Interface design for sustainable aviation

Functional Visualizations of a Hydrogen-Electric Aircraft Propulsion System for Supporting Pilot Decision-Making

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Thesis report

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Preface

The aviation industry is undergoing a transformative shift towards more sustainable and efficient technologies, with hydrogen-electric propulsion emerging as a promising alternative to conventional fossil fuel systems. This project, centered on the development of a novel display system for a Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system, represents a step in addressing the human-machine interface challenges that accompany such advancements.

The research presented in this project is grounded in the principles of cognitive work analysis (CWA) and ecological interface design (EID), frameworks that are particularly suited to managing the cognitive complexity inherent in modern aviation systems. The goal was to create an interface that not only supports the operational demands of pilots but also aligns with the novel and different characteristics of hydrogen-electric propulsion. The project draws heavily on the insights and experiences of seasoned professionals within the aviation industry, including a commercial pilot, an airworthiness engineer, and a test pilot, whose feedback was instrumental in shaping the final design recommendations.

This work would not have been possible without the contributions of the interview participants, who provided invaluable perspectives on the practicalities of display design and the operational realities of regional flight. Their expertise helped bridge the gap between theoretical design concepts and real-world applications, ensuring that the proposed solutions are both innovative and grounded in operational feasibility.

As aviation continues to evolve, the need for human-machine interfaces that enhance safety, efficiency, and usability will only grow. It is my hope that this project contributes to the ongoing discourse on interface design in the aviation sector and serves as a foundation for future research and development in this critical area. By integrating advanced design frameworks with cutting-edge propulsion technology, this work aims to pave the way for safer, more intuitive, and more sustainable aviation solutions.

Contents

Nomenclature

List of Abbreviations

AF Abstract Function

AH Abstraction Hierarchy

ATC Air Traffic Control

C&S Controls and Simulation

ConTa Control Task Analysis

CWA Cognitive Work Analysis

DL Decision Ladder

DURESS Dual Reservoir System

ECAM Electronic Centralized Aircraft Monitor

EID Ecological Interface Design

FMS Flight Management System

FP Functional Purpose

GF Generalized Function

HAPSS Hydrogen Aircraft Power Storage System

HMI Human Machine Interface

KBB Knowledge Based Behavior

MFD Multi-Function Display

PF Physical Function

Pf Physical Form

PFD Primary Flight Display

QRH Quick Reference Handbook

RBB Rule Based Behavior

RPM Revolutions Per Minute

SBB Skill Based Behavior

SME Subject Matter Experts

SRK Skills, Rules and Knowledge

SVG Scalable Vector Graphics

WDA Work Domain Analysis

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1 Introduction

The advancements in aviation technology, particularly with the advent of alternative propulsion systems like hydrogen-electric fuel systems, present new challenges and opportunities in aircraft design. As these technologies evolve, so too must the systems that support pilot operations, particularly the interfaces that aid in decision-making and situational awareness. The transition to next-generation aviation systems offers an opportunity for a reconsideration of how pilots interact with increasingly complex flight data, which directly impacts safety and operational efficiency.

This report delves into the application of CWA and EID methodologies in creating an innovative display system for a Dash 8 Q300 aircraft, which has been retrofitted with a hydrogen-electric fuel system. The study seeks to address the cognitive complexities associated with this new propulsion technology by designing interfaces that are tailored to the specific needs of pilots.

To achieve this, a series of interviews were conducted with regional commercial pilots, airworthiness engineers, and test pilots. These interviews provided qualitative insights into the practical considerations necessary for effective display design, especially in the context of time-sensitive regional operations where pilots often rely on short procedures. The study's findings underscore the need for simplicity and clarity in display systems, particularly in highlighting critical and abnormal conditions to minimize cognitive load. By exploring these issues, this report contributes to the ongoing discourse on human-machine interface design in aviation. The insights gained not only support the development of more effective display systems for hydrogen-electric propulsion but also lay the groundwork for future research involving controlled empirical testing of these designs.

1.1. Research Formulation

The primary research objective of this thesis is defined as:

Research Objective

To develop and evaluate a novel display system for the Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system, using CWA and EID principles.

In order to fulfill this research objective the following research questions were devised:

Research Question 1

How can CWA and EID be used to develop displays for a HAPSS aircraft?

Research Question 2

Which HAPSS concepts are relevant to display in future implementations of retrofitted aircraft?

Research Question 3

How are experts receiving the static and dynamic visualizations with regards to usability?

1.2. Structure of the Report

The structure of the report is as follows. Firstly, Chapter 1 will provide the necessary context to the understanding of this project as well as a structure of this report and an overall outline of this thesis project. This is then followed by a scientific article in Chapter 2 dedicated to displaying the most important findings of this project in a format that is ready to be published in a scientific journal, conforming to the IEEE publishing standard. Following this will be a preliminary analysis in Section 3.2 and a report completed under the requirements of the course AE4020: Literature Study. This preliminary report contains a survey of the existing literature as well as the progress made up to the halfway mark of this project. Then additional results will be shown in Chapter 4 and Chapter 5. A brief conclusion will be given in Chapter 6. Additional work will be included in the various appendices, in particular Appendix B which will provide the most important interviews, Appendix C which will provide a short documentation on Svelte animations, and finally Appendix D which gives a short overview of possible procedures associated with Hydrogen Electric Aircraft.

1.3. Project outline

The project timeline can be separated into three distinct sections that are represented in Figure 1.1. The literature review is composed of three different topics which are CWA and EID, the Hydrogen Aircraft Power Storage System (HAPSS), and the Dash 8 Q300. In-depth development of knowledge of these topics can be found in Chapter 3. The main development phase and result analysis are explained in the scientific article presented following this introduction.

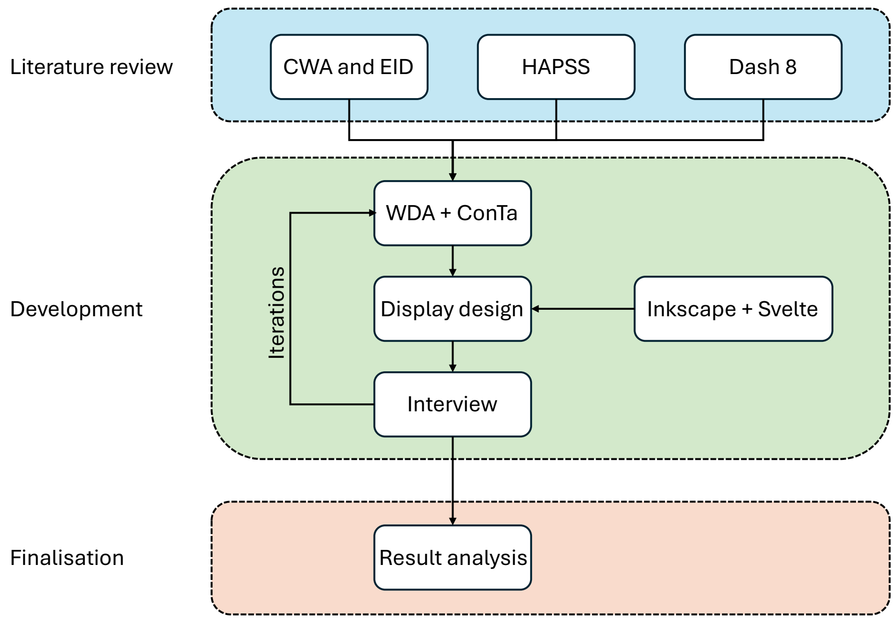

Figure 1.1: Project outline

Part I

Scientific Article

Functional Visualizations of a Hydrogen-Electric Aircraft Propulsion System for Supporting Pilot Decision-Making

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***Abstract*—This study explores the application of cognitive work analysis (CWA) and ecological interface design (EID) in the development of a novel display system for a Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system. By leveraging CWA and EID, this research aimed to address the challenges of managing cognitive complexity in next-generation aviation systems, focusing on designing interfaces that enhance pilot decision-making and situational awareness. These analytical frameworks informed the design process, ensuring that the displays were tailored to the cognitive demands of the pilots. To validate the effectiveness of the proposed designs, interviews were conducted with a regional commercial pilot, an airworthiness engineer, and a test pilot. These interviews provided qualitative insights that confirmed the applicability of the CWA/EID-based designs, particularly emphasizing the need for simplicity and clarity in time-constrained regional operations. The study highlights the importance of focusing display content on critical and abnormal conditions to reduce cognitive load, aligning with rule-based behavior (RBB) frequently employed by pilots. Future work should involve controlled human-in-the-loop experiments with a larger participant pool to empirically test the proposed display designs.**

I. Introduction

The evolution of aviation over the past century has led the industry to develop and adhere to stringent rules and regulations in the design of avionics systems. This adherence has contributed to making commercial aviation one of the safest forms of travel currently available [1]. However, with the growing emphasis on environmentally friendly aviation [2], hydrogen as a fuel source has emerged as a potential replacement for traditional kerosene-based powertrains [3][4]. This transition introduces additional complexity to traditional aircraft fuel systems by incorporating new energy transitional states and storage components [5]. As a result, pilots' existing mental models of fuel systems may no longer suffice, necessitating a re-evaluation of traditional aircraft display designs. Traditional display design methods often focus on optimizing the presentation of information based on established guidelines, such as color contrast and layout efficiency. While these methods enhance the clarity and accessibility of data, they primarily support rule-based operations and may not adequately assist pilots in understanding complex system relationships, especially during unexpected or emergency situations. This limitation highlights the need for interface design frameworks that better support knowledge-based behavior in complex systems.

Cognitive Work Analysis (CWA) and Ecological Interface Design (EID) offer structured approaches to designing human-machine interfaces that make complex system relationships more salient and visually insightful. These frameworks have been successfully applied in various safety-critical domains where operators need insight into the complexity of their control problems, such as process control [6], traffic supervision [7], nuclear power plants [8], and aviation [9][10][11]. Notably, the work of Dinadis and Vicente [9] demonstrated how EID could enhance pilot understanding and decision-making by providing deeper insights into the system interactions of a fuel system. This research inspires us to apply the same approach to new-generation propulsion systems, such as hydrogen aircraft powertrain storage systems (HAPSS), with which pilots are not yet familiar. The work presented in this article applies to both nominal and non-nominal conditions and as an illustrative example of the limitations of current display systems in non-nominal conditions the following section presents the case of Qantas Flight 32.

This article is structured according to the following sections: Section II discusses the theoretical foundations behind this research and how other domains of applications can be used in existing literature. Section III will explain a multi-step approach to understanding the overall work domain, the control tasks involved, and discussions with experts in the field that led to initial design ideas. Section IV presents the results of the research. Section V portrays an analysis of the results of the models and interviews, which are then summarized in the final Section VI which is the conclusion of this paper.

II. Background

A. *Case Study: Qantas Flight 32*

On November 4, 2010, Qantas Flight 32, an Airbus A380, experienced a catastrophic engine failure shortly after takeoff from Singapore Changi Airport. The number two engine exploded, causing significant damage to the aircraft's wing, fuel system, and hydraulic lines. The explosion also triggered multiple system failures and resulted in an overwhelming cascade of Electronic Centralized Aircraft Monitor (ECAM) messages, over 100 warnings and errors in total. The flight was fortunate to have five highly experienced pilots in the cockpit instead of the usual three due to the addition of a senior and regular check pilot. The presence of these seasoned aviators was crucial in managing the crisis. Their combined expertise of more than 71,000 flying hours and ability to prioritize and address critical issues enabled them to sift through the extensive and complex ECAM messages effectively. The overwhelming amount of ECAM messages led the pilots to misunderstand the scope of the issues they were facing. It took the unusually large crew of five pilots instead of two, 50 minutes to perform the initial assessment of the incident.

This abnormal event illustrates the importance of a well-designed Human-Machine Interface (HMI). Traditional display design methods often emphasize optimizing the presentation of information based on established guidelines, such as color contrast and layout efficiency. These methods typically prioritize the clarity and accessibility of data, aiming to enhance the user's ability to perceive and process information quickly and accurately.

There have been attempts to improve traditional display design by incorporating human factor considerations that have been proven to enhance operator performance and system safety [12]. Several approaches have been tested within the aviation industry [9]-[10]-[11] in which the Cognitive Work Analysis (CWA) and Ecological Interface Design (EID) framework have been applied. Indeed displays designed by EID seek to support the pilots by making complex system relationships more salient and visually insightful, such that it is easier for pilots to extrapolate the information beyond the ECAM messages. The research presented in this paper seeks to extend existing literature on the topic of CWA and EID to the field of sustainable aviation.

B. Cognitive Work Analysis

CWA differs significantly from other forms of display design in its approach and focus. It consists of five different methods of analysis of which two were explored in this project [12]. Work Domain Analysis (WDA) and the Control Task Analysis (ConTa) are the two aspects of operational demand that are explored in the following pages. By concentrating on WDA and ConTA, we aimed to capture the essential complexities introduced by the new hydrogen fuel cell technology and how these affect pilot interaction with the system. The subsequent phases of CWA, Strategies Analysis, Social Organization, and Cooperation Analysis, and Worker Competencies Analysis, while valuable, extend beyond the immediate scope of developing an initial interface design. These later stages typically address how tasks are carried out under varying conditions, team interactions, and individual competencies, which are areas best explored after establishing a solid understanding of the work domain and control tasks [13]. It is rooted in understanding the deeper functional and cognitive requirements of a work domain. CWA focuses on revealing the underlying structure of complex systems, including the constraints and affordances that influence operator behavior[14]. This approach aims to design displays that not only present information clearly but also support decision-making processes by aligning with the cognitive tasks and goals of users. For instance, in a traditional display design, a user interface might be optimized to show critical data like speed or altitude in a cockpit clearly and efficiently. However, CWA would go further by analyzing how these variables would interact with each other and other system components and the broader operational context[14]. CWA would consider not just how to present this information but also how to support the pilot's understanding and decision-making in varying scenarios, such as during an emergency.

Additionally, CWA accommodates the dynamic nature of complex environments, where unexpected events can occur. Traditional display design often assumes a more static context, focusing on typical tasks and scenarios. In contrast, CWA explicitly considers how operators might need to adapt to changing conditions, ensuring that displays can support a range of potential actions and decisions.

C. Ecological Interface Design

EID is a theoretical framework for designing human-machine interfaces that support effective decision-making in complex systems. Rooted in ecological psychology and cognitive systems engineering, EID focuses on creating interfaces that reveal the deep structure of the work domain, allowing operators to understand and respond to complex situations efficiently. Unlike traditional interface design, which often prioritizes ease of use and simplicity, EID emphasizes the importance of making system constraints and affordances visible to the user [14]. This approach aims to leverage the operator's perceptual and cognitive abilities to perceive higher-order relations in the data, facilitating a more direct interaction with the system's underlying processes.

The central tenet of EID is to present information in a way that is compatible with the user's mental models and the physical reality of the system. By doing so, it enhances situation awareness and reduces the cognitive effort required to interpret data and make decisions [11]. EID utilizes visual representations that map closely to the functional relationships within the system, allowing operators to intuitively understand the implications of their actions. This design philosophy is particularly useful in dynamic and high-stakes environments, such as aviation, process control, and emergency management, where rapid and accurate decision-making is crucial.

D. Opportunity for novel displays

The transition from conventional kerosene turboprop engines to hydrogen-electric fuel cell motors (as seen in Figure 1) presents an opportunity to explore and experiment with innovative display structures in cockpit design. The introduction of hydrogen-electric propulsion systems necessitates a reevaluation of the cockpit's informational architecture due to the distinct operational parameters and monitoring requirements associated with these advanced technologies (in contrast to traditional a dashboard as seen in Figure 2). Unlike traditional engines, hydrogen fuel cells

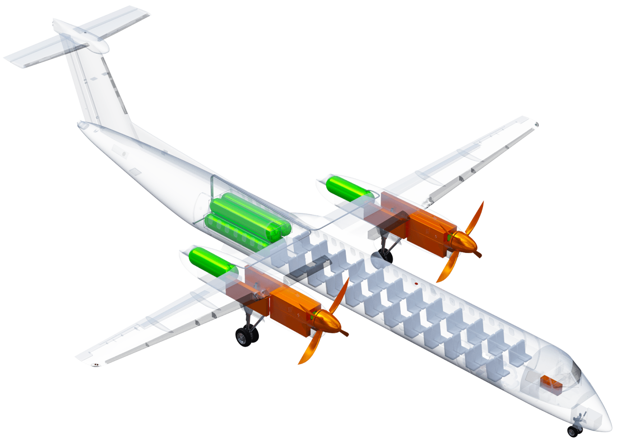


Fig. 1: Schematic representation of the Dash 8 Q300 retrofitted with HAPSS from the company Conscious Aerospace [15]

involve complex subsystems such as hydrogen storage and distribution, fuel cell stacks, and electrical power management, each requiring precise monitoring and control. This shift allows for the design and implementation of new display interfaces that can more effectively present real-time data related to hydrogen levels, fuel cell efficiency, electrical output, and safety systems. The opportunity to incorporate advanced data visualization techniques, such as connected graphics and historical analytics, can enhance pilot situational awareness and decision-making. Furthermore, this transition offers the potential to explore different frameworks to design the layout and hierarchy of information, prioritizing critical data.

III. Methods

A. Scope

The scope of this research is centered on propulsion system management within the context of a retrofitted hydrogen fuel cell Dash 8 Q300 aircraft. Unlike broader analyses that encompass the entire flight mission management, this study specifically focuses on the complexities introduced by integrating hydrogen-electric propulsion technology into existing aircraft systems. By narrowing the scope to propulsion system management, we aim to provide a detailed examination of how pilots interact with this new type of propulsion system during various phases of flight.

Fig. 2: Cockpit view of Dash 8 Q300 with highlighted superfluous dials when installing HAPSS [16]

B. Work Domain Analysis

The work domain analysis is a theoretical framework used to analyze and design complex socio-technical systems. The main tool of this framework is the Abstraction Hierarchy [12]. It organizes information at five levels of abstraction, from the most abstract to the most concrete, to understand how operators interact with these systems as seen in Figure 3. Developed to represent the constraints of the work domain, the framework illustrates that higher levels relate to a system's purpose, while lower levels provide more details about the physical implementation. For example, consider the powertrain of an aircraft, from the fuel tanks to the rotor. The hierarchy begins with the functional purpose, defining the overall goal of the system, such as "providing efficient and reliable propulsion for the aircraft." The abstract function level captures the fundamental principles governing the system's behavior, such as energy conversion, thrust generation, and power transmission. The generalized function level outlines the main operations necessary to achieve the system's goals, including fuel storage and delivery, combustion, and mechanical power transfer. The physical function level describes how these operations are physically implemented, such as the transfer of fuel from tanks to the engine, the combustion process in the engine, and the conversion of combustion energy into rotational energy driving the propeller. Finally, the physical form level deals with tangible components such as fuel tanks, fuel lines, engines, and rotor assembly. Links between elements in the hierarchy are either means-end links or parts-whole relationships, enabling one to search from top to bottom to find issues and understand the system's inner workings, and from bottom to top to gain a broader view of the system's purpose. Moving down answers how something is done, whereas moving up answers why it is done. Each level provides a different view of the system and comes with its own set of constraints affecting performance. The abstraction hierarchy supports a comprehensive understanding of complex systems, facilitating problem-solving by tracing issues from concrete elements to their impact on system goals. It aids design and analysis by ensuring all relevant aspects are considered, helping create user interfaces, and control systems that enhance operator performance.

C. Control Task Analysis

The main tool of the control task analysis (ConTa) is the decision ladder which is a conceptual tool used in cognitive systems engineering to model and analyze the decision-making processes of human operators in complex systems. Developed by Jens Rasmussen [17], the decision ladder provides a structured representation of the cognitive activities and actions involved in decision-making, mapping the transition from initial information acquisition to the final action. This model delineates a series of stages that individuals pass through when making decisions, which include the recognition of a need to

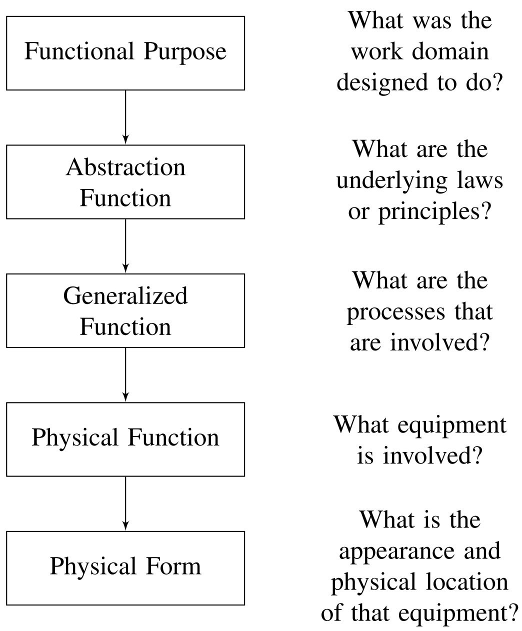


Fig. 3: The five levels of the Abstraction Hierarchy [14]

act, the formulation of goals, the selection of an appropriate course of action, and the implementation of that action. The decision ladder is closely tied to the Skills, Rules, and Knowledge (SRK) framework, also proposed by Rasmussen [17], which categorizes human behavior into three levels based on the type of cognitive control involved. The SRK model provides a theoretical foundation for understanding the nature of the cognitive processes represented in the decision ladder. At the Skill-based level, behavior is highly automated and occurs with minimal conscious effort. Operators rely on pre-learned sensorimotor patterns that are triggered by specific stimuli. This level of control is typically involved in routine tasks where the operator has extensive experience, allowing for fast and efficient responses. Within the context of the decision ladder, skill-based behavior is evident when actions are taken without the need for deliberation, often during routine monitoring and control tasks. The Rule-based level involves the application of stored rules or procedures in response to recognized patterns or situations. At this level, operators use heuristics or established procedures to manage familiar situations that are not completely automated. The rule-based level is crucial when the situation requires a decision-making process that can be guided by established guidelines, such as following checklists or standard operating procedures. In the decision ladder, this corresponds to the intermediate stages where the operator identifies a condition and selects a rule to apply. At the Knowledge-based level, behavior is governed by analytical reasoning and problem-solving processes. This level is engaged when the situation is novel or not covered by existing rules, requiring the operator to generate new solutions based on an understanding of the underlying principles and knowledge of the system. Knowledge-based control is critical in complex or unexpected situations where rule-based responses are insufficient as seen in the case study of Section I. In the decision ladder, knowledge-based behavior is represented in the stages that involve the diagnosis of the situation, evaluation of alternatives, and formulation of a plan. The decision ladder can be traversed in a linear manner, following the progression from data acquisition to action execution. However, experienced operators may shortcut the process, bypassing certain steps based on their expertise and the context, thereby moving directly from observation to action in familiar scenarios. These shortcuts reflect the influence of the SRK framework, where operators shift between skill-based, rule-based, and knowledge-based modes of control depending on the situation's complexity and familiarity.

D. Scenario design

In order to gain feedback on the decision ladders and the abstraction hierarchy, three different scenarios were devised to understand the interactions between the pilot and the avionics. This subsection is dedicated to explaining all three of these scenarios which were based on common scenarios seen by pilots during training and certification and are important to train for in aviation in general. They were devised in cooperation with a commercial regional airline pilot and were then subjected to feedback from the airworthiness engineer and the test pilot.

1) High oil temperature: The high oil temperature scenario (also referred to as Scenario 1) is characterized by engine oil temperatures exceeding the prescribed operational limits. This anomaly can manifest itself through various indicators such as cockpit alerts, analog or digital display readings, or warning lights signaling elevated oil temperatures. The underlying causes of such a scenario may include inadequate oil cooling, insufficient oil levels, contamination of the oil, or malfunction within the oil system components. The significance of training for high oil temperature scenarios lies in several critical factors. Primarily, maintaining engine integrity is paramount, as elevated oil temperatures can compromise the oil's viscosity. This degradation reduces the lubricant's efficacy, potentially leading to increased friction, wear, and subsequent damage to engine components. The temperature management on a HAPSS is also more complex, involving two separate cooling systems including an oil subsystem for the motor and an ethylene-glycol based subsystem for the fuel cell, batteries, and more. Adding to the relevance of this scenario.

2) Unequal fuel tanks: The inequality between the fuel tanks (also referred to as Scenario 2) occurs when there is an imbalance in the amount of fuel present in each tank. This imbalance can arise due to factors such as fuel pump malfunctions, unequal fuel burn rates, or fuel transfer issues. The manifestation of a fuel imbalance is typically detected through cockpit indications, such as fuel quantity gauges, warnings, or alerts indicating a discrepancy between the fuel levels in the tanks. Training for this scenario is crucial due to several considerations. Firstly, fuel imbalance can affect the aircraft's stability and control. An uneven distribution of fuel weight can lead to an asymmetric configuration, potentially causing difficulties in maintaining the desired flight attitude

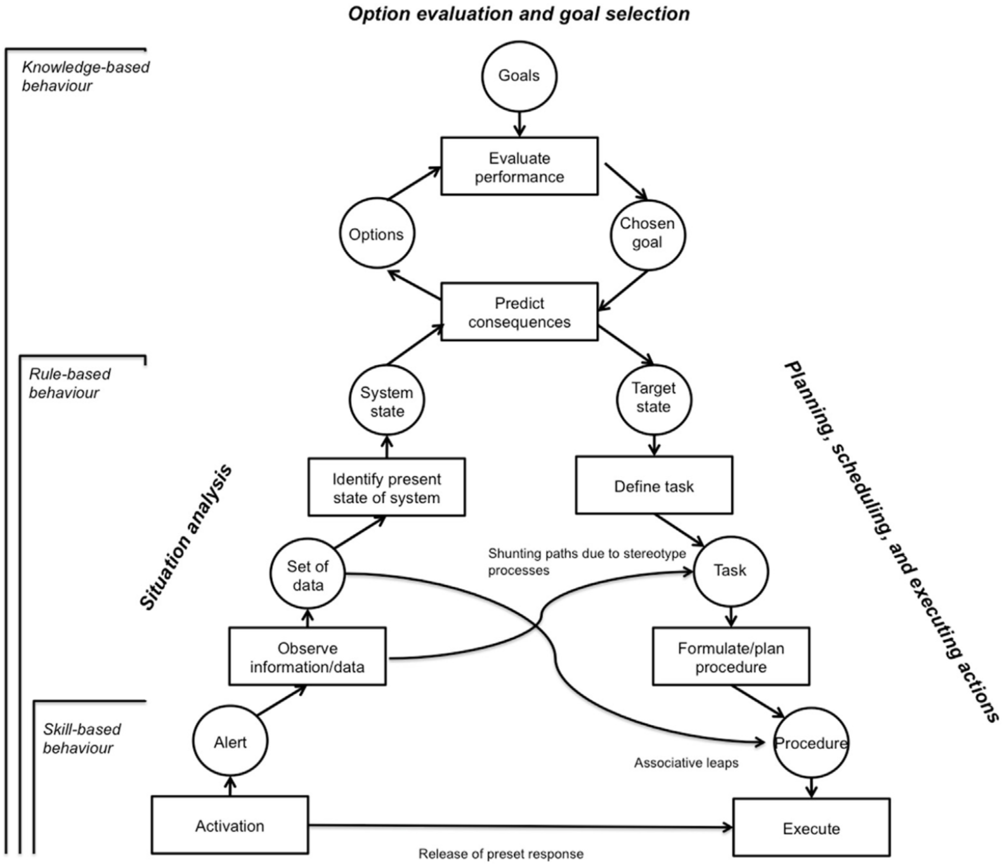


Fig. 4: Decision ladder template incorporating Rasmussen's skills, rules, knowledge framework [18] [19]

and handling characteristics. In severe cases, this could impair the aircraft's performance and compromise safety, especially during critical phases of flight such as takeoff, landing, or maneuvering in adverse weather conditions. The fuel tank inequalities scenario is also very relevant when integrating a HAPSS, indeed the fuel tanks and distribution system are prone to leaks and due to the lightweight and flammable nature of hydrogen, an inequality in the fuel tank represents a different kind of challenge to kerosene.

3) Loss of power on one motor: The loss of power on one engine (also referred to as Scenario 3) represents a critical scenario where one of the aircraft's turboprop engines experiences a significant reduction or complete cessation of thrust. This condition can arise from various causes, including mechanical failure, fuel supply issues, bird strikes, or environmental factors such as severe icing or ingestion of foreign objects. The loss of engine power is typically indicated by a decrease in thrust, abnormal engine instrument readings, or warning alerts in the cockpit. The loss of power on one engine necessitates immediate decision-making regarding the continuation of the flight. Pilots must quickly assess the situation, considering factors such as the aircraft's current altitude, airspeed, and position relative to nearby airports. This assessment informs the decision on whether to return to the departure airport, proceed to an alternate airport, or continue to the destination if it is within safe reach. The loss of power scenario is also relevant when integrating a HAPSS due to the different nature of the power distribution system. Indeed the loss of power can be much more gradual as even with a total failure of a single power lane of the HAPSS only 25% of the total power is lost.

E. Iterative Design linked to CWA and EID

The iterative design of cockpit displays, anchored in CWA and EID, serves as a systematic approach to developing interfaces that aim to enhance pilot interaction with complex aviation systems. It is possible to draw inspiration from existing literature and more specifically the display created by Vicente and Dinadis (see Figure 5). Figure 5 depicts a sophisticated fuel management system employed in a military aircraft. The display is divided into multiple sections and is intended for use by a flight engineer rather than a pilot. In the upper left corner, a map presents an estimate of the aircraft's achievable distance. Beneath it, general fuel levels for the left and right wings are shown, along with the levels of sub-tanks within the wings. Engine parameters are represented using polar graphs to emphasize concepts such as emergent features. This display serves as a prime example of ecological interface design, aiming to enhance the flight engineer's situational awareness and decision-making

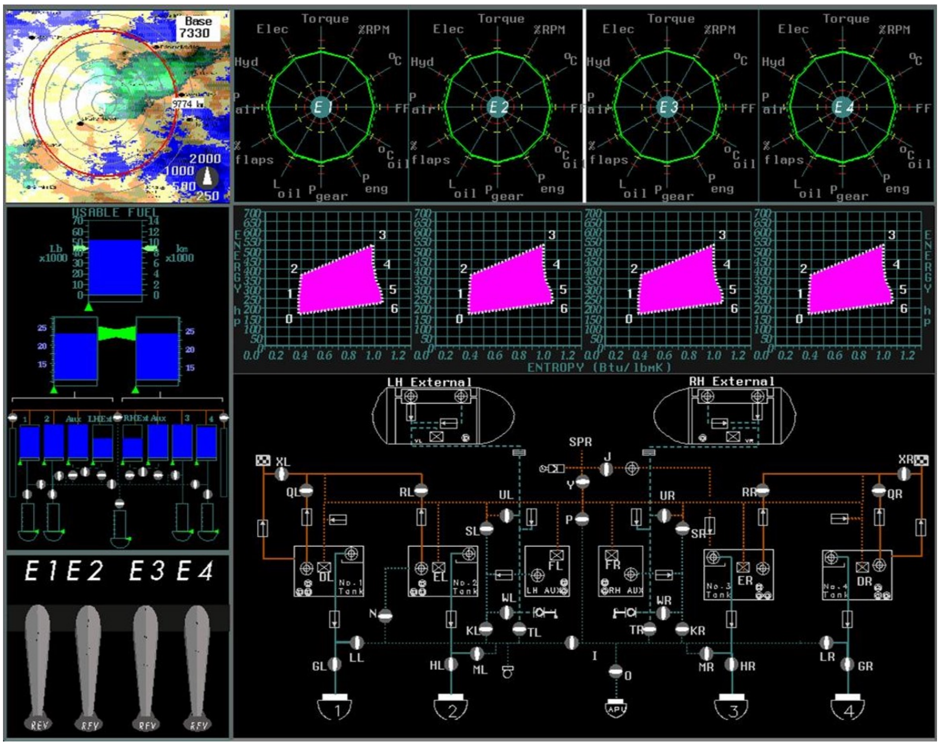


Fig. 5: Prototype fuel display for the Hercules C-130 [9]

by presenting system information that reflects the underlying physical and functional relationships. Indeed CWA provides a comprehensive framework for understanding the cognitive and contextual factors that influence pilot decision-making and task execution. By decomposing the work domain into various levels of abstraction, CWA helps identify the essential relationships between the system's components, their functions, and the overall goals. This decomposition facilitates the identification of information needs in cognitive processing, which are crucial for informing display design.

