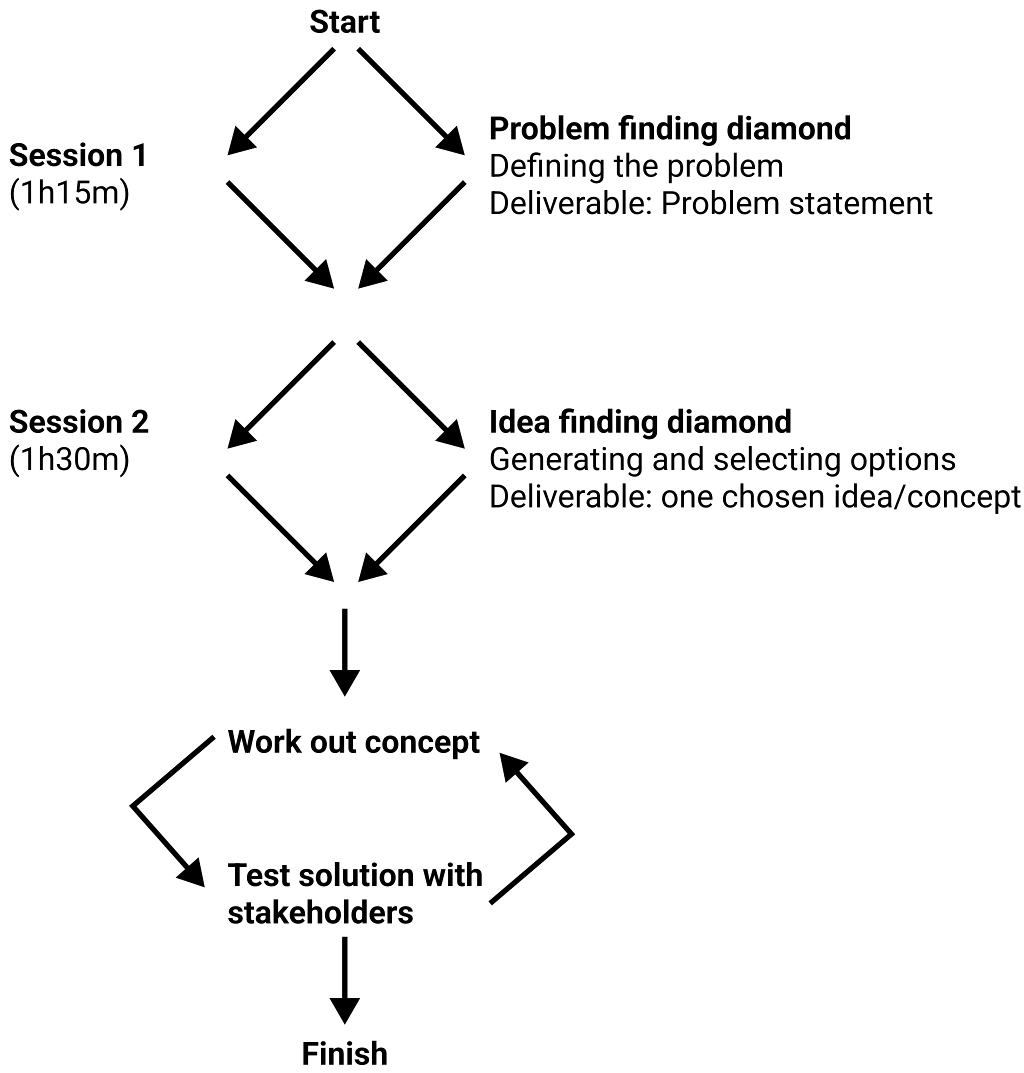


Figure 26: Approach to the design process based on iCPS (Heijne & Van der Meer, 2019).

Participants

For this design challenge, the main stakeholders are the engineering team members. As it is about collaboration, the suppliers are also important stakeholders. However, gathering all internal and external stakeholders together for all design diamonds is unrealistic due to schedule restrictions. On top of that, a supplier who is willing to participate in such sessions might not be fully representative of the various different types of suppliers that the engineers deal with on a daily basis. Therefore, the focus of the session will be on the engineering team members' perspectives of the supplier engagement.

The group size is limited to eight members (Heijne & Van der Meer, 2019). Table 5 shows the sessions' full participants list.

Table 5: Participants of the creative sessions.

Name	Session presence	Role in session	Notes
Jan-Willem van Zwieten	1 & 2	Facilitator	Remains neutral and only facilitates the participants' creative process.
Project manager	1 & 2	Problem owner	"Owns the problem and is or feels responsible for solving it." (Heijne & Van der Meer, 2019). Has extensive experience with dealing with suppliers, in and outside of ZEROe.
Engineer 1	1	Resource group member	Has experience in a previous job as an Airbus supplier. Says they are able to put themselves "in the world of the supplier". Has RFTI writing experience.
Engineer 2	1	Resource group member	Has experience in developing hydrogen equipment with suppliers and in writing RFTIs.
Engineer 4	2	Resource group member	Experienced in dealing with suppliers in ZEROe and in writing RFTIs.
Engineer 14	1 & 2	Resource group member	Is new to the ZEROe development processes and is currently writing an RFTI for the first time.
Engineer 15	1 & 2	Resource group member	Relatively new to ZEROe. Has experience with problematic supplier engagements and in writing RFTIs.
Engineer 16	1 & 2	Resource group member	New to ZEROe, has little experience with supplier engagements. Could bring in an outside perspective.

Session 1: Problem finding

To carry out the problem finding diamond of the iCPS process, the first creative session with the problem owner and the resource group is carried out. A total of one hour and thirty minutes is scheduled for it. As this first session is centred around the problem finding diamond, the starting point is a problem statement. Together with the problem owner, the following statement is defined:

"How can we improve the interaction between the engineering teams and suppliers during the RFTI-phase?"

Additionally, the problem owner highlights three topics that they believe relate to the problem:

- The **trust** between Airbus and its suppliers,
- The **value proposition** of ZEROe towards suppliers,
- The **credibility** of the ZEROe project towards suppliers.

These are included as key words next to the problem statement to be used as inspiration for the resource group.

Within each creative diamond of iCPS, there are three distinct consecutive phases: diverging, reverging, and converging. The creative tools and methods are chosen based on these phases from (Heijne & Van der Meer, 2019). Table 6 gives an overview of the tools and methods used during each of the phases. See Table 1 in Appendix D for an overview of the full session schedule.

Table 6: The problem finding diamond phases, their methods and explanations of the methods (Heijne & Van der Meer, 2019).

Phase	Methods	Explanation
Diverging	*What, When, Why, Where, Who, How? (5W1H)*	Participants were asked to answer *What, When, Why, Where, Who* and *How* questions related to the problem statement (see Appendix E for the questions). The goal of these questions is to gain a rich description of the problem statement that touches on most aspects of the problem.
Reverging	*Spontaneous clustering*	Answers to the questions in the previous phase are clustered into groups with similar themes. These themes emerge spontaneously and enable the resource group to get an understanding of the main themes in the problem landscape.
Converging	*Restating the Problem*	Based on the emergent themes from the previous phase, participants are asked to jointly develop a new problem statement. The problem statement must be Specific, Positive, Ambitious, Relevant and Simple.

The final deliverable of this first session is a reformulated problem statement that captures the essence of the problem at hand. This statement is then used as a starting point for the second session.

Session 2: Idea finding

The second session focuses on the idea finding diamond of the iCPS process. It uses the reformulated problem statement from the problem finding diamond as the starting point. Similarly to the first session, session 2 is structured in three phases: diverging, reverging, and converging. A total of one hour and thirty minutes is scheduled for the session. I selected applicable methods for each phase based on the recommendations in (Heijne & Van der Meer, 2019). A summary per phase and method is given in Table 7. The schedule of the full session can be found in Appendix D, Table 2.

Table 7: The idea finding diamond phases, their methods and explanations of the methods (Heijne & Van der Meer, 2019).

Phase	**Methods**	**Explanation**
Diverging	*Brainwriting 6.3.5*	Participants are each given a sheet with a 3 x 5 matrix on it. They are then tasked to generate three ideas to the problem statement and write them in one of the rows of the matrix sheet. In the next round, the sheet is passed on in clockwise direction to their neighbour and this continues until all five sheets contain 15 ideas. By transferring the sheets, participants can build on ideas of others to generate new ones.
	Criminal round	Participants are asked to think of ideas that are criminal in nature. This method unlocks ideas that participants are usually not willing to share. By creating an environment where it is safe to share illegal ideas, they step out of this restricting mindset. Participants reassured by the facilitator that these ideas are destroyed at the end of the session and will not be recorded in any way.
	Forced fit	In force fitting, participants are asked to turn the illegal ideas from the previous round into tamed versions that would be legal. It tries to capture the 'good' aspects of the criminal ideas which are often very out-of-the-box.
Reverging	*Spontaneous clustering*	All of the ideas from the previous phases (excluding the criminal ideas) are clustered based on emerging common themes. It gives the participants an understanding and overview of the idea/solution landscape. Once the clusters have emerged, they are each given a fitting name.
Converging	*UALo analysis*	UALo stands for Unique, Advantages, Limitations, and Overcoming limitations. Participants are asked to evaluate each of the idea/solution clusters based on these four aspects. The order is important as participants use affirmative judgement to analyse the ideas. The positives (Unique and Advantages) are discussed before the Limitations. In the end, through evaluating the pros and cons, the idea/solution cluster with the highest potential is chosen for the next phase.

Results

The two creative sessions were conducted together with all of the participants. The sessions took place with six days in between, making sure that the outcomes of the first session were still fresh on the minds of the participants. This section details summarised findings per session and elaborates on the debrief with the problem owner following session 2. A full report on the sessions including the procedures and pictures can be found in Appendix G.

Findings session 1

Session 1 showed strong evidence that the RFTI process needs reworking. There are three quotes from participants worth highlighting: *"RFTI not adapted for complex R&D, set new grounds", "Suppliers quit RFTIs/RFPs [Request For Proposal]",* and *"No document RFTI process"*. These findings support the need to tailor the process more towards the engineering team's needs.

Another aspect that was striking is summarised well in a Post-it® note from the Knowledge cluster: *"Lack of experience outside of 'comfy' legacy supplier exchange"*. This shows that the supplier engagements that the engineers currently face are less straightforward than they were used to in the legacy programs.

The resource group converged to the following reformulated problem statement:

> "How can we tailor the supplier engagement processes for ZEROe?
> - lessons learned
> - communication"

The participants included two additional topics (*lessons learned* and *communication*) into the statement as pointers for the idea finding phase.

Findings session 2

The second session started with the reformulated problem statement from Session 1. After going through the program of the session (see Appendix G for additional information), the resource group came up with four ideas. The two ideas with the largest potential are explained below. See Appendix H for explanations of the other two ideas.

1. Prototype (DMU)

The need to be better able to explain technical aspects to suppliers sparked this idea. The participants believe this could be accomplished if they could show a (3D-printed) prototype or DMU (Design Mock-Up). The DMU is a 3D drawing of a system or component that interfaces with the to-be-designed component or system (see an example in Figure 27). One of the participants reflected on an instance when they were stuck in discussions with a supplier. It was only when they showed them (part of) the prototype that all of a sudden it clicked and the discussions successfully continued. It enables suppliers to "see" what Airbus has been working on. It shows the "subconscious assumptions" that the Airbus engineers made during the design process which are not always clear on paper. Specifically on the integration aspect of a supplier's equipment into Airbus systems, it is very helpful for complex components such as hydrogen pumps.

The resource group identified IP issues as the main limitation to this idea. Sharing a prototype or a DMU with a supplier would put Airbus at risk of exposing confidential information. It could be overcome by not including sensitive parts ("black boxes"), by showing a different scale, or by only showing it on a need-to-know basis. See Appendix F Figure 1 for the outcomes of the UALo analysis for this idea.

Figure 27: 3D drawing of the Fast Make tank prototype which could serve as a boundary object. (Airbus, n.d.)

2. Define the process clearly

The fourth and last idea selected by the resource group relates to defining the RFTI/RFP processes more clearly. The participants expressed that there is some standardisation missing related specifically to the use cases within ZEROe. Having a clearer definition of the RFTI/RFP processes would lead to clearer Statements of Work & Product Technical Specification and increase the overall efficiency of the development process.

The greatest limitation to this idea relates to the alignment needed of the many different stakeholders to create a clearly defined process. Nonetheless, this could be overcome by identifying and collecting input from the various stakeholders. See Appendix F Figure 4 for the outcomes of the UALo analysis for this idea.

