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Development of the initial certification and technology roadmap for the FUTPRINT50 framework

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Abstract. The main goal of the research project FUTPRINT50 is the acceleration of the introduction of a hybrid-electric regional aircraft. One essential part of this project is to develop a roadmap which couples the technological development with its associated research infrastructure and regulatory aspects. This aims at maximizing the likelihood of a successful hybrid-electric 50-seat regional aircraft with a projected entry-into-service by 2035/2040. This article presents the roadmap framework and methodology worked out by FUTPRINT50. Additionally, it shows the findings of the consortium about key enabling technologies and testing infrastructures necessary to achieve the final integrated demonstrators that provide evidence for lowering the risk of adoption and for bridging mapped regulatory gaps in regard to hybrid-electric propulsion. Furthermore, links to other complementary roadmaps are highlighted. Detail is given on the status of work and follow-up actions towards its completion.

1. Introduction

Aircraft are highly integrated and complex products, with long life cycles explored in capital-intensive contexts. As such, the commitment to launch a new aircraft program needs proper de-risking for all stakeholders to minimize the possibility of failure. The FUTPRINT50 roadmap aims to provide to key stakeholders a proposal of how key capability gaps for the launching of a hybrid-electric 50 passenger aircraft between 2023/2024 and early 2030s can be addressed. Namely, it proposes the orchestration of projects that address the dimensions of technology, regulations and experimental research infrastructure. Domain-wise, it focuses on certain technology capability streams, in specific, “electric propulsion”, “energy storage”, “high voltage power distribution”, “thermal management” and “design and integration”. The FUTPRINT50 project partners understand that these streams are insufficient to fully address the needs to enable the selected strategic goal. Therefore, a Hybrid-Electric Aircraft (HEA) ecosystem vision is provided as well. This view connects to developments being pursued outside the scope of the FUTPRINT50 roadmap that complement it.

The roadmap is implemented in the platform Sharpcloud. This enables the exploration of its items' connections and allows the creation of different dashboards and/or decision boards, to satisfy the different stakeholders' needs. It will become available to the public as the Final Roadmap in June 2023.

2. Methodology

2.1. Roadmap framework

A Systems Engineering approach was taken to the establishment of the roadmap process and structure. The approach implies the definition of stakeholders and their needs. With the definition and needs analysis, an operational architectural model can be outlined. The model and effort is visualized and depicted in Figure 1.

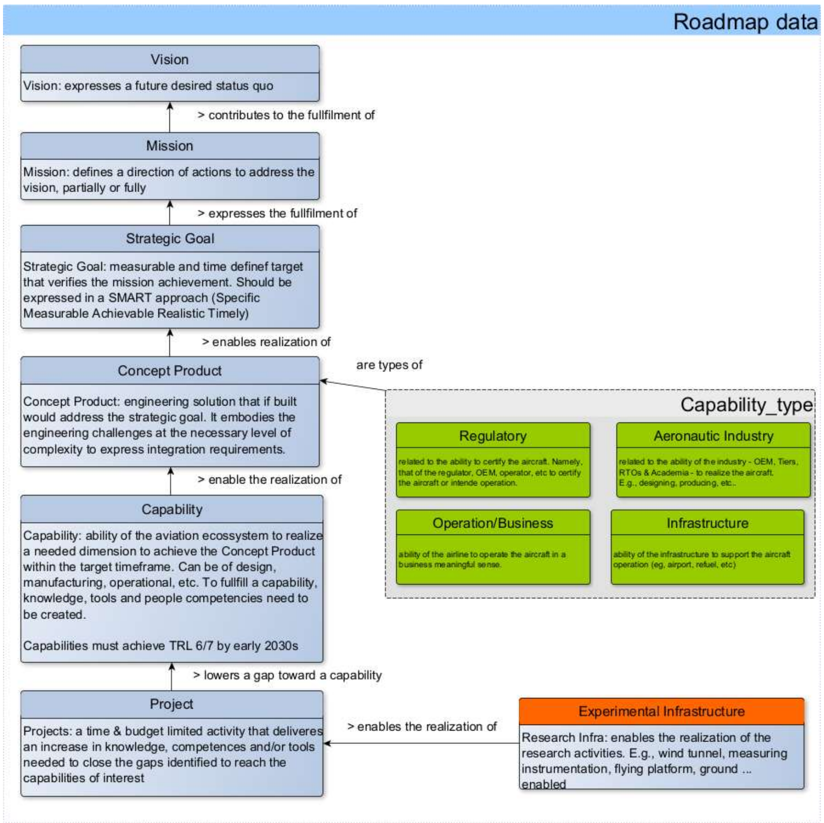

Figure 1. Layered architecture structure for the roadmap data.