EID complements this approach by focusing on the design of interfaces that support direct perception and action, minimizing the cognitive load on operators once they are trained properly [20]. The abstraction hierarchy, a core component of EID, represents the system's structure at multiple levels, from the physical forms and functions to the higher-level purposes and values. This hierarchy is critical in visualizing how different system components contribute to achieving operational goals, such as fuel efficiency and safety. For traditional kerosene-powered turboprop engines, this involves depicting parameters like fuel flow rates, engine performance metrics, and system health indicators. In contrast, the transition to hydrogen fuel cell powertrains introduces new variables, such as hydrogen storage levels, fuel cell stack status, and electrical power storage and distribution, requiring a reevaluation of the information presented on cockpit displays. The decision ladder model, another element of CWA, provides a structured representation of the cognitive steps involved in task performance, including information gathering, interpretation, and decision-making. By mapping these steps, the design team can identify critical junctures where pilots require specific information or decision support. This model is instrumental in crafting interfaces that align with pilots' mental models, thereby enhancing intuitive understanding and facilitating rapid decision-making in dynamic situations.

Incorporating test pilot interview feedback into this design process allows for the integration of empirical insights, ensuring the display system is grounded in practical experience. Test pilots provide valuable feedback on the usability and effectiveness of the prototypes, highlighting potential issues that may not be evident through theoretical analysis alone. Their input enables the design team to refine the interface, improving its alignment with real-world operational demands and user expectations. Through successive iterations, the cockpit display evolves, integrating findings from CWA and EID with practical feedback from pilots. This iterative process ensures that the final design not only supports the specific requirements of the hydrogen fuel cell powertrain but also maintains continuity with established practices for conventional engines.

F. *Proof-of-concept implementation*

The iterative design methodology, applied to cockpit display design using Inkscape [21] and Svelte [22], offers benefits by enabling continuous refinement and optimization. The iterative approach facilitates rapid prototyping and user feedback integration, allowing for the identification and correction of usability issues. Additionally, Svelte's lightweight nature supports quick updates and integration of new ideas.

During the different interviews, the display is presented either in a static or dynamic fashion, this can be associated with either low or high fidelity respectively. The purpose of the static visualization display is for the test pilot to interact with a still image of the display to give feedback on the layout and types of displays as well as the non-animated portion of the Scalable Vector Graphics (SVG) drawing such as the text or connections between the subsystems. The additional advantage of the static visualization is the time gain, which is due to the SVG file not having to be connected to the Svelte application. On the other hand, dynamic visualizations were used during the interview to test the interaction of the different subsystems and play out the pre-made problematic scenarios associated with the decision ladders. There is an associated time cost with animating the display as new code must be written in Typescript to animate it. Additionally, simulated data that reflect a problematic scenario needs to be created to feed the animation which requires more time to implement. This simulated data was created by setting the values of the graphical representations of the variables to a level that exceeds the operational limits set on the graphics; they do not represent the real functioning of the system.

G. Interview preparation

The interviews in this project were a means of gathering insight into how operators within the aviation sector interact with their respective systems and what their opinions are with regard to the design choices made during this project. This is due to the qualitative nature of the research. Qualitative research is justified when the goal is to understand complex issues in depth, explore perspectives and experiences, and capture the context and meaning behind behaviors or decisions, which cannot be achieved through numerical data alone. The format of these interviews is semi-structured, this means that a script is prepared ahead of time but natural discussion is encouraged on the part of the participant. In Table I it is possible to see samples of different types of questions that were prepared in the interview script. The interview process can be divided into three three distinct phases. The first phase is the scenario creation, the second phase includes preliminary static display feedback and the third phase includes dynamic display feedback.

1) Motivation for participant selection: While this study uses the inputs of three different participants, two of these three were used to develop the display and scenarios prior to testing while the other was used to gain feedback and to test the designs. The exclusion and inclusion criteria of this research were selected based on the phase of the research. Indeed in order to gain valid feedback on the displays, only experts were consulted so the exclusion criterion for the final section of the interview process was to only include experts in both the Dash 8 platform and HAPSS programs. The scenario development includes Subject Matter Experts (SME) of general aviation as well as specific to the Dash 8 technical knowledge while for display testing additional experience in Dash 8 and HAPSS knowledge were required.

Indeed the main participant feedback that was analysed and investigated was the interview with the test pilot of the company Conscious Aerospace because he has both knowledge of this aircraft type and hydrogen fuel cell technology. The motivation behind this choice of participant can be also relevant due to the educational position the test pilot occupies, indeed he trains other pilots on the Dash 8 platform as well as performs the certification. He is involved in the license certification process of other pilots on the Dash 8 platform in the Netherlands. Considering that the goal of this study was to investigate the potential of designing hydrogen-powered aircraft displays based on CWA and EID, it was judged necessary to find experts in this field to discuss this visualization as novice users would not be able to adequately give feedback. The test pilot is currently working in collaboration with a company that is planning to retrofit a Dash 8 Q300 to HAPSS as seen in Figure 1, making him a qualified interview participant based on the inclusion criteria. The recruitment process was initiated through a preliminary meeting with Conscious Aerospace in which interest in the study participation was expressed by the test pilot.

2) Participant demographics: The participants of this qualitative study are all involved in the aviation sector and their respective attributes are given in the following list:

Commercial Pilot: This participant was a pilot aged 26 years old. He flies regional commercial narrow-body aircraft with 2 years of flying experience. His education prior to pilot training is a bachelor's in mathematics. This interview lasted one hour. His contribution to this project (Phase 1 of the interviews) takes the shape of a series of discussions contributing to the preparation of the interview of the test pilot and the preparation of the different scenarios and explanations of pilot cognitive patterns (creation of the initial decision ladder and scenarios).

Airworthiness Engineer: This participant was a 29-year-old former airworthiness engineer on the De Havilland Dash 8 Q300 currently enrolled to obtain his master's in Aerospace Engineering. His previous education is a bachelor's in aeronautical systems. He has 5 years of relevant work experience. His type training gives him relevant information concerning the ATA regulations of the relevant aircraft. His contribution to this project (Phase 1 and 2 of the interviews) took the form of information gathering during a two-hour interview to gain knowledge about the existing base aircraft to create the kerosene-based powertrain AH of the turbo-propeller version of the aircraft which was then later modified to become the AH of the HAPSS.

Test Pilot: This participant was a 66-year-old test pilot who additionally flies for the Dutch Coast Guard on the Dash 8 Q300 and Fokker 100. Both interviews lasted around two hours for a total of four hours. The contribution of the test pilot can be associated with all phases of the interview process (1, 2 and 3). He is also currently the test pilot for the company Conscious Aerospace and is present in an advisory role on development. He became a certified production test pilot in 1995 and an engineering and experimental test pilot in 1997. His training was received in-house at Fokker Industries and additional training was received at the American National Test Pilot School. He possesses around 6000 hours of relevant flight time and also consults for certification with EASA. His educational background is in electrical engineering. His

TABLE I: Sample questions of the interviews

Example Questions	Question Type	Goal
How old are you? What type of training do you have?	Closed-ended	Demographic of the participant
How do you define the stability of the power system? How do you make sure the system is stable in its operations?	Open-ended	Mental model identification
Are they good representations to use to analyze the capabilities and limitations of these displays?	Closed-ended	Validation of the models
How do you check for the state of the system? How would you evaluate the causes of the issues and the options to solve these issues? What would be the target state?	Open-ended	Decision Ladder Exploration
What first stands out to you? Can you explain the symbols? Do they complement each other? Do they distract? Are the ratios of size appropriate?	Closed-ended	Direct display feedback

contribution to this project takes the shape of two interviews of 2 hours each where information was gathered about the system as well as the novel displays were tested. The feedback was then implemented in the iterative design process.

3) Technical Aspects: These interviews either took place in person or on the online meeting platform Microsoft Teams. They were recorded for audio when done in person and recorded for audio and video when done online. After the interviews, the audio was transcribed, anonymized, and stored on a password-protected computer as well as backed up to a Onedrive account associated with the University of Delft.

IV. Results

A. Evolution of the Abstraction Hierarchy

As stated in the Methods section of this paper, the goal of the AH is to incorporate domain information into our design. The AH can change and evolve during the course of a project and was subject to many changes evolving from a simple structure to the complex system presented in Figure 6. For this project, an initial AH was created for the traditional Dash 8 Q300 which was then modified to reflect the inclusion of the novel powertrain. In this case, it is representative of a hypothetical novel system and as such is based on previous literature concerning display design [9], HAPSS technology [23] and the interviews instead of being created by surveying diagrams. The structure of this specific AH will now be discussed according to its respective levels of abstraction.

1) Functional Purpose: The uppermost level of the abstraction hierarchy consists of two different blocks that make up the functional purpose of the powertrain. The two blocks in question are the fuel system and the engine system respectively. The fuel system defines its functional purpose as providing enough fuel to complete the mission while the engine system is defined by the need to provide sufficient thrust to complete the mission. A similar example of a non-hydrogen powertrain can be found in the existing literature where Nick Dinadis and Kim Vicente explore the fuel system for a Hercules C130 [9].

2) Abstract Function: The abstract function is composed of multiple blocks that relate to the laws of energy and mass conservation. These can be expanded to be more specific but are kept simplified in the diagram. Indeed the Energy Transmission block could be expanded to Ohmic losses and other transmission losses as an example.

3) General Function: The general function layer of this abstraction hierarchy is composed of the different processes present in this powertrain. These are mainly related to the balance and flow of air, fuel, temperature, oil, and electricity. There is additionally a component concerning the process related to thrust production.

4) Physical Function: The physical function layer of this AH is decomposed into all the different subsystems of the HAPSS. It is possible to analyze how these interact with each other by following their respective connecting segment to the general function layer. By doing this, it is possible to understand which variables are connected to which system and subsystem and how these work in collaboration with each other, and how these can be visually relevant for the pilot to interpret the state of the powertrain in its entirety.

5) Physical Form: Due to the prototype nature of the system, there is little use for a description at a component level (such as specific power switches or valves) because the system is not yet finalized and is subject to change and so the physical form layer of this abstraction hierarchy refers more to the human-machine interactions such as the settings, limits, and reliability of the system.

B. Adjusted Decision Ladders

The decision ladder is first constructed according to the existing procedure (kerosene-based powertrain) of the Dash 8 Q300 and then adjusted based on the feedback gathered during the interview with the test pilot. In Figure 10 and additionally Table II, it is possible to see the decision ladder for one of the three scenarios devised to develop and test the powertrain displays. In this case, the decision ladder is for the loss of power on one motor scenario. After feedback from the interviews, it was possible to adjust the decision ladders to more accurately depict the cognitive thought process of the pilot flying in the Dash 8 Q300 in an abnormal situation.

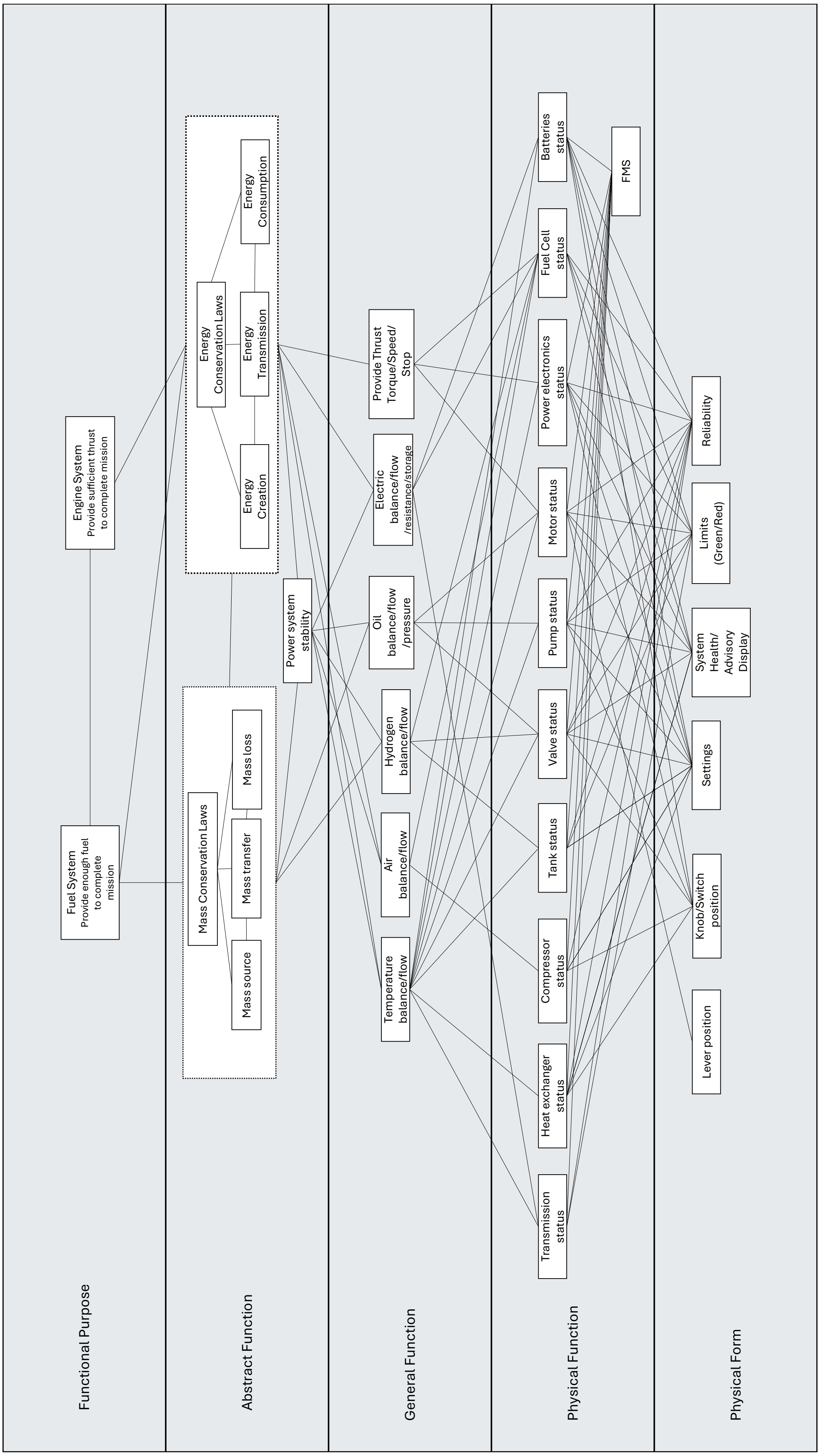


Fig. 6: Abstraction Hierarchy of the powertrain of a HAPSS

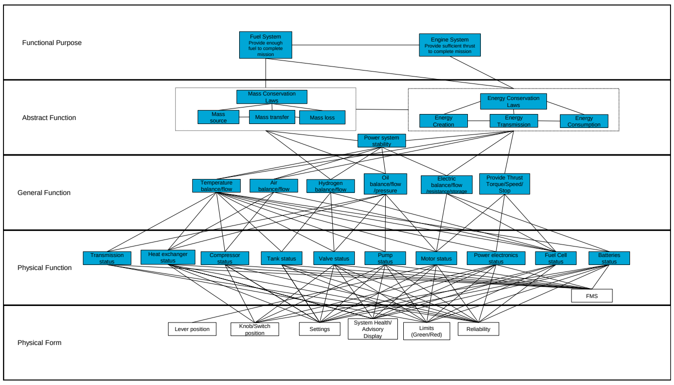
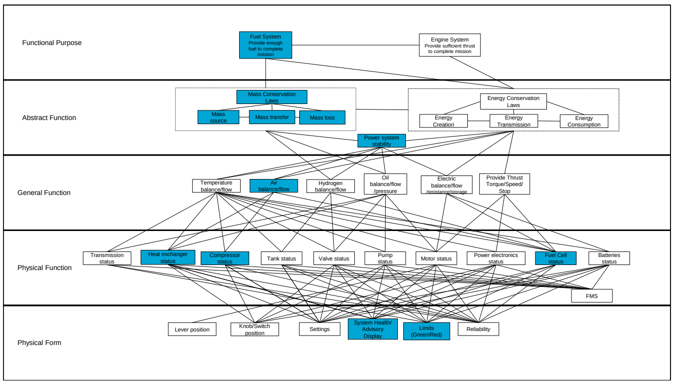
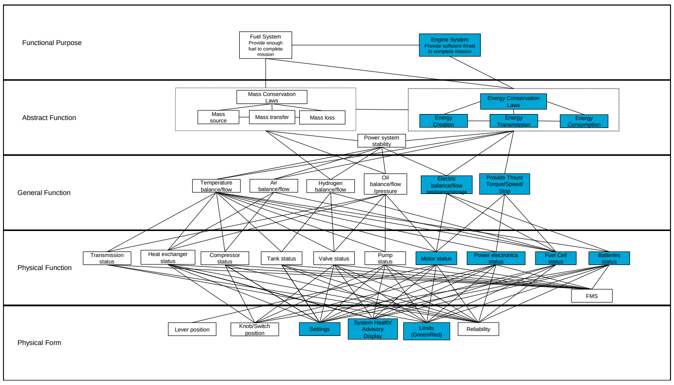


Fig. 7: Highlighted elements in the AH of the main display

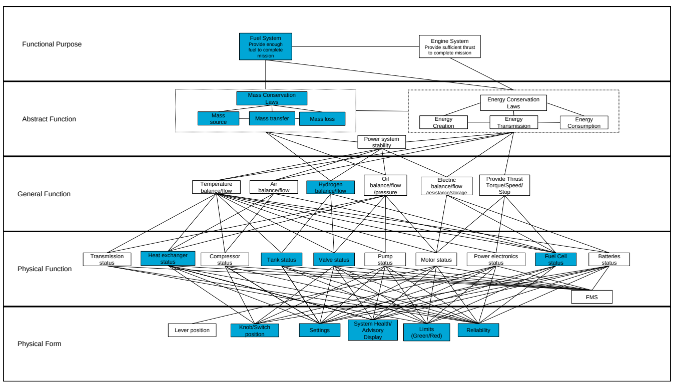


(a) Highlighted elements in the AH of the air display

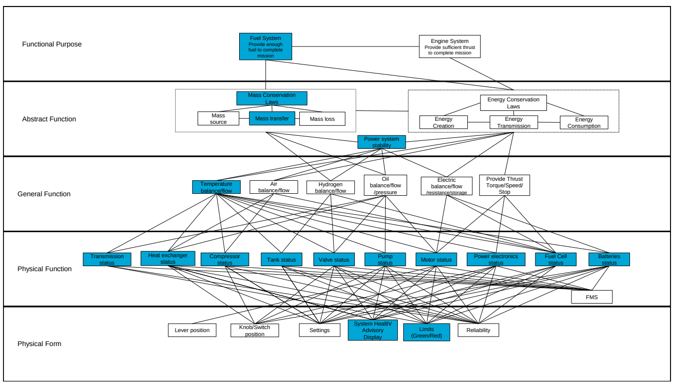


(b) Highlighted elements in the AH of the power display

Fig. 8: Highlighted elements in the AH of the air and power displays



(a) Highlighted elements in the AH of the fuel display



(b) Highlighted elements in the AH of the temperature display

Fig. 9: Highlighted elements in the AH of the fuel and temperature displays

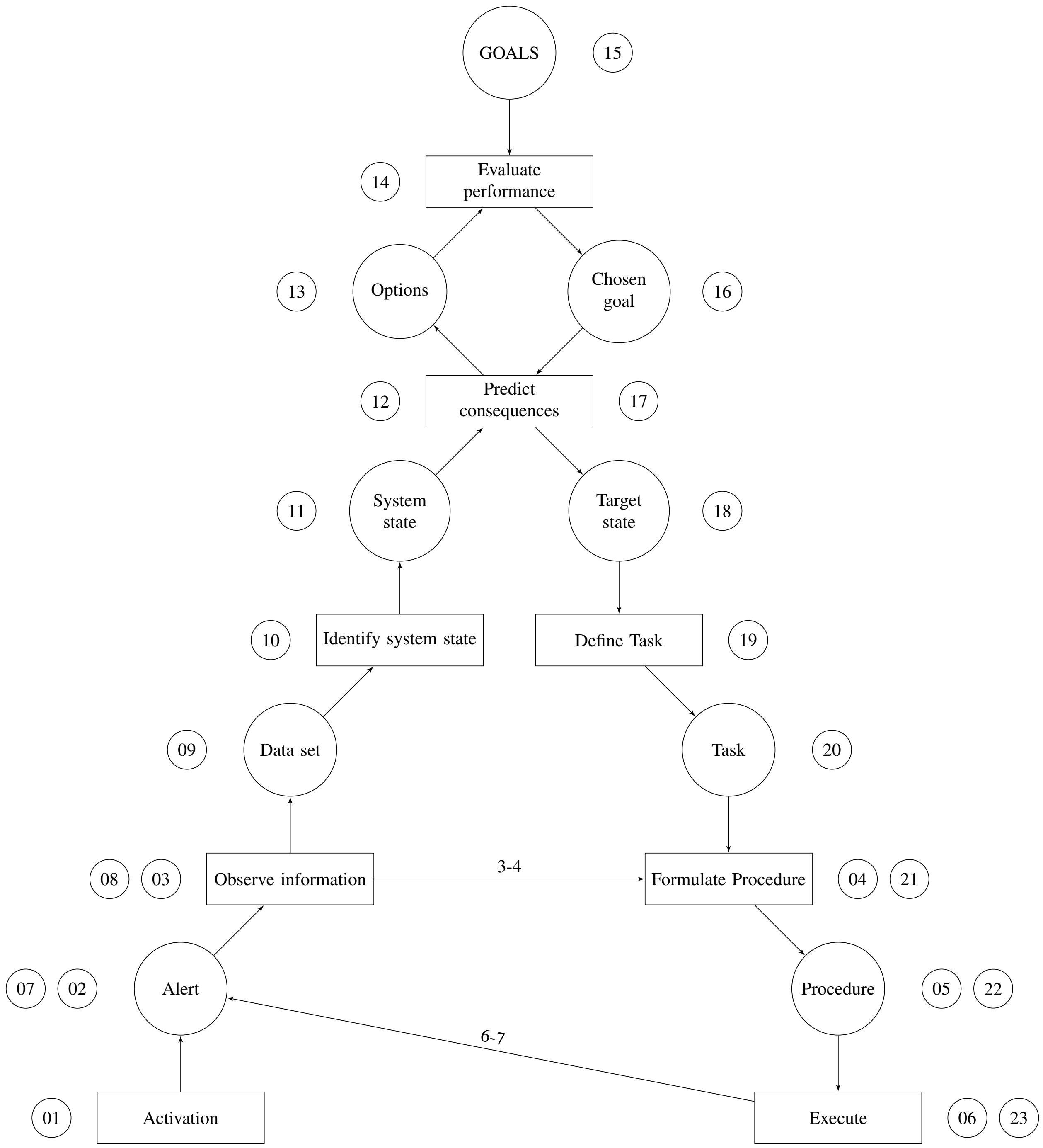


Fig. 10: Decision ladder for the loss of power scenario.

TABLE II: Steps associated with the decision ladder of the loss of power.

Step	Action
1	Visual, auditory warning of disparity in fuel quantity.
2	Dial readout. Advisory display lights.
3	Problematic value of fuel imbalance.
4	Use memory items and take QRH.
5	Match the conditions to the QRH.
6	Execute the procedure.
7	Monitor for change in alert level.
8	Check the fuel level evolution and other associated dials.
9	Make sure the aircraft is operational and no other secondary systems failures.
10	Put together information to understand the whole situation.
11	Determine the trend of the fuel tank. Determine the speed of degradation of the system.
12	Consequence on the mission profile. Prediction of range.
13	Review the current situation and understand why the imbalance is getting worse.
14	Change mission profile. Solve issue. Continue mission with imbalance of fuel.
15	Assess availability of resources and level of risk for every option.
16	Safe mission completion.
17	Use all available fuel from the problematic tank or transfer fuel.
18	Is the current situation deteriorating or keeping stable?
19	Maximum available resources for adjusted mission profile.
20	Define variables to monitor. Discuss variables with the co-pilot.
21	Select the correct procedure, fuel transfer or fuel shut-off. Prepare information for ATC.
22	Recall relevant memory checks, and checklists.
23	Procedures for necessary tasks confirmed.
24	Execute the procedures

TABLE III: Example of variable categorization

Visualization	Example variables	Type of display	Display options
Main	General health of cooling, Pump flow, Batteries SOC	Interconnected multivariable and structural	Configurable display, Mimic Diagrams, Multiple variable on constraint background
Power	Fuel Stack outputs, Battery output, Torque	Single variable Multivariable	Polar graphs, Summing bar graphs, Multiple variables on constraint background
Temperature	Oil temperature, Glycol temperature, Tank temperature	Single variable Multivariable displays Structural variable displays	Bar graph, Meter, Connected bar graph Polar graphs
Fuel	Fuel quantity, HEX Temperatures, Valve state	Single variable Multivariable displays Structural variable displays	Nomographs, Summing trend charts Connected meters
Air	Air humidity input vs output, Compression ratio, Air input to the fuel stacks	Single variable displays Multivariable displays	Analogue + Digital, Bar graphs Connected meters

C. Connection to design

Using the AH, it is possible to define interacting systems and components that could help represent the powertrain as a whole and not variables in isolation. In Figures 7, 8 and 9 one can see a graphical visualization of the connections made during the creation of the displays. Once these connections are made, it is possible to establish variables that are relevant to the model representation of the system. These variables represent different characteristics of components of each subsystem. These are categorized in tables to sort them by the appropriate display as seen, for example, Table III. Using the Visual Thesaurus for Data Relationships [14] it is then possible to associate the different variables with the corresponding representation. This is then used as a basis to create the different displays.

D. Display Design

This subsection will discuss the creation of five displays representing the different systems involved in the powertrain. All these displays represent the aircraft when it is in cruise. These visualizations would be visible on a Multi-Function Display (MFD) located in the space available due to the restructuring of the dial cluster as seen in Figure 2. The following displays are closely related to the displays created by Dinadis and Vicente [9] and can be seen in Figure 5.

1) Synoptic Main Display: The synoptic display shown in Figure 11 can be described as a system-wide representation of the hydrogen-electric powertrain. It does not provide specific values or limits and constraints but instead illustrates the interdependences of the subsystems. This enables the pilot to understand the general system's health. The symbols are connected through either electrical, mechanical, or fluid links that illustrate the state of these transmission links. Such a synoptic display also allows the pilot to locate the geographical location of an issue immediately and ensures that the pilot's mental model corresponds to the system. The different icons in the synoptic representation from top to bottom are the radiator cooling system, the additional compressor fans, the pumps, the battery management system, the fuel cells, and finally the hydrogen tanks. The electric motor and gearboxes are in the wings of the aircraft. Novel iconography was chosen over of classic process engineering iconography to try and evaluate the reaction of the test pilot to these symbols. Underneath the synoptic display are stability indicators which represent the other four displays accessible through the buttons under the screen namely fuel, air, temperature, and power. The stability indicators are an amalgamation of the variables present with each system display, they can be associated with the power system stability block located on the Abstract Function of the AH. The abbreviations L and R are left and right. All variables are combined and scaled to a left and right bar graph. This is implemented to reflect the symmetric nature of the system. The bar graphs are annotated with a yellow warning limit and a red action limit. The color of the bar graph is set to change when these limits are crossed. The intention behind these stability indicators is to be able to evaluate how close the system is to being unstable or problematic. The symbols

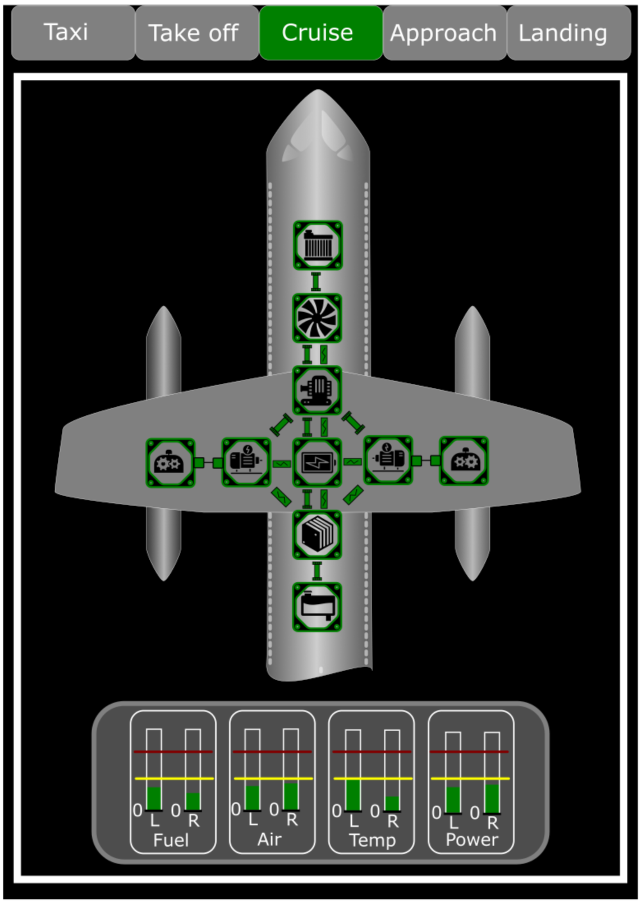


Fig. 11: Synoptic and stability display

used in the synoptic display will also change colors to yellow and red when a problematic scenario emerges. This allows the pilot to immediately identify the problematic subsystem.

2) Power monitoring: The power monitoring display shown in Figure 12 is a combination of multiple types of indicators and graphics to display the pathway of the electrical-mechanical energy from the fuel cells to the electrical motors and finally propellers. It is symmetrical in nature, with the left and right sides of the aircraft respectively shown on the display. From the bottom to the top, the order is determined by the pathway of the energy creation, transfer, management, and use that can be seen in Figure 6.

The fuel stacks (eight in total with four located on the left and four on the right), located at the bottom of the display, are represented as close proximity bar graphs due to the large number of individual fuel cells, this also allows for the use of a spread indicator in the shape of a white box surrounding the highest and lowest performing fuel cell. A lower limit associated with the color red is also included to display the recommended minimum output of the fuel cell. Under each duo of fuel stacks powering the individual lanes is a digital readout to indicate the total output power of the power lane. The colors of these vary with the state: indeed a safe state is green while a concerning state is yellow and an immediate action dangerous situation is red.