To come to a conclusion on which idea should be worked out further, I asked the participants one after the other which of the four ideas they believe to be the most relevant to their daily work. I gave each of the participants two votes they could place on two ideas. In the end, the Prototype (DMU) idea and Defining the process clearly tied with three points each while the Way of working got two points and Public awareness received one point.

Problem owner debrief and conclusion

The findings were debriefed with the problem owner. Having an overview 'on the wall' of the relevant topics the engineering team members face daily with regards to supplier engagement was greatly appreciated. Nonetheless, we both reflected on the fact that many of the topics that came up in the session were already identified at large during the identification phase of this research. On the one hand, this is a positive validation that the research highlights the real pain-points for the engineering teams. On the other hand, it feels like we have not made any progress on creating solutions to these pain-points. Nonetheless, the ownership of the problems is now shared more than ever among the team members which was one of the goals of these creative sessions. The Sessions section in the Reflections chapter details more reflections on this topic.

What became clear from the sessions is that the RFTI process needs reworking to fit the needs of the engineers. Therefore, it was decided that this would be the tangible deliverable that the engineers will use on a daily basis. Additionally, since there is an interplay between so many topics influencing supplier engagement, it was decided to map the evolution of these topics to two roadmaps, one strategic and one tactical. The next section goes over the design deliverables of this thesis.

Design form

From the exploratory, identification, and design phases, many different topics related to supplier engagement have become clear. One of the most relevant of these topics for this thesis is the processes that engineers use to be guided through the development of the different equipment needed for hydrogen-powered aircraft. These processes and the way they are followed highlight the mindset at Airbus and dictate the behaviour of the stakeholders within supplier engagement at ZEROe. Through the creative sessions, it has become clear that this mindset, combined with unfit processes are hindering (mostly slowing) successful technology development with suppliers. Therefore, the design should tackle both these problems.

This section details a strategic roadmap and a tactical roadmap. These roadmaps have the goal of helping (project) managers shift the mindset of the internal stakeholders to better fit the needs of the ZEROe engineers within supplier engagement. Additionally, this section highlights the improvements to the RFTI process by tailoring the communication materials that the engineers use when requesting technical information from suppliers.

Roadmaps

Roadmaps are commonly used in internal collaborations to map out resources and strategies when developing a new product/service in line with a company's vision. They serve to connect stakeholders of the collaboration around a plan (Kim et al., 2018, p.50). The Tank systems teams are mostly used to technological roadmaps with short- and long-term goals of reaching certain TRLs for the to-be-designed equipment. In the project management of ZEROe, there are also high level roadmaps, mapping the resources to the TRLs and the business objectives. However, as far as I have seen, there are currently no roadmaps taking into account explicit user needs within ZEROe, whether those 'users' are the suppliers, engineers, or future passengers. This is most likely due to the strong focus on the technological side of the developments, as is reflected by the extensive amount of internal technological roadmaps. Nonetheless, Airbus might benefit from implementing user/stakeholder centric roadmaps to complement their technological roadmaps and inform their engineering management strategies. Design Roadmaps can help display user needs and have shown to help firms embed an understanding of emerging user needs to technology development and management strategies (Kim et al., 2022).

If we consider the Tank systems engineers as 'users' of the various development processes, it seems natural that their (evolving) needs should be considered. In making these needs explicit and visual in roadmaps, it could help Airbus identify when certain processes are limiting the developments and find ways to improve them.

As a first proposal, this section details two roadmaps, one strategic and one tactical. They detail the Tank systems engineers' needs in an embedded way in what I have labelled as a ‘mindset’. This mindset shifts based on the context throughout the three horizons as the hydrogen technologies mature (adapted from Van der Linden et al., 2023). The roadmaps are meant to be used as ‘talking pieces’ within Airbus. It could be compared to the function of the aforementioned ‘boundary object’ that serves as a way for two parties to discuss the constraints and needs around an ‘object’, in this case the roadmaps (Star & Griesemer, 1989). It is a way for (project) managers to connect to internal stakeholders and discuss the challenges around an abstract topic such as supplier engagement in relation to the engineering teams’ needs. I believe the design roadmap serves this purpose as it allows to contextualise the challenges in a broader picture away from the strictly technological focus that the usual ZEROe roadmaps have. Therefore the ‘use’ of the roadmaps is not necessarily altering the timelines or shifting the components within them through time, but rather using them as supplier engagement guidelines during projects and discussions. They can serve as reminders of the importance of the engineering needs within supplier engagement in early stages. Additionally, these roadmaps serve as a visual summary of the most important findings from this research which makes it easier to handle than a long thesis report.

The following sections detail the strategic and tactical roadmaps.

Strategic roadmap

The strategic roadmap details three horizons from 2025 up until 2030 towards a future vision (see Figure 28 and Appendix I). The goal of the strategic roadmap is to link the desired mindset (with embedded engineering needs) to the support (project) managers can give to enable successful supplier engagement. Therefore, the target users for this roadmap are (project) managers.

The future vision is to have more confident supplier engagements thanks to a regained confidence in aircraft development; green hydrogen-powered aircraft development. See Appendix I for the full strategic roadmap.

FUTURE VISION

CONFIDENT SUPPLIER ENGAGEMENTS

Confidently lead component and system development for hydrogen powered aircraft. Be *the* authority with regards to green hydrogen powered aircraft development.

Figure 28: Future vision.

As was found throughout the research, engineers are not fully comfortable with the current equipment development due to the many uncertainties around the technology and the lack of expertise on hydrogen systems for aviation. Their present needs revolve around learning and developing capabilities. The future vision is to have regained the confidence in this type of development specifically for green hydrogen-powered aircraft.

Figure 29 shows part of the strategic roadmap, namely the first horizon. This horizon spans approximately two years until 2027. It highlights the desired mindset in this horizon: being humble. The mindset is not only relevant as a way to convey the engineering needs, it should also be regarded as desired for the other internal stakeholders involved such as procurement and quality managers. As Airbus does not yet have the required expertise to develop high performance liquid hydrogen fuel system equipment, it is crucial to focus on learning in this horizon. Learning can only be achieved through acquiring information from entities and experts with more knowledge. In this case, hydrogen equipment suppliers are these entities. In this horizon, it is also crucial to avoid conflicts. Conflicts are detrimental to trust building (Bstieler, 2006) and should therefore be avoided in the fragile early stages of the relationships with suppliers. This is especially important as the supplier pool is so small that

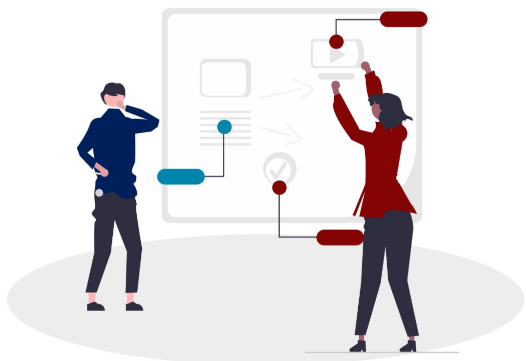
The lower section details the support (project) managers can give to the internal stakeholders to achieve the desired mindset. It suggests the (project) managers to continuously ask themselves the following question: *'How can I make my engineers learn as much and as quickly as possible?'* and adjust their management strategies accordingly.

The other two horizons are structured in a similar way to horizon 1. I invite the reader to Appendix I to explore the full strategic roadmap.

HORIZON 1 2025

MINDSET **BE HUMBLE**

Acknowledge that there is a knowledge and expertise deficit. Focus on **learning** as part of the TRL3 efforts. Be as **transparent** about your architectural considerations as you can. Start **building relationships**. **Avoid conflicts** at all costs to avoid scaring potential partners at the start. Break away from strict **contract dominant engagements**, you will not get the perfect price and delivery anyway in this phase.



Learn from your supplier's expertise

SUPPORT **Support learning**

*Enable the engineers to rapidly learn by encouraging early **intensive interactions** with (potential) suppliers. Send them on visits, have them test and **validate very early prototypes** with suppliers. **Compensate suppliers** for their efforts. Keep the technical explorations as **open** as possible, shielding the engineers from **unnecessary contractual discussion** and supporting them in **simplifying specifications**. Repeatedly ask yourself the question 'How can I make my engineers learn as much and as quickly as possible?'*

Figure 29: Horizon 1

Tactical roadmap

The tactical roadmap is meant to dive deeper into the mindset shift by linking and contextualising it with the development streams, value proposition, development deliverables, assets and processes, and the interaction balance between engineering and procurement. The target users of this roadmap are (project) managers and the Tank systems engineering team members. The roadmap is split into a bottom and a top section. In the top section, the mindset shift is detailed together with visualisations of the development streams and the value proposition towards suppliers throughout the horizons. The bottom section shows a singular equipment development process which is not necessarily linked to the three horizons timeline of the full ZEROe project. The length of such a development process depends on the type of equipment so the timeline can not be generalised. As was mentioned earlier, the RFTI process needs tailoring to the needs of the ZEROe project. The bottom section of the tactical roadmap summarises the splits in deliverables that were previously ambiguous between the RFTI and RFP phases. This has been done in several sessions with two Tank systems engineers. More on this will be discussed in the following section. Refer to the confidential Appendix J for the full tactical roadmap.

The tactical roadmap details the mindset shift through four key topics from the research findings: learning, uncertainty, relationship management, and tone-of-voice (see Figure 30). These topics have their counterparts in the future vision at the end of horizon 3: *deep expertise, certainty, trusting partnerships,* and *confidence*. Throughout the horizons, the mindset feeding the transition between these topics is highlighted. It starts with a negative mindset in pink and moves to the blue desired mindsets positioned at different stages of the horizons, dependent on the developments and context. The goal of this visualisation is to illustrate the behavioural change that is proposed through the mindset shift.

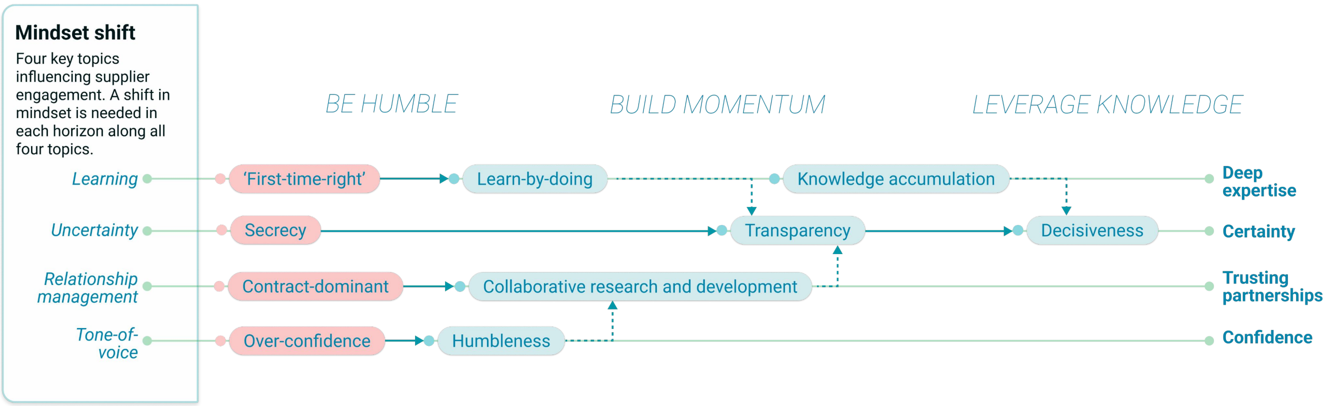


Figure 30: The mindset shift stream of the tactical roadmap.

As mentioned, the bottom section details the equipment development process in more detail. Figure 31 shows the assets and processes in the equipment development linked to the interaction balance with suppliers between engineering and procurement. This visual serves as a simple generalisation of the development process to illustrate what assets Airbus can leverage in each phase of the development. Additionally, the visual shows the supplier interaction balance between engineering and procurement. During interactions with suppliers, both engineering and procurement are involved. Currently, these interactions are led by procurement which in some cases leads to an emphasis on the commercial side of the collaboration. Especially in the early stages where learning is the most important, it would be better to have the interaction be balanced more towards engineering topics. Then, once the relationship becomes more serious and some of the uncertainties have been clarified, procurement should become more involved to make sure a good commercial deal is created. Of course, the two departments support each other throughout the development process which is also indicated in the visual.