Although Figure 1 is intended to be straightforward regarding the different logical elements of the roadmap data block, some key points should be highlighted nevertheless.

From vision to concept product: The vision frames a future desired state, usually quite ambitious. A mission is then defined, providing a specific scope and direction of action as a contribution towards achieving the mission. From the mission definition, the operational domain of the stakeholders becomes clear. This leads to the definition of SMART (specific, measurable, assignable, realistic, and time-related) strategic goals. Concept products/services should be defined using the goals as input, to enable the achievement of the strategic goal. To better define it, information regarding the target market, operational context and others should be gathered (information in the context of the roadmap mission). A top-level requirements activity for this concept solution – the System of Interest – should be performed, establishing clear targets for the concept product. As the end goal is to provide a research and technology roadmap to address novel products, the focus is on the new knowledge domains needed to enable this class of products. The function of the concept product is then to generate engineering integration requirements that help guide and assess if the needed capabilities are achieved. It must be emphasized that the concept product is not the future desired product to be launched by an original equipment manufacturer. Its core purpose and key quality is its ability to incorporate the technical challenges representative of the class of products to be enabled.

Capabilities. As the roadmap ambition is to support the ecosystem endeavour to achieve the mission goals, capabilities were also framed from an ecosystem perspective and not a single actor. Regarding the capabilities structure, it was divided into four different types: regulatory, aeronautic industry, operation/business, and infrastructure (see Figure 1). The capability must then be properly characterized to enable a clear evaluation of success and direction of development and assist the gap analysis process. Each capability should be characterized by key metrics for the class of problems it represents (for instance, for the thermal management system the order of magnitude of the heat load to be managed). Then, key targets and properties to be achieved are clustered around performance, industrialization and operation, and "undesirabilities". This last cluster groups issues and effects that need to be addressed as the lack in knowledge, tools, and competencies.

Projects. Projects are to be characterized by their duration, desired outcomes, research infrastructure needs and initial cost projection.

Hybrid-Electric Aircraft Ecosystem. Although not explicitly seen in Figure 1, a HEA Ecosystem will be integrated into the roadmap. This should provide situational awareness of other initiatives that complement the technology capabilities streams focused by FUTPRINT50. These other initiatives can be:

- Enabling/Upstream (e.g., manufacture and supply of suitable battery components enables the Energy Storage related capability);
- Complementary (e.g., airport infrastructure readiness);
- Follow-up/Downstream (e.g., programs like Clean Aviation can take up project results proposed in the roadmap).

2.2. General methodology

The goal of the roadmap is to organize and visualize the information and work that is needed for a successful entry-into-service (EIS) launch of a HEA. Creating this roadmap combines the ontology, which outlines the basic top-down structure on which the roadmap will be built, and bottom-up input from consortium partners on topics and projects that will be needed in the future to achieve the strategic goals of FUTPRINT50.

The ontology architecture creates the outline for the roadmap, which subsequently needs to be created. The vision and mission statements are straightforward. The proposed concept products introduced within the FUTPRINT50 project are derived from the strategic goals. To develop the concept products within the target timeframe however, capabilities need to be clearly defined and developed. The proposed method is to do a technology gap analysis and a certification gap analysis. The outcomes of both serve as input to define and create the information from the capabilities down to the research infrastructure. Sections 2.3. and 2.4. detail the execution of both, gap analysis for technology and regulations, respectively. The results of both gap analyses can be used to define and cluster characteristics per capability and define projects to realize them (further details in Section 3.4.). Two layers were created for the capabilities, L1 and L2. L1 provides the highest-level functionality into the aircraft (e.g., thermal management system) and L2 relates to major architectural choices (e.g., cryogenic). These layers were adopted to improve the roadmap management. With the first draft of projects, the first definition of research infrastructure can be obtained. This will direct a research infrastructure gap analysis, identifying existing research infrastructure that can support the projects or, if not, when the research infrastructure needs to become operational to do so (research infrastructure layer, further developed in Section 3.4.).