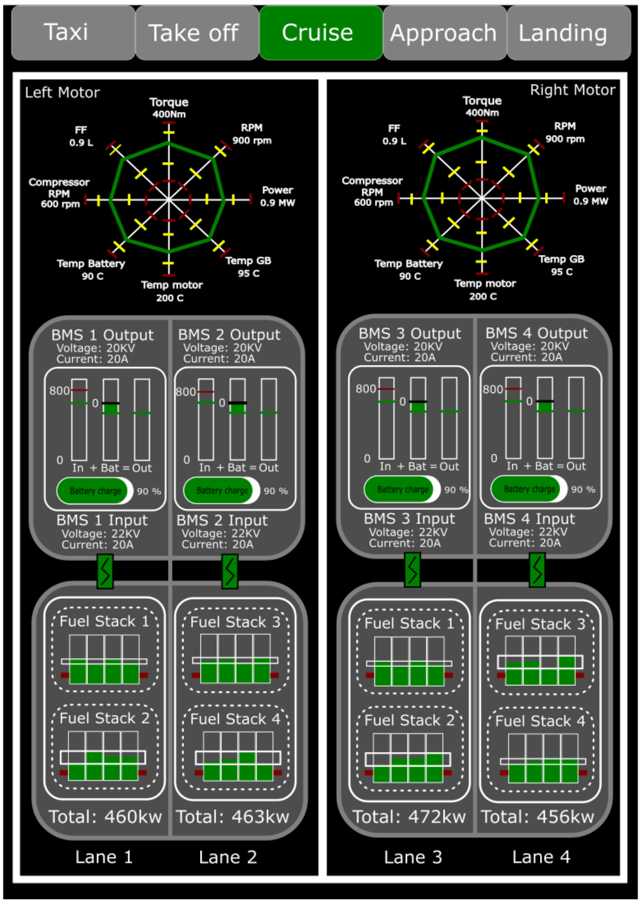


Fig. 12: Power monitoring display

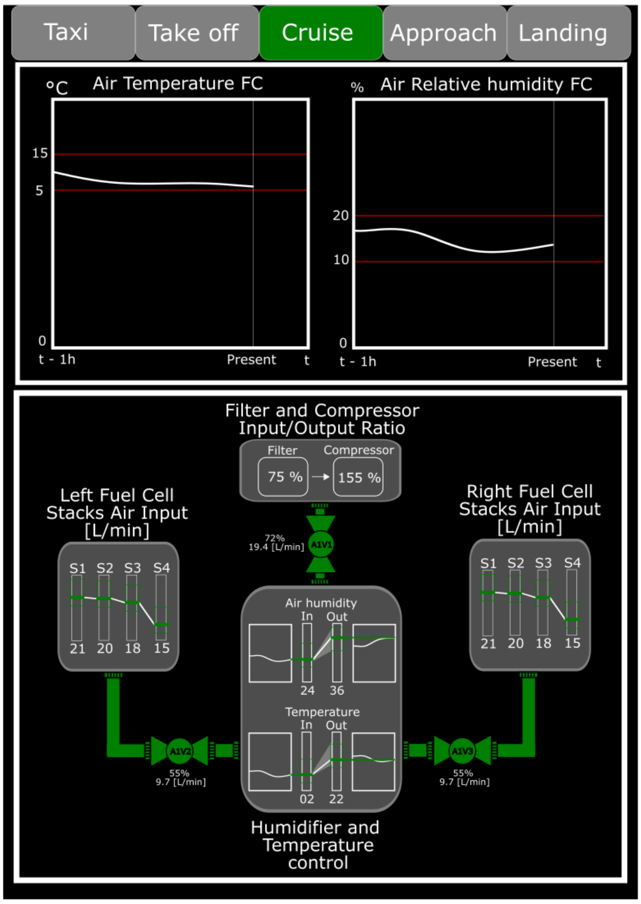


Fig. 13: Air monitoring display

The middle section of the display is used to display the BMS (Battery Management System) that manages the input energy from the fuel stacks, the output sent to the electric motors, and the battery systems that can either be charging, discharging, or keep level. This system display is composed of different elements, namely the additive monograph located in the middle of the display, the battery state of charge indicator located under the nomograph (represented by a percentage of the total horizontal bar graph), its respective color, the text, and digital readouts of the input and output values. At the bottom of the system display is a state of charge indicator of the battery to display the current charge level of the battery, the color of which is set to change under a certain level of discharge. The additive nomograph functions following the equations located under it. It displays three different variables namely the input power, the battery, and the output power. By adding the input power and battery, it is possible to obtain the output power. Finally, the upper section of the display contains a polar graph containing variables related to the functioning of the electric motor such as propeller torque or motor temperature. A summary of the variables can be found in Table III. The pilot can be trained to recognize certain scenarios simply by the shape of this polar graphic.

3) Air monitoring: The air monitoring display as shown in Figure 13 is sectioned into two separate spaces. The top section is composed of two trend graphs that represent the variables associated with the correct functioning of the air input to the fuel cell. This is a vital part of the proper functioning of the power train as the fuel cell is dependent on the air being at a certain humidity level and temperature. The left trend graph represents the air temperature of the incoming air to the fuel cell, the units of this graphic are Celsius on the Y-axis and minutes on the X-axis, there are also limits in red on this graphic. The right trend graph represents the humidity level of the air entering the fuel cell, the units of this graphic are the relative humidity percentage on the Y-axis and minutes on the X-axis. There are also limits in red on this trend graphic.

Abbreviations	Variables
RPM	Engine revolutions per minute
Power	Power draw
Temp GB	Gearbox Temperature
Temp Motor	Motor Temperature
Temp Battery	Battery Temperature
Compressor RPM	Compressor revolutions per minute
FF	Fuel flow out of the hydrogen tanks per minute

TABLE IV: Polar graphic abbreviations

Deviation even if only slight can compound over time and as such trend graphs can illustrate this proximity to the limit of operations and indicate any potential saturation within the system. The trend graphics include limits to the operational functioning of the fuel cell in order to give context to the pilot of the state of the air entering the fuel cell system.

The lower section of the display is a series of connected subsystems, namely the filter and compressor section located at the top of this section of the display followed by the humidifier and temperature control section located at the bottom of this section of the display and the left and right fuel stack air inputs respectively. The filter and compressor are only represented by the respective pressure ratios of their inputs and outputs while the fuel stack inputs are represented by connected meters to display any out-of-the-ordinary behavior by one or more of the cells. The humidifier and temperature control section of this display uses connected meters with expected variable shading. These types of displays are used to represent two variables that have an expected behavior associated with them. In this specific case, the air humidity and temperature entering the conditioning unit and exiting the unit. This allows the pilot to verify the correct functioning of the subsystem. There are also corresponding trends to show a history of the variables to ensure that the past behavior was not problematic to the proper functioning of the system.

4) Fuel monitoring: The fuel monitoring display as shown in Figure 14 can also be divided into two separate sections. The upper section of the display is dedicated to two trend graphs displaying the variables associated with hydrogen capacity and power output while the lower section represents the flow of hydrogen from the tanks to the fuel stacks while also involving variables important to the correct transformation of the hydrogen from chemical energy to electrical energy.

This lower section is structured symmetrically along the vertical axis to represent the left (1-8) and right (9-16) fuel systems of the aircraft. The output of the fuel cells is displayed in kW. The most relevant valves connecting the subsystems are displayed as well as the thermal exchangers and the air system. If the air system displays an oddly shaped polar graph defined by the flow of air in L/min, the temperature in Celsius, the pressure in PSI, and the humidity in % (oddly, in this case, means a polar graph that does not represent a square), it would then be possible to switch to the air display shown in Figure 13 to investigate the matter more. It would also be possible to switch to the thermal monitoring display as depicted in Figure 15 if the heat exchanger monitoring becomes problematic.

The tank section (located in the lower section) of the display has information about temperature (represented as "T"), pressure (represented as "P"), and percentage of fill (represented as "%") which are the three most important variables of the two tank system. The digital readout of the meters is located under each of the meters and allows the pilot to obtain a precise readout of the value of the variable. The valves connecting the subsystems also include information about fuel flow and the current state of the valves, from 0% open to 100% open.

5) Temperature monitoring: The temperature monitoring display shown in Figure 15 is divided into two distinct sections

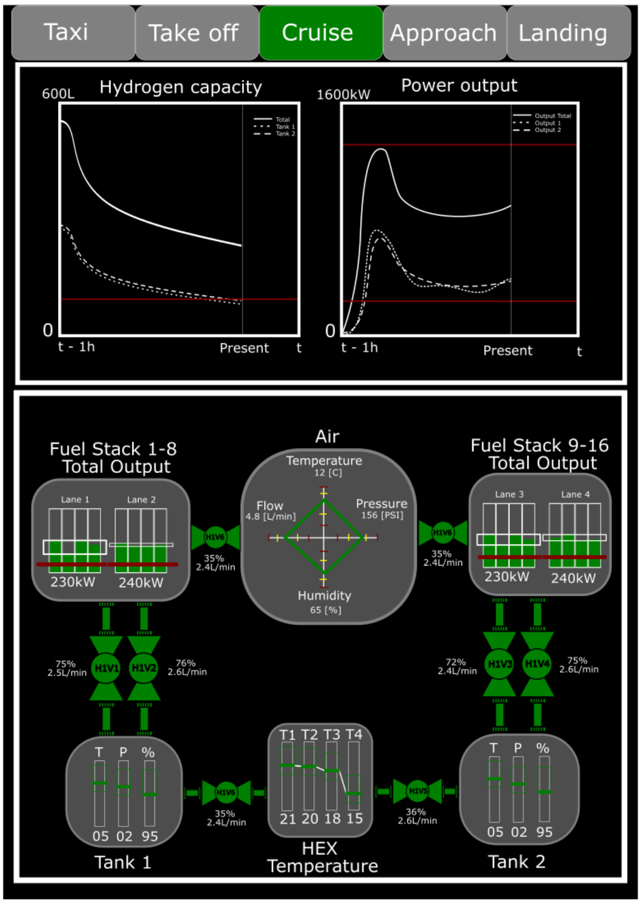


Fig. 14: Fuel monitoring display

that represent the oil temperature management in the upper section and the fuel cell temperature management in the lower section. The oil temperature monitoring section of the display uses a schematic representation of the oil system including the 4 radiators, the three coils of the heating system, the pumps, the gearbox temperatures, and the motor temperatures. These are not the only variables associated with the oil in the aircraft but are related to the temperature monitoring of this subsystem. The meters in the oil radiators section are separated into left and right and are connected by a line that follows the value in the meter. This is done to immediately indicate the trend of these series connected radiators. As an example, if there is an issue with airflow, then it would be possible to see an unusual trend between the temperature of the two radiators located on the left or right of the aircraft. The oil heaters section of the display also includes an indication of the heaters either being on or off. The glycol temperature monitoring system is located in the bottom section of the display and, in a similar fashion to the oil section of the display, uses a schematic representation of the system to illustrate the connection between the subsystems. This section contains six subsystems which are connected schematically by valves. The heat exchangers provide the system with cooling or heating and are connected to the pumps. The pumps in

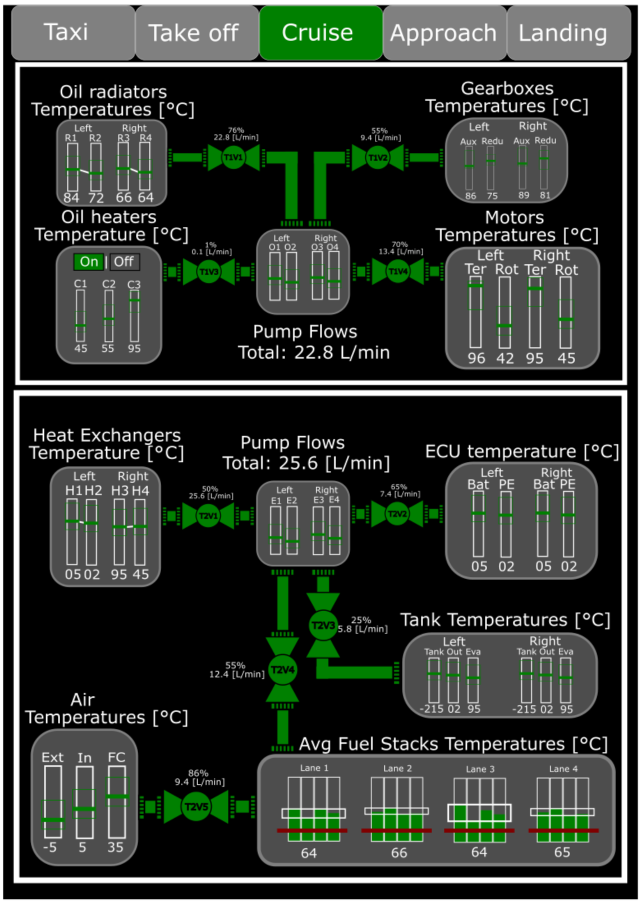


Fig. 15: Temperature monitoring display

turn provide the electric conditioning unit, the tanks, and the fuel stack with heated or cooled glycol. The fuel stacks use close proximity bar graphs to illustrate the average temperature while the tank temperature and BMS temperature use meters as they are not directly correlated variables. All the temperatures on the display are in Celsius and the flows are in liters per minute. The oil heaters sections of the upper part of the display also show an example of a digital switch representation. All the meters in this representation are also equipped with a box around the meter which is the expected range of the variable, it will turn red if the real value does not fall within the range of the expected variable.

E. *Interview analysis*

An inductive coding approach was used to analyze the interview transcript. Inductive coding is a method of analyzing data that focuses on interpreting raw contextual information to uncover underlying patterns, themes, or concepts directly from the data. This technique is often described as a bottom-up process, where one starts without any pre-established codes and lets the coding framework emerge naturally during the analysis of the data [24]. The results of this analysis are the themes of the interviews. These themes were then discussed by the members of this research project to determine if the same conclusions could have been drawn across multiple researchers. The main themes that emerge across the different interviews are that the display visualization would be more adequate for supporting information or would be more appropriate in a prototype or training environment for aircraft development. The short air time of the Dash 8 makes the amount of time dedicated to KBB limited. There is an emphasis on immediately following the QRH which can be associated with RBB.

1) Interview with commercial pilot: The participant, a regional commercial pilot, is presented with the project as well as the three different scenarios. A discussion ensues about the realism of these training scenarios; how pilots are trained to deal with these types of situations (this interview relates to phase 1 of the interview process). The main themes of this interview concern how pilots are more oriented toward using the QRH than trying to understand the information at face value. The behavior can be associated with RBB.

2) Interview of the airworthiness engineer: The participant, an airworthiness engineer with extensive experience on the Dash 8, discusses his familiarity with the aircraft, the common scenarios involving the fuel and power displays, and their approach to diagnosing and addressing issues related to high oil temperature, fuel imbalances, and loss of engine power (this interview relates to phase 1 and 2 of the interview process). The participant provides insights into the interpretation of the display indicators, the troubleshooting procedures, and the decision-making process in addressing these scenarios. The discussion involves the potential integration of a new hydrogen-electric propulsion system and the participant's perspectives on the design and presentation of the associated displays, emphasizing the importance of intuitive and straightforward interfaces for operational personnel. The end of the interview also touches on the participant's experience with common mistakes and

TABLE V: Feedback on specific displays from the test pilot

Display	Positive feedback	Improvement feedback
Main	Synoptic visualisations, Overview of the entire system	Similarity between the pump and motor symbols. Fuel Cell symbol wasn't clear. Mechanical connections too similar to electrical
Fuel	System limits. Polar plot.	Trend graphs. Doesn't like the continuous limit on the fuel stacks section
Air	Likes the input/output humidifier control meters	Trend graphs, they are too focused on monitoring and not on system state
Power	Polar plot representation. Close proximity bar plots	Limits representation, would rather have markers on the edge of the display. Complexity of the additive nomographs
Temperature	Composition of the oil temperature monitoring. Connected meters within the radiator section.	Visibility of the expected value box on the bar graphs

TABLE VI: Main themes of the interviews

Interview	Main themes of the interviews
Interview with commercial pilot	Main training scenarios involve problematic situations to be solved by the pilots. These situations are all RBB-based problems. The pilot is obligated to use the QRH in order to perform these procedures.
Interview with airworthiness engineer	Approval and feedback on the scenario preparation for the test pilot. Concerns about implementation of KBB. Positive feedback on the display design but concerns about complexity.
Interview 1 with test pilot	Preference of pilots for simplicity in displays. Obligation of the pilots to follow the QRH. Preference for analog representations. Limit of time for reflection. Support for integration of multiple systems into a display similar to ECAM
Interview 2 with test pilot	Preference for system automation. Only abnormal conditions should be displayed. Differences between commercial aviation and prototype aviation. Absence of time for KBB due to regional aviation restrictions. Pilots are not trained to understand systems like engineers.
Overall common themes	Pilot behavior is strongly in favor of RBB. Necessity of development and testing of QRHs. Short time of operations.

slips related to the fuel and power systems, highlighting the criticality of accurate readings and the importance of robust system design. The airworthiness engineer also highlights the pilot's SRK behavior (including a legal obligation to follow the QRH) and comments on the fact that the pilot shouldn't do any knowledge-based behavior in his opinion and can be quoted as saying "So it's like rule-based behavior. They cannot do knowledge-based behavior, they shouldn't do it. They won't be able to act fast, yeah.".

3) Interview test pilot 1: The test pilot has a background as an electrical engineer and has extensive experience as a test pilot, including involvement in the certification process and providing feedback on HMI design (this interview relates to phases 1 and 2 of the interview process). The test pilot emphasizes the importance of the test pilot's role in the pre-flight process, where they are involved in defining risk control, hazards, and error mitigation. They also provide feedback on the workload and human factors aspects of the aircraft, including the HMI. The test pilot highlights that in a professional project, the test pilot will be heavily involved throughout the development process.

Regarding the traditional powertrain and fuel displays, he explains that the main parameters of interest are engine torque and propeller rpm, which are monitored during routine flights. He also discusses the importance of quickly scanning the entire dial cluster to ensure the dials are in the green, indicating system stability. The interview then explores three representative scenarios: a high oil temperature alert, an inequality in the fuel tanks, and a loss of power on a single engine/motor.

The test pilot outlines the thought process and decision-making steps involved in addressing these issues, emphasizing the importance of following established procedures and evaluating all available options. When presented with potential digital display designs for a novel hydrogen powertrain system, he also provides feedback on the use of graphical representations and images, suggesting that their number should be limited to avoid overloading the pilot's cognitive capabilities, particularly for infrequent events. He also expresses a preference for simpler, more specific displays that focus on highlighting abnormal conditions rather than showing the entire system architecture.

One of the most important conclusions of this interview is that the test pilot suggests that the most important aspect of information display is to only give the relevant information of the system if there is a problem with the specific variable, this can be gathered by the direct quote *"Well my personal opinion, is that pilots know the system architecture. It is not really necessary to show everything that is normally operating in a diagram. You can show if there is an abnormal such as a valve that is closed that should be open. You know sometimes less is more."*.

4) Interview test pilot 2: The test pilot is presented with different sections of the displays (this interview relates to phases 2 and 3 of the interview process). The displays aim to provide the pilot with detailed information about the system's performance and status. The participant initially comments on the synoptic display, noting that some of the symbols are not immediately intuitive, but that the overall layout and color-coding make the information reasonably clear. The participant suggests that additional annotations or a legend would not improve the representation as after training the pilot should be able to immediately recognize the symbols of the display.

Furthermore, the participant provides valuable insights into the design and presentation of information. The test pilot emphasizes that for commercial aviation, the displays should be designed to minimize the pilot's need for interpretation and provide clear, unambiguous indications of system status and required actions. The participant suggests that detailed trend information and complex visualizations may be more appropriate for test environments than for regular flight operations, where the pilot's workload is already high.

He highlights the importance of automating system monitoring and only presenting information that requires the pilot's immediate attention or action. He also recommends that any abnormal situations should be clearly communicated to the pilot (by for example displaying information in text on the FMS), rather than requiring them to interpret the display and deduce the problem. The pilot suggests that the information presented on the display could be summed as worded sentences on the FMS and can be quoted as saying *"You can do that in two sentences on the FMS. That would be quicker to understand. I think for me than giving a set of graphs where I have to draw that conclusion myself."*.

The participant's feedback reflects a deep understanding of the needs and constraints of commercial aviation and provides valuable guidance for designing effective and user-friendly display interfaces that support the pilot's decision-making and workload management. Even though the complexity of these displays might be too high as a main source of information for the powertrain in normal operations, he did encourage the implementation of such information presentations for either support display or for development in test scenarios and can be quoted as *"If you would be in a prototype airplane, then this would be great."*

V. Discussion

This section of the report is dedicated to presenting the analysis of the results, more specifically the findings, interpretation, weaknesses, and recommendations related to the interview results. The primary objective of this research was to explore the application of CWA and EID in developing a novel display for a Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system. This research contributes to the theoretical discourse on CWA and EID by demonstrating their applicability in designing interfaces for complex, modern aviation systems. The use of these frameworks in the context of hydrogen-electric propulsion highlights their potential to manage cognitive complexity in next-generation aircraft.

A. Findings

One of the main themes gathered during this project was the stark difference between designing displays for engineering purposes rather than for pilots: designing visualizations that are too complex to be used as a main display, but are more adapted as support displays, in case of large-scale malfunction during flight and pre-flight post-flight checks. The main feedback gathered during all rounds of interviews focuses on the pilot's lack of time on regional flights. The test pilot can be quoted as saying "The flights are no more than 90 minutes. There's little time.". This showcases the importance of only displaying relevant information that can be established during the WDA and ConTa. The accessibility of the different displays in this case leads the pilot deeper into the system architecture but only if the pilot decides this is a necessary step in order to understand the issue that arises.

B. Interpretation

Full system representation, as seen in previous literature[9] is in this case not the best representation due to the expressed need for a limited workload. It is also important to note that previous research was conducted with pilots having the support of a flight engineer while this project is focused on providing visualization for pilots having no support crew. The pilot should have access to the information by using a navigational tool such as buttons located under the display if this information is needed. The main display should represent the overall health of the system, as seen in Figure 11.

C. Weaknesses and limitations

The choices of selecting participants with both knowledge of the Dash 8 platform and the functioning of HAPSS systems severely limited the pool of available candidates. Additionally, the test pilot also was not available to participate in person, making the interview process online forcing him to interact with the display through the screen-sharing feature of a video-conferencing application. This could have led to some low-fidelity interaction or details that were lost due to image quality deterioration. The Svelte development platform also only supports local hosting and as such does not allow for remote testing. Additional dynamic testing with a more complex scenario could reveal the real strength of these displays as a more complex scenario would likely increase the system-wide interactions.

D. Recommendations

In order to further test the theory laid out in this project, a next step expansion would be to dedicate more research to connect the visualization to a representative simulation of the novel system instead of the fabricated data. This would allow one to experiment with a higher fidelity. The representations could still be altered on the basis of the feedback of the test pilot found in Table V to provide more support for the experiment participant. It would also be advisable to create a display that reflects the traditional information presentation methods currently found in the Dash 8 Q300 and compare them with the performance of these displays to provide quantitative empirical backing to this research. The pilots should then be trained to become experienced operators.

VI. Conclusion

This study investigated the application of CWA and EID in the development of a novel display for a Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system. The findings are informed by interviews conducted with a regional commercial pilot, an airworthiness engineer, and a test pilot, which provided critical insights into the practical requirements and challenges associated with display design in aviation. The interviews revealed that pilots and engineers prioritize simplicity and clarity in display interfaces, particularly in the context of time-constrained regional flight operations. The commercial pilot interview underscored a preference for RBB facilitated by the QRH, rather than relying on real-time interpretation of complex visualizations. The airworthiness engineer similarly emphasized the necessity of intuitive interfaces that minimize the potential for operational errors, advocating for designs that limit the need for KBB during high-stakes situations.

The test pilot provided further validation of these preferences, highlighting the importance of minimizing cognitive load by focusing on displays that clearly present only critical or abnormal system conditions. Their feedback suggests that while detailed visualizations may have utility in test environments, they are less effective for routine flight operations, where rapid and unambiguous communication of system status is essential.

In the context of this research, it was possible to answer a gap in existing literature defined by the research question:
How can CWA and EID be used to develop displays for a HAPSS aircraft?
Despite the valuable qualitative insights gained, the study is limited by its small sample size and the lack of empirical testing, which constrains the general applicability of the findings. Future research should address these limitations by conducting controlled experiments with a broader participant base to empirically validate the proposed display designs and assess their effectiveness in operational settings. In conclusion, this research contributes to the theoretical understanding of CWA and EID by demonstrating their relevance to the design of pilot interfaces in modern aviation systems. The feedback obtained from the interviews provides a solid foundation for further refinement and suggests that these frameworks hold significant potential for improving the usability and safety of next-generation aircraft displays.

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Part II

Preliminary Analysis

*This section has been assessed for the course AE4020 Literature Study.

3 Literature Review

3.1. Introduction

In the realm of modern aviation, the quest for sustainable and eco-friendly flight solutions has become more pressing than ever. As the global community faces the challenges of climate change and environmental conservation, the aviation industry and, for the purpose of this report, the company Conscious Aerospace, is bound to introduce new technologies and face new challenges. Innovations in aircraft design and fuel systems are not just wanted; they are needed for the future of air travel. Among these innovations, the exploration of alternative energy sources, particularly hydrogen fuel cells, represents a significant leap towards cleaner, greener skies. The Dash 8 Q300 aircraft, known for its reliability and efficiency in regional aviation, now embarks on a pioneering journey of being retrofitted with hydrogen fuel cells. This thesis focuses into this endeavor, navigating the complexities of integrating advanced fuel cell technology into an established aircraft model. At the heart of this integration lies a critical component: the cockpit fuel process and power-train display. This equipment present in the original Dash 8 Q300 only as a collection of dials that needed to be interpreted to understand the available kerosene now sorely needs to be upgraded in order to reflect and present the complexity of this new system. Without these changes, the pilot is left under-equipped to deal with the intricacies of this new power-train. The effective design and implementation of this display, guided by Cognitive Work Analysis and Ecological Interface Design, are paramount in realizing the full potential of this technological leap. This research aims to shed light on the intricacies of this retrofitting process, offering insights and solutions that could chart a new course in sustainable aviation.

3.1.1. Problem Definition

In the following section, we present a comprehensive analysis of the challenges and needs that justify the initiation of this project. It systematically outlines the scientific and technological rationale behind retrofitting the Dash 8 Q300 with a hydrogen fuel cell system. This part of the thesis critically examines the existing gaps in sustainable aviation technology and how this project addresses these through innovative solutions. By dissecting the key factors driving this research, we aim to establish a clear and evidence-based understanding of why this project is not only timely but also useful in the context of current aviation industry trends.

Background information

The pursuit of sustainable and environmentally friendly aviation has intensified in recent years 3.1, driven by escalating concerns over climate change and the environmental impact of fossil fuels. This shift is steering the aviation industry towards exploring and adopting alternative energy sources, notably hydrogen fuel cells, known for their high energy efficiency and zero-emission capability. Hydrogen, as a fuel, presents a promising avenue for reducing the carbon footprint of aircraft, making it a focal point of contemporary aviation research and development.

The Dash 8 Q300, a classic choice in regional aviation, emerges as an ideal candidate for such innovation. Designed for short to medium-haul flights, this aircraft has carved out a niche in the aviation industry, prized for its operational efficiency and versatility. It is due to these characteristics that Conscious Aerospace has chosen to use this aircraft as a platform to prototype upon. The decision to retrofit the Dash 8 Q300 with hydrogen fuel cells is not merely a technological upgrade; it represents a pivotal shift in the

aircraft's operational paradigm. This transition underscores a broader movement in aviation - a shift from conventional jet fuels to more sustainable alternatives, marking a stride towards eco-friendly air travel.
However, integrating hydrogen fuel cell technology into an existing aircraft model like the Dash 8 Q300 is a complex undertaking. It involves addressing numerous technical, safety, and regulatory challenges. The aircraft's design must accommodate the unique properties and requirements of hydrogen fuel cells, such as storage, weight distribution, and energy conversion systems. Additionally, the retrofitting process must comply with stringent aviation standards and regulations to ensure safety and reliability.
One of the facets to this retrofitting process is the implementation of an effective fuel process display within the cockpit. This aspect is highly important as it directly impacts pilot interaction and the overall operational dynamics of the aircraft. The display must not only provide critical information regarding the hydrogen fuel system but also do so in a manner that is intuitive and conducive to decision-making in flight. This necessitates a thoughtful and informed approach to display design, one that leverages the principles of Cognitive Work Analysis and Ecological Interface Design. EID, as a framework, aims to visually highlight constraints and intricate relationships in the work environment of the operator. Theoretically, this approach frees up the pilot's cognitive resources, enabling them to focus more on advanced tasks such as problem solving and decision making. EID differs from other classical design methodologies, such as User Centered Design, by concentrating on the work domain or environment instead of prioritizing the end user or a particular task. This makes it an ideal candidate for this research.
In this context, the present research seeks to explore the multifaceted process of retrofitting the Dash 8 Q300 with hydrogen fuel cells. By focusing on the cockpit display design using CWA and EID, the study aims to contribute valuable insights into how advanced aviation technologies can be integrated effectively into existing aircraft models.

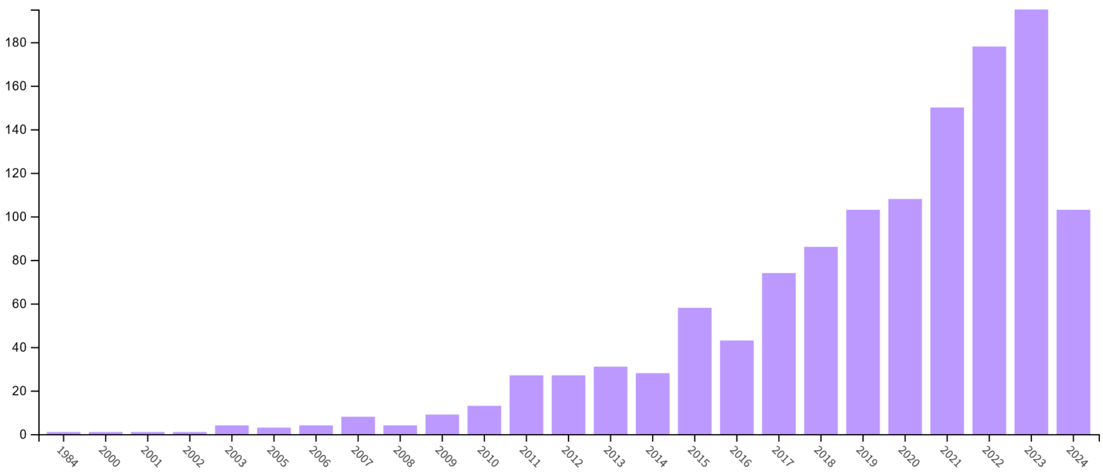


Figure 3.1: Publications on sustainable aviation according to Web of Science

Motivation
A critical aspect of this research addresses the notable gap in existing studies on the integration of hydrogen fuel cells in aviation, particularly focusing on the adaptation of cockpit displays for pilots. The introduction of new powertrains could significantly affects operational procedures compared to conventional fossil fuel powertrains due to the added complexity of the fuel cell as will be explored in Chapter 3.2. These revised procedures will be explored in the rest of the necessitate the development of advanced displays and information systems to assist pilots in their execution. Consequently, the motivation for designing new displays arises from the need to accommodate these updated operational needs. As an example, it is possible to compare the process for diagnosing and operating with high temperatures in a traditional fossil fuel power-train in comparison with a fuel cell system. In the traditional system, the options are limited to reducing the output of the powertrain, whereas the novel fuel cell involves interconnected system of

heat exchangers and heat sinks and sources. The pilot must understand how a variable in the subsystem affects the system as a whole. Due to the complexity of this scenario, it is interesting to explore new representations of cockpit displays. Ensuring that pilots can safely and efficiently operate aircraft equipped with new technologies is paramount, and this necessitates a thorough exploration of interface design. The research objective shifts to examining to what extent it is necessary to convey the complex interactions within hydroelectric powertrains to pilots and assess how this information might affect their cognitive workload.

Objectives

The primary objectives of this research are multifaceted, encompassing both the technical and cognitive aspects of retrofitting the Dash 8 Q300 aircraft with a hydrogen fuel cell and implementing an effective fuel process display.

A significant portion of the study is dedicated to developing a comprehensive framework for cockpit display design, guided by Cognitive Work Analysis (CWA) which will be explored in 3.2. This involves understanding the cognitive tasks and requirements of pilots when operating an aircraft powered by hydrogen fuel cells and identifying the essential information and functionalities that should be incorporated into the cockpit displays. Building on this, the thesis aims to design and propose an ecological interface for the fuel process display, applying principles of Ecological Interface Design (EID) to ensure that the display effectively communicates critical information about the hydrogen fuel process, enhancing situational awareness and decision-making capabilities in the cockpit.

Furthermore, the research seeks to evaluate the usability of, and pilot interaction with the new display system through tests, pilot studies, and feedback from aviation experts. One of the goals of this research is to contribute to sustainable aviation practices through technological innovation. By demonstrating the feasibility and benefits of retrofitting an existing aircraft model with hydrogen fuel cells, the study aims to provide valuable insights that could be applied to other aircraft models, advancing the aviation industry's sustainability efforts.

Lastly, the research encompasses an analysis of the regulatory and safety considerations involved in retrofitting and display implementation.

Together, these objectives aim to provide a holistic understanding of the challenges and opportunities presented by retrofitting an aircraft with hydrogen fuel cell technology, from technical feasibility to pilot interface design, contributing to the field of sustainable aviation.

Research Question

Multiple research questions emerged from the initial exploration of the topic:

- How can CWA and EID be used to develop displays for HAPSS aircraft?
- Which HAPSS concepts are relevant to display in future implementations of retroffited aircraft?
- How are expert in the field receiving the static and dynamic visualisations with regards to usability?

Scope

The scope of this project is concentrated on the retrofitting of the Dash 8 Q300 aircraft with a hydrogen fuel cell, emphasizing the implementation and analysis of a new fuel process display within the cockpit. The choice of the Dash 8 Q300 is a deliberate decision by Conscious Aerospace, reflecting its prominence in regional aviation and its suitability for such a technological upgrade. The core technical aspect of this research involves the comprehensive assessment and modification of the aircraft's structural, propulsion, and energy systems to integrate the hydrogen fuel cell technology. This focus excludes an in-depth exploration of other alternative energy sources.

An important element of the project is the design and implementation of the cockpit fuel process display. This task will be informed by methodologies such as Cognitive Work Analysis (CWA) and Ecological Interface Design (EID), ensuring that the display is both functional and user-friendly. The project will also examine pilot interactions with this new display system, focusing on usability, cognitive load, and the overall effectiveness of the design. This will likely involve simulations to gather actionable feedback.