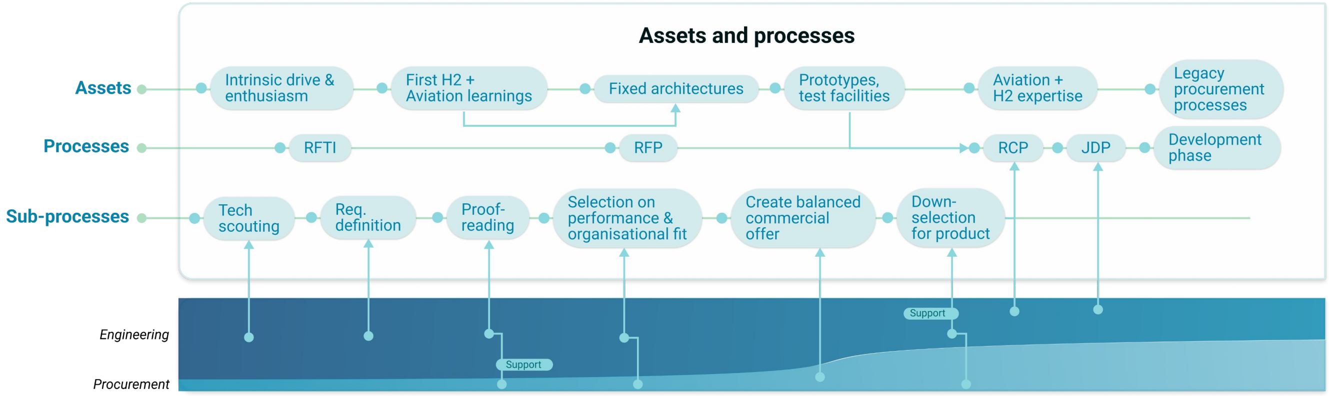


Figure 31: Assets, process, and interaction balance linked and visualised.

The next section details how the RFTI process has been tailored to suit the needs of the engineering team members.

Implementation of tailored RFTI process

Next to the two roadmaps aimed at (project) managers, the design deliverables should also be usable for the engineering team members. To this end, I discussed with two Tank systems engineers how they would tailor the RFTI process to their needs. They were in the process of writing the RFTI for equipment in the fuel system which would be sent out to suppliers in the following weeks. In writing this document, they followed an internal process that details all of the deliverables that need to be delivered and validated at each development phase (see Figure 8 in Background). Many of the data that make up these deliverables will come from suppliers (e.g. durability test data). For the RFTI, the internal process does not detail any deliverables, it is only at the RFP phase that many deliverables are requested. As we have seen, requesting many of these data to develop the deliverables at once can overwhelm suppliers. To smooth the amount of requested data to validate the requirements from the suppliers over the development phases, we decided to split the deliverable list for the RFP phase and request some data during the RFTI. To illustrate this split, an example is given of one of the deliverables: Development plan (see ‘Plans’ under ‘Development deliverables’ in the Tactical roadmap and Figure 32).

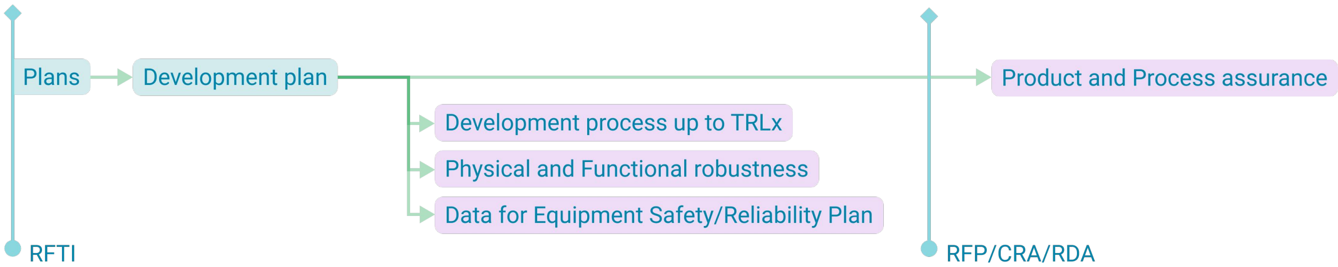


Figure 32: Split between Development plan deliverables in the RFTI and RFP phases.

As can be seen from Figure 32, the Development plan deliverable (in blue) holds four sub-deliverables (in pink). The split between what is requested in the RFTI versus what is requested in the RFP was made based on roughly two aspects:

1. Complexity and workload for the suppliers to deliver the requested data
2. Importance of the data to enable a robust down-selection of the supplier proposals

In the case of the Development plan deliverable, the engineers found it important to ask the suppliers in the RFTI for a development process, the physical and functional robustness of the equipment, and data on the proposed equipment's safety and reliability. It was decided that the product and process assurance was something that could be requested in the RFP phase as this is something that is hard to deliver data on and is too time consuming in the very early stages of equipment development. The Development plan was one of over ten deliverables that were considered and split between the RFTI and RFP phases. The full split can be found in the tactical roadmap in confidential Appendix J.

Another aspect of requesting data for these deliverables from suppliers is the form of the data request. The form of the request is not described in the internal process, resulting in widely varying descriptions between different RFTIs, and hence widely varying responses from suppliers. To implement some of the learnings from this thesis into a live RFTI, I was requested by the aforementioned engineers to go through the document and suggest changes. The major proposed changes are summarised in the list below:

1. **Closed questions**: Many of the questions to the suppliers were closed questions. Based on the research in this thesis, open questions solicit richer responses which enables learning. This is crucial in early stage technology development. Therefore, the questions were reformulated to open questions.
2. **Sense of influence**: Many of the passages of text include commanding language (e.g. *"The supplier shall provide detailed performance figures"*). Although this is necessary for the requirements, it deteriorates the sense of influence the supplier has on the potential collaboration. Therefore, passages were added emphasising that the supplier has influence on the architectures and the decision-making process within Airbus: *"This is an opportunity for suppliers to gain a head start and pioneer hydrogen-powered commercial aviation together with Airbus by developing* [equipment] *for a hydrogen aircraft fuel system and influencing the* [equipment] *architecture of the hydrogen aircraft fuel system."*
3. **Follow up meetings**: As was highlighted in this research, one of the keys to successful engagement is regular exchanges (see Results section Group 1). Passages were added to the RFTI encouraging the suppliers to contact and meet with Airbus throughout the writing of their proposals to clarify uncertainties: *"The supplier is encouraged to request a follow up meeting with Airbus to ask for clarification of the RFTI, receive further guidance on the expected technical response and provide initial feedback to Airbus."*

4. **Visualisation of development process**: The request to suppliers to deliver a development process up to a TRL was made in text in the RFTI. This resulted in widely varying responses. Some proposals included detailed roadmaps while others just included a small table of expected milestones. This makes it difficult to compare apples to apples between proposals. I suggested to include a visualised example of what was expected for the development process. As this was a debated topic, it is discussed in more detail in the Validation section of this chapter.

The Validation section will go over iterations of the design based on the stakeholder feedback. Specifically for the tailored RFTI process, this section will clarify the details of the implementations.

Validation

To validate the designs made, I discussed and tested the design proposals with the relevant Tank systems team members. Additionally, I implemented the learnings from this research into a live RFTI document used in supplier engagements. This section rolls back the design phase and discusses the evolutions of the design proposals. Stakeholder feedback is discussed and implemented.

Roadmaps validation

The first version of the strategic and tactical roadmaps was presented to the company's internal stakeholders to gather their thoughts and feedback. As many of the improvements have been made in small steps, the validation is described in two major iterations.

Iteration 1

In order for the internal stakeholders to understand the required mindset shift, it is important to understand the context. This includes aspects that the engineering team members cannot control but still influence the mindset of the internal stakeholders. To implement this feedback, an additional row was added to the strategic roadmap detailing the context (see Figure 33).

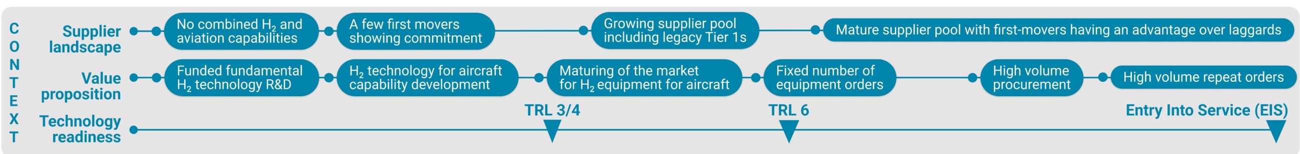


Figure 33: Context row in strategic roadmap.

In order to use the strategic roadmap in internal discussions in the future, the internal stakeholders gave feedback on what should be included in the context: 'ZEROe strategy', 'business case', and an 'overall supplier landscape'. Additionally, the feedback suggested to include some of the 'carrots' that Airbus has to engage suppliers. I translated that feedback into three topics:

1. **Supplier landscape**: describes the evolution of the supplier landscape through the horizons.

2. **Value proposition**: describes what Airbus can offer suppliers (‘carrots’) and which major opportunities arise throughout the horizons.
3. **Technology readiness**: describes to what levels the technologies should mature at system level throughout the horizons.

The mindset shift and the support needed to achieve it are better contextualised by detailing these three topics within the strategic roadmap.

Regarding the tactical roadmap, the first version detailed specific amounts of requirements per horizon for simple, moderate, and complex equipment types (see Figure 34). The idea was to give engineers targets per phase so that they would not create an unnecessarily high number of requirements which would scare away suppliers at the start. When presenting this to the internal stakeholders, they agreed that the amount of requirements should be limited, but putting a number to it could be misleading and counterproductive. Each equipment is different and requires careful consideration of the required amount of requirements.

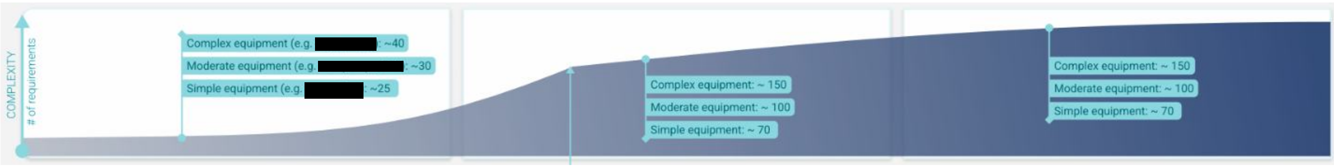


Figure 34: Removed row from tactical roadmap.

Nonetheless, the idea of building up the complexity by tailoring the workload throughout the development was positively received. This led to the idea of splitting the requested data for the deliverables between the RFTI and RFP phases based on what the engineers deem to be required in each. This was implemented into the tactical roadmap (see Figure 32 as an example).

Iteration 2

In a second iteration of the tactical roadmap, I added the three major development projects within ZEROe: ground demonstrators, flight demonstrators, and products. This came from feedback expressing the need to have a visual high level perspective of what the technological developments are. This way, it could be easier to align the understanding of the development steps. Figure 35 shows these development steps. Making them visual in a simple way makes it easier to relate to the proposed mindset per horizon.

Figure 35: Major development projects visualised per horizon.

Tailored RFTI process validation

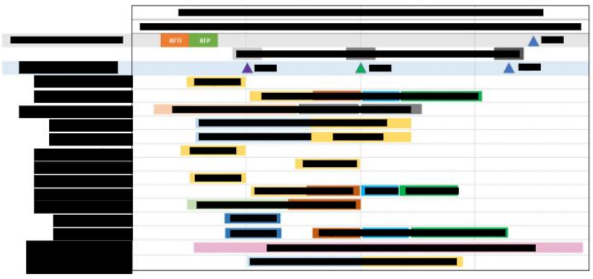
The learnings uncovered in this research were implemented in a live equipment RFTI document. Together with the engineers working on the RFTI, I discussed possible improvements and additions as mentioned in the above sections. Most adjustments were accepted but there was resistance towards implementing visualisations of the development process. This section discusses this in more detail.

To gather the needed data to make a realistic development process for the to-be designed equipment, the engineers request the suppliers to propose a timeline/roadmap that aligns with the TRL timeline Airbus has set. This request is formulated in a short piece of text, see the example below:

“The supplier shall propose a high level roadmap to develop its technology, with support from Airbus, up to TRL6. The roadmap should consider key steps required to achieve the TRLs at the development target dates [...]. *The development roadmap to achieve TRL6 should consider the technical gaps to close and some consideration on how to extend the technology performances to the aircraft requirements when needed.”*

When suggesting to include some kind of visualisation of the start of the development process as a guidance, the idea was met with resistance. The engineers argued that the text describing Airbus’ desired TRL milestones and the request to develop a high level roadmap were sufficient guidance for the suppliers.

Supplier 1



Supplier 2

Milestone	Due Date
Request for Information (RFI) Proposal Submittal	[redacted]
Concept Selection [redacted]	[redacted]
Product Selection [redacted]	[redacted]
Product Design	[redacted]
Entry into Service	[redacted]

Figure 36: Difference between supplier responses to the request of delivering a development roadmap.