In a parallel activity, taking stock of the capabilities definition and its scoping, a survey is made regarding enabling, complementary and upstream projects and large research and technology programs addressing the same interest space. As a first approach, three major vectors are explored:

- Horizon 2020 and Clean Sky 2 projects targeting the same space (namely but not limited to EASIER [1] and IMOTHEP [2]);
- Joint Undertaking initiatives that have synergy with the HEA roadmap;
- International initiatives that address the same space of interest, through the international partners and collaborators of the project.

2.3. Technology gap analysis

The roadmap framework and ontology as discussed before, provides the means of structuring the roadmap. The content to be visualized within the framework comes from a gap analysis. This section elaborates on the gap analysis, which creates the content below the capabilities within the framework.

To be able to define the capabilities that are required, the major hybrid-electric technology streams were selected, as the change is primarily focused on these technologies. Per technology stream, a required capability has been defined. The technology streams within FUTPRINT50 are defined as follows:

- Energy storage system
- High voltage power distribution
- Thermal management system
- Electric propulsion system
- Aircraft design and integration for a hybrid-electric propulsion system

To understand what needs to be achieved per capability, a gap analysis methodology based on the systems engineering V-model, combined with a breakdown of the life-cycle aspects of an aircraft, was adopted. It consists of a set of unknowns, which are formulated as research questions. A cross reference matrix, shown in Table 1, was created to position these research questions per category of the V-model and the life cycle. The purpose of this cross-reference approach is to ensure that the design process and the life cycle of the aircraft are considered, highlighting potential gaps and unknowns.

Table 1. Cross reference matrix technology gap analysis.

	To design	To manufacture	To certify	To operate, sustain, decommission
Concept of operations and system requirements				
System design and verification				
Sub-system design and verification				
Detailed design				
Unit/device testing				
Implementation				
Operations and maintenance				

The approach automatically creates sub-capabilities, defined by the life-cycle categories. The approach considered is to group research questions into these sub-capabilities, per (technology) capability accordingly. The gap analysis defines whatever is unclear or unknown during the design and life-cycle phases, based on the need to answer research questions. The research questions can finally be grouped and sorted into projects to be performed, linked to key performance indicators (KPIs). The proposed methodology for a gap analysis will be iterated to enrich the capabilities by stating gaps in technology and potential research questions which need to be addressed.

2.4. Regulatory gap analysis

A regulatory gap analysis is performed to identify potential gaps in the regulations and to determine regulatory aspects where a hybrid-electric aircraft design requires additional attention. The analysis focuses on the CS-25 (Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes) from EASA [3].

The first step of the analysis focuses on the identification of the deltas and points of interest between a hybrid-electric design and a conventional CS-25 aircraft design. For example, regulatory gaps are expected about the fuel system specification as this is based on liquid fuel (i.e., kerosene fuel), whereas with a hybrid-electric aircraft design a part of the fuel is replaced with electrical energy. Therefore, such specifications are considered as a gap in the regulations. As a next step, the applicability of the specification is identified about the technologies taken into account within the FUTPRINT50 project, i.e.: “energy harvesting”, “electric propulsion”, “energy storage with batteries”, “energy storage with liquid hydrogen” and “thermal management systems”. The specifications are checked for applicability with these technologies and allocated to these technologies if they are applicable. Next, the allocated specifications are rated to the extent of the challenge that lie ahead. According to expert judgement it is determined if the certification aspects with respect to a HEA design require a large focus, high focus, moderate focus or minimum focus. The final step in the analysis is the identification of a proposed means of compliance for the applicable specifications. The proposed means of compliance follow from Appendix A to AMC 21.A.15(b) “*Means of compliance codes”* from AMC/GM to Part 21 — Issue 2, Amendment 9 [4].