Regulatory and safety considerations are also a critical part of this project's scope. This study will namely address the regulatory challenges and safety requirements associated with introducing hydrogen fuel cells and new display systems into the Dash 8 Q300. However, the research will not extend to a comprehensive analysis of the aviation industry's overall regulatory framework.

It's important to note that the geographical and operational context of the project will be tailored to the typical usage of the Dash 8 Q300 in regional aviation. Furthermore, the project is concentrated on non-emergency operations of the aircraft.

3.1.2. Preliminary Thesis Definition

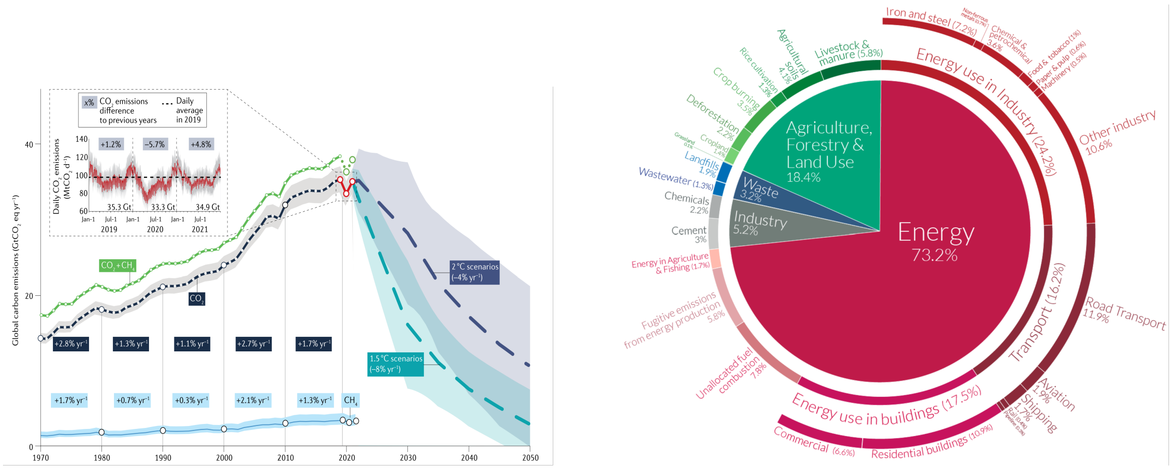
This thesis is defined according to the following hierarchy. The project is overseen and managed by the Technical University of Delft and more specifically the Aerospace Controls and Simulation department and the results are presented to the company Conscious Aerospace. The topic of this thesis is limited to the representation of the HEPS cockpit fuel process display of a generic regional aircraft (De Havilland Dash 8 Q300) and will include a representation of time as a factor when all other parameters are kept constant.

3.2. Literature review

The following section of this report focuses on the present literature and state of the art related to this project. Due to the novel aspect of this research, this specific topic has not yet been considered in literature. In order to gain sufficient knowledge, it was then necessary to examine other fields of study that have already applied and implemented similar methodologies.

3.2.1. Trend of global emissions

The general consensus among the scientific community is that the emissions of global greenhouse gases are trending upwards. This creates one of the great challenges of the 21st century in which to assure the survival of the global ecosystem as we know it, it is necessary to reduce emissions. Global agreements have been put in place to pledge reductions of nefarious gases in every sector.



(a) Trend of global emissions [27] **(b)** Contribution of aviation to global emissions in 2016 [28]

Figure 3.2: Global contribution present and future of aviation

3.2.2. Contribution of aviation

The global contribution of CO_2 emission due to aviation is estimated to be 2.5% [29] and is expected to steadily rise due to the increase in flight demand which will likely triple in the coming two decades as well as the implementation of ecological restrictions on other industries [30]. This emphasizes the development of environmental aviation as an important part of a more sustainable future. Due to the restrictive nature of innovation in the aviation industry, it is also estimated that it will take 50 years before the entire fleet is renewed to be sustainable due to the long asset life of planes. Understanding these restrictions implies that is necessary to develop technologies and invest in research as quickly as possible.

The figure [3.3] shows that the passenger growth of aviation has been growing at a faster rate every year since its inception. It also shows the different possibilities for future fuel use and revenue passenger kilometers (RPK) in the coming century. All models show us that the best-case scenario for future aviation is the stagnation of emissions (CO_2 and NO_x) if we follow the current trends. It is then imperative to promote research and development to counteract the potential ramifications of increasing aviation. The

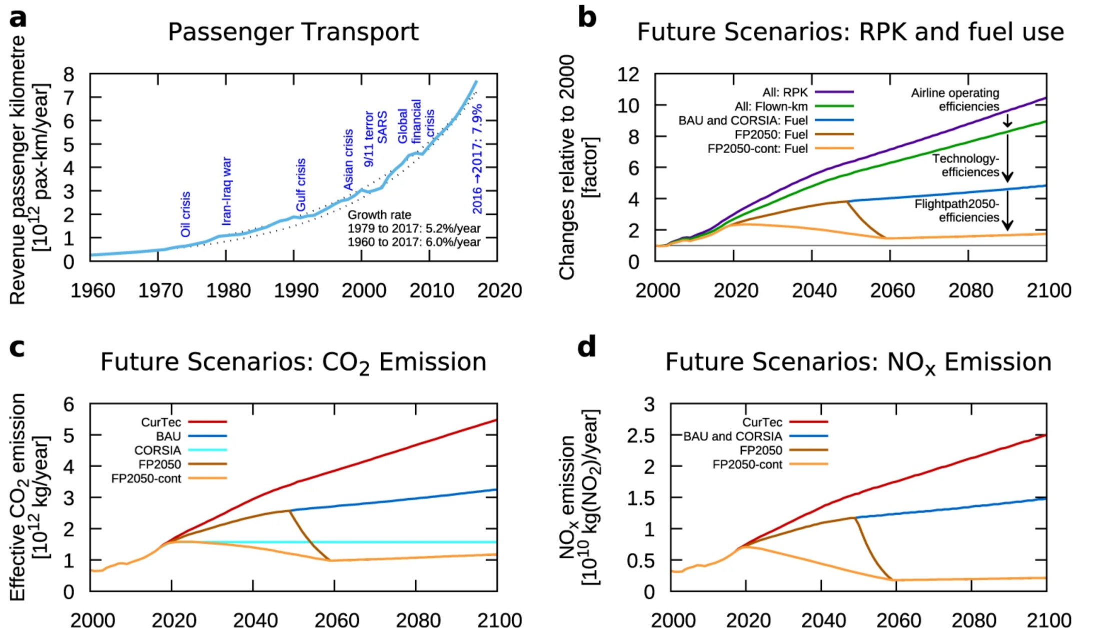


Figure 3.3: Trend of commercial aviation use and emissions [31]

different scenarios presented are current technologies (CurTec), business-as-usual future technological improvement (BAU), the offsetting scheme of the international civil aviation organisation (CORSIA), and 2 Flightpath 2050 scenarios which differ in the speed of technology improvements (FP2050 and FP2050-cont).

3.2.3. Demand for alternative fuels

The necessity for alternative fuels in the development of sustainable aviation is underscored by several pivotal factors: Firstly, the significant contribution of the aviation industry to global CO_2 emissions, estimated at approximately 2.5% [29], is a compelling reason for this shift. With the anticipated rise in air travel demand, the industry faces challenges in meeting decarbonization targets and minimizing the climate impact of carbon emissions. Alternative fuels are thus critical in reducing these emissions and steering the aviation sector towards sustainability [32].
Moreover, alternative fuels offer much-needed diversification away from traditional fossil fuels. Options like Sustainable Aviation Fuel (SAF), which can be produced from biological or waste materials, hydrogen, eFuel, and battery electric alternatives, each present unique benefits and challenges. However, they collectively contribute to a more sustainable, diverse, and resilient aviation sector [32]. The transition to alternative fuels also necessitates significant technological and infrastructural advancements. For instance, the adoption of hydrogen as a fuel requires the development of new storage systems, aircraft, and engine design modifications, and the establishment of new fuel distribution infrastructures. These advancements are crucial not only for the integration of alternative fuels but also for fostering innovation in the aviation industry at large.
Finally, international collaboration and policy support play a vital role in this transition. Initiatives like the Third ICAO Conference on Aviation and Alternative Fuels are instrumental in assessing progress, facilitating knowledge sharing, and establishing global frameworks for alternative fuel adoption. Such collaborative efforts are key in shaping policies and standards that support the shift to more sustainable aviation fuels and technologies [33].

3.2.4. Alternative fuels aviation

Due to this shift away from fossil-based fuels, multiple options have emerged as promising. These can be divided into two factions. Making classical engines and the fuel more efficient or converting the powertrain to electric motors and an electric power source.

Sustainable Aviation Fuel Sustainable Aviation Fuel (SAF) significantly reduces carbon emissions compared to traditional jet fuel. This is largely due to its production from sustainable sources like biomass, which absorbs carbon dioxide during growth. Additionally, SAF is compatible with existing aircraft, allowing immediate utilization without major modifications. Its production from a variety of renewable sources, including waste oils and agricultural residues, further enhances its environmental appeal by utilizing resources that would otherwise go to waste [34].
However, SAF also faces several challenges. The cost of production is currently higher than that of conventional jet fuel, posing a barrier to widespread adoption and potentially leading to higher air travel costs. Additionally, the production of SAF is not yet scalable enough to meet global aviation fuel demand, limiting its immediate impact. Finally, although SAF reduces in-flight emissions, its production can be energy and resource-intensive, and the overall environmental benefit varies depending on the biomass source and production method. Balancing these environmental benefits with economic and practical considerations is crucial for SAF's broader adoption and effectiveness in reducing aviation's carbon footprint [35].

Battery powered electric aircraft Battery-powered electric planes represent an innovative shift in aviation technology, but they come with a mix of notable advantages and significant disadvantages. On the positive side, these planes offer zero-emission operation (with the exception of contrails), a key benefit in reducing environmental impact since they entirely eliminate the carbon emissions associated with conventional jet fuel. Additionally, battery-powered electric planes generate considerably less noise compared to traditional aircraft, reducing noise pollution around airports and improving passenger comfort. Furthermore, these planes potentially have lower maintenance and operating costs due to the higher efficiency and fewer moving parts of electric motors.
[36] However, several challenges hinder the widespread adoption of battery-powered electric planes. The most pressing issue is their limited range. Current battery technology does not provide the same energy density as fossil fuels, which greatly restricts the travel distance of electric planes on a single charge. Moreover, recharging these batteries is a time-consuming process compared to the relatively quick refueling of conventional aircraft, leading to longer turnaround times. Another significant drawback is the weight of the batteries. To store enough energy for flight, batteries tend to be large and heavy, which can limit the aircraft's payload capacity and overall efficiency.[37]

Hydrogen fuel cells Hydrogen fuel cell-powered electric planes represent a significant advancement in aviation technology, offering a set of advantages tempered by notable challenges. The most significant advantage is their zero carbon emission operation; these planes produce electricity through a chemical reaction between hydrogen and oxygen, with the only byproduct being water vapor, which reduces environmental impact. Hydrogen also boasts a higher energy density than conventional batteries, potentially enabling greater range and payload capabilities, crucial for longer flights. Additionally, hydrogen fuel cells can be refueled relatively quickly, akin to traditional jet fuel, which enhances operational efficiency.
[4] However, this technology faces several hurdles. Storing hydrogen poses a challenge due to its low density, necessitating high-pressure tanks or cryogenic temperatures, which raises concerns about weight, space, and safety. Another significant obstacle is the lack of hydrogen refueling infrastructure at airports, which requires substantial investment and development time. Furthermore, while hydrogen is potentially abundant, producing green hydrogen (from renewable sources) efficiently and at scale remains a challenge; most hydrogen production currently relies on fossil fuels, thereby diminishing the overall environmental benefits. [25]

3.2.5. Hydrogen Electric Power System

It is important to understand the different subsystem configurations of a HEPS as they will be individually represented later in this project. The following figure is the representation of the Dash 8 Q300 retrofitted to HEPS.

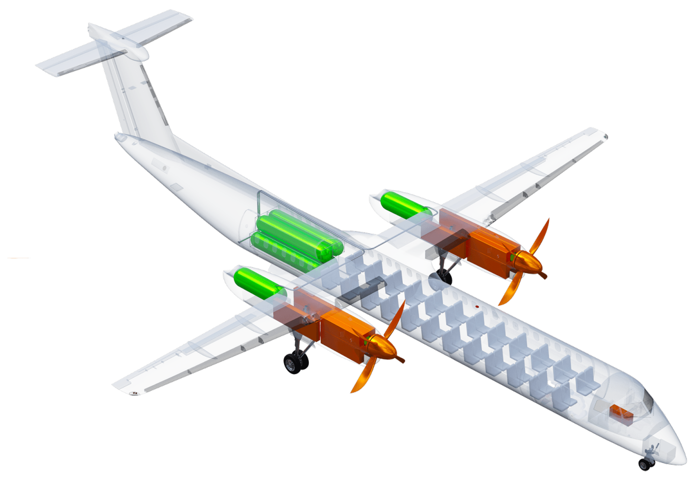


Figure 3.4: Preliminary design by Conscious Aerospace [38]

Hydrogen Storage Tanks:
Advancements in hydrogen storage for aviation, such as the development of cryo-compression tanks, mark a significant stride in overcoming the challenges associated with onboard hydrogen storage in hydrogen-powered propulsion systems. These tanks are designed with substantial insulation and are capable of operating at low pressures, maintaining the hydrogen in a cryogenic state. The research sheds light on the application of such technology, specifically focusing on Multi-Layer Insulation (MLI) vacuum tanks tailored for regional aircraft [39]. A key aspect of these tanks is their ability to efficiently warm the hydrogen boil-off to operational temperatures before it is fed into the fuel cell stack. This is particularly noteworthy given hydrogen's relatively lower volumetric energy density compared to traditional hydrocarbon fuels.

Electric Motors:
In the context of evaluating motor types for their applicability in HEPS, a set of metrics is employed to conduct a qualitative analysis. These metrics encompass a range of factors including energy losses, thermal and mechanical constraints, as well as the achievable power and current densities. Additionally, the complexity of the motor types and their behavior under short-circuit conditions are assessed. In a comprehensive study, an extended set of these metrics was applied, leading to the identification of Permanent Magnet Synchronous Motors (PMSM) as the most suitable motor type for application in HEPS [40][41].

Oxygen Supply System:
The Oxygen Supply System (OSS) is an integral component, designed to ensure the consistent and efficient delivery of oxygen to the fuel cells, where it serves as a vital reactant in the electrochemical process that generates electricity. The system's design varies depending on the specific requirements of the aircraft and its operational environment. In most aviation applications utilizing HEPS, ambient air is the primary source of oxygen. This approach employs high-efficiency air filters and compressors to draw, purify, and pressurize the ambient air before channeling it into the fuel cells. This is crucial for maintaining the efficiency and longevity of the fuel cells, as impurities in the air can degrade the fuel cell components over time. In specialized applications, particularly where higher efficiencies are desired or in high-altitude operations, the system might incorporate liquid oxygen tanks. These systems store oxygen in a liquid form, which is then vaporized and supplied to the fuel cells as needed.

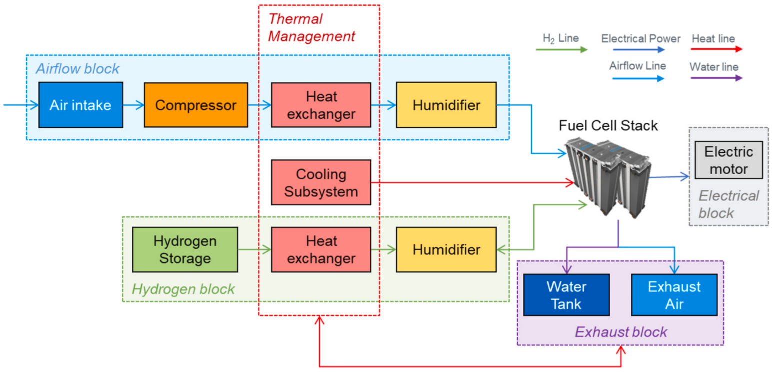


Figure 3.5: Fuel cell system architecture [42]

Power Distribution System:
The Power Distribution System (PDS) in a HEPS is essential for managing the electrical power from the fuel cells to the aircraft's subsystems, ensuring efficient and reliable operation. This system includes inverters for converting direct current (DC) from fuel cells into alternating current (AC) for use by the electric motors. These inverters are designed for high efficiency and to handle substantial power within a compact form factor, suitable for aviation. Additionally, DC-DC converters are employed to adjust the voltage from the fuel cells to suit the requirements of the aircraft's electronic systems. Power Control Units (PCUs) dynamically manage the distribution of power across the propulsion motors, avionics, and other electrical components, adapting to various operational phases such as takeoff, cruising, and landing [37]. The system incorporates redundancy and safety features, including circuit breakers and isolation monitors, to ensure continuous operation and protect against electrical faults. Energy management and monitoring systems are integrated to optimize the use of electrical power, monitoring the performance of fuel cells, the state of battery reserves, and the energy demands from different loads.

Fuel Cells:
At the center of a HEPS are the Proton Exchange Membrane (PEM) fuel cells. These cells operate by channeling hydrogen gas into the anode side, where it is broken down into protons and electrons. The protons move through the electrolyte membrane to the cathode, while the electrons create a flow of electricity through an external circuit before recombining with the protons and oxygen to form water. The fuel cell stack, comprising multiple individual cells, is meticulously optimized for power density and efficiency, and it's capable of rapid responses to changes in power demand. Managing the waste heat and water produced in this process is crucial for maintaining operational temperatures and optimal membrane performance. [43]

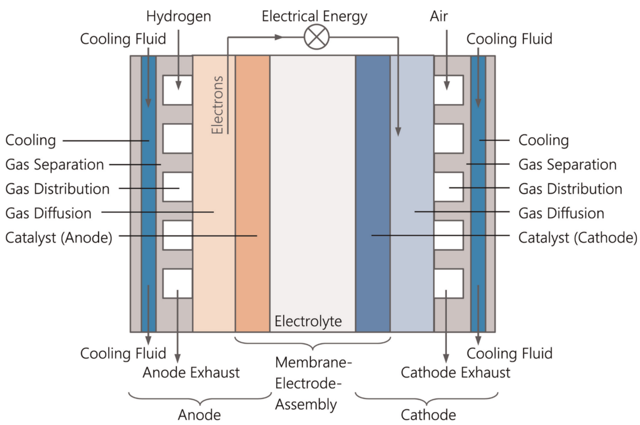


Figure 3.6: Schematics of a Proton Exchange Membrane [44]

Battery Backup:
In the architecture of a HEPS, particularly in aviation applications, the integration of a battery backup system is a strategic design choice that significantly enhances the overall functionality and reliability of the system. This component serves multiple critical roles, from providing supplemental power during peak demands to acting as a reserve power source in case of fuel cell system under-performance or failure. The choice of battery technology in HEPS is predominantly focused on high-density energy storage solutions like lithium-ion batteries [45]. These batteries are favored due to their high energy density. Additionally, lithium-ion batteries exhibit excellent charge and discharge efficiency, a vital characteristic that ensures rapid power availability when needed. In the operational context of HEPS, the battery backup serves as a power reservoir that can be rapidly deployed to meet sudden spikes in power demand, which are not uncommon in various phases of flight, such as during takeoff or sudden maneuvering. This capability not only provides an additional layer of safety but also allows for more flexible and efficient management of the fuel cell output, as the fuel cells can be operated at a more constant and efficient power level rather than having to adjust rapidly to meet peak demands.

Cooling System:
This system is engineered to effectively manage the heat generated by the fuel cells and electric motors, which are the primary heat sources in HEPS. The cooling system is designed to handle high heat fluxes while maintaining the components within their optimal temperature range. In fuel cells, efficient thermal management is crucial to prevent overheating, which can lead to a decrease in efficiency and potential damage to the cell membranes. Similarly, in electric motors, overheating can reduce efficiency and lead to wear on the motor's components [46].

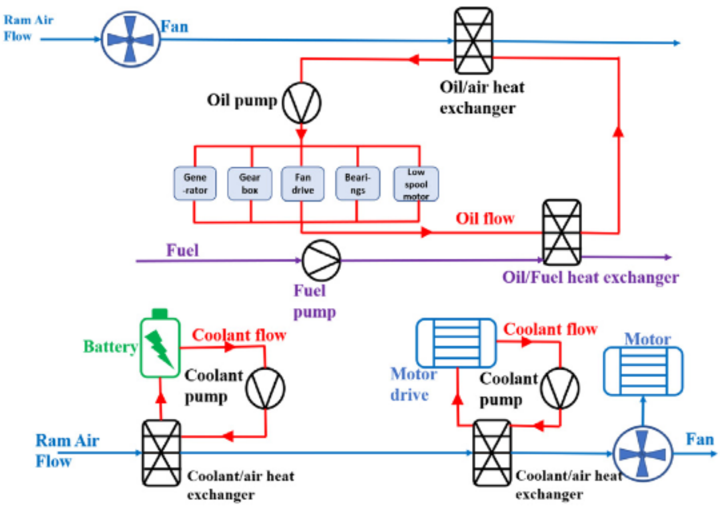


Figure 3.7: Example of a thermal management [47]

The cooling system typically employs heat exchangers that utilize either air or liquid coolants. Air-cooled systems are commonly used for their simplicity and lower maintenance requirements. In these systems, ambient air is used to dissipate the heat, often aided by fans or blowers to enhance the cooling effect. However, in scenarios where more efficient heat dissipation is required, liquid cooling systems are employed. These systems use coolants like water-glycol mixtures to absorb heat more effectively than air. The coolant is circulated through radiators or heat exchangers to remove the absorbed heat. Additionally, the system includes pumps and valves that control the flow of the coolant, ensuring that it is directed to where it is most needed [47].

3.2.6. Cognitive Work Analysis

Cognitive Work Analysis (CWA) is a comprehensive framework used in the field of human factors and ergonomics. It's designed to understand complex socio-technical systems, especially those where human decision-making plays a crucial role. The approach is particularly effective in environments that are dynamic and unpredictable. Developed by Jens Rasmussen and his team, CWA is instrumental in designing systems that support human operators effectively. In 1983 they developed the Skills, Rules, and Knowledge model which is instrumental when analyzing the performance of human-machine interaction [48]. The history of CWA's implementations dates back to the 1980s, originating at Denmark's Risø National Laboratory. It emerged primarily in response to the need for improved safety in high-risk industries like nuclear power, especially following incidents like the Three Mile Island accident. Early applications of CWA were seen in the nuclear power industry, where it was used to design safer control rooms [11]. Soon after, CWA principles were adopted in air traffic control systems to enhance the support for controllers' decision-making processes. The healthcare sector also saw early implementations, particularly in managing the complex environments of surgical and emergency rooms to improve patient safety. The military sector applied CWA in designing command and control systems, addressing the challenges in decision-making during military operations. By the late 1990s, CWA's versatility led to its application in various other fields, including transportation, manufacturing, and emergency management [11]. Initially focused on safety-critical systems, CWA's ability to handle system complexity and uncertainty has made it a foundational tool in the realm of human factors and ergonomics.

Structure and overview

The following structure of the CWA is taken as a summary of the book Cognitive Work Analysis by Kim Vicente [11].

Work Domain Analysis: This component focuses on understanding the system's structure, constraints, and resources. It involves identifying the system's functional purposes, values, and priorities, and breaking down the system into constituent parts like physical components, processes, and environmental factors. The goal is to create an abstraction hierarchy that maps out the system's goals, general functions, physical forms, and potential states, helping to understand how different elements contribute to overall goals.

Control Task Analysis: This phase analyzes how tasks are managed within the system, focusing on routine tasks and potential emergency situations, as well as the temporal aspects of tasks like sequencing and timing. The analysis is crucial for designing interfaces and decision support systems that align with how tasks are controlled and managed.

Strategies Analysis: This section of CWA explores the strategies used by operators, particularly in decision-making. It involves understanding how decisions are made, how operators adapt to changing conditions, and the use of heuristics in various scenarios. The insights gained are critical for designing systems that support flexible decision-making strategies.

Social Organization and Cooperation Analysis This component examines the social aspects of the work environment, including teamwork, communication, roles, organizational structures, and collaborative processes. The focus is on designing systems that facilitate effective communication and collaboration, aligning social and organizational factors with technical design. This is beyond the scope of the project.

Worker Competencies Analysis: This section identifies the skills, knowledge, and attitudes required by operators. It covers both technical skills and cognitive abilities like problem-solving, adaptability, and situational awareness. Insights from this analysis guide training programs, selection criteria, and the design of tools to enhance operator competencies. This is beyond the scope of the project.

3.2.7. Ecological Interface Design

Ecological Interface Design (EID) is a theoretical framework in the field of human-computer interaction and system design that aims to support user understanding and decision-making in complex systems. Developed as a part of Cognitive Work Analysis, EID focuses on creating interfaces that represent the underlying system constraints and relationships in a way that aligns with human cognitive abilities, particularly in the context of problem-solving and decision-making tasks. Central to EID is the concept of the SRK framework, which categorizes human behavior into skill-based, rule-based, and knowledge-based levels. EID aims to support these levels of cognitive processing by providing representations that are directly perceivable (affording skill-based performance), interpreted in terms of meaningful patterns or rules, and explorable at a deeper, structural level for knowledge-based reasoning [10][49].
One of the key principles of EID is to represent the affordances of the work domain rather than simply mirroring the physical appearance of system components. This involves displaying functional relationships and constraints that govern system behavior, enabling operators to perceive critical information directly and intuitively. By presenting data in a way that maps onto the natural decision-making processes of the user, EID facilitates a more intuitive understanding of complex systems. It provides operators with the ability to understand not only the current state of the system but also its potential future states. This foresight is crucial in scenarios where operators must anticipate problems and take proactive measures to prevent them.

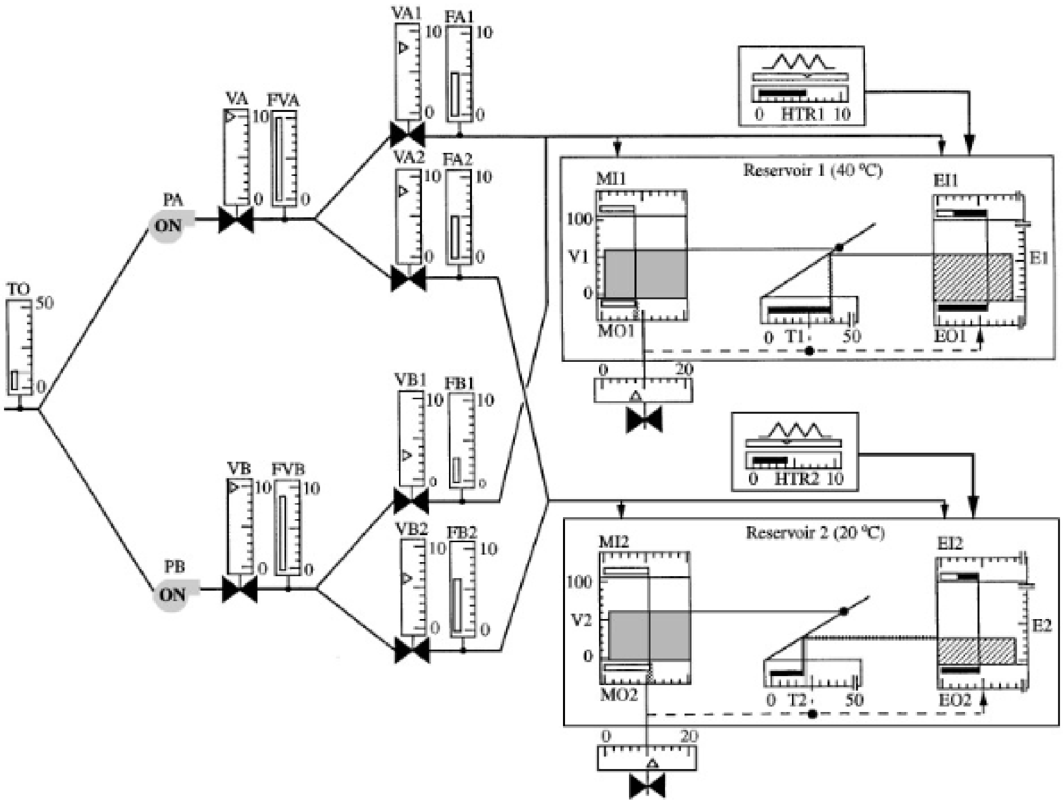


Figure 3.8: EID developed display for DURESS [50]

The DURESS platform was a specialized system used for research in the areas of ecological interface design and cognitive work analysis. The system in question is a thermal-hydraulic process control simulation, designed to be a simplified yet accurate representation of industrial plant operations. It features interconnected subsystems and purposes, introducing complexity through components that exhibit time delays. This means the impact of control adjustments isn't immediately apparent, especially to beginners. The system includes interdependent goals and a level of risk; ineffective management can lead to process failure, halting the simulation. This setup is designed to mimic real-world industrial challenges, where decisions have delayed and interlinked consequences [50].

3.2.8. Ecological Interface Design applied to aviation

Ecological Interface Design (EID), when applied to aviation, embodies a novel approach to cockpit display design that enhances pilot awareness and interaction with complex flight systems. The core principle of EID in aviation is the design of interfaces that articulate the functional relationships within an aircraft's systems. Traditional cockpit displays often focus on presenting discrete pieces of data, such as altitude, speed, or engine performance metrics. EID, in contrast, emphasizes the display of this information in an integrated manner, illustrating how different parameters interact and affect each other. For instance, instead of separately displaying fuel quantity and consumption rate, an EID-based interface might visually represent the relationship between these variables, offering a more intuitive understanding of the aircraft's current and projected fuel status. This approach is particularly crucial in aviation, where understanding the inter-dependencies of various flight parameters is key to effective decision-making, especially under high-stakes or emergency conditions. In the design of EID interfaces for aviation, the focus is on representing the affordances and constraints of the aircraft's operational environment. This means designing displays that help pilots understand not just what the aircraft is currently doing, but what it can do under different conditions.

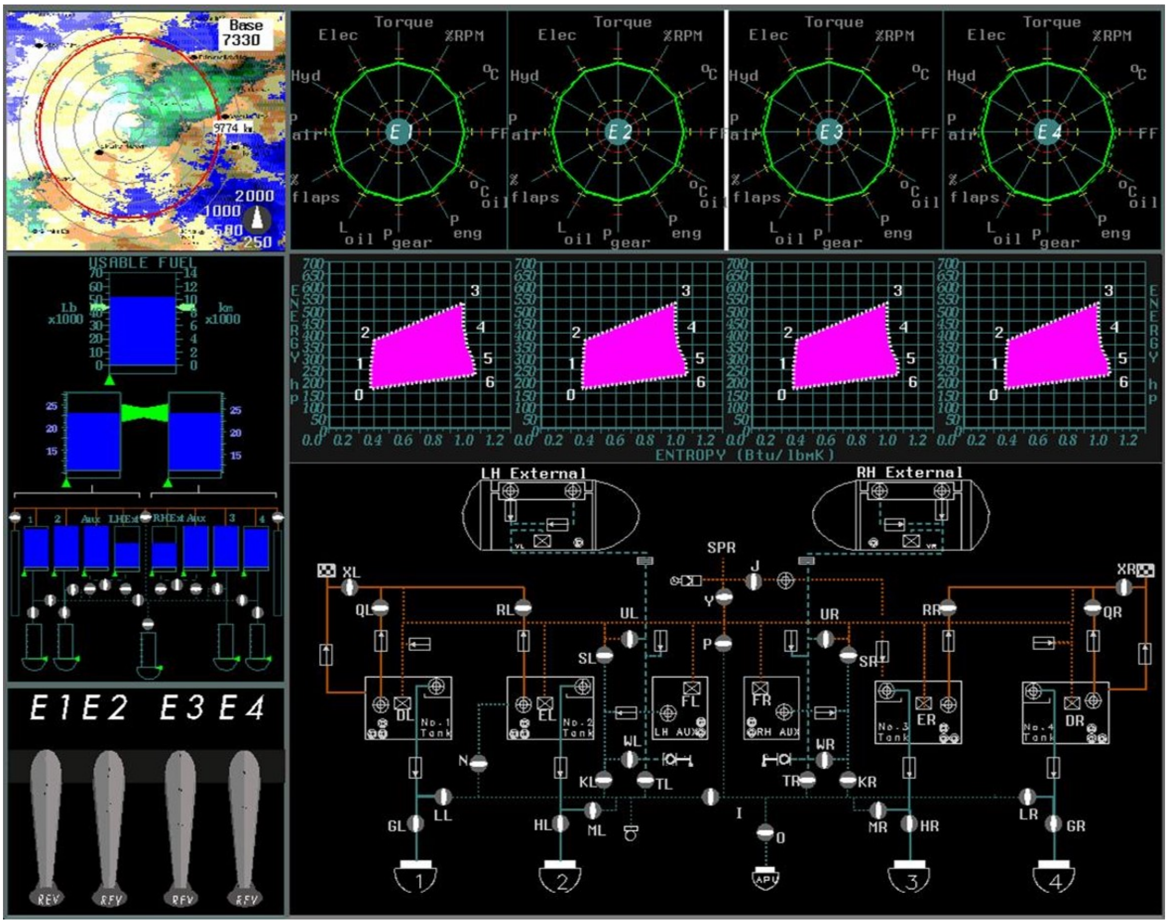


Figure 3.9: Prototype EID interface for the fuel and engines of a Lockheed Hercules C-130 [51]

The figure 3.9 is a representation of a complex fuel management system found on a military aircraft. The display is split into multiple section and is meant to be viewed by a flight engineer and not a pilot. In the left top corner, it is possible to observe a map with an estimate of the achievable distance of the aircraft. Below it are general fuel levels of the left and right wing and levels of the sub-tanks inside the wings. Engines parameters are all represented in polar graphs form in order to promote concepts such as emergent features. This display is a fine example of ecological interface design as it aims to improve flight engineer's situational awareness and decision-making by presenting system information in a way that reflects the underlying physical and functional relationships.