When presenting the difference between the supplier responses to this request from previous RFTIs, it became clear that the suppliers’ responses varied wildly. Figure 36 shows just two examples of the response to this request. Supplier 1 delivered a very detailed roadmap that includes many intermediate milestones and activities while Supplier 2 delivered a simple table with only basic development information. The engineers acknowledged that giving more visual guidance could be beneficial to improve the comparability between supplier proposals and hence enable a more informed down-selection.

Additionally, I suggested requesting information on a ‘usual’ development process for the type of equipment from suppliers. For example, how does a normal development of a new liquid hydrogen pipe (e.g. for industrial uses) usually go? This could serve as a reference for the Airbus engineers to understand how much their request deviates from what the suppliers are usually able to develop and consequently adjust their expectations. After several iterations, a simple roadmap template was made (see Figure 37) and an accompanying text was written based on the existing text (with adjustments in red) to be included in the request to suppliers:

"The supplier shall propose a high level roadmap to develop the requested equipment based on its experience from prior development roadmaps for similar equipment. A blank template is given in section X which serves as an example of what is expected in a response as a minimum. The roadmap should consider key steps required to achieve the TRLs at the development target dates stated in section X. The development roadmap to achieve TRL6 should consider the technical gaps to close and some consideration on how to extend the technology performances to the aircraft requirements when needed. Does the supplier foresee deviations from a traditional development roadmap? If so, the supplier is requested to elaborate on these deviations and explain their causes."

Activities	TRL3 <date>			TRL4 <date>			TRL6 <date>		
Concept selection									
Finalise design concept									
Prototyping									
Testing									
Qualification testing									

Figure 37: Development roadmap template to be used as a reference for suppliers.

The roadmap template includes the target TRLs and the dates at which Airbus wishes to reach them for the requested equipment. On the rows of the template several activities are mentioned: Concept selection, Finalise design concept, Prototyping, Testing, and Qualification testing. These activities are deduced from previous supplier RFTI responses and offer a way to structure the high level roadmap. Suppliers are encouraged to add or remove activities and fill in the roadmap however they feel is fit. Appendix K details the considerations, feedback, and iterations I went through to arrive at this final design proposal.

Although many of the design proposals were validated with the Tank systems engineers and improvements were implemented into live RFTI documents, not all proposals were directly implemented into the development process. I felt that some suggestions came too early for the engineers, especially with regards to the visualisation aspects. More reflections on this topic can be found in the Reflection chapter.

Conclusion

The goal of the research phase of this thesis is to uncover the drivers of supplier engagement in early stage technology development in the context of hydrogen propulsion technology development for aircraft. Through the research findings, it can be concluded that there are two major forces at play driving supplier engagement:

1. **Uncertainty** around the development of hydrogen technologies for aircraft. This is mostly technological uncertainty but commercial and organisational uncertainty also play significant roles.
2. **Legacy ways of working** dominate the development of liquid hydrogen equipment which slows down and hinders supplier engagements in this early stage.

In the design phase, two design interventions are implemented with the aim to improve supplier engagement. The first intervention consists of design roadmaps which inspire a mindset shift of the internal stakeholders away from legacy ways of working in early stage development. The roadmaps highlight the engineering needs of the equipment development within ZEROe. The second intervention is the tailoring of the communication materials for the Request For Technical Information (RFTI) process in which Airbus engineers interact with suppliers in early stages. Through spreading the workload and complexity of the deliverable requests to suppliers across the early development stages, suppliers will be less overwhelmed and less likely to quit the engagement early on.

With these two design interventions, a start has been made to improve the supplier engagement within liquid hydrogen propulsion equipment development at ZEROe. Nonetheless, the challenges around supplier engagement are multi-faceted. Solving the challenges related to uncertainty in this domain will require time and behavioural change within Airbus. The roadmaps will serve as kickstarters for internal discussions around this topic. Through implementing the findings from this research into live RFTI documents, tangible improvements have already been made. The topic is now on many of the internal stakeholders’ radar which makes it more likely that improvements will follow.

Reflection

This section details reflections about the research process and the writing of the thesis. It is written along the way of the project to capture as many reflective moments as possible.

Research execution

Although the research approach was mostly structured, it was not always easy to collect the data in a fully structured and complete way. This section goes over some of the inconsistencies that occurred throughout the execution of the research method. As they are mostly unrelated to each other, the points are described in distinct paragraphs. The reliability and validity of the research is discussed in the next section.

1
In gathering data from observational studies, there was no plan beforehand on which meetings I would attend. The meetings were attended based on invitations from the internal stakeholders. Although this could have impacted the research results' validity, I do not believe it did in a major way. Since the body of collected data is rather big and the types of meetings that I attended covered many different types, I believe that there is sufficient coverage of the context.

2
Data gathering between observational studies varied slightly. As all notes were taken by me, some discussions were captured more richly than others. This depended on my focus but also on the participants in the meeting. Some discussions were easier to follow and to document than others. For example, discussions with an American supplier were easy to follow whereas discussions with a Japanese supplier were harder to follow due to a language barrier.

3
Interview transcripts first included negative formulations of questions. For example, participants were asked about “pain-points”. After discussions with the university coaches, these questions were reformulated into more neutral questions.

4
After being in the team for a month and a half, I realised that I had a biassed perspective on what was going on in the research. I had taken some of the input from the engineering team for granted and considered it as ‘how it is’. In a meeting with one of my university supervisors, they asked me if I contested the form and purpose of a graph that one of the engineering team members showed me during an interview. I had not even thought of contesting it at that moment as the purpose of the graph seemed totally clear to me. It was only when my supervisor started asking questions about it that I realised that I lost a bit of the ‘outsider’ perspective which I had at the start of the research project. This moment showed me that it is important to keep reflecting on this topic to be aware of my own personal biases which apparently also emerge during the research process. With this increased awareness, I continued the research being open to the participants’ inputs while staying critical and reflective to be able to accurately record and process their experiences (Dwyer & Buckle, 2009).

Validity, reliability and generalisability

I deem the validity of the research outcomes to be adequate thanks to the context in which it takes place. Due to my integration as an action researcher into an environment where supplier engagements take place in early stage technology development, the collected data are rich and 'real'. Data were gathered from different sources (documents, interviews, observational studies) and were validated through workshops with the stakeholders. As the same findings emerged throughout, I deem the outcomes reliable for this context. It does beg the question if the findings are generalisable to other contexts. For example, the findings relating to the difficulties of developing equipment due to aircraft requirements is specific to the aeronautics industry. Nonetheless, there are many other industries with stringent safety requirements such as the chemical and nuclear industries for which the research outcomes could also be applicable.

A critique can be given on the sampling for the interview participants. Due to convenience, four out of ten interview participants were Tank systems engineers which means that this perspective is overrepresented in the dataset. Since the engineering perspective is the focus of this research, I believe that this overrepresentation is not necessarily bad. For the identification phase, it was my intention from the start to identify challenges in the context of the Tank systems teams. For the design phase, I tested and deployed design interventions within the Tank systems teams context. Therefore, it was important to have the perspective of the Tank systems engineers clear.

Sessions

In the debrief with the problem owner, we came to the conclusion that many of the outcomes of the sessions were already found during the earlier research phases. This could have been due to the formulation of the first problem statement which was not clear enough in hindsight. Perhaps a different approach than iCPS could have been taken which would have been more efficient. I could have presented the results from my research and ideated on solutions together with the Tank systems engineers. However, there would have been less ownership of the problems and it would have taken away the possibility to validate the research findings. Since the sessions gave similar results to the prior research phase, it is a positive confirmation that what I found was actually happening.

Additionally, the fact that the sessions did not result in one concrete solution is a key indicator that supplier engagement is multi-faceted. The challenges around engaging a supplier for early stage liquid hydrogen equipment development are not just technical, they are financial (e.g. self-funding), commercial (e.g. IP), and even organisational (e.g. communication forms). This supports the need for behavioural change within the Airbus as a way to tackle these challenges at once.

Applying strategic design methods to a technological context

This thesis project is not a traditional design project. I have not designed a new product or service concept. However, I have used methods from the strategic design field to explore and identify challenges to which solutions can be found. The design roadmaps are a concrete example of this. As far as I have found in literature, using design roadmaps to map behavioural change in an organisation is novel. There is a large body of literature on design for behaviour change (Cash, 2022) and a growing body of literature on design roadmapping (Kim et al., 2015). A combination of both in a technology-centred organisational context has not been explored extensively yet, to my knowledge. The Limitations & Further research chapter elaborates more on this topic.

With regards to the implementation of incremental improvements to the RFTI process and its communication materials, most of the proposed changes were implemented. However, and as mentioned in the Validation section of the Design phase chapter, I felt resistance towards implementing more visual tools into the communication materials. Perhaps this highlights a design-centric versus engineering-centric way of thinking. I found it interesting to reflect on this topic as it is something I had not yet experienced throughout my studies at Industrial Design Engineering. Future research could explore how these different ways of thinking influences supplier engagement in these contexts.

Recommendations

This section goes over the main recommendations that flow from the research findings. It is split into three sections covering communication, collaboration, and development processes.

Communication

As good communication is one of the most important factors driving supplier engagement (Tidy et al., 2016), and timely, reliable and adequate communication are essential for trust creation between Airbus and its suppliers (Bstieler, 2006), it is of utmost importance that managers manage these communication streams effectively. The Airbus ZEROe context is especially sensitive to ways of communicating due to the Airbus name that is attached to the project. This name carries expectations and prejudices of which some are detrimental to the supplier engagement. Take for example Imperative 3 of the Airbus tone-of-voice taken from the official website (see Figure 38):

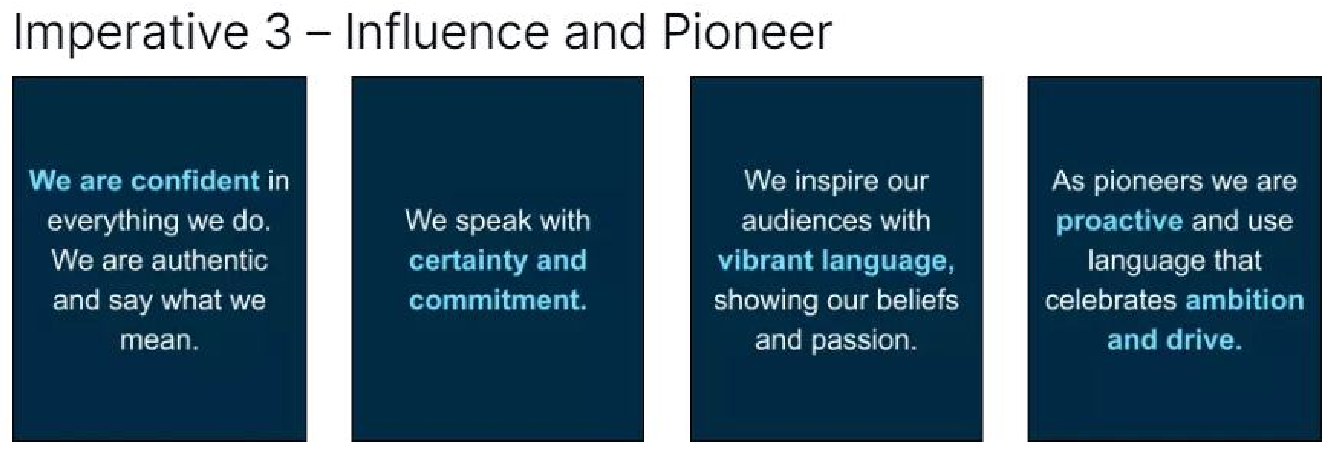


Figure 38: Airbus tone-of-voice (Airbus, n.d.).

This imperative states that Airbus employees are confident in everything they do and that they speak with certainty. For the legacy aircraft programs, this might be true. Airbus has been building kerosene aircraft for decades and knows exactly what works and what does not. However, in the highly uncertain ZEROe environment, it is very hard for the engineers to uphold this imperative. In trying to do so, there is a chance of overconfidence (see Tactical roadmap in confidential Appendix J). This can be interpreted as arrogance by suppliers, especially when the topic of discussion is not within Airbus' field of expertise (i.e. hydrogen).

Therefore, managers should be sensitive to the communication behaviour of not only their engineers but also the other internal stakeholders towards suppliers. The usual Airbus tone of voice is not always adequate for the types of early stage engagements that ZEROe is in. Managers should also be aware of the reputation Airbus has from past experiences with suppliers from both the legacy programs and the past ZEROe interactions. This reputation should be compensated for in order to regain suppliers' trust. This is especially important while Airbus is in this vulnerable (non-expert) position.

Open collaboration

Airbus adheres very strictly to fair competition rules to make sure all suppliers are treated equally. This is extremely important, especially in highly competitive environments to ensure there is a level playing field for all competitors. However, there is no hydrogen aviation playing field yet. Airbus (and its potential partners) are in a phase of exploring the 'field' of hydrogen systems for aviation. Once this is established, only then will there be 'play' in the form of fierce competition between companies to win bids for hydrogen equipment and systems.