3. Roadmap development

3.1. Strategic goals and concept products

The high-level vision of the roadmap is the ambition set in the latest “Fly the Green Deal – Europe’s Vision for Sustainable Aviation”, namely "(..) deliver, by 2050, a fully climate neutral air mobility system, meaning that from 2050, emissions do not add to climate change” [5]. Within this vision, FUTPRINT50 defined the scope of its roadmap mission, i.e. “Enable the Entry into Service of aircraft that deliver neutral to zero emission regional aviation by 2035–2040”. As such, the focus of the roadmap is enabling the sufficient de-risking of technologies and readiness of the regulatory context to allow the launching of a 50-seat class regional aircraft in the 2035–2040 timeframe. In summary, FUTPRINT50 focuses on accelerating the technologies for and the integration of hybrid-electric regional propulsion.

Aligned with the FUTPRINT50 mission, an overarching set of top-level aircraft requirements (TLARs) was defined for the strategic goals. They include a maximum flight distance of 800 km plus reserves and other relevant requirements on performance, operations, market and environmental aspects. A more detailed analysis and reasoning on them can be found in Eisenhut et al. [6]. This led to an aircraft design activity to generate different configurations and approaches to address the TLARs. These included various hybrid-electric architectures like parallel and series hybrids. These different powertrain also triggered investigations on implementing different propulsion types, like boosted turboprops, wing tip propellers, distributed propulsion and boundary layer ingestion concepts. Furthermore, it involved initial sizings of hydrogen-propelled powertrains.

From these, the most interesting to encode the perceived integration challenges of the different technology capability streams were chosen as concept product references and further support the detailing of capabilities and their related engineering integration requirements. The two strategic goals to investigate are enabling CO_2-neutral regional air travel and enabling true zero-emission regional air travel. The first strategic goal is approached with a concept product which features a parallel-hybrid powertrain. This includes a turboprop which is propelled by SAF, therefore CO_2 neutral. In addition, the gas turbines can be boosted by electric motors and are supplemented with wing tip propulsion as well. To reach true zero-emission aviation, the use of the fuel cell propelled by liquid hydrogen is considered. This setup leaves no emissions but water which can be captured or reused. The electric propulsors are distributed over the entire wing span including wing tip propulsion as well. A more detailed description of the different configurations and designs can be found in Moebs et al. [7].

3.2. Technology capability gap analysis

The roadmap methodology, following the ontology resulted in a first breakdown of two strategic goals, with two corresponding concept products, where per product five capabilities are defined. Each capability consists of four sub-capabilities (aligned with the life-cycle categories). Per sub-capability, a first set of projects was defined, grouped by research questions raised by the technology partners within the FUTPRINT50 consortium.

The result is visualized within the Sharpcloud environment [8], linking the goals to the projects with all in between together on a digital platform. For each level of the ontology, a visualization was made. Each element, capability, sub-capability and project has corresponding KPIs and information to define what needs to be done.

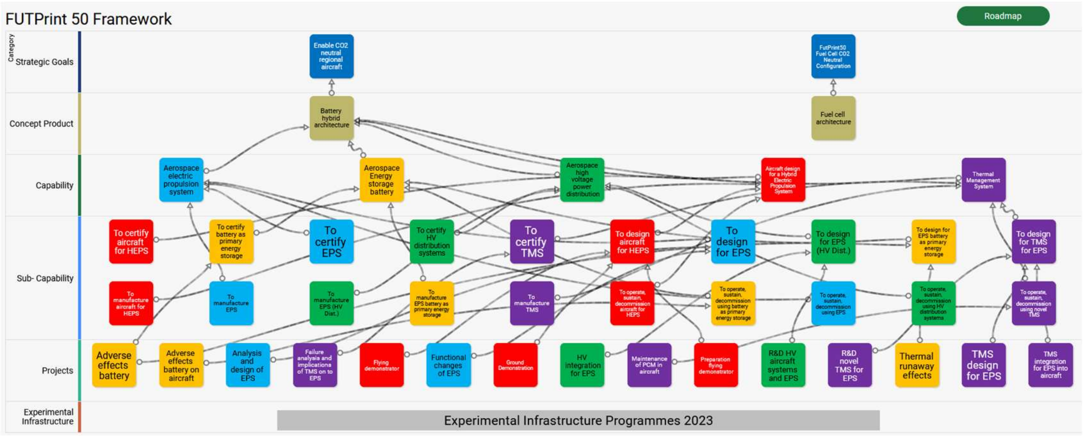

Figure 2. Sharpcloud visualization of the FUTPRINT50 roadmap.