3.2.9. Principles of Display Design

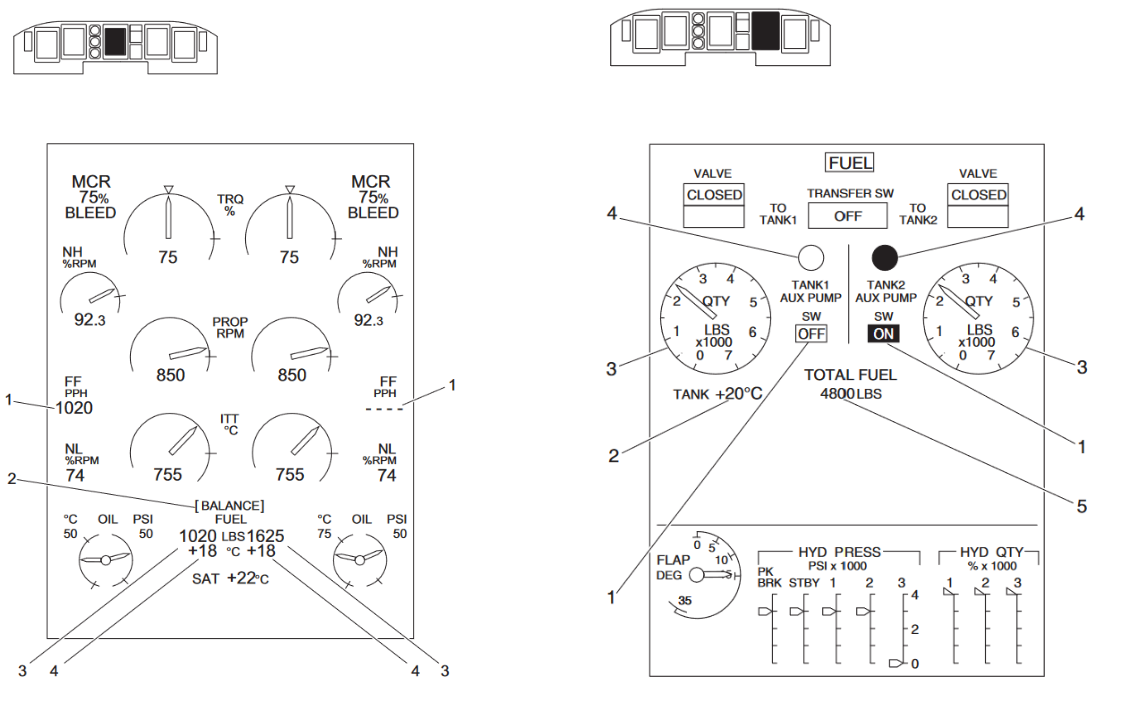
When designing a new display, it is also important to reflect and check if the display follows the thirteen principles of display design. These are split into four categories [52].

Perceptual Principles	Attention Principles	Memory Principles	Mental Model
1. Make displays legible. **2.** Avoid absolute judgment limits **3.** Use discriminable elements **4.** Support top-down processing **5.** Redundancy gain	**6.** Minimizing information access cost **7.** Principle of multiple resources **8.** Proximity compatibility principle	**9.** Principle of consistency **10.** Principle of predictive aiding **11.** Replace memory with visual information	**12.** Principle of pictorial realism **13.** Principle of the moving part

Table 3.1: Principles of display design

3.2.10. Displays in aviation

Traditional display designs follow strict regulations and advisory documents to ensure safety standards are followed [53]. Many older aircraft are still using displays that do not follow simple rules of display design. The following figure is an example of displays on the Dash 8 Q300. In this particular case, the display represents the state of the power unit and the fuel capacity of the aircraft.



(a) Powerunit information display [54]

(b) Fuel information display [54]

Figure 3.10: Example of displays on the Dash 8 Q300

Design Philosophy
The design philosophy encompasses several critical aspects:

- Information Presentation: Clear and concise presentation of information is vital to avoid pilot overload. The design should prioritize critical data and present it in an easily digestible format.
- Color Usage: Effective color coding is crucial for differentiating between various types of information and alarms, enhancing quick recognition and response.
- Information Management: It's essential to manage the flow and quantity of information presented to the pilots to prevent information overload, especially in critical flight phases.
- Interactivity: The design of interactive elements of display systems should be intuitive, minimizing distraction and maximizing ease of use.
- Redundancy Management: Ensuring that backup systems and alternative information sources are in place and easily accessible in case of primary system failure.

Human Performance Considerations
Human performance considerations focus on optimizing the display design for pilot interaction:

- The design must take into account human capabilities and limitations, particularly under stress or during emergency situations.
- Consideration of flight crew workload, training, and the potential for human error is crucial to ensure that the display systems are intuitive and reduce the likelihood of mistakes.

Display Hardware Characteristics
Physical and functional characteristics of display hardware are pivotal:

- Specifications such as size, resolution, brightness, and refresh rates must be tailored to ensure readability and reliability under various flight conditions.
- The hardware should be designed considering the pilot's need for quick data assimilation and ease of interaction.

Safety Aspects
Safety is a paramount concern in the design of aviation displays:

- The design process should include a thorough identification and mitigation strategy for potential failure conditions that might affect the display system.
- It's essential to ensure that the displays maintain critical functionality and continue to provide essential information even in failure scenarios, thereby enhancing overall flight safety.

3.2.11. Dash 8 Q300
The De Havilland Dash 8 Q300 is a twin-engine, medium-range turboprop airliner, known for its reliability and efficiency in regional air travel. Developed by Bombardier Aerospace, it represents the third generation of the popular Dash 8 series, with the 'Q' in its name denoting 'Quiet' due to its noise-reduction features.

3.3. Preliminary Design
3.3.1. Design Background
In order to create the knowledge necessary to start prototyping the preliminary design of the aircraft, it is necessary to complete the CWA as described in the literature study. Considering the exact details of the system are confidential to Conscious Aerospace, this display will be created to fit a generic application of a HEPS system on a regional aircraft. The first step of the process is to perform a work domain analysis of the system. Following this, a task analysis will be performed.

Work Domain Analysis
This subsection presents a Work Domain Analysis (WDA) of the informative fuel display for a Dash 8 Q300 aircraft. The analysis aims to dissect the system into its fundamental components and functions. It focuses on understanding how each element of the fuel display contributes to the overall operation of the aircraft's power system, emphasizing the support provided to pilots for efficient and safe flight management.

Constraints *Operational Constraints:* The system must be seamlessly integrated into the existing cockpit setup without requiring significant modifications. Additionally, pilot training on the new system is essential for smooth operation.
Regulatory Compliance: The display system and its components must comply with aviation standards and regulations for aircraft using alternative fuels and electric propulsion systems.

Functional Purpose *Purpose of the display:* To provide pilots with critical information about the aircraft's hydrogen fuel system and electric motors. This information should be presented in a way that corresponds with the values of EID.

Abstract Function *Energy Management:* Monitor and offer the opportunity to manage the hydrogen fuel cell, batteries, and electric motors to ensure optimal power distribution.
System Health Monitoring: Keep track of the health and functionality of all components, including but not limited to, pumps, heat exchangers, and power electronics.

General Functions *Fuel Cell Monitoring:* Include data on hydrogen levels, fuel cell output, efficiency, and any anomalies.
Electric Motor Monitoring: Display motor performance metrics, including power output and status.
Battery and Power Distribution: Show battery charge levels, health, and power distribution between the fuel cell, batteries, and motors.
Cooling System Status: Monitor pumps, coolant levels, and heat exchanger performance.

Physical Functions *Hydrogen Tanks:* Monitor the temperature, pressure, and level.
Power Electronics: Monitor the status of inverters, converters, and control units.
Gearbox: Monitor the temperature and losses.
Pumps: Monitor the flow, temperature, pressure, and power draw.
Batteries: Monitor the charge, output, input, and temperature.
Heat Exchangers: Monitor the temperature, flow, and pressure.
Fuel Cells: Monitor the oxygen level, output, humidity, temperature, and pressure
Power transmission: Monitor the temperature and resistance.

Abstraction Hierarchy

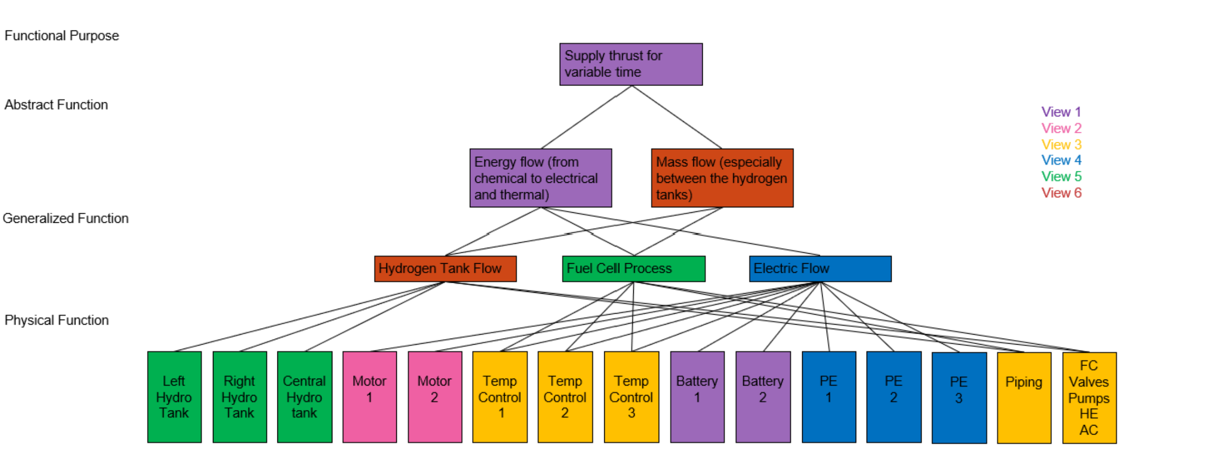


Figure 3.11: Abstraction Hierarchy of a retrofitted Dash 8 Q300

Task Control Analysis

Monitoring Tasks Continuous Vigilance: Pilots are tasked with the monitoring of fuel and motor parameters through the display. This includes keeping a vigilant eye on the hydrogen fuel levels, which are crucial for determining the aircraft's remaining operational range, and monitoring the performance metrics of the electric motors, such as their output and efficiency. This level of continuous monitoring is essential for ensuring the safe and efficient operation of the aircraft.

Diagnostic Tasks Issue Identification and Analysis: The display is instrumental in diagnosing issues related to the aircraft's propulsion system. When the system presents anomalies or unexpected readings, pilots use the display to quickly identify and analyze these irregularities. The system's ability to provide clear and actionable alerts and warnings is critical for allowing pilots to understand the nature of potential problems and to initiate appropriate corrective actions.

Planning and Decision-Making Tasks Strategic Operation: Pilots use the information provided by the display to make strategic operational decisions. This involves using real-time data to adjust flight parameters, such as altitude or routing, to optimize fuel efficiency and ensure the safety of the flight. The display plays a pivotal role in enabling pilots to make informed decisions that balance energy consumption with flight performance.

System Management Tasks Energy Resource Management: One of the key tasks for pilots is managing the balance between the usage of hydrogen fuel cells and the operation of electric motors. The display aids in this by providing real-time data that allows pilots to effectively distribute power between these two sources, ensuring optimal energy use and maintaining the best possible aircraft performance under varying flight conditions.

Adaptive Tasks Responsive Adaptation: The display supports pilots in adapting their management strategies in response to changing flight conditions and system status updates. This includes adapting to technological changes inherent in the retrofitted system, ensuring that pilots can efficiently transition to and utilize the new systems and interfaces.

Emergency Response Tasks Crisis Management: In emergency scenarios, the display's role becomes even more critical. It provides vital information that assists pilots in quickly assessing the situation and making swift decisions. The display's effectiveness in conveying urgent and clear information is crucial for the successful execution of emergency procedures and the safe handling of the aircraft during unforeseen events.

Feedback Interpretation Operational Effectiveness: An important aspect of the display system is its ability to provide immediate feedback on the pilots' actions. For instance, if a pilot adjusts power settings, the display shows the resultant impact on fuel consumption and motor performance. This feedback loop is vital for pilots to understand the immediate consequences of their actions and to learn the intricacies of operating the aircraft with its new propulsion system.

3.3.2. Iterative design philosophy

Iterative design is key in reducing common design errors and enhancing the overall usability and effectiveness of aviation displays in the demanding environment of flight operations. The following figures are a demonstration of design evolution at the early stages of this project. The first sketches are done by hand to save time and are then transposed into a drawing software such as Inkscape.

Early design This simple design emphasizes how the information is presented in an integrated manner, illustrating how different parameters interact and affect each other. In this early display, it is possible to see a phase of flight indicator which is a representation of the current state of the aircraft.

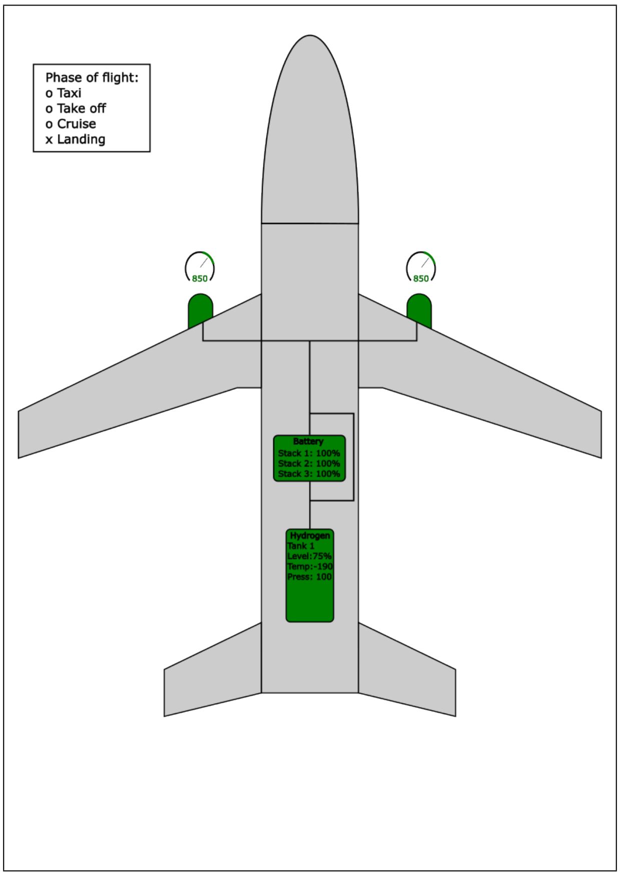


Figure 3.12: Initial EID display design

This display is far from being representative of the final product but already gives insight into certain characteristics that have evolved from an EID perspective. Indeed the synoptic display promotes understanding the model while the representation of the electric flow from the hydrogen tank to the batteries to finally the motors shows the interdependence of the subsystems. The display is clearly lacking information but it is representative of the beginning of this project.

Advanced representation The displayed figure represents a further advancement in the iterative design process. Figure 3.13 presents the design of a prototype Ecological Interface Design (EID) interface. This interface is segmented into seven distinct areas, with four playing a specific role in conveying information. Each of these four display areas, marked by their respective functions, corresponds to elements identified in the Abstraction Hierarchy (AH) analysis through the information they display. The design incorporates both motor and fuel system elements as outlined in the preceding analysis.

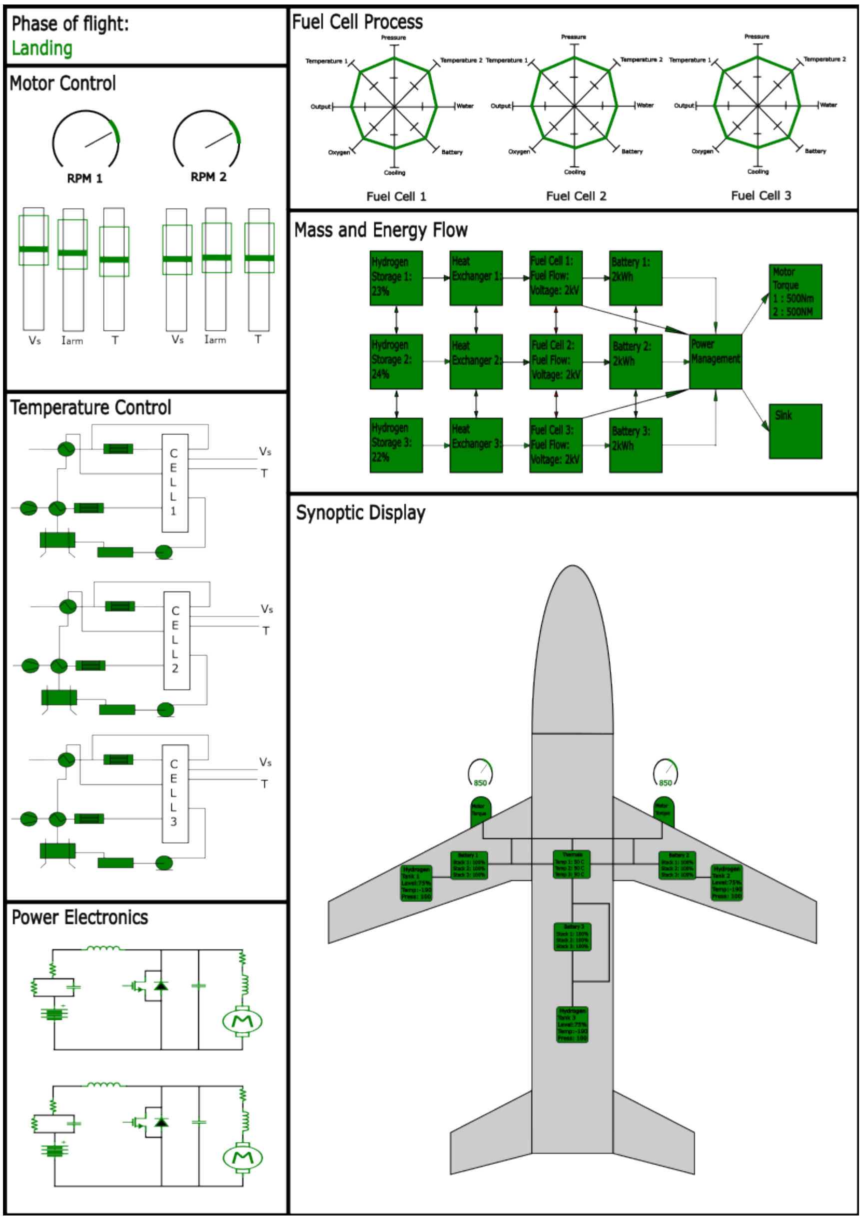


Figure 3.13: Integration of the Abstraction Hierarchy into the display

The consolidation of system representations into a smaller number of display areas is a strategic design choice, reflecting the integration of multiple system perspectives into single, coherent visual representations. This approach optimizes the interface for efficiency. It is possible to associate the different sections of the display with the different views that are colored in the abstraction hierarchy of figure 3.11. The following table shows the equivalence between the display and the AH as well as a short description of the representation and the corresponding level of abstraction.

Sections Fig. 3.13	Cells in Fig. 3.11	Abstraction	Description
Synoptic Display	View 1 (Purple)	Functional Purpose and Abstract Function	Represents the health of the aircraft
Motor Control	View 2 (Pink)	Physical function	Represents the motor state
Temperature Control	View 3 (Yellow)	Physical Function	Represents the temperature state
Power Electronics	View 4 (Blue)	Generalized Function and Physical Function	Represents the power electronics
Fuel Cell Process	View 5 (Green)	Generalized Function and Physical Function	Represents the fuel cell
Mass and Energy Flow	View 6 (Red)	Abstract Function and Generalized Function	Represents the piping

Table 3.2: Display layout equivalence to the Abstraction Hierarchy

Inclusion of time as a variable The figure presented here is a synoptic display for an aircraft, enhanced with a feature that predicts future states based on time. In this instance, the display focuses on projecting the available torque at the propeller over time. Utilizing the current operational data can theoretically enable the forecasting of the HEPS system's future state. This marks the project's initial start in incorporating temporal data. Given the intricacies associated with the power dynamics of a HEPS aircraft, especially when contrasted with traditional turboprop aircraft, integrating a display that provides time-sensitive insights is crucial. This feature is particularly valuable for alerting pilots to potential issues, such as the battery's charge and discharge rates, especially under circumstances where the fuel cell system might be compromised.

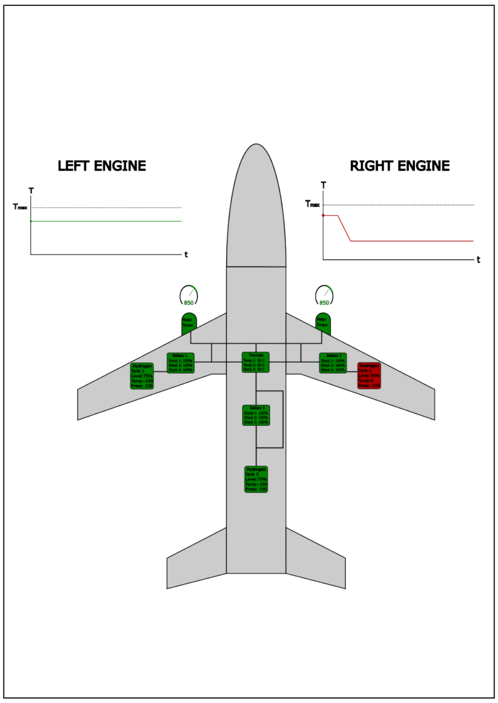


Figure 3.14: Synoptic display with a time estimator

This is only the first iteration of the time-dependant display and as such future iterations will be more appropriate for a pilot to understand. Indeed the scientific representation of a graph with time as the x-axis is an academic way of representing time on a display and isn't appropriate to use in the aviation environment.

Graphical representation with buttons The following figure is a graphical representation of a display with corresponding touch-sensitive buttons. This figure illustrates the possible pyramid structure of the main display being connected to the subsystem via a system of cascading pages traveling down the abstraction ladder to end at the physical function. This provides the pilot with the opportunity to diagnose a fault by following the errors on the screen. Another interesting aspect of this display is the visualization of the thermal and electro/mechanical connections. Indeed it is possible the see how the different subsystems interact with each other. This leads to the diagnosis of a fault as skill-based behavior and no longer as a rule or knowledge-based behavior.

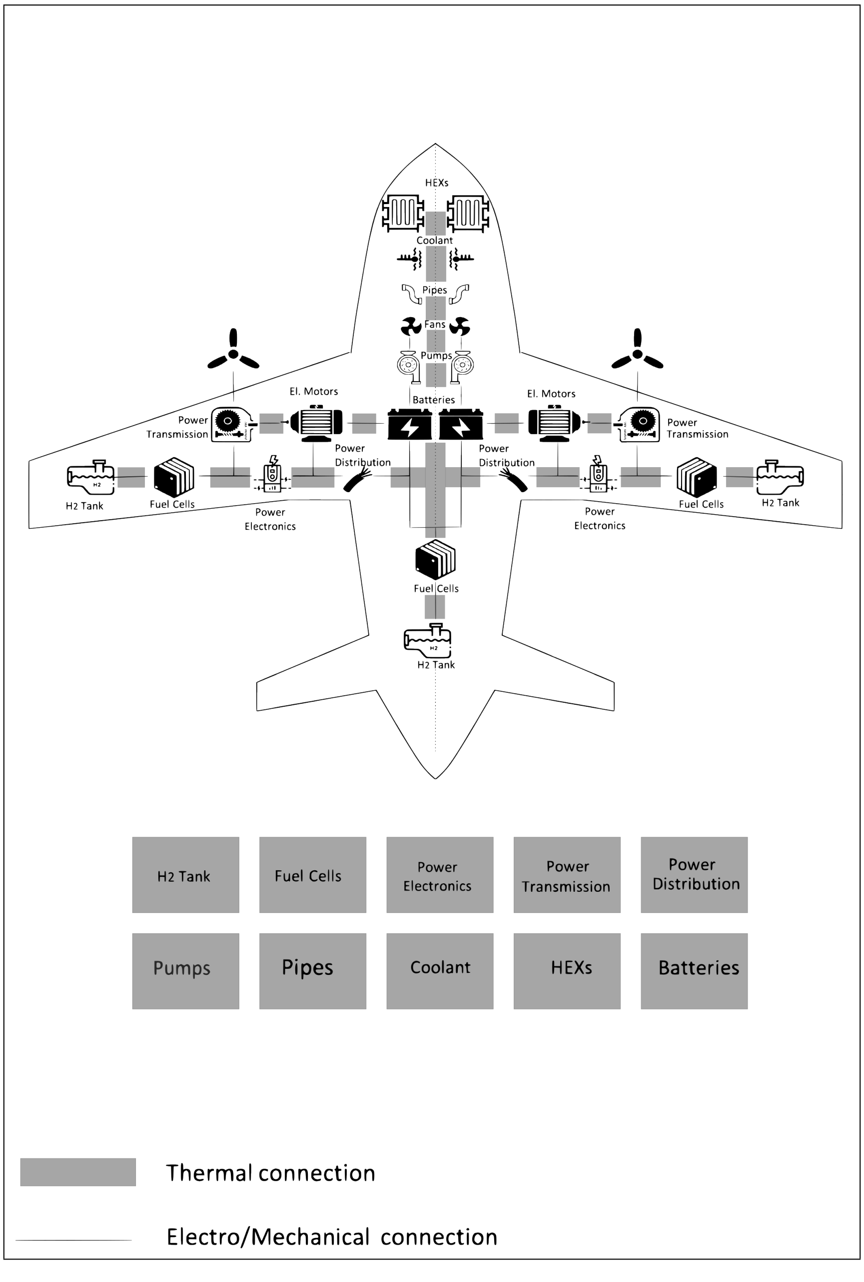


Figure 3.15: Graphical illustration of a synoptic display

This display is not appropriate to use in an aircraft but it is more an exercise in how to apply the knowledge gained by the analysis done earlier in this project. The final display will need to obey the regulations imposed by the governing bodies of the aviation industry.

The following figure is similar to that of figure 3.15. It is only presented similarly to the style seen earlier in this report. In this figure, it is possible to see a synoptic display of the aircraft with all elements of the HEPS system being present. This display is meant to represent the general health of the system, as requested by the test pilot of Conscious. At the bottom of the display are 10 buttons to access the subsystems. This is necessary to diagnose a problem as the current display only provides general information about the state of the systems of the aircraft.

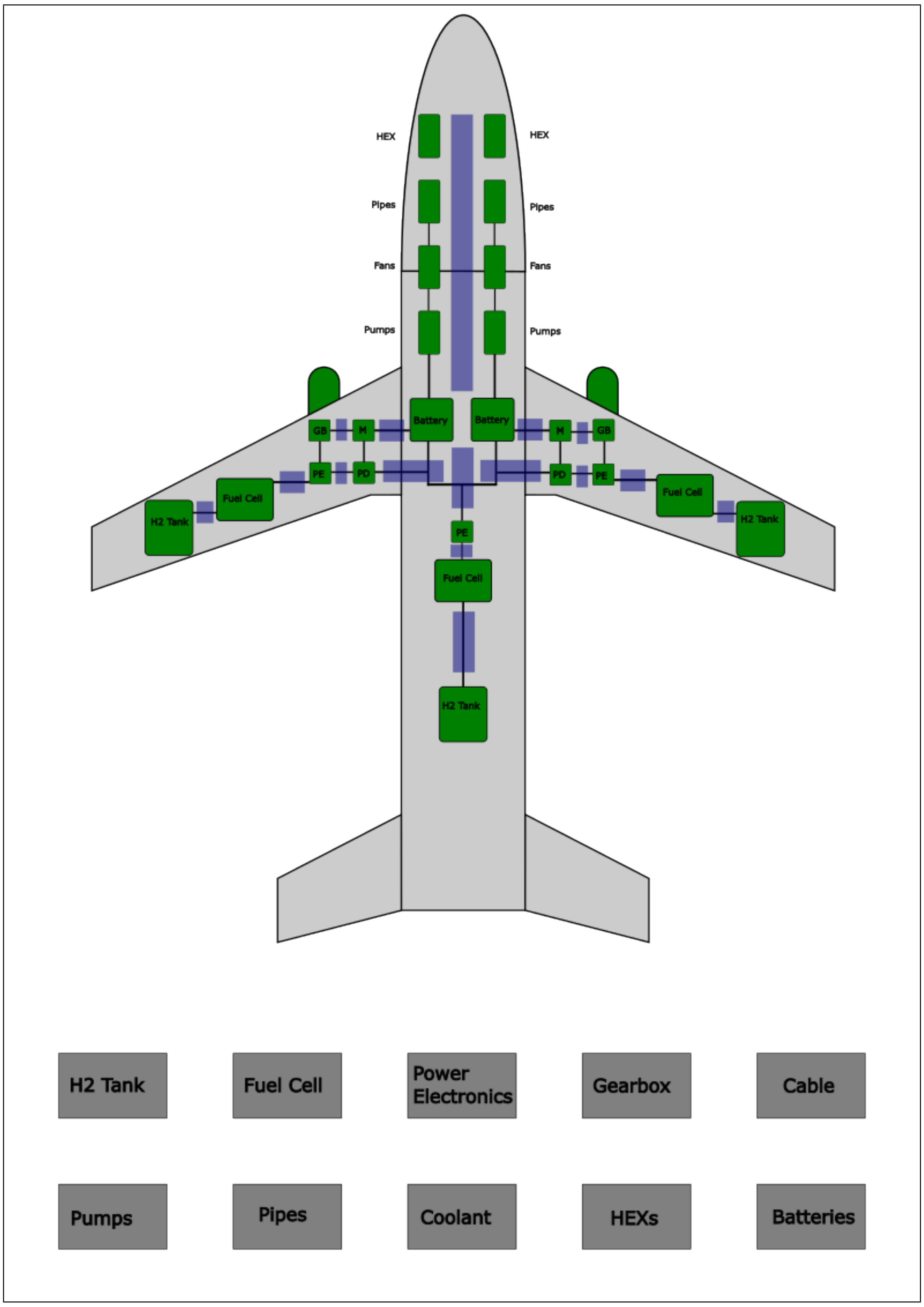


Figure 3.16: Updated Synoptic Display

3.3.3. Planned Tasks

As this project progresses, several critical tasks remain to be addressed to ensure the successful completion and implementation of the redesigned aviation display for the Dash 8 Q300 aircraft.