These fair competition practices take a lot of time and effort which slows down the development. On top of that, smaller companies in this space are under less scrutiny to adhere to these same principles, giving them an edge over Airbus in technology development speed. The ethics & compliance processes regarding supplier engagement should NOT be discarded, let that be clear. Nonetheless, I do believe it is important to realise that this is an aspect that plays a role.

A recommendation to this point could be to experiment with more open and collaborative ways of exploring the field of hydrogen aviation technologies in these early stages. For example, making use of just an NDA up to a certain TRL level to avoid long IP discussions and conflicts that could bite back later on. Once the technology is deemed promising enough, more elaborate contractual obligations with regards to IP can be put in place. This would enable faster learning for Airbus and lower the threshold for (small) suppliers to explore opportunities together with Airbus.

Development processes

Many of the technologies that are being developed within the Tank systems teams are at a low TRL and outside of Airbus' core expertise. Nonetheless, the TRL development timelines for these equipment have been set and planned far ahead. In the early phases of the development process, it seems more logical to have the suppliers define TRL timelines for the development of the requested equipment, perhaps jointly with Airbus through roadmapping activities. Of course, Airbus can define the system level TRL timelines but this should be based on how long the equipment development takes and this cannot be judged without extensive information from suppliers.

When considering the development processes for the equipment themselves, there should be clearer definitions of the RFTI and RFP processes. The requested deliverables and the data that are contained within them should be scrutinised together with suppliers to come to a generalised Data Requirement List for this type of development. Having this would lead to clearer Statements of Work & Product Technical Specifications and increase the overall efficiency of the development process.

This research found that most of the uncertainty in the project relates to technological uncertainty (see page 40). To lower the uncertainty in this regard, learning should be the highest priority within this phase. As stated in horizon 1 of the strategic roadmap, managers should support and facilitate learning potential for their engineers.

Limitations & further research

The research performed in this thesis has several limitations. This section highlights the most important limitations and details further research

A first limitation is the generalisability of the results of this research to other contexts. Since it takes the case of liquid hydrogen equipment development for aircraft, there are some specificities that might not occur in early stage technology development in other industries. For example, the research found that the safety focus was one of the drivers of poor supplier engagement. In a context where new technology is developed without a strong focus on safety, the findings might not be applicable. Nonetheless, the results are relevant for early stage radical technology development within the aeronautical industry.

A second limitation has to do with the design outcomes. As Airbus has a successful current business, there are tensions between the current and the future business (e.g. development processes used). This tension has driven me to design for behavioural change through defining a mindset-shift and implementing it in design roadmaps. In situations where early stage technology development does not take place at an organisation where such tensions exist, these design interventions might not be relevant.

There are several topics that are relevant for further research. One of them is defining the incentives for suppliers to engage in joint technology development when there are large technological uncertainties. This is a topic the Airbus stakeholders have identified as relevant for future research. Additionally, the use of design roadmaps to solicit behavioural change within an organisation is something that should be further explored. The roadmaps developed in this thesis can be used as starting points for this purpose.

Literature

Airbus. (2023, January 10). *Airbus and VDL Group join forces to produce an airborne laser communication terminal.* https://www.airbus.com/en/newsroom/press-releases/2023-01-airbus-and-vdl-group-join-forces-to-produce-an-airborne-laser

Airbus. (2023). *Development flow.* Unpublished internal company document.

Airbus. (2023). *Manage Airbus Systems Suppliers (MASS).* Unpublished internal company document.

Airbus. (n.d.). *Airbus Aerostack.* https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe/airbus-aerostack-gmbh

Airbus. (n.d.). *Airbus and CFM International to pioneer hydrogen combustion technology.* https://www.airbus.com/en/newsroom/press-releases/2022-02-airbus-and-cfm-international-to-pioneer-hydrogen-combustion

Airbus. (n.d.). *Our History.* https://www.airbus.com/en/our-history

Airbus. (n.d.). *Program Preparation Phase*. Unpublished internal company document.

Airbus. (n.d.). *Tone of Voice.* https://brand.airbus.com/en/guidelines/publish/tone-of-voice

Airbus (n.d.). *What we do*. https://www.airbus.com/en/what-we-do

Amir, A. R., & Weiss, S. I. (2024). *Boeing Company | Description, history, & Aircraft*. Encyclopedia Britannica. https://www.britannica.com/topic/Boeing-Company#ref754473

Awan, U., Sroufe, R., & Krasławski, A. (2019). Creativity enables sustainable development: Supplier engagement as a boundary condition for the positive effect on green innovation. *Journal of Cleaner Production, 226*, 172–185. https://doi.org/10.1016/j.jclepro.2019.03.308

Backhurst, J., & Harker, J. (2001). Pumping of fluids. In *Elsevier eBooks* (pp. 109–124). https://doi.org/10.1016/b978-0-08-049422-7.50012-2

Bcomp. (2023). *AmpliTexTM - BComp.* https://www.bcomp.ch/products/amplitex/

Bidault, F., Despres, C., & Butler, C. (1998). New product development and early supplier involvement (ESI): the drivers of ESI adoption. *International journal of technology management, 15*(1-2), 49-69.

Blessing, L. T., & Chakrabarti, A. (2009). *DRM: A design reseach methodology* (pp. 13-42). Springer London.

Boeing. (2020, January 25). *Meet the 777X*. Retrieved February 23, 2024, from https://www.boeing.com/commercial/777x#overview

Bowen, G. A. (2009). Document Analysis as a Qualitative Research Method. *Qualitative Research Journal, 9*(2), 27-40. https://doi.org/10.3316/QRJ0902027

Bstieler, L. (2006). Trust formation in collaborative new product development. *Journal of product innovation management, 23*(1), 56-72.

Buijs, J. A., & van der Meer, J. D. (2013). *Integrated creative problem solving.* Eleven international publishing.

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C. H., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C. D., . . . Ha, M. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* https://doi.org/10.59327/ipcc/ar6-9789291691647

Cash, P., Gamundi, X. V., Echstrøm, I., & Daalhuizen, J. (2022). Method use in behavioural design: What, how, and why?. *International Journal of Design, 16*(1).

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*. SAGE.

Cooper, R. G. (2000). Winning with new products. *Ivey Business Journal, 64*(6), 54-60.

Copernicus. (2024, February 5). *Copernicus: February 2024 was globally the warmest on record – Global Sea Surface Temperatures at record high.* https://climate.copernicus.eu/copernicus-february-2024-was-globally-warmest-record-global-sea-surface-temperatures-record-high

Cummings, M. L. (2020). Factors that Influence the Acceptance of New Aerospace Risk Assessment Techniques. *AIAA Scitech 2020 Forum.* https://doi.org/10.2514/6.2020-0707

Drisko, J. W., & Maschi, T. (2016). *Content analysis.* Pocket Guide to Social Work Re.

Dwyer, S. C., & Buckle, J. L. (2009). The Space Between: On Being an Insider-Outsider in Qualitative Research. *International Journal of Qualitative Methods, 8*(1), 54-63. https://doi.org/10.1177/160940690900800105

EASA. (2018). Proposed Special Condition on Folding Wing Tip on CS 25.415, 25.703, 25.1385 at Amdt 18. In *EASA*. Retrieved February 23, 2024, from https://www.easa.europa.eu/en/downloads/46782/en

Edwards, T. (2002, July). " Kerosene" Fuels for Aerospace Propulsion-Composition and Properties. *In 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit* (p. 3874).

Farokhi, S. (2014). *Aircraft Propulsion.* John Wiley & Sons.

Federal Aviation Administration [FAA]. (2024, January 21). *FAA statement on recommending visual inspections of Boeing 737-900ER Mid-Exit door plugs*. Federal Aviation Administration. Retrieved February 15, 2024, from https://www.faa.gov/newsroom/faa-statement-recommending-visual-inspections-boeing-737-900er-mid-exit-door-plugs

Gangoli Rao, A. (2015). Ahead: paving the way for next generation aircraft and engine. *AeroDays*. London: United Kingdom.

Gibbert, M., & Scranton, P. (2009). Constraints as sources of radical innovation? Insights from jet propulsion development. *Management & Organizational History, 4*(4), 385-399.

Goraj, Z. (2016). Design and optimisation of fuel tanks for BWB configurations. *Archive of Mechanical Engineering*, 605-617.

Grabaskas, D. (2022). Risk Management and Risk Aversion, from Benefit to Impediment. *16th Probabilistic Safety Assessment and Management Conference*. https://www.anl.gov/argonne-scientific-publications/pub/175401

Haglind, F., Hasselrot, A., & Singh, R. (2006). Potential of reducing the environmental impact of aviation by using hydrogen Part I: Background, prospects and challenges. *The Aeronautical Journal (1968), 110*(1110), 533–540. doi:10.1017/S000192400000141X

Hall, N. (Ed.). (2021, May 13). *Turbofan Thrust*. Retrieved April 4, 2024, from https://www.grc.nasa.gov/www/k-12/airplane/turbfan.html

Heijne, K., & Van Der Meer, H. (2019). *Road map for creative problem solving techniques: organizing and facilitating group sessions*.

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., & Hanke-Rauschenbach, R. (2022). Hydrogen-powered aviation and its reliance on green hydrogen infrastructure–review and research gaps. *International Journal of Hydrogen Energy, 47*(5), 3108-3130.

Huete, J., Nalianda, D., & Pilidis, P. (2021). Propulsion system integration for a first-generation hydrogen civil airliner? *The Aeronautical Journal, 125*(1291), 1654–1665. https://doi.org/10.1017/aer.2021.36

IATA (International Air Transport Association). (2021, October 4). *Net-Zero Carbon Emissions by 2050*. Retrieved March 11, 2024, from https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/

Johnsen, T. E. (2009). Supplier involvement in new product development and innovation: Taking stock and looking to the future. *Journal of Purchasing and Supply Management, 15*(3), 187-197.

Kim, E., Beckman, S. L., & Agogino, A. (2018). Design roadmapping in an uncertain world: Implementing a customer-experience-focused strategy. *California Management Review, 61*(1), 43-70.

Kim, E., Simonse, L., Beckman, S. L., Appleyard, M. M., Velazquez, H., Madrigal, A. S., & Agogino, A. M. (2022). User-Centered Design Roadmapping: Anchoring roadmapping in customer value before technology selection. *IEEE Transactions on Engineering Management, 69*(1), 109–126. https://doi.org/10.1109/tem.2020.3030172

Kim, E., Yao, S., & Agogino, A. M. (2015). Design roadmapping: Challenges and opportunities. In *DS 80-6 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 6: Design Methods and Tools-Part 2 Milan, Italy, 27-30.07. 15* (pp. 085-094).

Langton, R., Clark, C., Hewitt, M., Richards, L., Moir, I., & Seabridge, A. (2009). *Aircraft fuel systems*. John Wiley & Sons.

Lufthansa Technik. (n.d.). *Cabin interior made from renewable material for environmental-friendly cabin concepts.* Retrieved February 22, 2024, from https://www.lufthansa-technik.com/en/aeroflax

Mangold, J. (2021). Economical assessment of hydrogen short-range aircraft with the focus on the turnaround procedure. *ResearchGate*. https://www.researchgate.net/publication/352816096_Economical_assessment_of_hydrogen_short-range_aircraft_with_the_focus_on_the_turnaround_procedure

McIvor, R., & Humphreys, P. (2004). Early supplier involvement in the design process: lessons from the electronics industry. *Omega, 32*(3), 179-199.

Melander, L., & Tell, F. (2014). Uncertainty in collaborative NPD: Effects on the selection of technology and supplier. *Journal of Engineering and Technology Management, 31*, 103-119.

Mikkola, J. H., & Skjøtt-Larsen, T. (2003). Early Supplier Involvement: Implications for New Product Development Outsourcing and Supplier-Buyer Interdependence. *Global Journal of Flexible Systems Management, 4*(4), 31-41.

Murman, E. M., Walton, M., & Rebentisch, E. (2000). Challenges in the better, faster, cheaper era of aeronautical design, engineering and manufacturing. *The Aeronautical Journal, 104*(1040), 481–489. doi:10.1017/S0001924000091983

Ng, K. S., Farooq, D., & Yang, A. (2021). Global biorenewable development strategies for sustainable aviation fuel production. *Renewable and Sustainable Energy Reviews, 150*, 111502.

Norman, D. A., & Verganti, R. (2014). Incremental and radical innovation: Design research vs. technology and meaning change. *Design issues, 30*(1), 78-96.