For the CO_2-neutral strategic goal concept products, the following L1 capabilities were selected as FUTPRINT50 focus (seen in the "Capability" layer in Figure 2):

- Energy storage battery
- High-voltage power distribution
- Electric propulsion
- Thermal management system
- Aircraft design and integration for a hybrid-electric propulsion system

For the L2 sub-capabilities, the generic breakdown was applied to each of the L1:

- To design an aircraft with [capability *n* L1]
- To manufacture [components/sub-systems] related with [capability *n* L1]
- To certify a [component/sub-system/aircraft] with [capability *n* L1]
- To operate, sustain, decommission an aircraft with [capability *n* L1]

The continuation of the work is to further develop and evolve the gap analysis and cluster elements together in projects. A first KPI set is allocated per project, where each individual project will further refine itself as soon as it starts.

3.3. *Regulatory gap analysis*

EASA's CS-25 are analyzed to identify potential gaps in the regulations and to determine regulatory aspects where a hybrid-electric aircraft design requires additional attention. The analysis is initially done in collaboration between the consortium partners. In the follow-up stages, EASA will also be involved to review, as well as technology experts of each partner will be invited to provide more in-depth information and review. The current result are 124 specifications from this analysis seen as a gap or a point of interest. These specifications are given a rating, i.e., the estimation of focus required. The distribution of the ratings is shown in Table 2.

Table 2. Certification readiness items overview.

Rating	Number of specifications
1 – Large focus required	26
2 – High focus required	44
3 – Moderate focus required	24
4 – Limited focus required	30

The information of the certification gap analysis is also disseminated within the Sharpcloud environment [8]. The link to the technology, (sub-)capabilities and associated projects is still to be created in the future work. It shows the power of the used environment, where interactions on multiple levels can be created and made insightful.

3.4. Projects and research infrastructure gap analysis

The projects that need to be set up and orchestrated address the identified capabilities. In this way, they should fill the gaps in a clear way.

In these projects, trade-off studies should be performed for each technology alone, at the system level, but also with other technologies and sub-systems at the integration level. In this way, the potential of each technology and the impact on other technologies and sub-systems can be studied and assessed. The uncertainty of the projected technology level should be considered to enable and support the decision-making process of identifying the potential and impact of the different technologies, infrastructure, and regulations.

Two waves of projects are foreseen, as depicted in Figure 2, where a first draft of notational projects is given. The first wave focuses on improving sub-system readiness and should be executed between 2023–2026. The second wave involves large-scale demonstrators and addresses the integration of the different technologies within the full aircraft and operation and should be addressed between 2025 and the early 2030s.

Following the first draft of projects, a clearer understanding of their needs for experimental infrastructure will emerge. From this, an infrastructure gap analysis will ensue. This gap analysis will benefit from results of projects like RINGO [9] and similar, as well contacts within the FUTPRINT50 international network. The result will be a layer mapping when new research infrastructure needs to be operational to support the research projects that address the technological and regulatory gaps.

As already mentioned, the technological capability streams focused by FUTPRINT50 are not sufficient by themselves to fully enable the desired outcome of an EIS by 2035–2040 of a regional HEA. Also, several of the projects proposed depend on technology achievements to be realized by other industries. It was thus decided to do an “HEA ecosystem” study, mapping potential connections, synergies, and constructive dependencies with other on-going or complementary projects and programs that accrue to the final EIS goal.

A first desired line of alignment is planned with the sister projects of FUTPRINT50, EASIER and IMOTHEP, as well as the Clean Aviation JU, Clean Hydrogen and Battery2030+. As resources allow, further mapping will target similar initiatives in the UK, USA, Canada, and Brazil.