- **Continuation of iterative design of the display:** The iterative design process, a cornerstone of our project methodology, will continue to play a significant role. This process involves repeated cycles of design, testing, feedback, and refinement. By continually iterating on the design, we can enhance the usability and functionality of the display, ensuring it meets the specific needs of the situation.
- **Validation:**
  - Integration with the Simulated Model: A critical phase of the project is the integration of the display system with a simulated model of the aircraft. This step is essential to evaluate how the display performs under various flight conditions and scenarios. The integration process will help in identifying potential issues and areas for improvement.
  - Development of a Testing Methodology: Establishing a robust testing methodology is imperative. This involves designing tests that accurately assess the display's performance, reliability, and usability in various operational scenarios. The testing phase will include simulations, pilot feedback interviews, and possibly simulated in-flight trials to ensure the display system meets all required standards and enhances pilot decision-making and situational awareness. The testing will be based on the EASA CS 25 standard for certifying large airplanes.
- **Understanding Aviation Display Design Regulations:** An important task is to thoroughly understand and adhere to the regulations surrounding aviation display design. Navigating these regulatory frameworks is crucial, as they dictate the standards for the safety, usability, and reliability of aviation displays.

These are the planned tasks that await the continuation of this project, but it is also important to grasp that there are also unknown additional tasks.

3.4. Conclusion

The evolution of aviation technology, especially the transition toward cleaner energy sources like hydrogen fuel cells, necessitates a fundamental reevaluation of traditional fuel systems and their information displays. This report has explored the transformation of information display mechanisms within the Dash 8 Q300's fuel system as it adapts to hydrogen fuel cell technology. The shift to hydrogen-based propulsion is not merely a change in energy source; it represents a significant shift in how we manage and monitor aircraft fuel systems. The integration of hydrogen fuel cells into the Dash 8 Q300's propulsion system introduces unique comprehension challenges linked particularly to the domain of human-machine interaction and displays. The pilots of this novel aircraft would be faced with complex interconnected system such as the battery charging and discharging or the fuel cell output that if misunderstood could lead to errors. By applying methodologies found in Cognitive Work Analysis and Ecological Interface Design, it is possible to analyze the reconfiguration of the aircraft's fuel system information display. This report details the background knowledge necessary to understand the challenges faced during this thesis. It additionally describes the advancement made, notably the different stages of the iterative design of the display. Future stages of this research will involve detailed prototyping and feedback session with different experts in the field to validate the design concepts and assess their practical feasibility and impact on flight operations.

Part III

Additional Results

4

Cognitive Work Analysis

The following chapter covers the additional abstraction hierarchy created to reflect the Dash 8 Q300 equipped with a traditional powertrain as well as the decision ladders for the other two scenarios presented in Part I.

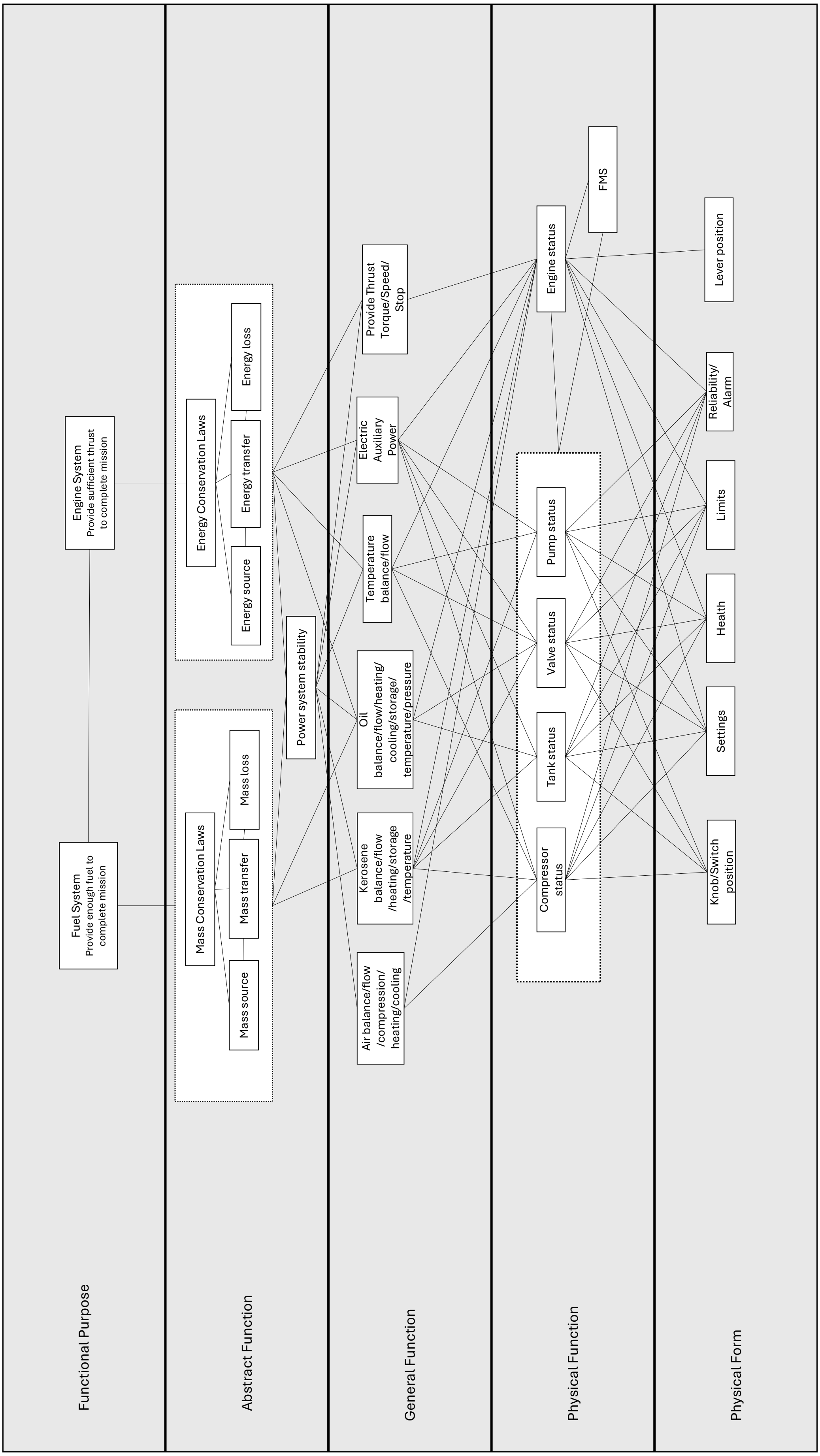


Figure 4.1: Abstraction Hierarchy of the powertrain of a traditional powertrain

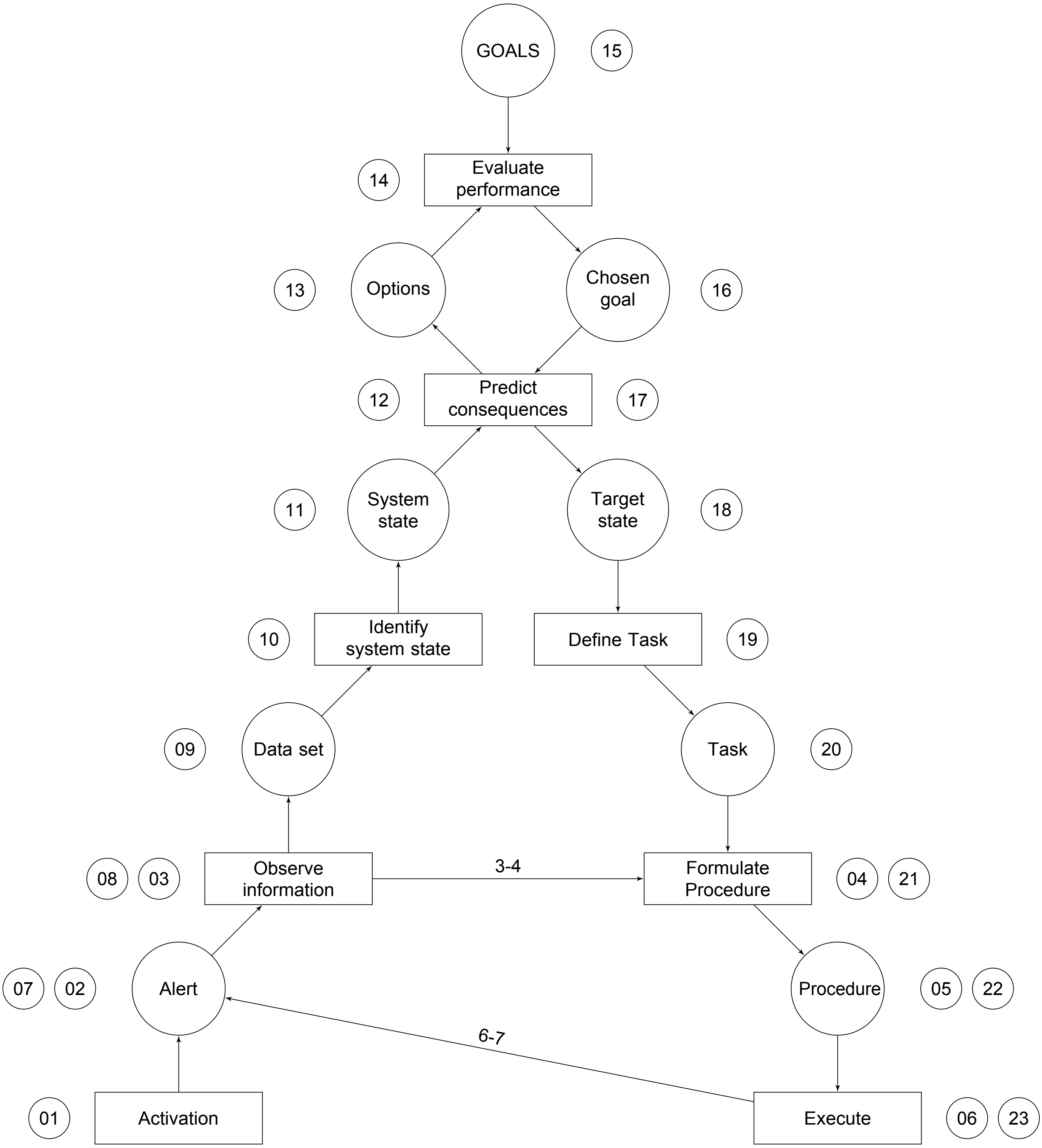


Figure 4.2: Decision ladder for the high oil temperature scenario.

Step	Action
1	Visual, auditory warning of high oil temperature.
2	Dial readout. Advisory display lights
3	Problematic value of high oil temperature.
4	Recognition of low numeric values on dials. Advisory display lights.
5	Make sure the aircraft is operational and no other secondary systems is also failing.
6	Select relevant QRH procedure. Reduce power output
7	Setting and procedures confirmed.
8	Execute the procedure.
9	Check the power level outputs and other associated dials
10	Put together information to understand the whole situation.
11	Determine the affected oil subsystem. How bad is the output of the engine? RPM, Torque, NH.
12	Consequence on the mission profile. Prediction of range.
13	Review the current situation and understand if the engine and gearbox are getting worse.
14	Change mission profile. Solve issue. Continue mission with degraded flying qualities.
15	Assess availability of resources and level of risk for every option.
16	safety of the aircraft and passengers.
17	Reduction of power or increase of altitude to promote potential energy.
18	Is the current situation deteriorating or keeping stable?
19	Maximum available resources for adjusted mission profile.
20	Define the variable to monitor. Discuss the variable with the co-pilot.
21	Select the correct procedure and prepare for single-engine flying. Prepare information for ATC.
22	Recall relevant memory checks, QRH, and checklists.
23	Procedures for necessary tasks confirmed. Single engine landing, new trim, max RPM.
24	Execute the procedures

Table 4.1: Steps description of the high oil temperature scenario.

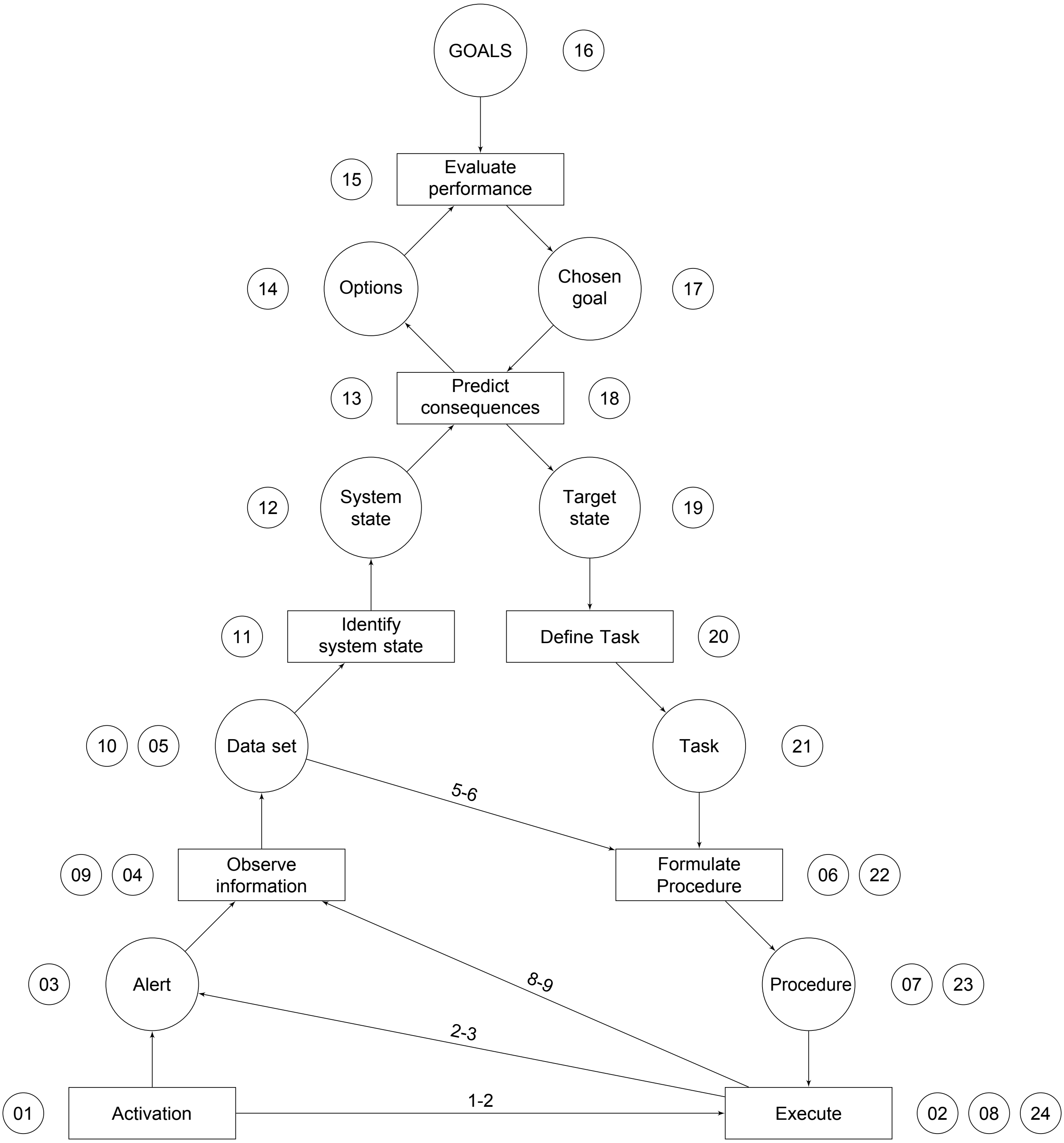


Figure 4.3: Decision ladder for the loss of power scenario.

Step	Action
1	Visual, auditory warning of loss of power.
2	Full throttle on the second engine to stabilize the total output power.
3	Perception of a problematic subsystem. Located in the left motor.
4	Recognition of low numeric values on dials. Advisory display lights.
5	Make sure the aircraft is operational and no other secondary systems failures.
6	Select relevant QRH procedure.
7	Setting and procedures confirmed.
8	Execute the procedure
9	Check the motor output
10	Put together information to understand the whole situation.
11	Determine the affected auxiliary subsystems.
12	Consequence on the mission profile. Prediction of range.
13	Review the current situation and understand if output is getting worse.
14	Change mission profile. Solve issue. Continue mission with degraded flying qualities.
15	Assess availability of resources and level of risk for every option.
16	Safety of the system and the passengers and crew.
17	Situation dependent. Fly with a single engine or reroute to land.
18	Is the current situation deteriorating or keeping stable?
19	Maximum available resources for adjusted mission profile.
20	Define the variable to monitor. Discuss variables with co-pilot.
21	Select the correct procedure and prepare for single-engine flying. Prepare information for ATC.
22	Recall relevant memory checks, QRH, and checklists.
23	Procedures for necessary tasks confirmed. Single engine landing, new trim, max RPM.
24	Execute the procedures

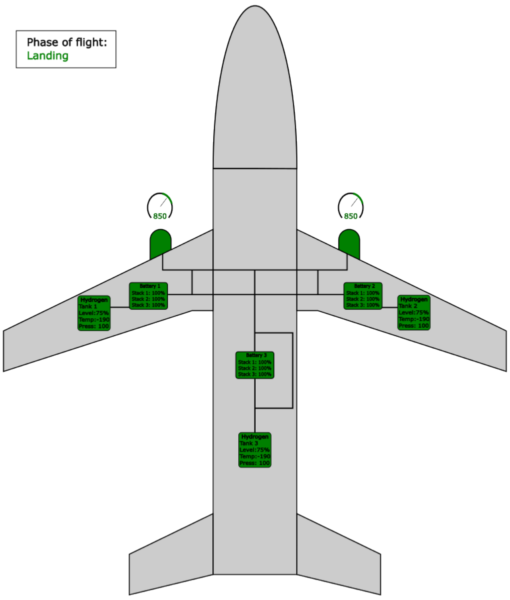
Table 4.2: Steps description of the loss of power scenario.

5 Iterative display design

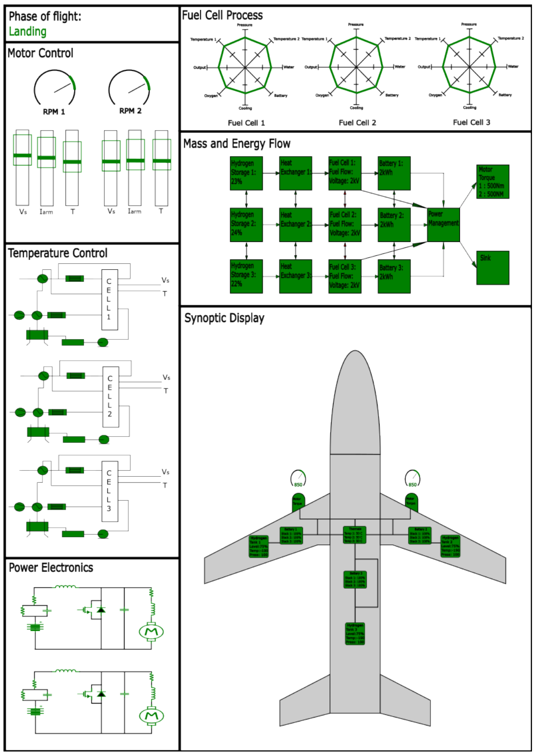
The following chapter adds an overview of the different display designs that were created during the iterative process.

Figure	Description
Figure 5.1 (a)	Based on the EICAS synoptic representation, this representation only displays hydrogen tanks, batteries, and electric motors.
Figure 5.1 (b)	Based on the representation of Dinadis and Vicente [12], this representation shows sections of the AH.
Figure 5.2 (a)	A more complete representation of the synoptic display, the different subsystems are still only represented by text. The bottom does include mock buttons.
Figure 5.2 (b)	A more graphical representation of the synoptic display including for the first time the phase of flight indicator at the top of the display.
Figure 5.3 (a)	First representation and inclusion of trend graphs to show motor output. Inclusion of upper limit of motor output.
Figure 5.3 (b)	Early representation of the power display, including a small synoptic display, an interconnected power flow display, and trend graphics with prediction capabilities.
Figure 5.4 (a)	Early representation of the temperature control display including a synoptic display, a trend graphic, and an interconnected subsystem representation of the temperature.
Figure 5.4 (b)	Early representation of the fuel display including a small synoptic display, a section with important variable and their respective history and trend, and bar graphs for the 3 tanks
Figure 5.5 (a)	The final power display, more information about this display can be found in the scientific article.
Figure 5.5 (b)	The final air supply display, more information about this display can be found in the scientific article.
Figure 5.6 (a)	The final fuel display, more information about this display can be found in the scientific article.
Figure 5.6 (b)	The final temperature control display, more information about this display can be found in the scientific article.
Figure 5.7 (a)	The main synoptic display during the low power scenario
Figure 5.7 (b)	The power display during the low power scenario
Figure 5.8 (a)	The main synoptic display during the high-temperature scenario
Figure 5.8 (b)	The temperature display during the high-temperature scenario

Table 5.1: Iterations of display during the project

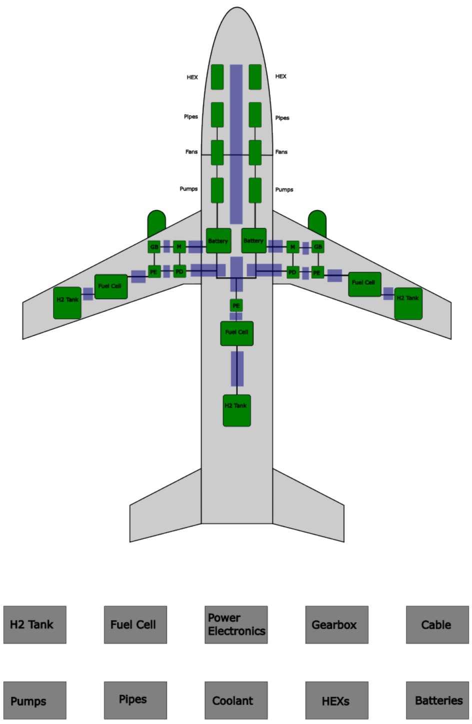


(a) Early attempt at synoptic representation

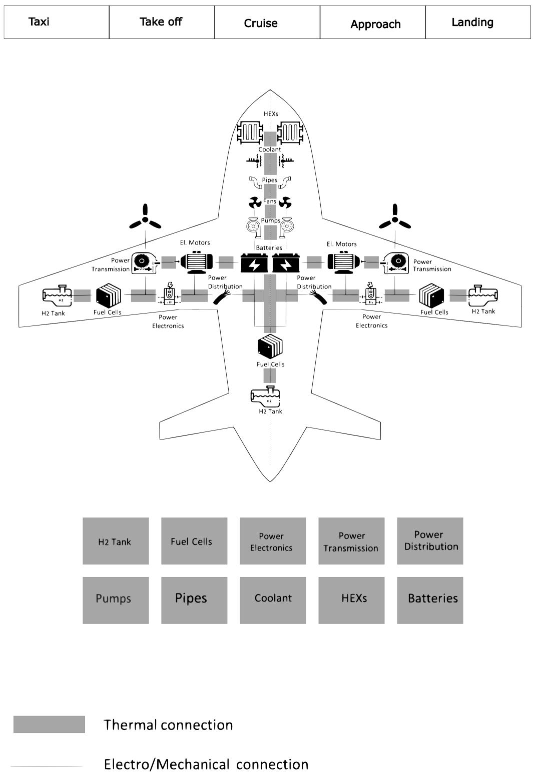


(b) Early integration of multiple subsystems using the AH

Figure 5.1: First generation of visual representation

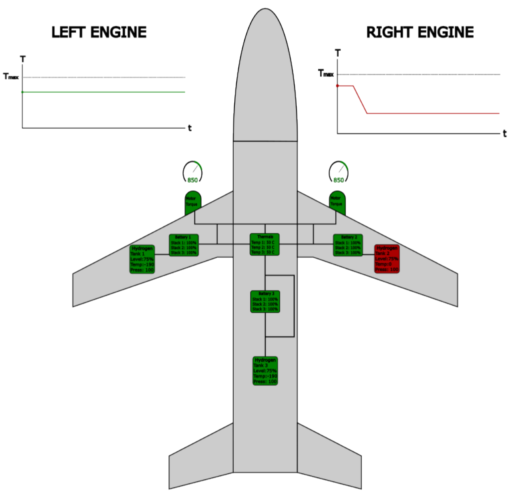


(a) Early iteration of the Main display

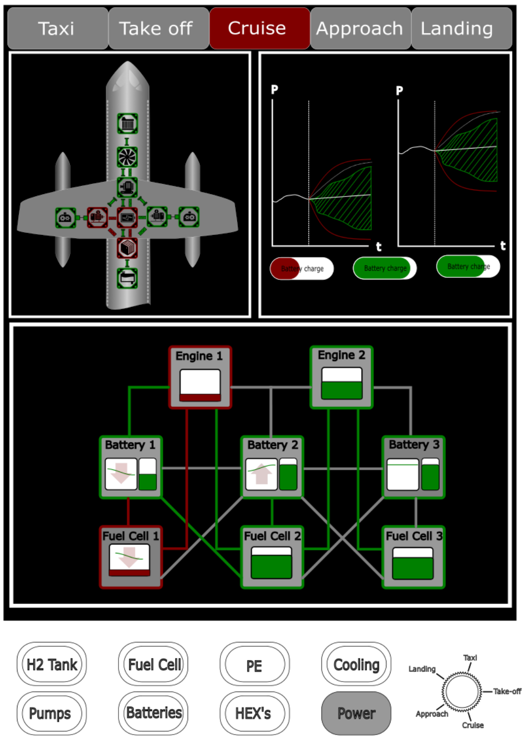


(b) Additional representation of the Main display

Figure 5.2: Second generation of representation

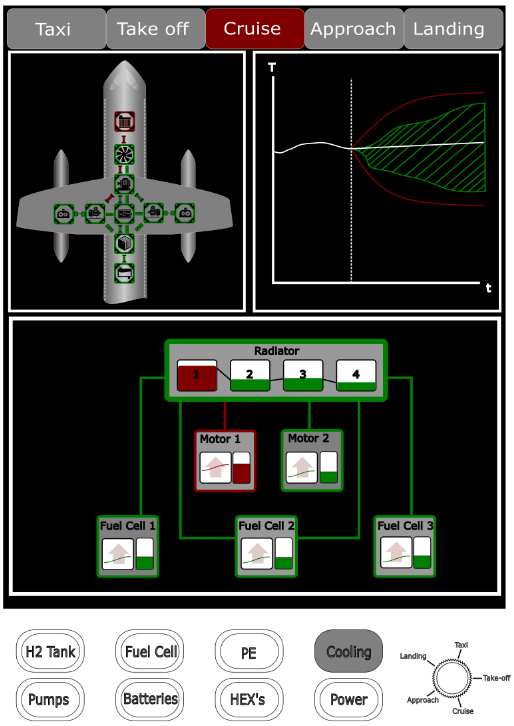


(a) First try on trend graphs for power output

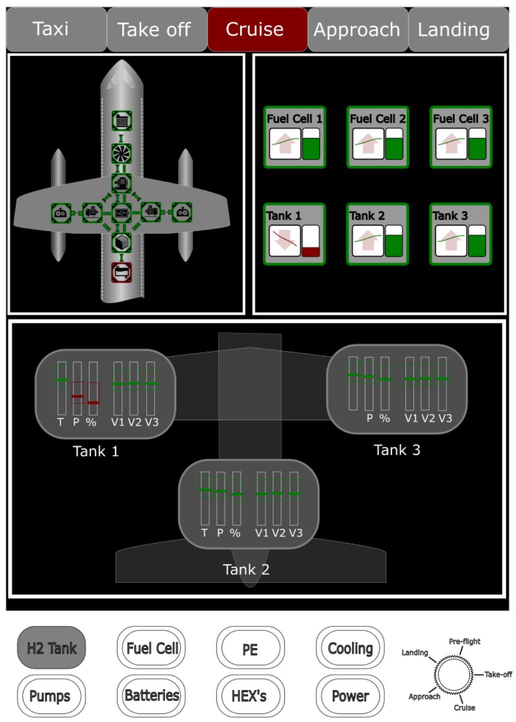


(b) First iteration of the power display

Figure 5.3: Trials with trends and displays design

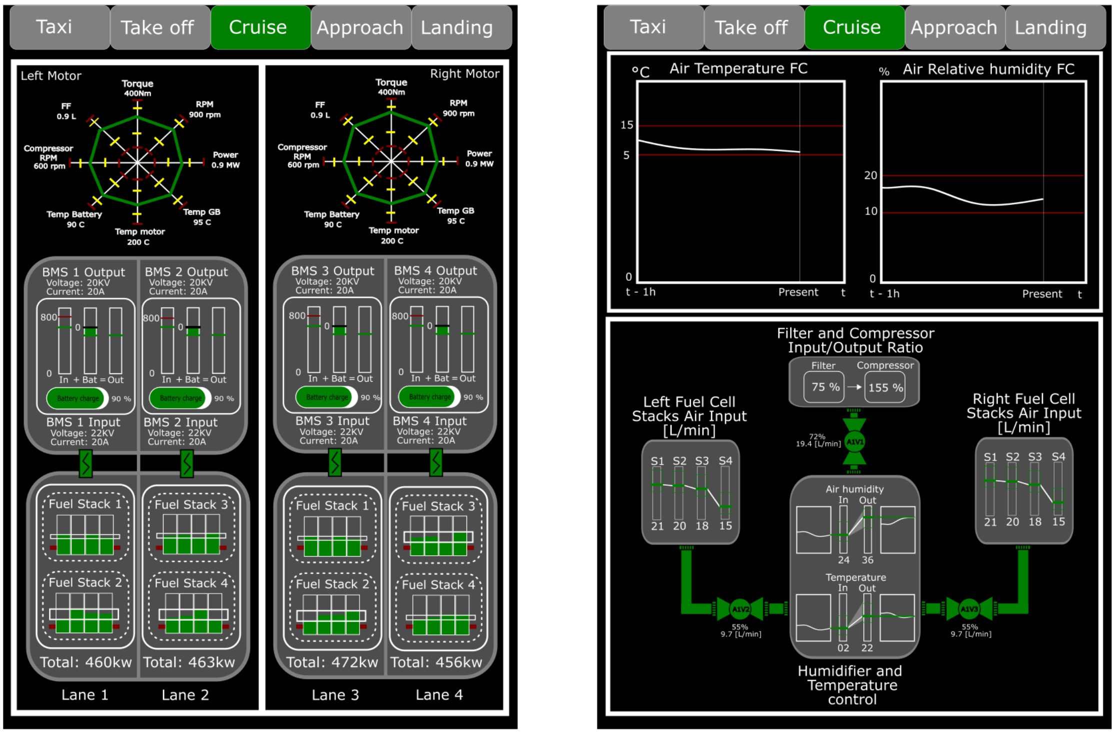


(a) First iteration of the cooling display



(b) First iteration of the fuel display

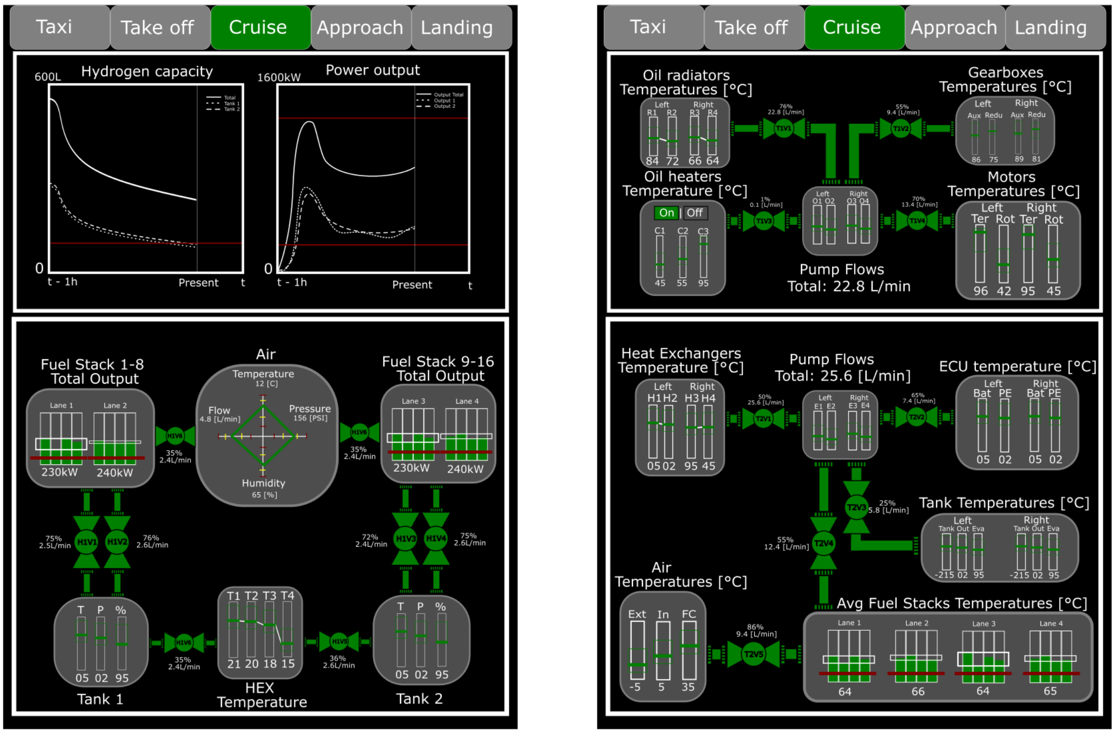
Figure 5.4: First iterations of the full display design