Ogston, A. R. (1981). A Short History of Aviation Gasoline Development, 1903—1980. *SAE Transactions, 90,* 2587–2600. http://www.jstor.org/stable/44643969

Olson, E. M., Walker Jr, O. C., & Ruekert, R. W. (1995). Organizing for effective new product development: The moderating role of product innovativeness. *Journal of marketing, 59*(1), 48-62.

Perry, D. (2023, September 7). *EasyJet wants to be 'first customer' for Airbus ZEROe aircraft: Lundgren. Flight Global.* https://www.flightglobal.com/airlines/easyjet-wants-to-be-first-customer-for-airbus-zeroe-aircraft-lundgren/154826.article

Primo, M. A., & Amundson, S. D. (2002). An exploratory study of the effects of supplier relationships on new product development outcomes. *Journal of Operations management, 20*(1), 33-52.

Rolls Royce plc. (1996). *The jet engine (5th ed.).* Wiley.

Saldaña, J. (2021). *The Coding Manual for Qualitative Researchers.* SAGE.

Smithsonian's National Air and Space Museum. (n.d.). *1903 Wright Flyer Engine Diagram.* Retrieved February 22, 2024, from https://airandspace.si.edu/multimedia-gallery/gl-107-280-015jpg

Smithsonian, National Air and Space Museum. (n.d.). *Heinkel (von Ohain) HeS 3B Turbojet Engine, Reproduction.* Retrieved February 22, 2024, from https://airandspace.si.edu/collection-objects/heinkel-von-ohain-hes-3b-turbojet-engine-reproduction/nasm_A19810039000

Star, S. L., & Griesemer, J. R. (1989). Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science, 19*(3), 387–420. http://www.jstor.org/stable/285080

Tidd, J., & Bessant, J. R. (2020). *Managing innovation: integrating technological, market and organizational change*. John Wiley & Sons.

Tidy, M. S., Wang, X., & Hall, M. (2016). The role of Supplier Relationship Management in reducing Greenhouse Gas emissions from food supply chains: supplier engagement in the UK supermarket sector. *Journal of Cleaner Production, 112*, 3294–3305. https://doi.org/10.1016/j.jclepro.2015.10.065

Utterback, J. M. (1996). *Mastering the dynamics of innovation*. Harvard Business School Press.

Van der Linden, L., Van Zwieten, J.J., Prévot, F., L., Kortenbach, T., Anwar-Hameed, A. (2023). *Design Roadmaps for Design Strategy Project. Prior coursework*.

Wheelwright, S. C. (2011). *Revolutionizing product development: Quantum Leaps in Speed, Efficiency and Quality.* Free Press.

Yepeng, W., Jiao, Y., Hui, X., & Lyu, C. (2022). The more engagement, the better? The influence of supplier engagement on new product design in the social media context. *International Journal of Information Management,* 64, 102475.

Zheng, X. S., & Rutherford, D. (2020). Fuel burn of new commercial jet aircraft: 1960 to 2019. *Washington DC, United States of America: ICCT.* Retrieved from https://theicct.org/wp-content/uploads/2021/06/Aircraft-fuel-burn-trends-sept2020.pdf

Züttel, A. (2004). Hydrogen storage methods. *Naturwissenschaften, 91*, 157-172.

Appendix A

Randomisation method

Randomisation method to sample 3 codes from each interaction.
Excel was used as the main way to store and categorise the codes. By using the RAND() function, the codes could be sorted in a random order after which the top three codes with the corresponding lowest random score were selected. See Figure 1 for screenshot of the spreadsheet.

AH	AI	AJ	AK
Partnerships officer 1	**Project manager 1**	**Fuel cells engineer 1**	**RANDOM**
help small suppliers understand ABDs	motivation + technical abilities	open and honest discussions	0.007598053332
natural caution prevents progress	it's obvious that ZEROe is nice	crazy requirements	0.01302017249
more commitment from Tier 1s	focus on engineering things	prerequisite to become aviation supplier	0.03832308796
			0.04600988011

Figure 1: Spreadsheet containing the randomly selected codes including the random numbers from the RAND() function.

Clustering approach

I started by clustering similar codes together. The only predetermined lens I was looking through was the research question of the identification phase: *What challenges do the stakeholders face in engaging in joint early stage hydrogen propulsion technology development for aircraft?* To facilitate the process of clustering the codes, I wrote them down on Post-It notes and started sticking them on a whiteboard. Similar codes were stuck together in groups. After about 10 codes, small groups started to form and I was able to give the groups preliminary category names. This continued until all the codes from the random sample were placed or discarded. By the end, code groups had overarching category names and sub groups had subcategory names. Relations between codes and groups were drawn with arrows (see Figure 2). Four codes were discarded that did not seem relevant to the research question after all.

Figure 2: Whiteboard with initial clusters and relations.

Appendix B

Table 1: Results of the second cycle coding. Preliminary category and sub-category names with corresponding codes.

Category name	Sub-category name	Code
Responsibility & power		supplier is responsible for quality of the delivered product
		interested in how sub-contractors are controlled
		false decision if plan is not delivered to management
		very few levers to influence the supplier
Opportunity		it's obvious that ZEROe is nice
		being part of the serial aircraft
Engagement enablers		supplier has to be enthusiastic and see commercial potential
		vision between supplier and Airbus should be aligned
		Supplier 1 collaborates well on topics they are interested in
		give suppliers a bit more time for in-depth analysis
		Motivation + technical abilities
Certainty & confidence	General	understand how it compares to a reference kerosene aircraft
		Knows what will come during testing
		Reliability should be leak tight
		Very surprised with CFD calculations as it's costly
		Can't be more down-selected than this
		Prerequisite to become an aviation supplier
	Technological	Minimum development time based on supplier feedback
		"Based on solid evidence"
		Kerosene suppliers for non-LH2 equipment
		Mostly engineer 7's assessment on supplier selection
		Would be interested in if they researched more obscure equipment
	Commercial	Products already in service
Uncertainty	General	Holistic approach to technical risk management
		Afraid to jump in unknown

		Difference in level of interest shown from suppliers
		Scared to take decisions
		Difficult to estimate when external party is involved
		Hard to find suppliers with aviation AND hydrogen knowledge
		Low confidence in planning due to issues with supplier 1
		Politics don't believe Airbus can build hydrogen aircraft yet
	Technological	Need to understand what are relevant future technologies
		Clearer picture on use cases later on
		One architecture will be selected
		wondering if it is sensible to have flame arrestors on an aircraft
		Bunch of suppliers will be contacted for RFTI
		extra supplier needed for part of the equipment
		looking for partners on the demonstrator and the product
		different components quoted between supplier offers
		what is a significant change and what isn't
		Complexity is not clear
	Commercial	Unclear for supplier how many prototypes to produce
		Unclear what is requested from the supplier
		Supplier interested in Airbus commitment
		BIP access on tier 2 unclear
		Practicality of the development is a risk
		Not clear how suppliers can get ROI
		The market uncertainty is a problem
	Organisational	ZEROe team not very experienced in aviation
		will be a bit uncomfortable for some people
		over complicating placement of modelling team
		Procurement skipped
Interacting		Visit the suppliers IRL
		Open and honest discussions

		Help small suppliers understand ABDs
		small companies have no resources for documentation
		Take some responsibility from supplier
		intermediary meeting very helpful in assessing supplier progress
		Don’t leave suppliers alone
		Describe needs instead of going into technical rabbit holes
		“This office is a shame.”
		Requirement list often thrown over the fence
		Is there a priority on the requirements?
		idea to guide suppliers during creation of the requirements
		Design tailored to Airbus interface
		How to talk to supplier 19
		Questions asked through procurement
Process frustrations		Focus on engineering things
		Things are slow when there is no focus on engineering topics
		Frustration about focus on politics rather than engineering
		Waiting for contract before testing
Barriers	Safety focus	Safe product
		H2 technology sensitive novelty
		3 extra safety barriers for sensitive novelties
	Challenging requirements	Crazy requirements
		Requirements make product development challenging
		Biggest problem is compliance with aviation requirements
	Overly cautious	Engineers “scared” to remove requirements
		All requirements are needed in the end
		Natural caution prevents progress
	Asking for the impossible	Airbus needs to be free to use the result
		New NDA needed for discussions
		First need a formal engagement confirmation

		refuse that the customer holds all the IP
		NDA problems inhibiting information exchanges
		not technical but contractual problems that delayed the project launch
		Low volumes compared to legacy
		“They still think we’ll steal it.”
		Escalation not successful
		manufacturing capabilities are there but design space is challenging
		scope was 150% which was overwhelming suppliers
Fear-of-missing-out		not able to follow in the serial aircraft
Lack of capabilities		No mention of H2 in cryo experience
		not strong in managing lessons learnt
		combine space and aviation experiences for development
		hard to use suppliers as advisors when we don't know much

Table 2: Uncertainty’s subcategories and their topics with code exemplars.

Subcategory	Topic		Code exemplar
Technological	Changing architectures	Requirements	requirements depend on the architecture and scenarios
	Changing timelines	New technical knowledge	changing timelines dependent on needs is possible
Commercial	Quoting the risk		not easy to quote the risk of exposure
	Future market		the market uncertainty is a problem
	Development roadmap		requesting procurement strategy to know what to develop
	IP		clarify licences
Organisational	Transparency		transparent technical discussion to reduce uncertainty
	Reusable knowledge		supplier learnings from earlier projects
	Common understanding		technical workshop to get common understanding

Table 3: Actionable subcategories and their codes.

Having a clear strategy	Finding an efficient way of collaborating	Learning with suppliers	Defining the right incentives and fit	Defining needs clearly
for some hydrogen aligns with business strategy	empathise with supplier	fast paced suppliers	ZEROe is hot	previously there was a common expectations
more clear path for ZEROe needed	seeing hardware is nice	better understanding of development for aircraft	hydrogen is hot	suppliers knew what was being asked of them
need official Airbus view of hydrogen market	open and honest communication	more flexible with first-time-right	being pioneers forever	need to understand full process
communicate Airbus strengths	open and honest discussions	change mindset of non-aviation suppliers	paying a supplier for pilot project is good	nice when suppliers understand what we want
clear communication on commercial potential	less focused on established safety concepts	take supplier feedback seriously	don't force a supplier to engage if they don't want to	suppliers should understand better the Airbus needs
communication material has gotten better	Airbus tries to help suppliers	mindset should be curiosity driven	supplier has to be enthusiastic and see commercial potential	
Airbus end-to-end vision	feel momentum and spirit	Airbus is reliant on suppliers' designs	known aviation supplier knows Airbus processes	
make sure suppliers know Airbus' plans	demistify processes	learn from suppliers with less fit	gauge potential early on	
Airbus needs to clearly demonstrate interest in techno bricks	meeting supplier IRL is needed	willingness to share information important	good RFTI response if worked with Airbus before	
Airbus should show whole strategic view	meet with problematic suppliers	learn from them IRL	"balanced workload"	
always having a way forward	informal communication speed up contractual process		part ways without wasting time	
show that supplier's role is important to us	trustful relationship		advisory work from suppliers should be paid	
suppliers are now more aware of Airbus' commitment	united team towards suppliers		suppliers need to have the ambition to enter aerospace	
	more collaborative interaction would help Airbus		pleasant with suppliers that want to enter aerospace	
	open mindset in ZEROe		vision between supplier and Airbus should be aligned	
	weekly supplier meetings			
	track what suppliers are doing			
	ask open questions in selection phase			
	assess willingness to collaborate openly			
	suppliers' progress is monitored weekly			
	be very close to the suppliers' development process			
	open way of working also a requirement			
	physically go to the supplier to check if sensitive info can't be shared			

	check and see everything to be able to think along			
	keep pushing for open collaboration, it will work			
	continuous sharing enables identification of problems early on			
	said that Airbus isn't the expert here			
	intermediary meeting very helpful in assessing supplier progress			
	adding extra column to ABD100			
	more open Q&A sessions			
	"exchange freely and build knowledge" in RFTI phase			
	more meetings with "back and forth"			
	good feedback is rewarding			
	intermediate supplier progress reporting needed			
	more transparency and collaboration			
	visiting suppliers IRL is fruitful			
	good to show that supplier is important to us by involving management			
	important to align communication			
	more transparency in engagement			
	need for the ability to gauge if supplier is engaged			
	need "clear conversations in revision with them"			
	have a partner phase at the start			
	show interest in the supplier's business			
	Visit the suppliers IRL			
	help them out of the shit			
	discuss together what would be needed to bring it on the aircraft			

Appendix C

Design challenge: *Learning with suppliers*

One of the major points within the current development phase of ZEROe is the need for learning and building a knowledge base. Hydrogen technology for aviation has many unknowns while hydrogen technologies for ground-based applications have been operating for decades. Suppliers from these established ground-based hydrogen technology companies are now being involved in creating airworthy equipment. However, Airbus mostly learns from suppliers that it eventually contracts with while there might be an opportunity to learn from those that do not necessarily want to enter into contracts. This was brought up in an interview with a procurement officer who said: *"...if I could change something I'd do that. I'd spend more time learning from suppliers."*

Designing a way to engage with existing hydrogen technology companies to learn from them without necessarily engaging in multi-year development contracts could be beneficial for Airbus. This could build the relationship between the companies in a more collaborative way (code: *have a partner phase at the start*) which could eventually even lead to a contract in which both parties see the opportunity and want to continue (code: *keep pushing for open collaboration, it will work*).