3.5. Exemplary path in the roadmap framework

In order to make clear how the navigation through the FUTPRINT50 roadmap works, this is explained in a short example. The roadmap describes the gap of being able to fully understand the batteries degradation during the use within their lifetime (see Figure 3). The strategic goal considered is to enable CO_2-neutral regional air travel. This leads to the concept product of a parallel-hybrid regional aircraft using SAF-powered and electrically boosted turboprops.

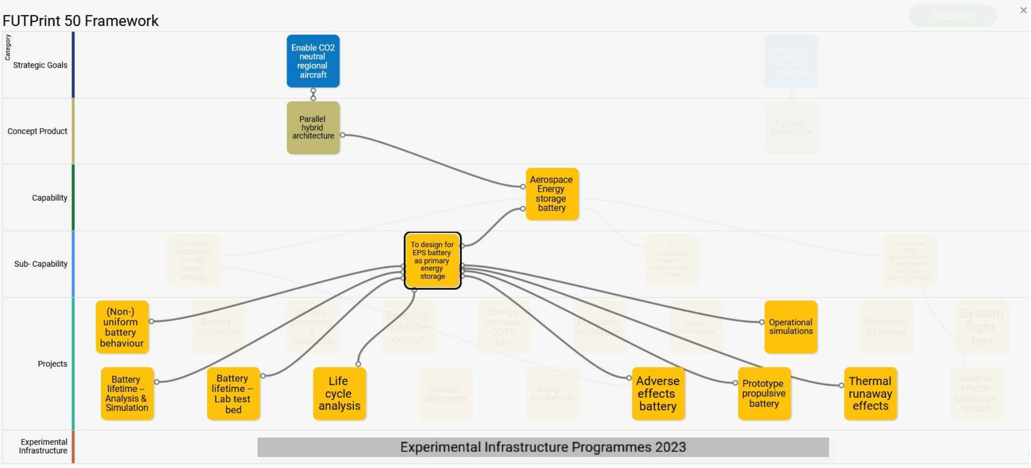

Figure 3. Exemplary path for gaps when designing in regard to battery lifetime.

The capability is the energy storage system while the sub-capability depends on which step of the development is investigated. The design effort contains analysis and simulation of accurate battery models. Their verification happens on a laboratory testbed which features the manufacturing sub-capability. The operations effort is then tested in a ground demonstrator and later the full-scale battery integration testing with regard to system interactions needs to be done on a full-scale flight demonstrator. All of those sub-capabilities can be translated back into concrete projects which require corresponding experimental infrastructure programs. Furthermore, specific KPIs can be formulated for all of those projects. In this case, e.g. accurate calculations, simulations and experimental verifications of the batteries' state of health, voltage levels, life-cycle expectancy and physical integrity can be relevant indicators to what the projects can deliver as an output.

This shows how a path in the framework depicted in Figures 2 and 3 can be followed through either in a top-down or also in a bottom-up manner.

4. Conclusion and outlook towards the final roadmap

The current achievements of the roadmap development consist of structuring the roadmap architecture and development methodology, including chaining with technology evaluation activity in FUTPRINT50. In addition, the roadmap top layers (vision, mission, concept product, capabilities) have been defined. Furthermore, initial work on the technology and regulatory gap analysis was done and an initial mapping of the HEA ecosystem was explored.

The future work in order to develop the final stages of the roadmap especially includes detailing and incorporating metrics and KPIs to the different capabilities, sub-capabilities, projects and research infrastructure. Further investigations will be done to achieve more level of detail on the technology gap analysis and the certification gap analysis as well. This includes forming a link between the certification gap analysis to the technology gap analysis, detailing the capabilities and sub-capabilities. Project proposals must be developed to address the identified gaps in technology and regulations. In addition to this, a research infrastructure gap analysis from the defined projects should be executed. This gap will then translate to a layer of research infrastructure needs, connected with the time vision of the roadmap projects. Finally, an HEA ecosystem analysis needs to be done, connecting it to FUTPRINT50 projects.

These activities will be pursued through internal work sessions with experts and joint workshops with other projects, the project's advisory board and invited experts. In addition, it will benefit from the work contracted with EASA for improved robustness regarding the regulatory view.

Acknowledgments

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