(a) Final representation for the power display

(b) Final representation of the air supply display

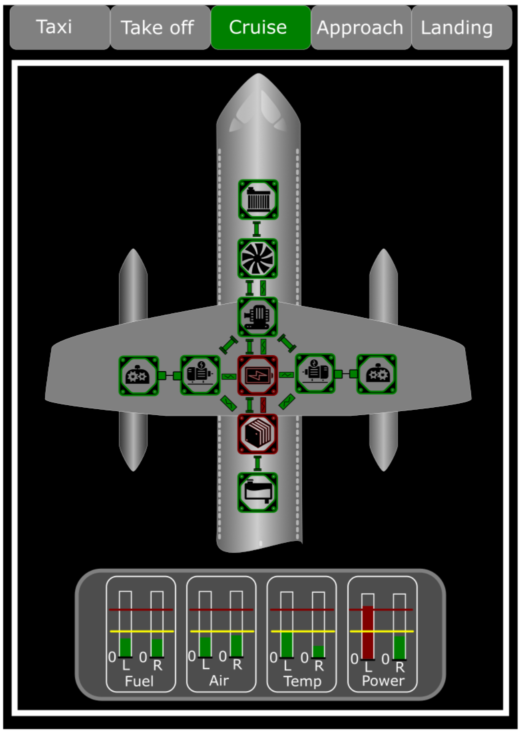
Figure 5.5: Final versions of the air and power display



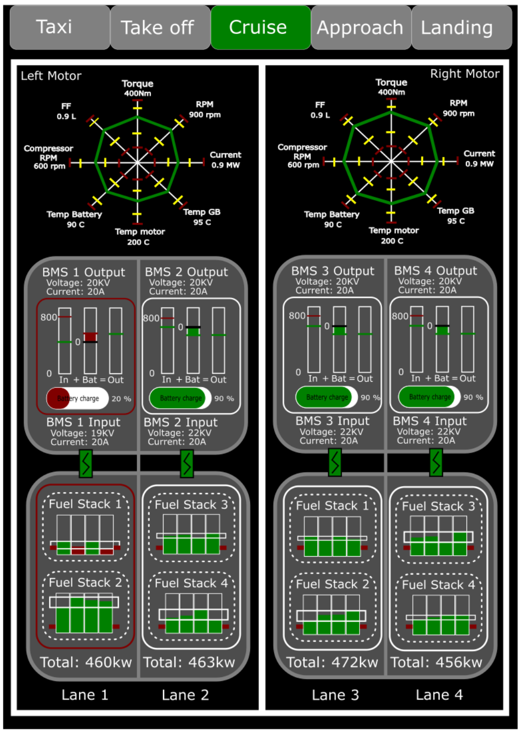
(a) Final version of the fuel supply display

(b) Final version of the temperature monitoring display

Figure 5.6: Final versions of the fuel supply and temperature monitoring displays

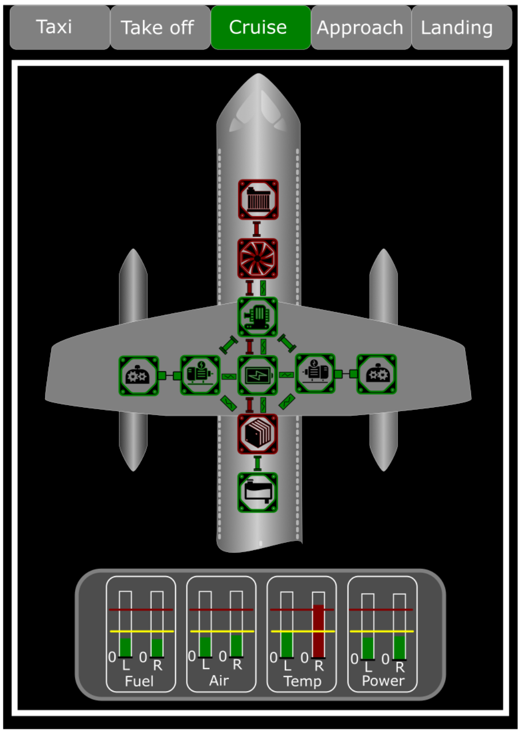


(a) Main display with the low power scenario

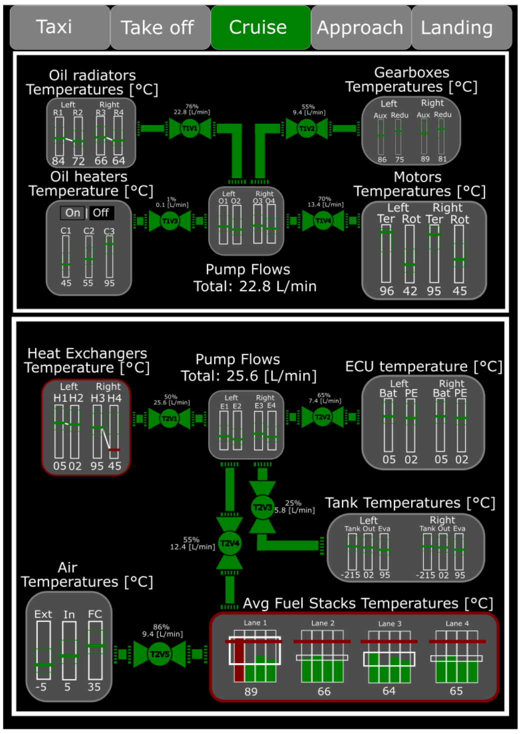


(b) Power display with the lower power scenario

Figure 5.7: Displays associated with the low power scenario



(a) Main display with the high-temperature scenario



(b) Temperature display with the high-temperature scenario

Figure 5.8: Displays associated with the high-temperature alert scenario

6 Conclusion

The primary research objective of this thesis was defined as:

Research Objective

To develop and evaluate a novel display system for the Dash 8 Q300 aircraft retrofitted with a hydrogen-electric fuel system, using CWA and EID principles.

In order to fulfill this research objective the following research questions were devised:

Research Question 1

How can CWA and EID be used to develop displays for a HAPSS aircraft?

It can be used as a systematic approach to design displays that represent the complete interactions of the system. In this aspect, it could contribute to the pilot becoming an adaptive problem solver.

Research Question 2

Which HAPSS concepts are relevant to display in future implementations of retrofitted aircraft?

The relevant HAPSS concepts are mainly related to energy creation, transfer, and utilization. These main topics are represented on the abstraction hierarchy.

Research Question 3

How are experts receiving static and dynamic visualizations with regards to usability?

The most common theme received during the feedback session can be resumed as an inclination not to over-complicate the representations and to promote RBB. These patterns can be found both in static and dynamic visualizations.

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A

Interview Script

Participation Information

- Participation in this study is voluntary.
- You may choose not to answer any question and still remain part of the study.
- You can withdraw from the study at any time, for any reason, even partway through.
- If you withdraw, we will ask how you would like us to handle the data collected so far—whether you prefer it returned to you, destroyed, or used.
- You can request the removal of your data from the study until approximately August 2024.
- All data will be de-identified and securely stored on password-protected computers.

Online Consent Questions

1. Do you agree to participate in this study? (YES/NO)
2. Do you agree to your session being audio recorded for accurate transcription and analysis? (YES/NO)
3. Do you agree to your study session being screen recorded to analyze your actions on the interface? (YES/NO)
4. Do you agree to the use of anonymous quotations in any thesis or publication resulting from this research? (YES/NO)
5. Do you consent to the storage and future use of de-identified study data for research? (YES/NO)

Phase 1: Static Visualization Feedback

Synoptic and Stability Indicators

- What first stands out to you?
- Can you explain the symbols?
- How do the graphical symbols relate to each other?
- Do the symbols complement or distract from each other? Are the size ratios appropriate?
- Based on your understanding, what is the state of the aircraft?
- How do the upper and lower parts interact? (Revisit in the dynamic phase)

Power Display (Polar Graph)

- Have you seen this graph before?
- What do you think this graph represents? Consider variables, units, ranges, colors.
- Is there anything missing?

Fuel System (Half)

- What do the graphs represent? What do the fuel stack combinations show? (Look for observations on symmetry and composition)
- If one graph is changed to red, what does that signify?

Electrical Conditioning Unit (ECU)

- What does ECU mean to you?
- What do you think the additive bar graph represents? How do you correlate it with battery charge?
- What do the connectors indicate? Consider an abnormal scenario with low and discharging battery.
- Is there symmetry? How do the subsystems relate to each other? Show an imbalance and ask what it suggests.

Temperature Display

- What first stands out to you?
- Can you explain the symbol on the right side of the image?
- **Valves:**
  - What does the symbol mean?
  - What are the variables next to it? Is green the appropriate color? Is it necessary?
  - Is the ON/OFF symbol appropriate?

Air Display

- Can you describe the trend graph? (Comment on the axes)
- Comment on the lines (continuous/dotted). What does the red line represent?
- Do the limits make sense? What are the units? Do the units make sense to you?
- **Humidity and Temperature Control:**
  - What do the colors represent? Consider abbreviations as well.
  - How do you feel about the labels, titles, and wording in general?
  - What do you think is happening?

Hydrogen Display

- Can you describe the trend graph? (Comment on the axes)
- Comment on the lines (continuous/dotted). What does the red line represent?
- Do the limits make sense? What are the units? Do the units make sense to you?
- Describe the different parts of the display as shown (one by one), and explain what each represents. (Note the terms used)
- What do the colors represent? Consider abbreviations as well.
- How do you feel about the labels, titles, and wording in general?

Fuel Stack 1-8

- What do the meters represent? What does the operational range mean? What do the bottom numbers indicate?

Tank 1

- What do the abbreviations mean? What do the numbers represent? What are the units? What are the limits? What do the connections to other systems signify?

HEX (Heat Exchanger)

- What do the abbreviations mean? What do the numbers represent? What are the units? How do the different bar graphs interact?

Air

- What are the variables/units? Is the range important? Would you prefer dials, graphs, or something else? Should anything be added?

Full Display

- How do the subsystems interact? Is there any symmetry? If not mentioned, ask about it.
- What do you think of the connectors between symbols?
- How do the trends relate to the variables in the bottom half?
- Is the structure of the display logical (top/bottom, left/right)?
- Do the elements complement or distract from each other? Are the size ratios appropriate?

A.1. Phase 2: Dynamic Visualization Feedback

A.1.1. General interaction of the system

- How do the displays interact with each other?
- To what level do you understand how to navigate and interact with these displays?

A.1.2. High oil temperature scenario

- What do you first notice?
- What is your initial reaction?
- How would you describe the state of the system?
- Is the system stable?
- What would be the desired system state relative to the current state?
- How would you reach this state?

A.1.3. Inequalities of fuel tanks scenario

- What do you first notice?
- What is your initial reaction?
- How would you describe the state of the system?
- Is the system stable?
- What would be the desired system state relative to the current state?
- How would you reach this state?

A.1.4. Reduction of power to the left motor

- What do you first notice?
- What is your initial reaction?
- How would you describe the state of the system?
- Is the system stable?
- What would be the desired system state relative to the current state?
- How would you reach this state?

B

Interviews

B.1. Interview 1

Participants: Misha, Interviewer 2, Test Pilot

Misha: We can start with the demographic question to obtain a more specific background. We know that you are a test pilot. How long have you been a test pilot? You graduated as an electrical engineer; when did you transition to being a pilot?

Test Pilot: I became a production test pilot in 1995 and an engineering and experimental test pilot from 1997.

Misha: Is it possible to know how old you are?

Test Pilot: I'm 66 years old.

Misha: What type of training do you possess?

Test Pilot: I'm currently flying on the Fokker 100 and the De Havilland Dash 8 and other small airplanes. Being a test pilot, I am authorized and can fly every type. I don't need type training. I have had on-the-job training with Fokker within the Fokker industry when they still made aircraft. I also took an additional course at the test pilot school of the US. I have a background in Electrical Engineering.

Misha: You said you contributed to certification; what role does a test pilot have when developing display design?

Test Pilot: The most important thing a test pilot does is pre-flight. The whole process going towards that first flight. In a good organization with large funding, the test pilot should be involved very early on, involved in defining risk control hazards mitigations. You can also be involved in the design, especially when it comes to HMI. When it comes to flying, it is your role to verify if the aircraft is complying with the regulations. You must give feedback on items that can be improved. I'm not only talking about aircraft handling but also, for example, the workload of the pilot and human factors feedback. So your role is giving feedback on man-machine interface.

Misha: So you are heavily involved then?

Test Pilot: If it is a professional project, you will be heavily involved indeed. There will be a lot of measuring equipment and flight test instrumentation equipment, but in the end, when it comes to the handling qualities and feel of the aircraft, it is the test pilot who has the final say.

Misha: How familiar are you with the Dash 8 family: the Q100, Q200, Q300, and Q400?

Test Pilot: Well, I started flying the Dash 8 because the coastguard flies the Dash 8, and I've had about 500 hours in the last one and a half years. On the Fokker 100, I have 5500 hours.

Misha: Which Dash 8 does the coastguard fly?

Test Pilot: The Q100, which has the same instrumentation cluster and type rating as the Q200 and Q300.

Misha: Yes, perfect. That concludes the demographics section of the interview, and we will now pivot towards the traditional powertrain and fuel displays. These are the focus of this research topic. Indeed, this project tries to understand how a new powertrain and fuel cell system can be represented in a way that is representative of the pilot's mental model. We want to get some additional background information about these displays. With what frequency and duration do you interact with these displays and dials on a routine flight?

Test Pilot: The main parameters you are looking for are engine torque and propeller rpm. The other ones, such as NH and fuel flow, are used at engine start-up. How often do you look at it—that is a bit difficult for me to say because we do a lot of abnormal flight, a lot of altitude changes, special operations, speed

changes. Every time you change the profile, you check your powertrain. At takeoff, you're at 1200 rpm, then you take off, and then you select climb power where you set at 1050 rpm or 900 rpm, and it stays there until landing on a standard flight. You then only change your engine torque during the rest of the flight. Is that a good answer?
Misha: Yes, for the powertrain it is good, but for the fuel monitoring could you give some additional details?
Test Pilot: On a standard passenger flight, there are certain moments during the flight where you can scan the entire dial cluster. And you can do this very quickly because it's just looking if the dials are in the green and if left and right matches. If one dial has significant deviations, then you know that something is up, and when you have experience, you then know immediately what the situation is.
Misha: How do you define the stability of the power system?
Test Pilot: As I said, it should be possible to know immediately by checking that the corresponding needles are in the green section of the dials. To me, that defines stability.
Misha: Perfect. Now this concludes the powertrain and fuel display questions of the interview, and we will now progress to the potential scenarios devised to get insight into the cognitive steps needed during troubleshooting of an event during cruise. This is also intended to map your thought process. To begin with, could you tell us a common occurrence of situations that relate to powertrain and fuel displays for which you train in simulations.
Test Pilot: The most common use case for use of these scenarios is when I want to change the energy level of the aircraft. That can be potential energy or kinetic energy. When I want to change the total energy of the aircraft, that is when I use those parameters. Apart from just routine checks.
Misha: I am now going to present you with the three scenarios that are, in our opinion, representative of interactions with the systems on both the original analog dials and new powertrain digital display design. The three scenarios are a high oil temperature alert during your cruise, an inequality in the fuel tanks during cruise, and a loss of power on a single engine/motor. Are these scenarios representative of the type of training you train as a pilot?
Test Pilot: Yes, these are representative. We train for all these scenarios. I'm an instructor for my organization, so I teach all three of these scenarios to all members of the organization twice a year.
Misha: Oh perfect, well in that case that is even better. I will now present you with the first of the three scenarios. You notice that the oil temperature is high. What do you first observe?
Test Pilot: Well, for a high oil temperature you don't get an alert, so you first observe on the dial the oil temperature is high. It depends on whether I'm the pilot flying or monitoring, but suppose I'm the captain flying. We state the alert and ask for any memory check or any memory items that need to be completed. In this case, there are no memory checks, then I will ask for the abnormal procedures, and he will take the QRH for high oil temperatures and follow the procedure.
Misha: Right, we would like to go even more into detail about your thought process. How do you identify the problems related to this issue?
Test Pilot: Well, if you have high oil temperature, the first thing I will check is my oil pressure because they can be related. I will then also check my fuel temperature because there is an oil-cooler-fuel-heater involved. You try to find any relation in those variables.
Misha: Understood. Would you, and if you do, how would you evaluate the causes of the issue and the option to solve this issue?
Test Pilot: Well, as I told the first step is to check if there is a procedure and then to follow the procedure. When the procedure is completed, then we do an evaluation and look at all the options we have. We look at the outcome of the procedure and check if it had the effect that we expect it to have. What are the available options we have according to those options? We then check if we can continue the flight. Do we need to divert to an alternate destination? So we take all the options and we evaluate the pros and cons of all the options, and then finally we make a decision accordingly.
Misha: So these decisions are made after the QRH?
Test Pilot: Yes, definitely we follow the procedure as published by the OEM. If there is a situation where there is no procedure published, which shouldn't happen, I first evaluate my options and then ask my colleague what are his observations. Maybe he sees something that I didn't catch. The two of us together will come to a decision together. But except in this limit case, the first thing is always: Is there a procedure from the OEM? Then we execute that procedure.
Misha: Okay, perfect, thanks for that answer. We will now proceed to the second scenario, which is an inequality in the fuel tanks. We can assume a leak. What do you first observe?
Test Pilot: The first thing you are going to do is make some calculations. I mean, if this is unexpected—because

if you are flying sidesteps or single engine you know that an asymmetry will occur so then you know that you have to transfer fuel to come into balance again. But suppose that there is no reason to expect an asymmetry, then you first have to make calculations. You know the fuel you departed with on the FMS; we can find an integrator (it's not that accurate but accurate enough for our case) that tells you what the fuel used is. So the fuel indications plus the fuel used should be your departure fuel. If there is a large difference, apparently you didn't use the fuel and it's not in the tank; if the indication is correct, then you might expect a fuel leak. And number one, if you have a fuel leak, we are not starting to transfer fuel from one tank to the other tank to bring it into balance because then we bring fuel from the non-leaking tank to the leaking tank, and you don't want to do that. In such a case you have to make an evaluation. Are we going to make it to the destination? This depends on the distance of the destination but also on how quickly this asymmetry is evolving. And then you may decide if you want to divert or continue on your course.
Misha: Okay, perfect. How do you formulate planning of a procedure to reach this target state?
Test Pilot: We follow the QRH.
Misha: Okay, perfect. We will now progress to the most time-sensitive scenario, which is the loss of power on one engine or motor. What do you first observe?
Test Pilot: There are a number of steps of memory items. If it is suddenly a loss of power, the first thing I will ask for is max power on the other engine. And then I will ask the pilot monitoring, "Confirm engine failure number 1 or 2." He will then confirm that. I will then call for the memory check of engine fail number one. And we perform those memory checks—for example, power lever to idle, confirm condition lever number one. After that, we pull the above-head fuel off lever to seal the fuel tank. The pilot monitoring will then confirm the memory checks are completed. I will then ask for the abnormal checklist engine failure. He will then take the QRH, which will confirm the memory checks and a couple of extra items. We will then do an evaluation—first, we will verify that everything we have done, the outcome is what we expect. We now have a shut engine. The other engine is now okay. If the outcome is what we expect, then we are going to plan and formulate the options that we have. If we are high, then we will probably descend to single-engine ceiling.
Misha: If we go back to the beginning of this scenario, how do you first identify this loss of power?
Test Pilot: If it happens suddenly, you will have a yaw moment with the airplane. So you will have to immediately apply directional control. You will get a warning light. And then you have three situations, and this is in the Dash 8 specifically hard for new pilots, which are a challenge sometimes because all three situations may give some change in directional control of the airplane, but they are very different. The first one is an engine failure; second is an over torque of the propeller; and third is an overspeed of the propeller. All three of these will give a warning light, and it is up to the pilot monitoring to figure out which specific case it is. I always tell the students or colleagues take into account in your scanning pattern the value of NH; don't look only at torque and rpm because NH tells you that the core of the engine, the gas turbine, is still working or not.
Misha: Do you think that there is a better way of representing this information that would lead to a higher degree of understanding from the pilots in this case?
Test Pilot: Yes, but this would be difficult to implement, and unfortunately it is not there.
Misha: Okay, well that leads me to an additional question that concerns any mistakes or slips that are common on the Dash 8, if there are any?
Test Pilot: Well, in engine handling, the three situations I just described are pretty common and need training to recognize. But that is a matter of good training. If we further talk about mistakes and slips, the auto-flight controls of the Dash 8 are a human factors disaster, but that has nothing to do with the engine powertrain display. I don't know who designed that, but there was definitely not a pilot involved.
Misha: Good to know that there is room for improvement.
Test Pilot: Yes, there is definitely room for improvement. If we talk just about the powertrain, I can't really think of anything at the moment. But I will come back to you if I do.
Misha: That would be great, thanks. We will now progress to the next part of the interview, which is to gain feedback on the display designs for the new novel hydrogen powertrain system. We take a couple of assumptions in this research, namely that conscious in the future will implement a digital display comparable to the Q400 display. We will now show you four example displays.
[Shows synoptic displays]
What are your first impressions and what draws your gaze?
Test Pilot: Well, that it at least gives me an overview of flows of hydrogen or electricity. I'm not sure exactly what everything is. It gives me a quick overview of what I assume are active and inactive systems.

Misha: How do you feel about using graphical representations and images instead of abbreviations?
Test Pilot: Depends on how many images are used. If there are only five different images, then it should be easier to recognize, but if there are many, then it would lead to an overcharging of the pilot's capabilities. In particular, if the images aren't used often. If you are using images in a synoptic display, their number should be limited.
Misha: That seems reasonable.
Test Pilot: I'm familiar with the Airbus EICAS system, and that is indeed very simple to interpret and to use. But even in my car, I experienced a couple of weeks ago a light go on and I had no idea what it was and had to take the manual to figure out that it was an issue with the brakes. So in particular with things that are not happening often, you must be very careful with using graphical representations.
Misha: That makes sense, thank you. The following representation is a more complete rendition of the display. *[Shows cruise motor and fuel cell failure]* What are your first impressions?
Test Pilot: My first impressions are that the synoptic display is too small and that the images are too small to recognize immediately. The exception is when the symbols are always in the same position and the pilots are trained on it. The lower images had too many lines intersecting in the display.
Misha: Okay, that's good feedback. How would you approach the representation of a complex system such as fuel cell-battery-motor combinations?
Test Pilot: Well, my personal opinion is that pilots know the system architecture. It is not really necessary to show everything which is normal operating in a diagram. You can show if there is an abnormal, such as a valve that is closed that should be open. You know, sometimes less is more.
Misha: Very interesting, thank you for that feedback. We can now proceed with the following display.*[Shows high oil temperature display]* What are your first impressions?
Test Pilot: This is much better than the previous diagram. I don't know if it represents the same information, but this is a lot better. Even without knowing how the system architecture works, I understand there is a malfunction in my radiator and it is affecting motor 1.
Misha: Okay, perfect. If you had a scanning pattern of going left to right and top to bottom, would you be able to recognize that the issues were localized in the cooling subsystem thanks to the synoptic display?
Test Pilot: In the upper left display you mean. No, I couldn't figure that out immediately. And in these representations, I am not a huge fan of those synoptic displays.
Misha: No problem, thank you for the feedback. We will now progress to the final display.*[Shows display associated with mismatch in fuel tanks]* Again, please give your first impressions.
Test Pilot: I'm not sure what the parameters mean in the bottom display, but they are bars, and I am very much in favor of those types of displays. I can see at a glance which parameters are not where they are supposed to be. And again, the synoptic display doesn't add much in this display.
Interviewer 2: Does that mean that you are looking for more specific information, or do you simply think that the visualization is too small and that that is the reason it is not useful?
Test Pilot: Well, of course I am not trained on it, but in this case, I find it to be too small. The pictograms are too small to recognize in my case.
Misha: Okay, no problem. Now, I don't know if you noticed this, but all three of these displays had a malfunction scenario which can be associated with the three scenarios we talked about earlier. Do you think you would be able to associate the displays with the specific scenario?
Test Pilot: Yes, I can definitely recognize the problems, but that is only because of the colors and how to compare them to the other healthy subsystems. *[Then proceeds to identify the displays associated with the correct scenarios]* Display 1 with scenario 2, display 2 with scenario 3, and display 3 with scenario 1.
Misha: Okay, perfect. Well, you've answered most of the questions that I wanted to ask with regards to the novel displays. One of my last questions is how would you improve consistency with traditional displays when trying to represent these new complex technical systems? In the goals of making this transition easier.
Test Pilot: Well, it is not comparable, but I like the displays you made; they give you a quick overview of the health of the system. They are easier to scan.
Misha: That concludes the interactive part of this interview; thank you a lot for your participation.

B.2. Interview 2

Misha Schweitzer: OK now let's start.
Test Pilot: Ok.

Misha Schweitzer: Let's start with a synoptic display. Last time we quickly talked about it, but I would like to go maybe a bit more into depth in this display. What first stands out to you in this display?
Test Pilot: What do you mean with that?
Misha Schweitzer: What can you identify? Can you explain the symbols? Can you explain the connections between the symbols? Anything that comes to mind for you?
Test Pilot: Well the symbols are I would say not immediately intuitive but what I would say on the on the bottom you see the hydrogen storage then a stack of fuel cells and then. What is in the centre? Maybe an electrical distribution. Uh and then going to the left looks like a motor and a reduction gearbox then and on top. Then cooling unit and a kind of heat exchanger.
Misha Schweitzer: OK you've got them all except one. The one I think where you had trouble was the pump system.
Test Pilot: Ah.
Misha Schweitzer: Do you find other symbols to be more appropriate?
Test Pilot: Well once you know what it is no but let's say the second from below. The fuel stack? My first impression was document storage but now it's fine. And I think the symbology can be optimized but I think that's not the most important thing now.
Misha Schweitzer: OK.
Interviewer 2: Just to follow up on that, do you think it would be interesting to have annotations or something on the side or something interactive that would show what it would what it means? Like how would it be a better representation?
Test Pilot: No. You mean kind of a legend. No not really. The pilot should be sufficiently trained on this.
Interviewer 2: OK.
Misha Schweitzer: Can you let can you see can you explain what you understand of the connections between the symbols?
Test Pilot: Actually not really because if you look around the centre unit there are you can distinguish between two kind of symbols but one is a connection and one I assume is not but that's not very clear to me.
Misha Schweitzer: OK. Well that's OK. There's three different types of connections. Electrical connections, mechanical connections, and fluid connections let's say so pipes and hydraulics for example. So between the radiator and the fan for example and the pumps we can see a fluid connection, between the fuel cells and the BMS an electrical connection, and between the motors and the gearbox there's mechanical connections. Is there a way that you maybe would have wanted that to be clearer?
Test Pilot: Well you know it it will be clear I think but if you look to the mechanical connection that can also be an electrical connection I mean.
Misha Schweitzer: OK. Let's continue to the next slide. Uh here we now have the lower part of the synoptic display. Can you give us your first impressions on the colours the positioning the legends.
Test Pilot: Oh my first impression is it's all green so it's OK and then continue with what I was doing.
Misha Schweitzer: OK perfect. Yeah. Are the colours clear? Or let's say what do the legends mean?
Test Pilot: Oh well I see green part and then it's yellow line or amber. And that's the caution area and the above is the red area. That's the no go or immediate action. I mean everything between yellow and red requires the immediate attention of the pilot.
Misha Schweitzer: Hmm.
Test Pilot: And he can decide whether he takes actions on that or not. Everything above red would require immediate action of the pilot.
Misha Schweitzer: Yep. OK perfect. What about L and R? Does that make sense intuitively to you?
Test Pilot: Well normally it means left, right?
Misha Schweitzer: That's correct.
Test Pilot: But my preference would not be to make one long yellow line in one long red line but just keep it in the box of the indicator.
Misha Schweitzer: OK. Any particular reason why? Is this personal preference or just how it's done in the industry?
Test Pilot: Well it's personal. I would just, you know, limit that indication to the indicator itself.
Misha Schweitzer: Okay can you tell us how the two parts of the synoptic complement each other these two parts of the display?
Test Pilot: You mean what the relation is between the indicators on the bottom and the Synoptics display?
Misha Schweitzer: Uh yes.

Test Pilot: Well fuel has to do with the bottom part of the synoptics. Air would be the top part. Yeah I think so. And temperature also and oil will be the gearbox probably reduction gearbox and power will be related to the engine.
Misha Schweitzer: How would you describe the state of the system to be?
Test Pilot: Yeah. Well it's green. So it's good. Although the left temperature is on the edge. Might require some attention.
Misha Schweitzer: Perfect. Yeah. That finishes the first of the displays. We can now go to the second display.
Test Pilot: I don't know if you can go to the previous one and I'm not sure you come back on this display. I would suggest if for instance one of those parameters would exceed yellow or the red line. I would suggest in that case to light up the associated system in the synoptic display.
Misha Schweitzer: Well you've gotten ahead of yourself because that's exactly how it works. But we'll get to that a bit later OK? This this is the next part of the displays.
Misha Schweitzer: [Shows Polar plot] Have you seen this before and can you explain for example what this represents to you what the variables are the units the range the colours? Is it missing anything?
Test Pilot: I forgot the name of such a display but I know it. You know it's many times you used to show performance of organizations and other things.
Misha Schweitzer: Umm.
Test Pilot: But you can also yeah you know. I think it's pretty unusual to use these kinds of graphics for systems. At least I didn't see it before. And on the other hand maybe I'm not an expert in these kinds of diagrams but it could be interesting. In cases where it nears extremity it works well.
Misha Schweitzer: It's both. You can see it as a bar graph that's been angled and so the constraints are apparent. As long as you're between the two yellow lines you're correct and you're in the clear. Your system is healthy.
Test Pilot: I know what you mean.
Misha Schweitzer: OK.
Test Pilot: And this kind of presentation is this a common way of representing information?
Misha Schweitzer: It's a lot more common in process control and within the framework that I'm using they use it regularly.
Test Pilot: Ah really.
Misha Schweitzer: It's to show a large amount of non-correlated variables. That's one of the options that is given.
Test Pilot: All right. Well I'm not familiar with it in aviation.
Misha Schweitzer: OK. That's good feedback. Yeah we can go on to the next one. What's a what does this graph represent to you? What does the composition represent?
Misha Schweitzer: [Shows close proximity meter with spread indicator]
Test Pilot: Well the way I see it is that there is a minimum output apparently which is represented by the red line. But I don't know what the square box in the middle means.
Misha Schweitzer: OK so quick explanation. I'll just run through it. There's a minimum output and the box in the middle indicates the spread of the output within the fuel cells of the stack.
Test Pilot: Within a certain time frame?
Misha Schweitzer: Yes indeed which would be known by the pilot so he can quickly see OK there's something off. Three of them are outputting at full blast and one of them is just on the edge of being let's say unhealthy.
Test Pilot: OK.
Misha Schweitzer: Then that would become immediately apparent. Is this something that you would like as a representation?
Test Pilot: What I don't like in this presentation is the red line.
Misha Schweitzer: OK.
Test Pilot: Because it's strange for me that uh on both sides of the red line it's green. But I understand I mean I understand what you want to say but I would prefer just to put a little red line on the outside of the stack.
Misha Schweitzer: Mm-hmm.
Test Pilot: Just as in kind of a marker and the moment that it drops below that marker you turn the colour off the whole bar in red but not like this.
Misha Schweitzer: OK.