On the other hand, this design challenge could be problematic as many collaborations hinge on which party owns the intellectual property rights at the end of it. Many suppliers could be reluctant to share information needed for Airbus to learn (from a procurement interviewee: *"that's their IP and they want to protect it"*).

Analysis challenge: *Defining needs clearly*

One of the main issues identified by the interview participants and recognised during the meetings with suppliers is the need to be clear in what Airbus wants towards the suppliers. This relates to the unknowns within Airbus where the engineers are not sure about their designs. Due to the changing architectures and the specifications being updated constantly, it is hard to know what to request and how to define these needs in a clear way.

In this analysis challenge, the goal would be to define the needs at a high level which could give the engineers the handholds to define the lower level requirements further. Then, it would be important to understand how these high level needs would be transferred to the suppliers so that they understand the lower level requirements in a larger context (code: *nice when suppliers understand what we want*).

This analysis could be challenging as I would need to dive deeper into the equipment's requirements which are different per equipment. Also, the root cause of these issues is most likely the lack of clear Top-Level Aircraft Requirements (TLAR) (code: *no cascading from TLAR*) which is something I will not be able to change as it hinges on strategic trade-offs between architectures.

Appendix D

Table 1: Schedule of session 1

Stage	Time	What?	Goal/Aim	Phase + session duty	Materials needed	Individually / in a group	Notes / Important
Problem finding	5 min 13:15 - 13:20	Welcome, introduction facilitator and share goal of the session Schedule of the session on flip-over		Intro Welcome & introduction	Write down PaG by PO on flip-over	Group	No answers, ideas or questions are wrong. Postpone judgement.
	5 min 13:20 - 13:25	Problem owner explains problem Goal of the session: *"Find what is really problematic for engineers during the RFTI phase when collaborating with suppliers."* Problem statement: *"How can <u>we</u> improve the interaction between the engineering teams and suppliers during the RFTI-phase?"*	Brief the RG	*Briefing by the problem owner*	Flip-over, markers	Group	Do people recognise the problem?

		Pointers: *Trust, Value proposition, Credibility* Questions?					
	5 min 13:25 - 13:30	Share existing ideas on what can be improved rapidly. Write or draw them on post-its.	Free up the mind and enable generating new ideas	Purge	Post-its, markers, Flip-over	Start individually but you can look at each other's ideas	The goal is not yet to solve the problem. Think of just the things that can be improved.
	2 min 13:30 - 13:32	Poem intermezzo *I Keep Six Honest Serving Men - Rudyard Kipling*	Step out of previous task and show importance of asking questions		Flip-over with poem	Group	Message: curiosity should be constant
	23 min 13:32 - 13:55	*WWWWWH* What, When, Why, Where, Who, How	Provide a rich description of the problem as given	Diverging	Post-its, markers, wall with questions	Group	Has its origin with Greek rhetorician Hermagoras
	5 min	*Break*			coffee/drink		

	13:55 - 14:00	Be back at 13:58!			s		
	10 min 14:00 - 14:10	*Spontaneous clustering* Clarify the goal. Emphasise spontaneity Try naming the clusters with a verb phrase	Gain an overview of all of the options	Reverging	Post-its, wall or flip-over, markers	Group	If time is really running out, this can be skipped
	20 min 14:10 - 14:30	*Restating the Problem* Einstein quote: *"If I were given one hour to save the planet, I would spend 59 minutes defining the problem and one minute resolving it."*	Coming up with a clear problem stateme nt that invites ideation	Converging Specific, Positive, Ambitious, Relevant, Keep-it-sim ple	Large post-its, markers, flip-over, Einstein quote, SPARK abbreviation	Group	Remind about SPARK, get to one essence of the problem

Table 2: Schedule of session 2

Stage	Time	What?	Goal/Aim	Phase + session duty	Materials needed	Individually / in a group	Notes / Important
Idea finding	5 min 13:00 - 13:05	Welcome & introduction facilitator Recap session 1 Schedule of the session		Intro Welcome & introduction	Write down PaP by PO on flip-over	Group	No answers, ideas or questions are wrong. Postpone judgement.
	5 min 13:05 - 13:10	Icebreaker - Force-fit Example milk → white → snow → skiing → holiday	Chain of association			Group	Start with two words: orange ⇒ trust. Everyone can say just one word
	5 min 13:10 - 13:15	Problem owner re-iterates problem Goal of the session: *“Find ideas to solve the PaP.”* Problem statement: *“How can we tailor the supplier engagement processes for ZEROe? With focus on:*	Brief the RG	*Briefing by the problem owner*	Flip-over, markers	Group	

		- *Lessons learnt* - *Communication* Questions?					
	5 min 13:15 - 13:20	Share existing ideas rapidly. Write or draw them on post-its. Park them on flip-over	Free up the mind and enable generatin g new ideas	Purge	Post-its, markers, Flip-over	Start individuall y but you can look at each other's ideas	
	20 min 13:20 - 13:40	*Brainwriting 6.3.5* Write 3 ideas per round on a flip-over, then pass on clockwise to neighbour.	Find incremen tal improve ments to process	Diverging	6.3.5 worksheet on flip-over, post-its, markers	Individual	Try and do it in silence. Can be skipped.
	10 min 13:40 - 13:50	*Criminal round* Write criminal ideas on post-its and put on flip-over. Choose your worst idea.	Find new and novel ideas	Diverging, excursion	Post-its, markers	Group	No pictures of sheet and destroyed after session. Prime with specific areas of crime
	10 min 13:50 - 14:00	*Forced fit* Write down a tamed version on top of	Get back to reality	Reverging ?		Group	

		criminal ideas that could work.					
	10 min 14:00 - 14:10	*Spontaneous clustering* or *Sequencing* (depending on ideas) Clarify the goal. Emphasise spontaneity Try naming the clusters with a verb phrase	Gain an overview of all of the options	Reverging	Post-its, wall or flip-over, markers	Group	
	5 min 14:10 - 14:15	*Break*			coffee/drink s		
	20 min 14:15 - 14:35	*UALo analysis*	Weigh the different options	Convergin g	UALo worksheet, markers, post-its		Emphasise affirmative judgment

Appendix E

WWWWWH Questions based on Heijne & Van der Meer (2019)
What:

- What is the actual problem?
- What is the root cause of poor interactions between engineering and suppliers?
- What if this problem was solved?

When:

- When do the problems occur?
- When do you feel most affected by the problem?

Why:

- Why does the problem exist?
- Why isn't it solved yet?

Where:

- Where does the problem occur?
- Where does the problem have the highest effect?

Who:

- Who is affected by the problem?
- Who can solve the problem?

How:

- How was the problem dealt with before?
- How should a new solution be implemented?

Appendix F

Figure 1: UALo outcome of idea “Prototype (DMU)”

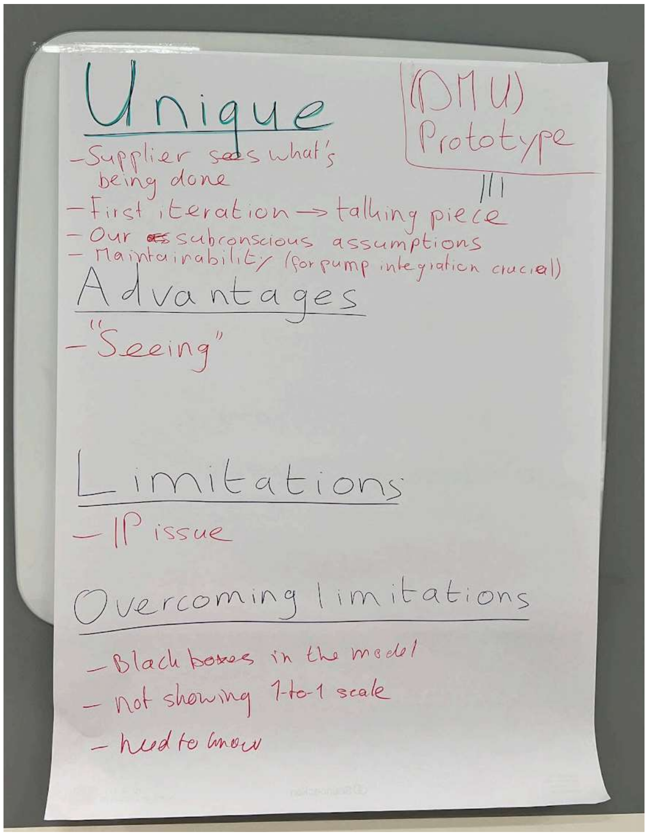


Figure 2: UALo outcome of idea "Way of working"

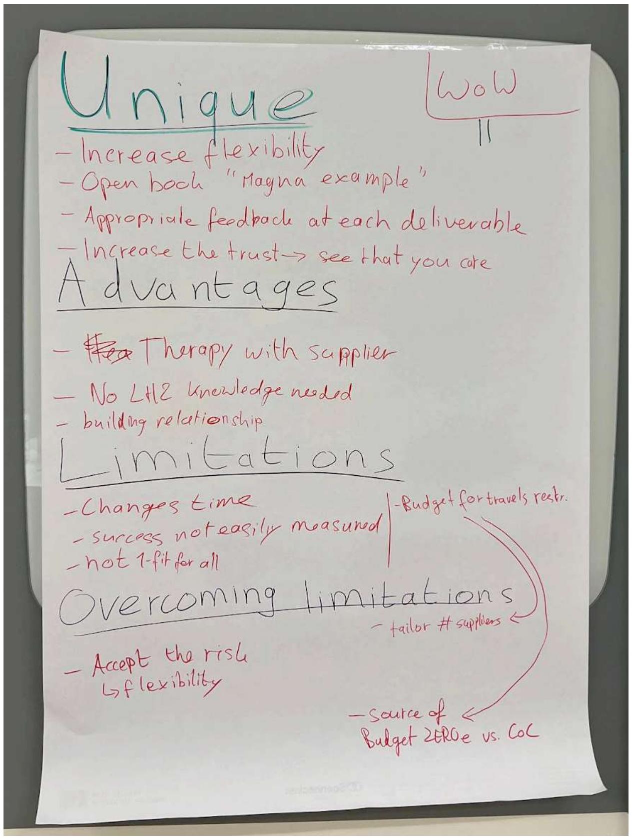


Figure 3: UALo outcome of idea "Public awareness"

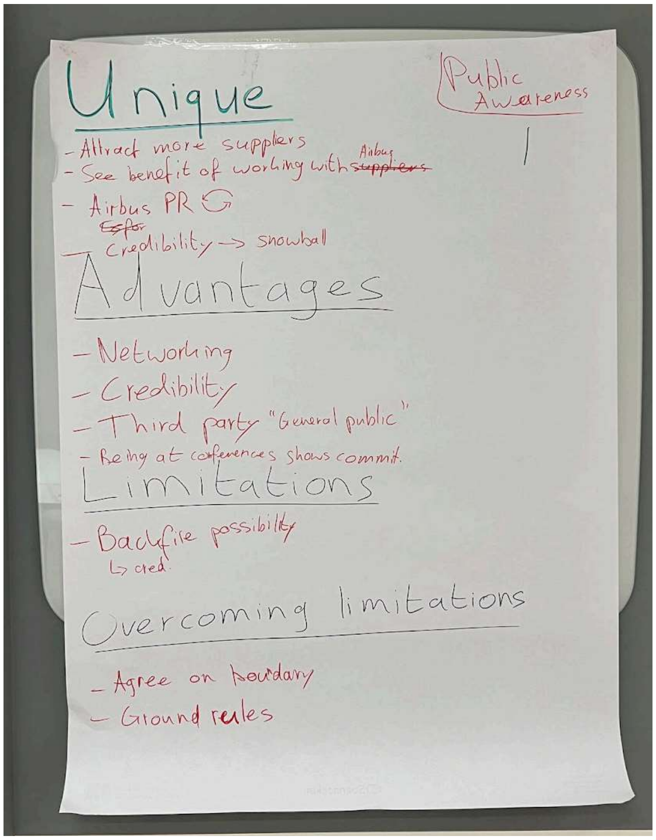
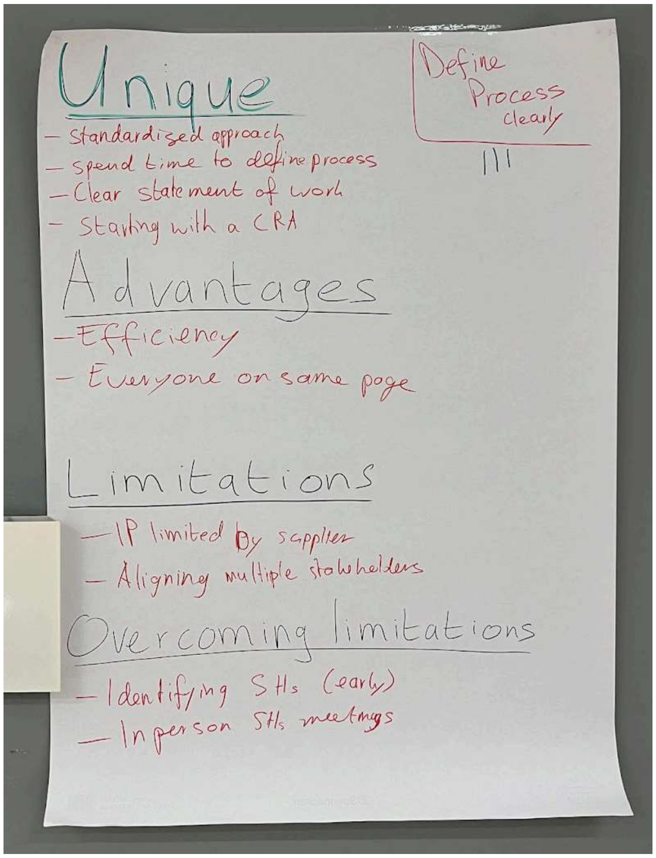


Figure 4: UALo outcome of idea “Define the process clearly”



Appendix G

Findings session 1

The first creative session went smoothly and the participants were actively engaged. In total, there were seven participants in the resource group (including the problem owner). The session yielded interesting results, both in terms of observations and in the actual content that the participants produced. During the session, I used a notebook to note down any observations I made. The participants discussed among themselves and wrote down their ideas on Post-it® notes and on large flip-over paper. Figure 1 shows a picture of the session and the materials that were used in it.

Figure 1: Picture showing the participants and the setting of session 1.

Clusters

The goal of the session was to come up with a reformulated problem statement. Nonetheless, some of the intermediate steps also yielded interesting results such as the clusters that the participants came up with. After the diverging phase, the participants had answered the 5W1H questions and were tasked to cluster all of their answers. Figure 2 shows the flip-overs with the cluster names in red above the corresponding Post-it® notes.

Figure 2: Flip-overs with Post-it® notes from 5W1H and (sub-)cluster names in red.

The resource group came up with seven clusters in total: *Process, Willingness, Knowledge, Requirements, Pain-points, Stakeholders*, and a miscellaneous cluster. Of the clusters, *Process* had the most amount of Post-it® notes and I observed that this cluster also stirred up most of the discussion within the group. There are three notes worth highlighting within this cluster: *"RFTI not adapted for complex R&D, set new grounds"*, *"Suppliers quit RFTIs/RFPs* [Request For Proposal]*"*, and *"No document RFTI process"*. These findings support the need to tailor the RFTI process more towards the developments the engineering teams are doing currently.

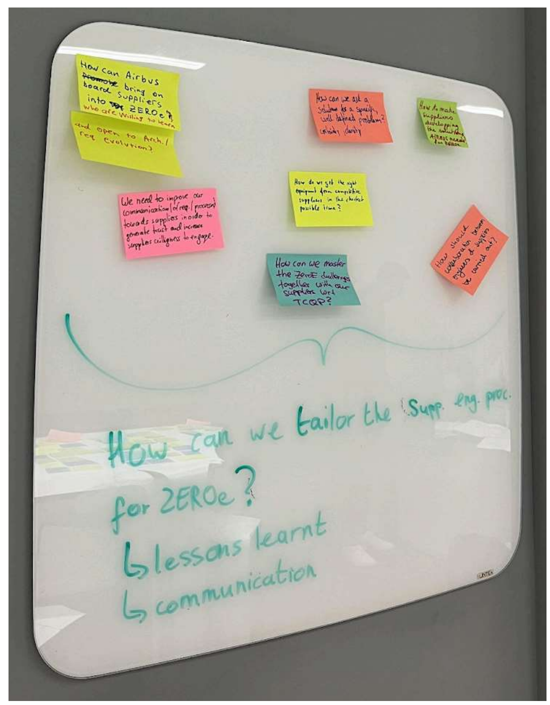


Figure 3: Individually formulated problem statements on Post-it® notes and the consolidated problem statement written on the whiteboard.

Another aspect that was striking is summarised well in a Post-it® note from the *Knowledge* cluster: *"Lack of experience outside of 'comfy' legacy supplier exchange"*. This shows that the supplier engagements that the engineers currently face are less straightforward than they were used to in the legacy programs. A participant added verbally during the session that there is *"no need to create relationships in legacy"*. They meant that the mindset in the legacy programs is different. The supplier engagements are transactional and therefore do not necessitate extensive relationships to get good results. This implies that for the participants, there *is* now a need to create relationships with suppliers and that the supplier engagement processes in place do not allow for that currently.

Problem statement

With the clusters and discussions in mind, the participants were asked to discuss and write down a reformulated problem statement on a Post-it® note. Each participant wrote down one reformulation. All reformulations were gathered and stuck on a whiteboard together for all to see (see Figure 3).

After discussing the statements, the resource group together with the problem owner and me as the facilitator formulated the following consolidated problem statement:

> *"How can we tailor the supplier engagement processes for ZEROe?*
> - *lessons learned*
> - *communication"*

The *"supplier engagement processes"* refer in a joint term to the RFTI and RFP processes that the engineers use to engage with suppliers. The RFP process was added to the scope as it has components in it that are sometimes used in the RFTI and vice versa. "Tailor" refers to the need to adapt the old processes to the current needs of the stakeholders. *"ZEROe"* refers specifically to the Tank systems engineering teams to which the participants belong. Then, the resource group requested to add two additional terms to the phrase: *"lessons learned"* and *"communication"*. *"Lessons learned"* refers to the need to capture the lessons learned in the good/bad engagements that the teams have had with suppliers and implement them in the tailored process. *"Communication"* refers to the way the engineers communicate with the suppliers in the processes. The participants expressed that the way of communicating is not always adequate for their engagements. This could be related back to the legacy 'mindset' that is not fit for the Tank systems equipment developments. As it was a recurring topic during the earlier phases in the session, the participants believe that a tailored process should also give guidance on this topic.

In the end, the resource group reached consensus over the problem statement in its current form. All participants including the problem owner felt that this was a relevant starting point for the second session.

Findings session 2

The second session used the problem statement formulated at the end of session 1 as a starting point: *"How can we tailor the supplier engagement processes for ZEROe?"* and the two additional topics *"lessons learned"* and *"communication"*. The session was held one week after the first session and was set in the same setting as the first session (see Figure 4). Due to time constraints, three participants could not attend the second session. As these were all experienced ZEROe engineers, I decided to invite another engineer with similar levels of experience who was not present at the first session. In total, there were five participants in the resource group (including the problem owner). The new resource group member was briefed before the session on the outcomes of session 1. Since the outcome is a clear problem statement, it was easy to get them up to speed.

Figure 4: Picture showing the participants and the setting of session 2. The fifth participant is standing outside of the frame.

Idea generation

Before the session, I was expecting the participants to come up with incremental improvements to the existing RFTI/RFP processes. I was expecting them to draw out new timelines or new templates of the process deliverables for example. To this end, I had selected the *Brainwriting* method as it is geared towards incremental improvements to a problem (Heijne & Van der Meer, 2019). I was surprised to see participants come up with ideas varying widely in the level of abstraction. One of the ideas generated during the *Brainwriting phase* with a high level of abstraction read *"Provide as much info to suppliers as possible"*. An example of a very concrete idea generated during the same phase was: *"Increase the number of face to face workshops"*. As the goal of this session was to identify one or two concrete ideas for further development, I had to adjust my facilitation slightly and push the participants to come up with concrete ideas away from the high abstraction levels. Luckily, the criminal and forced fitting rounds helped in this regard. It enabled the participants to step into the bizarre for a moment and come out with a different, more concrete perspective. It also resulted in concrete ideas such as: *"Show actual hardware or testbeds"*.

Figure 5 shows a collage of the *Brainwriting* sheets that the participants used to generate ideas. Throughout all diverging phases, about 100 ideas were generated. Although there were varying levels of abstraction, most of the ideas were concrete enough to take on to the next phase of clustering.

Figure 5: Ideas from the Brainwriting exercise.

Clustering

The participants were asked to cluster their ideas onto a whiteboard and come up with cluster names. Ten clusters emerged: *Way of working*, *Public awareness*, *Sharing*, *Support*, *Defining the process*, *Prototype*, *Funded projects*, *Bottlenecks*, *IP*, and a miscellaneous cluster (see Figure 6).

Figure 6: Whiteboard with idea clusters.

As mentioned before, some of the ideas were highly abstract and this transferred into the cluster names: *"Sharing"*, *"Way of working"*, and *"Support"*. It posed a challenge for the next round, as UALo analysis needs concrete ideas to judge and analyse. Therefore, I asked the resource group to pick their favourite four concrete ideas from the clusters to take on to the next round.

Appendix H

Additional ideas from Session 2:

1. Way of working
   This idea relates to defining the way of working between the Airbus engineers and the suppliers. The resource group found that by defining the way of working more clearly, it could increase the trust between both parties as the suppliers will see that Airbus cares. It would also force Airbus to give appropriate feedback to the suppliers at each deliverable which currently does not always happen. The resource group found that it could possibly build better relationships. The participants also expressed a desire to meet the suppliers more in face-to-face meetings. However, this also highlights one of the major limitations of improving the way of working as the travel budgets will have to be increased to allow for more face-to-face meetings. See Appendix F Figure 2 for the outcomes of the UALo analysis for this idea.

2. Public awareness
   The third selected idea is related to increasing the public awareness of ZEROe. The resource group selected this idea as it could attract more suppliers which Airbus is currently not reaching. Companies could more easily benefit from the PR potential of working with Airbus if ZEROe would gain more public awareness. It would also increase the credibility among suppliers that Airbus is committed to developing hydrogen-powered aircraft. Concretely, the participants mentioned the need to be present at relevant conferences presenting ZEROe or even "Organise [an] Airbus ZEROe supplier conference".
   The greatest limitation to this idea is that it could backfire should Airbus' plans change. A mitigation to this risk could be to set clear boundaries about what can and what cannot be presented publicly while still showing the developments. See Appendix F Figure 3 for the outcomes of the UALo analysis for this idea.

Appendix I

Strategic roadmap (see next page)

Appendix K

Iteration 1
This first version of the tailoring includes rows in the roadmap in which suppliers can add the *Possible deviations* of the equipment's development process compared to a normal development process they are used to.

"The supplier shall propose a high level roadmap to develop the requested equipment based on its experience from prior developments of similar equipment. The roadmap should consider key steps required to achieve the TRLs at the development target dates [...] *and highlight where this development deviates from the usual equipment development process in the roadmap (see a template below). The development roadmap to achieve TRL6 should consider the technical gaps to close and some consideration on how to extend the technology performances to the aircraft requirements when needed."*

Activities & deviations from normal development process	TRL3 <date>			TRL4 <date>			TRL6 <date>		
Concept selection									
Possible deviations									
Finalise design concept									
Possible deviations									
Prototyping									
Possible deviations									
Testing									
Possible deviations									
Qualification									

testing									

Figure X: Development roadmap template to be used as a reference for suppliers.

Iteration 2

In discussing the proposed adjustments to the RFTI process and documentation, the engineers gave feedback about the roadmap template and the accompanying text. It became clear that the proposed template was trying to include two aspects into one design: the request for a development process and the request for information around a usual equipment development roadmap. Based on this feedback from the engineers, I decided to simplify the roadmap template. Instead of adding rows for possible deviations in the template, an open question was formulated in the accompanying text. This leaves it up to the supplier to choose the form of communication to convey their development experience with the type of equipment. This was a compromise between me wanting to make things visual versus the engineers wanting to define everything in text. Nonetheless, the engineers emphasised the need to show suppliers a reference of what Airbus expects as a minimum of the roadmap. The roadmap template serves this purpose. See Figure X in section *Tailored RFTI process validation* for the finalised roadmap template and the accompanying text with adjustments in red.