Test Pilot: I don't like this presentation.
Misha Schweitzer: OK that's good.
Test Pilot: So I would. So you change the colour if it's below the red limit and put a little red line indicator on the side.
Misha Schweitzer: Well one of those things is already the implementation currently that it changes the colour when coming underneath a certain value so that's easy and the other implementation putting let's say an indication just on the left or on the right that's something that's OK yeah that's easily adaptable and an interesting comment. I'll be sure to maybe talk about discuss and integrate maybe.
Misha Schweitzer: This is another type of display which might be a bit more complicated so don't worry if you don't immediately understand what's going on. What does this mean to you? Take a couple of seconds to try and interpret it.
Misha Schweitzer: [Additive nomographs]
Test Pilot: So we have input on the bottom output on the top. The green lines for example and the input and the output are the real values. The red lines is the let's say limit and in this case we can see that the battery is charging and that the output is then lower than the input for example. Is that something that makes sense?
Misha Schweitzer: Uh the battery is draining. You can if you add let's say the input plus the battery. Then you have the output let's say on the same scale. It's a bit of an interesting visualization.
Test Pilot: It's a bit strange but it's clear to me. But it probably is my lack of knowledge of the system to understand the display in this case.
Misha Schweitzer: And is it something that you would be that you would use or is it too complicated?
Test Pilot: Well maybe you can explain it one more time because I just want to make sure I understand.
Misha Schweitzer: OK no problem. There's three bar graphs and the left in green is the actual value and in red is the constraint of the input so.
Test Pilot: Yeah. I mean you mean charge current or?
Misha Schweitzer: Input of the electrical conditioning unit.
Test Pilot: OK. Yeah.
Misha Schweitzer: The battery can either be charging or discharging. You can see that the zero is the black line and this will be either the green line is either so if it's underneath it's discharging. If it's above it's charging.
Test Pilot: Yeah.
Misha Schweitzer: And once you understand it it's simple. Do you think this is too complicated? Do you think the pilots might not want to use it because of its complexity?
Test Pilot: Difficult to say.
Misha Schweitzer: OK no problem. Now that you know the subsystems themselves I will now show you the full display. So this is the power display now. How do these subsystems complement each other? Does this layout make sense to you and can you describe to your knowledge what the state of the system is for example?
Test Pilot: Well it's very small. But you know you can see in a glance on the polar diagram. Uh that you know it's almost a circle. It's all green so I think my system is healthy. But that's just my quick interpretation of the top of the display.
Misha Schweitzer: Umm.
Test Pilot: So it's correct or not?
Misha Schweitzer: Yes yes it's correct. Does the location make sense? Does that make it simple to interpret? The fact that all of the displays are symmetrical down the middle to symbolize the different systems? And does this make sense immediately or would you rather have them all combined into one?
Test Pilot: Well I think it's clear.
Misha Schweitzer: OK perfect.
Test Pilot: Yep.
Misha Schweitzer: Let's head on to the next one. OK this is a bit more of a simple display.
Test Pilot: You first have to explain to me what you on and off indication means.
Misha Schweitzer: Well in this case it would be simply is the oil heater on or off?
Test Pilot: So they're not permanently on.
Misha Schweitzer: No they can be off. For ground for example.
Test Pilot: Okay and C1, C2, C3 at different locations or?
Misha Schweitzer: Different coils of heaters. In this case the variables aren't the most important

parameter.
Test Pilot: OK for the rest it's great to me I think.
Misha Schweitzer: OK. Can you describe what the symbol is on the right of the screen?
Test Pilot: Well I assume it's the oil heater.
Misha Schweitzer: OK. No in this case just to make it clear then these are valve representations.
Test Pilot: Oh okay now I see.
Misha Schweitzer: Perfect and what does the green box around the value represent?
Test Pilot: Sorry but is there a green box around it?
Misha Schweitzer: That's a valid response. That has to be a lot visible.
Interviewer 2: Yes again it is kind of a range indication again but there is a thick green line that is more visible to see but the surrounding is not very visible.
Test Pilot: Yeah. Now I can see.
Misha Schweitzer: That's good feedback.
Test Pilot: Maybe because it's just too small here but what degree I assume that the green box can move over the range and maybe it's dependent on RPM or dependent on other factors.
Misha Schweitzer: Yes that is correct.
Test Pilot: I don't know but the green area is let's say the lower and upper value. The values are dependent on another input value.
Misha Schweitzer: This is correct. Yeah these are expected. This is how the system expects the value to behave.
Test Pilot: Yeah that's clear.
Misha Schweitzer: Now we have this one. Note that there's not much difference with the previous one but there is one slight difference that I would like to discuss. There's a white line between the current values.
Test Pilot: Well apparently there's a reduction in temperature between R1 and R2.
Misha Schweitzer: Perfect that is what it is. These are let's say connected systems in series. So that would then you can immediately see the decline in temperature for example.
Interviewer 2: Do you think it's useful to have these connections between the graphs? And is it easier to understand?
Test Pilot: It's quicker to interpret it. I mean 84 or 72 are just values and you may expect that there is a temperature drop.
Interviewer 2: Yeah.
Test Pilot: And if that's not the case or when it's flat or. Then that might be an indication something is wrong. So yes I think it is and at least it's easier to see here that there's temperature drop between the two radiators.
Interviewer 2: Yeah. Right.
Misha Schweitzer: Alright perfect. Let's continue. This would be the oil flow. In your opinion is there are too much information. Is it the are the representations too different in size?
Test Pilot: That's very difficult to say because you really need system knowledge to say that. I have insufficient system knowledge to tell you any mutual relationships between these parameters to say anything about that.
Misha Schweitzer: OK. And if we ignore the parameters would this be something you're comfortable let's say using to gather information? Or is it too much information on one part of the screen?
Test Pilot: Not necessarily.
Misha Schweitzer: OK.
Test Pilot: And the valves can we also distinguish between open and closed?
Misha Schweitzer: Yes they do. They have a percentage above them to describe in what state they are and the corresponding amount of liquid or fluids that are in movement.
Test Pilot: Okay.
Misha Schweitzer: OK we can continue now. Now we have another grouped proximity meter so probably the same comments but these are averaged which means it takes the average of let's say the four independent variables and then at the bottom they give you a number to say what the average is. Is this something that is let's say different or bad in some way?
Test Pilot: That depends on over what time frame the average is taken.
Misha Schweitzer: OK.
Test Pilot: I mean on average over the whole flight doesn't say me anything, same for over 5 seconds doesn't say me anything.

Misha Schweitzer: OK. I understand. Do you have any let's say comments on this temperature management display.
Test Pilot: How big is the display?
Misha Schweitzer: A bit bigger than an A4 for example. Well talking maybe 13 inch or so. Do you think this size would be appropriate with this amount of detail or?
Test Pilot: No I think that will work. I mean you must design it in such a way that you know the parameters can be read also in turbulence if you make it too small you can't read it anymore.
Misha Schweitzer: Yeah. OK. Yeah that makes sense.
Test Pilot: Sorry. Yeah yeah.
Misha Schweitzer: Let's go quickly. And these are known as trend graphs. You've obviously seen this before at some point in this case the relative air temperature at the fuel cell and the relative humidity at the fuel cell. Can you describe the trend graph? Can you comment on the axis the lines the limits and anything that makes sense to you?
Test Pilot: Well it stays within limits. If the upper and lower red line is in limits it stays within limits. There is a downward strength in air temperature and humidity which thereafter increase again but I don't know what you want to do with this in the cockpit.
Misha Schweitzer: Well in this case it has to do with the saturation in the fuel cell. So for example it's not enough to know if it's within the limits. If it stays let's say close to the limit for an extended period of time say let's say an hour then that's also an issue. Do you understand?
Test Pilot: Yeah.
Misha Schweitzer: OK. So that's the representation that seemed most appropriate to display that.
Test Pilot: OK.
Misha Schweitzer: Good. So we have a small trend graph and then we have the input and output of the humidity. The important part is the representation between the two values. We have a connecting line and behind that we have a gray let's say polygon which indicates what we want the system to do. Does that sort of make sense?
Test Pilot: Yeah but I see a kind of a trend here. Now we're talking about trends to make the display a kind of an engineering display and you must be careful.
Misha Schweitzer: Umm.
Test Pilot: That a pilot is not an engineer like you and me. I'm an engineer and a pilot but most pilots I know aren't engineers and you must take care that you're not. Let me say how can I say that? The pilot is not that much interested you know in trends and in how engine behaves in it should behave. I mean the pilot is just interested in. Does it work? And not: How should it work?
Misha Schweitzer: Mm-hmm. OK.
Test Pilot: And I say that without you know having sufficient system knowledge. But I notice here a kind of a trend to make the information available as an interpretation to the pilot.
Misha Schweitzer: I understand you know what you mean and that makes sense.
Test Pilot: And for test pilots it's perfect. It's you know a lot of graphs I love. But it might not be what we're looking for in a commercial flight.
Misha Schweitzer: OK so for commercial applications this might be too much information.
Test Pilot: I have the feeling yes.
Misha Schweitzer: OK.
Interviewer 2: For a new display do you think this would be still relevant though? I mean at least for training purposes or to see like any relevance of having a lot of these type of trends or umm yeah this very specific representations of the variables.
Test Pilot: I'm hesitating.
Interviewer 2: Hmm. OK OK.
Misha Schweitzer: Okay perfect. Let's continue. This would be then the representation.
Test Pilot: Same here I'm you know for an engineer this is perfect data. Umm I think you have to limit it into cockpits to information that is required to perform safely the flight.
Misha Schweitzer: OK.
Test Pilot: And if you know systems are going out of limits that's important to know.
Misha Schweitzer: OK.
Test Pilot: But I see it growing and growing now to much more complicated diagrams. And we end up in a nuclear power plant display if you know what I mean.
Misha Schweitzer: That's true yeah. But it is also a complex system but I understand your point that the

pilot doesn't really have time for interpretation. So what are the most relevant parameters?
Test Pilot: The parameters where you have a procedure to act on and if that isn't necessary you don't display it. Those are parameters you want to know. Uh but you also must for everything that let's say exceeds a certain value. Or there's a threat that it will exceed that failure.
Misha Schweitzer: Umm. OK.
Test Pilot: I mean we designed the airplane now for I don't know what the flight time will be but definitely not more than 90 minutes I think and if you go from Amsterdam to London there's lots on the radio. There's a lot of you know things you have to do to control that flight. And we I mean we don't have the flight engineer anymore on boards and that should all be automated.
Misha Schweitzer: OK. Then you say the workloads are already high.
Test Pilot: Yeah yeah yeah.
Misha Schweitzer: OK. That makes sense yeah.
Test Pilot: You know I'm all always very cautious. Engineers are not too much how do you say that. Uh making a design which meets engineering requirements. It must meet pilot requirements and it is very often it's a little bit difficult to uh with your mind in the head of a pilot I can imagine that. But we still need to do that. Uh so the whole let's say HMI design must be such that the design gives the proper information on the on the right moment and not much and not more. And maybe a little things can be automated and only the already automated function will be acknowledged to the pilot if you know what I mean.
Misha Schweitzer: As for example that a certain system is working according to the automation?
Test Pilot: I mean the system status there is no need to monitor that at that moment. I should not display it.
Misha Schweitzer: OK. Would it still be interesting to access that information if something's wrong?
Test Pilot: If something is wrong and if there is a procedure for instance that the pilot can do or he needs that information in his decision making. It should be presented.
Misha Schweitzer: OK. Well and that is in line with the design. You would just be faced with the main synoptic display and only would you access the sub-displays if something's wrong.
Test Pilot: But the reason I say is that if you look to this display you know it gives you graphs. It gives you trends and that needs interpretation by the pilot. You should ask the question is it necessary that the pilots? Makes an interpretation of this data. Or can we just automate that?
Misha Schweitzer: OK thank you that's a very good comment. We'll now continue on the presentation but I'll take it definitely under consideration for the discussion and recommendation section of my report. This is the hydrogen flow and balance monitoring screen and does the layouts seem adequate? As in we have the left and right fuel system and according to the left and right and cells and they're connected in the middle by the air management and heat exchangers. Does this make sense to you?
Test Pilot: What do you mean with hex temperature?
Misha Schweitzer: Uh sorry that's a heat exchanger.
Test Pilot: Oh heat exchangers. Clear.
Misha Schweitzer: This would be then the complete hydrogen display to monitor the capacity the power output and just the available hydrogen to the system.
Test Pilot: Yeah.
Misha Schweitzer: I think we have a recap now which is we have the full synoptic display which is the main display. As you said if everything's alright you only see this display when pressing on the powertrain display and these then link up to these four displays. When we want more information. So there's five buttons at the bottom of the screen that enable you to switch between the synoptic and these four more detailed displays.
Test Pilot: Yeah.
Misha Schweitzer: Now I've created a couple of scenarios to see if you could perhaps now that you have a bit more knowledge about these displays perhaps interpret what the situation of the aircraft is.
Test Pilot: Okay.
Misha Schweitzer: Now this is the first static scenario.
Test Pilot: Yeah. Well we have a left power in red and using the synoptic display I can say where the problem is localized. The fuel cells and the battery management systems are the only one concerned right?
Misha Schweitzer: Yeah they are the two connected subsystems that are affected in that case?
Test Pilot: Yeah.
Misha Schweitzer: So then in this case you would be presented with the four buttons at the bottom. You

can directly access the power display and it would lead you to this visualization.
Test Pilot: Yeah. Which gives me a new quick glance that something is wrong with the BMS as well as outputs.
Misha Schweitzer: Yes good.
Test Pilot: There is an issue with the charging rate of the battery.
Misha Schweitzer: Indeed.
Test Pilot: Yeah. So something wrong with the battery management system.
Misha Schweitzer: That's because the battery is discharging because the input level is lower and the battery is discharging and we have a lower input level.
Test Pilot: Yeah.
Misha Schweitzer: So this is a problematic scenario obviously.
Test Pilot: Yeah. And so apparently something is wrong with the fuel stack number one I assume.
Misha Schweitzer: Indeed. What action could you see for example to remedy this problem?
Test Pilot: Fuel stack one and two are there in parallel.
Misha Schweitzer: Yes.
Test Pilot: So what would you suggest? Increasing fuel stack two or compensating with fuel stack three or four I would imagine since they both go through the same reduction gearbox to the same propeller that would work.
Misha Schweitzer: Yes that would be possible. What are things that you like about this visualization? What are things that you don't like?
Test Pilot: Well. Something is wrong with fuel stack one. Apparently the consequence is that the battery management system one output or the output is still good but it's draining battery one. So basically there's a lot of information here. But the only thing I'm interested in is. OK I'm draining my battery and I need to do something to fuel cell 1 and need to compensate that in whatever way.
Misha Schweitzer: Yes.
Test Pilot: And I assume there is a procedure connected to it.
Misha Schweitzer: You can assume yes. Do you think there would be a more efficient way to present this information with less? Let's say detail would that be more appropriate?
Test Pilot: You can do that in two sentences on the FMS. That would be quicker to understand. I think for me than giving a set of graphs where I have to draw that conclusion myself.
Misha Schweitzer: OK.
Test Pilot: Instead of reading the problem in the display. It would be easier to just tell the pilot that's the problem is and which procedure he has to do.
Misha Schweitzer: Of course yeah. But that leads to situations where if there isn't a specific scenario predicted on the FMS or a text scenario predicted that can lead to a moment where the information isn't presented to the pilot in an understandable way.
Test Pilot: I mean the question would be. Basically you should for each abnormal situation you should create an abnormal procedure.
Misha Schweitzer: OK. So the pilot would have to be prepared for this procedure for these situations no matter what.
Test Pilot: Yeah but instead of letting him find out what the problem is. If I look to these pictures basically what you say OK I present system status and the pilot have to has to find out what his problem is. He can see on the system status then OK that battery one is draining and that something is not OK with fuel cell #1. Instead of leaving room for interpretation by him you're telling what is wrong. Tell him: Battery one and discharging fuel cell #1. You could always decide to give this information additionally as supporting information which might also be helpful in case of troubleshooting.
Misha Schweitzer: OK.
Test Pilot: But in first instance I think tell him right away what's going on and don't leave room for interpretation based on the set of indicators.
Misha Schweitzer: OK. That's extremely good feedback. So just as a first response there has to be no room for the pilot to make a mistake.
Test Pilot: No room for misinterpretation of instruments.
Misha Schweitzer: And the more complex the display the more room there is for misunderstandings.
Test Pilot: Definitely yeah.
Misha Schweitzer: That's valuable insight.
Test Pilot: And it can be supporting information. So let's say first on the display it will show just discharging

fuel cell #1. Uh I don't know what is wrong. Let's see what procedure is on it and if he has time and he wants to look what really is the fact then he pushes the right electrical push button and he gets the page and then he has supporting information on the troubleshooting on the fault.
Misha Schweitzer: OK that's very good. We'll go on to the next scenario now.
Misha Schweitzer: [Show high temperature in the cooling loop to the FC]
Test Pilot: Well it's something like right temperature. And here I have two reds. One of them is the fuel and the other one is the air cooling.
Misha Schweitzer: OK perfect. So in this case you click on the temperature display and you end up here.
Test Pilot: On the bottom I see average fuel stack temp number 1 not OK. You could say that the left heat exchanger is maybe malfunctioning.
Misha Schweitzer: OK.
Test Pilot: Is that the case?
Misha Schweitzer: Mostly yes. Can you see my mouse?
Test Pilot: Yep.
Misha Schweitzer: These are the average fuel stock temperatures so this would be in the left lane. Indeed the left is malfunctioning as you said and the first fuel cell maybe because indeed uh a humidity was too low. Then in that case it would be overheating and it's best if the procedure allows it to just maybe turn that one off if there can be compensation for that. That's sort of the scenario as I saw it. It should also be then clearer you can see the spread here is much larger than the rest to give a quick indication as well.
Test Pilot: Yeah.
Misha Schweitzer: Or the cooling should be increased. OK that's the second static one. And now just to show you what the display could look like when it's properly running. We have a third scenario and this one we can interact with as well.
Test Pilot: OK I see a left view so I would ask for the fuel page. And I can see I would say saying tank 1 percentage she's low. I can't see it. It is outside the constraint box.
Misha Schweitzer: Yes.
Test Pilot: Yeah it's outside of the constraint box.
Misha Schweitzer: OK.
Test Pilot: So take the procedure for number one has a low fuel.
Misha Schweitzer: So maybe there is a leak or something that needs to be resolved.
Test Pilot: Yeah.
Misha Schweitzer: Well those are the three scenarios.
Test Pilot: But also in this case you know it's out of the box but it's not told. To me it's gives him display and it's I have to scan the whole display and find eventually. Tank number one. Uh there's a low content of whatever. I'd prefer a direct warning on the FMS and then an additional display such as this one.
Misha Schweitzer: OK. That's a great response. I really like that the fact that you first want a direct let's say interpretation from the FMS and then you leave it up to the pilot to if they want more additional information.
Test Pilot: I mean apparently there is a condition which the system flags.
Misha Schweitzer: Yes.
Test Pilot: In this case it's the low quantity. Then I think you make it a lot easier and more a lot let's say more foolproof. I mean displaying what the full condition is.
Misha Schweitzer: OK.
Test Pilot: The trigger was caused. Tell them one low quality.
Misha Schweitzer: I agree with that but there's just something.
Test Pilot: And then you can cross check that with the display.
Misha Schweitzer: I agree with your reasoning.
Test Pilot: Yeah.
Misha Schweitzer: OK. Well that brings us to the end of this interview. Do you want to discuss anything else? Do you have any questions for us or?
Test Pilot: No. I think I made a lot of comments and maybe it's not what you want to hear because you know I'm an engineer myself too. And being a test pilot in the past I have had lots of discussions with engineers. And sometimes you have to. And you how can I say that very in a polite way? Push them back into their books or something like that.
Misha Schweitzer: Sure.
Test Pilot: You know what I mean?

Misha Schweitzer: I see what you mean. Yeah we have a tendency to want to see the whole picture instead of just what we need.
Test Pilot: Exactly. You are thinking in an engineering way. And when I'm in a an airplane sometimes when it's a test flight I'm also thinking in an engineering way but if it's a regular flight there is no room for engineering. There is no room for interpretation. There's no room for engineering. I just have to do the procedure which is connected to this condition.
Misha Schweitzer: Umm so.
Test Pilot: And only in rare cases. There is you know pilot interpretation necessary which is still possible if you call for the right information on the right displays like yours.
Misha Schweitzer: OK. Yeah these displays in your opinion would be then a lot more appropriate in a test environment than in a commercial environment.
Test Pilot: In a test environment? Definitely. I mean if you would be in a prototype airplane. Then this would be great. I hope this helps a little bit.
Misha Schweitzer: It certainly does.

C

Svelte Documentation

Documentation on Svelte animation

Software versions:

- Windows 11
- Visual Studio 2022
- Inkscape 1.3

Step by step creation of a Svelte project:

Download and install Node.js from nodejs.org. This will also install npm (Node Package Manager) which is necessary to manage project dependencies.

Open a terminal and go to your desired file location (using *cd*).

Create a new Svelte project using the following commands:

- *npm create svelte@latest name-of-the-project*

Now select Skeleton project, Add type checking with TypeScript (and any other preference)

- *cd name-of-the-project*
- *npm install*
- *git init && git add -A && git commit -m "Initial commit" (optional for git)*
- *npm run dev -- --open*

Hopefully you've now opened your project for the first time in a web browser.

To close it use Ctrl-C

Your script containing all the action that you will want to perform are located in +page.svelte (*src/routes/+page.svelte*). You can see this file as your main.

Further useful configuration for testing

- *npm install xlsx* (to use excel files as source)
- *mkdir -p src/lib/assets*
- *mkdir -p src/lib/assets/SVGs* (make a folder for the SVG files)
- *mkdir -p src/lib/assets/Excels* (make a folder for the Excel files)

Now create a new SVG in Inkscape and under the properties of the object (in this case a rectangle) there will be an ID which you should change to something recognizable (avoid rect-1). Don't forget to save. Now put the SVG file in your svelte project folder (*src/lib/assets/SVGs*).

Now open your project folder in Visual Studio and open your SVG file. Find your object by using CTRL-F and typing in your recognizable ID. If you want to change the color for example, the fill is under the style section as follows:

```
style="fill:#808080;stroke:#008000;stroke-width:1.13766;paint-order:markers fill stroke"
```

Then remove the fill from the style and put it separate.

```
style="stroke:#008000;stroke-width:1.13766;paint-order:markers fill stroke"
fill="green"
```

This makes it a lot easier to access the color. You need to do this for every single attribute you want to use.

If you want to connect your attribute to data in an excel file to prototype behavior of the display, follow the next steps. Feel free to change as much as you want, the way I did it is in no way the best way and if you know better, please change everything that needs changing.

You need to make the first row is the identifier row setting the name of the cells to **exactly** the same name as the ID of the object you want to control in the SVG file as these two will now be linked. You can also set threshold values (values where the color will change for example) by adding *"-threshold"* at the end of the ID of the object.

I've tried to comment as much as possible in the code of +page.svelte to help understand what's going on.

Further debugging is really nice, just add either

console.log('Whatever the message you want'); (for logging purposes)

console.error('Something has gone terribly wrong'); (for error logging)

You can see the console in the web browser by pressing F12 on your keyboard (depends on the manufacturer) and looking at the console. This is really useful to understand where something has gone wrong.

D
Procedures

The following appendix is included in the report as examples of hypothetical procedures for normal operations of the HAPSS retrofitted Dash 8 Q300.
The included procedures are:

- Pre-flight checks procedure
- Taxi procedure
- Take off procedure
- Descent and approach procedure
- Landing procedure
- Post-flight procedure

Pre-Flight Checks for Hydrogen-Electric Dash 8 Q300

1. **Hydrogen Fuel Level and Storage Inspection:** • Check hydrogen fuel levels, ensuring enough fuel for the flight plus reserves. This might involve interpreting data from pressure and temperature sensors in the hydrogen storage tanks. • Visually inspect hydrogen storage tanks for any signs of damage, stress, or leaks. Pay special attention to valves, fittings, and connections.	
2. **Hydrogen Leak Detection System Check:** • Test the functionality and calibration of the hydrogen leak detection system. This is a critical safety check due to the volatile nature of hydrogen.	
3. **Hydrogen Fuel Cell System Checks:** • Ensure that the hydrogen fuel cells are in 'standby' mode to start the system safely. • Check the pressure gauges of the hydrogen system to ensure they're within operational limits. • Inspect the fuel cell cooling systems for functionality and signs of leaks, as maintaining operational temperatures is crucial for safety and efficiency.	
4. **Electric Motor System Checks:** • Conduct diagnostic tests on the electric motors, ensuring they respond correctly to control inputs. • Test the responsiveness of electric motor controllers, verifying smooth operation without lag or erratic behaviour.	
5. **Power Management System Initialization:** • Initialize the power management system, which regulates the distribution of electricity from the fuel cells to the electric motors. • Verify the system's capability to distribute power efficiently and respond to varying power demands.	
6. **Safety Equipment Check Specific to Hydrogen-Electric Systems:** Ensure the presence and functionality of safety equipment specifically designed for hydrogen risks, such as appropriate fire suppression and protective gear.	
7. **System Integration and Function Check:** • Check the integration of the hydrogen-electric system with the aircraft's avionics and control systems. • Perform a system function test, simulating various power demands and monitoring the hydrogen-electric system’s response and performance.	

Taxi Procedure for Hydrogen-Electric Dash 8 Q300

1. **Initial Power-Up:** • Ensure the hydrogen fuel cells are activated and stabilizing at the correct output level for taxiing. • Confirm that the electric motor systems are responsive and ready for operation.	
2. **Instrument Panel Check:** • Verify that all relevant displays are showing correct information regarding hydrogen fuel levels, electric motor status, and battery (if applicable) charge levels. • Ensure that the hydrogen leak detection system shows no warnings.	
3. **Throttle and Brake Tests:** • Test the responsiveness of the throttle control, noting the immediate torque availability of the electric motors. • Conduct a brake check to ensure proper functioning, as regenerative braking systems (if installed) might behave differently from traditional brakes.	
4. **Steering and Control Surface Check:** • Test the aircraft's steering system for responsiveness. Due to the electric motors, the aircraft might respond differently than with conventional turboprop engines. • Conduct a quick control surface check (ailerons, rudders, elevators) for responsiveness and freedom of movement. 5. **Taxi Speed Management:** • Begin taxiing at a slow speed, gradually increasing to a standard taxi speed. Monitor how the electric motors respond to throttle adjustments, as the response might be more immediate and smooth compared to traditional engines. • Continuously adjust throttle settings as needed to maintain a safe and controlled taxi speed.	
6. **Energy Consumption Monitoring:** • Keep an eye on the energy consumption readouts. Although electric motors are more efficient, it's good practice to monitor the hydrogen fuel cell’s output and remaining fuel levels.	
7. **Approaching the Runway:** • As you approach the runway, perform any final checks and preparations for take-off. • Ensure that the electric motors are set to transition smoothly from taxiing to take-off mode.	

Take-off Procedure for Hydrogen-Electric Dash 8 Q300

1. **Take-off Checks:** • Ensure that the hydrogen fuel cells are operating efficiently and providing stable power output. • Check the electric motors for readiness, ensuring they are set to provide required take-off power. • Confirm that all flight controls are responsive and in the correct positions for take-off. • Verify that the hydrogen leak detection system shows no warnings or abnormalities.	
2. **Final System Checks:** • Review the power management system for any alerts or issues. It should display readiness to handle the increased power demand during take-off. • Conduct a final check on the electric propulsion system, ensuring that the motors and related systems are fully operational.	
3. **Communication:** • Communicate with air traffic control (ATC) to receive clearance for take-off. • Announce intentions on the appropriate frequency, especially in uncontrolled airspaces.	
4. **Lining Up on the Runway:** • Taxi onto the runway and align the aircraft with the runway centreline. • Ensure the aircraft is stable and stationary before initiating take-off power.	
5. **Take-off Power Application:** • Smoothly and progressively advance the throttle to apply power to the electric motors. • Monitor the power output and responsiveness of the electric motors as power increases.	
6. **Monitoring Acceleration:** • As the aircraft accelerates, keep an eye on the airspeed indicator. Electric motors may provide a smoother acceleration compared to traditional engines. • Monitor the hydrogen fuel cell output to ensure it is keeping up with the power demand.	
7. **Post-Lift-Off Checks:** • Once a positive rate of climb is established, retract the landing gear. • Monitor the electric propulsion system's performance, ensuring it remains stable and efficient during the climb.	

Descent and Approach Procedure for Hydrogen-Electric Dash 8 Q300

1. **Descent Power Management:** • Reduce the output from the hydrogen fuel cells to decrease power to the electric motors, initiating a gradual descent. Monitor the power reduction to match the desired descent rate. • Be aware of the responsiveness of the electric motors to power changes, as they can adjust thrust levels more rapidly than traditional engines.	
2. **System Monitoring During Descent:** • Continuously check the status of the hydrogen-electric system, including the hydrogen fuel cell output and the electric motors' performance. • Pay attention to the cooling systems of both the fuel cells and motors, ensuring they're effectively managing the heat during the descent phase.	
3. **Approach Configuration:** • As you prepare for the approach, carefully manage the hydrogen-electric system to maintain the required approach speed and descent profile. • Adjust power settings as necessary for different stages of the approach, especially if dealing with variable wind conditions or ATC-directed speed changes.	
4. **Hydrogen Fuel Monitoring:** • Keep an eye on hydrogen fuel levels to ensure sufficient fuel remains for the approach and possible go-around scenarios. • Note any discrepancies between expected and actual fuel consumption rates during descent.	
5. **Final Approach Power Settings:** • On final approach, use delicate throttle inputs to control the descent rate and airspeed, considering the immediate power response characteristic of electric motors. • Regularly monitor the hydrogen-electric system for any signs of irregular performance.	
6. **Go-Around Preparedness:** • Be prepared for a potential go-around. Ensure quick and efficient power availability from the electric motors, understanding how the hydrogen fuel cells ramp up to meet sudden increases in power demand.	

Landing Procedure for Hydrogen-Electric Dash 8 Q300

1. **Final Approach Power Management:** • As the aircraft transitions to the final approach, finely adjust the power output of the electric motors to achieve the desired glide slope and airspeed. The responsiveness of electric motors requires precise throttle management. • Monitor the hydrogen fuel cell output continuously to ensure it is providing consistent power to the electric motors.	
2. **Electric Motor Thrust Adjustment:** • Adjust motor thrust as needed for precise airspeed control. Electric motors provide immediate thrust changes, which can be advantageous for small adjustments during the final approach. • Be prepared for the different deceleration characteristics of electric motors compared to traditional turboprop engines.	
3. **Pre-Landing Checklist:** • Complete the pre-landing checklist, ensuring all systems, including the hydrogen-electric propulsion system, are set for landing.	
4. **Touchdown:** • Manage the throttle carefully to control the descent rate and achieve a smooth touchdown. The electric motors' instant power adjustment can be utilized for fine-tuning the descent rate just before touchdown. • As the aircraft touches down, progressively reduce motor power, and utilize braking systems as necessary.	
5. **Post-Landing:** • After touchdown, continue to monitor the hydrogen-electric system as the aircraft decelerates on the runway. • Once at a safe speed, taxi off the runway and switch the electric motors to a lower power setting suitable for taxiing.	
6. **Shutdown Procedure:** • Upon reaching the gate, follow the specific shutdown procedures for the hydrogen-electric system. This typically includes powering down the electric motors, followed by shutting down the hydrogen fuel cells.	

Post-Flight Procedure for Hydrogen-Electric Dash 8 Q300

1. **Power Down Electric Motors:** • After reaching the parking position, safely reduce power to the electric motors. • Ensure that the electric propulsion system is completely powered down and in a secure state.	
2. **Shutdown Hydrogen Fuel Cells:** • Initiate the shutdown sequence for the hydrogen fuel cells. This typically involves closing the hydrogen supply and allowing the fuel cells to cool down. • Monitor the fuel cell system during the shutdown process for any anomalies or warning indications.	
3. **System Cooling Check:** • Verify that cooling systems for the hydrogen fuel cells and electric motors are functioning until they reach a safe temperature. • Look for any signs of overheating or system distress that occurred during the flight.	
4. **Hydrogen Storage and Leak Check:** • Conduct a post-flight inspection of the hydrogen storage tanks, checking for any signs of structural damage or leaks. • Ensure that the hydrogen leak detection systems are reset and show no warnings.	
5. **Electric System Diagnostics:** • Run a post-flight diagnostic on the electric propulsion system. Check for any error messages or maintenance advisories that need addressing before the next flight.	
6. **Visual Inspection:** • Conduct a walk-around of the aircraft, paying particular attention to the electric motors and propellers for any signs of damage or unusual wear. • Inspect the hydrogen fuel system components accessible from the exterior for any abnormalities.	