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System Analysis and Design Optimization of Future Aircraft for Power Management in Ground Movement Process

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This study investigates the optimization of aircraft system architecture for power management during ground operations to reduce CO2 emissions and improve energy efficiency. Focusing on the taxiing, take-off, and landing phases, this research evaluates the potential of electrified systems—such as electric taxiing technologies, electro-mechanical actuators (EMAs), and regenerative braking—to minimize environmental impact. A multi-level functional decomposition method is developed, enabling comparisons between system architectures that incorporate conventional and electrified components. Simulation results highlight the energy-saving potential of EMAs over traditional hydraulic and electrohydraulic actuators. Additionally, hybrid propulsion systems using Sustainable Aviation Fuels (SAF) and Liquid Hydrogen (LH2) are analyzed for their suitability in future aircraft platforms. The findings suggest that electrification and hybridization can significantly reduce fuel consumption during ground operations, and that liquid hydrogen offers the most promising long-term potential for net-zero emission aviation. This research provides a structured framework for designing next-generation aircraft systems that align with sustainability targets and support continued advancements in aviation energy management and system integration.

I. Introduction

The aviation industry faces increasing pressure to mitigate its environmental impact, particularly by reducing CO2 emissions. Aviation accounts for approximately 2.0 to 2.5% of total global CO2 emissions annually, and this share is projected to grow due to rising demand in commercial aviation. As air traffic expands, so does the challenge of addressing the contribution of aviation to climate change [1]. The International Civil Aviation Organization (ICAO) has introduced stringent fuel efficiency standards for new aircraft designs, which will be practical from 2020 for new models and from 2023 for in-production aircraft. These measures are expected to be reinforced by national regulations, guiding the industry toward improved fuel efficiency and reduced emissions.

Aligned with global initiatives such as the Paris Agreement, the International Air Transport Association (IATA) has pledged to achieve net-zero carbon emissions by 2050 [2]. This ambitious target highlights the urgent need for more sustainable aviation technologies. One key focus is the electrification of aircraft systems and optimizing energy management. Electric propulsion and hybrid and fully electric aircraft technology advancements offer substantial

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potential to improve energy efficiency and lower emissions. However, significant challenges remain—notably the limitations of current battery technologies—which hinder the widespread adoption of fully electric propulsion systems in commercial aviation [3].

For larger aircraft such as commercial airliners, independent taxiing systems have been a significant area of research. These systems enable aircraft to taxi without relying on tugs or main engines. Although turbofan engines are efficient in-flight, they consume disproportionate fuel during ground operations, particularly on short- and medium-haul flights, where taxiing time constitutes a notable share of total operational time. Electric taxiing systems (ETS), which draw power from the auxiliary power unit (APU), have emerged as a promising solution. For instance, by employing ETS, the Airbus A320 can achieve up to a 4% reduction in block fuel consumption on a 500-nautical-mile flight [4]. Despite such advancements, most studies on electric or hybrid propulsion have focused primarily on energy sources, with less attention paid to optimizing energy use during terminal mission segments such as taxiing, take-off, and landing.

This study investigates the optimization of airframe systems and power management strategies for future aircraft, using a narrow-body, single-aisle commercial jet as the reference platform, with particular emphasis on ground movement operations. By analyzing energy consumption during key ground phases, the research aims to enhance the performance of electrified components and optimize power distribution. These efforts contribute to reducing carbon emissions in the aviation industry and support the transition toward net-zero emissions.

The study methodology, outlined in Fig. 1, involves the development of feasible system architectures for three configurations: baseline, SAF, and LH2 systems. The analysis focuses on power management by comparing key components—including powerplants, actuation systems, flap systems, control connection systems, and regenerative systems—during the ground operations of electrified aircraft. The taxiing, take-off, and landing phases pose unique energy management challenges, as they can draw from multiple power sources, unlike the flight phase, which predominantly relies on the main engine. Effective integration and optimization of these sources are essential for achieving energy efficiency. Traditional systems rely solely on jet engines during these phases and operate at low efficiency because their design is optimized for high-thrust conditions. This research adopts a systematic approach involving functional decomposition and architecture design to assess the energy demands of electrified aircraft systems.

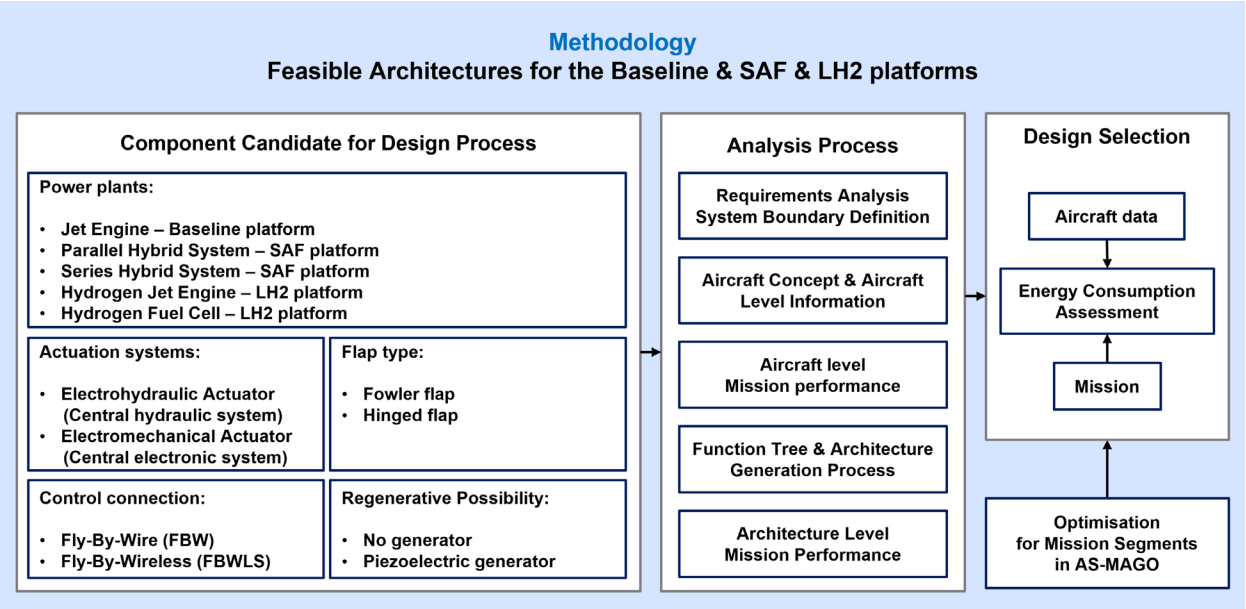


Fig. 1 Methodology for optimizing power management.

II. Optimization Methodology

This study employs a systematic optimization methodology based on functional decomposition and architecture design. The process begins with a structured breakdown of the aircraft system into functional units, enabling comprehensive analysis of subsystems that may differ in parameters, configurations, and types [5]. These functional

requirements are then mapped to corresponding physical components, forming the foundation for subsystem development aligned with aircraft and subsystem-level objectives.

This study supports the analysis by simulation tools and the AS-MAGO (Airframe Systems Multi Architecture Generation and Optimisation) framework, which models and optimizes energy management strategies during terminal flight phases [6]. Detailed descriptions of the optimization procedures are provided in Ref. [6].

A. Functional decomposition and knowledge database

The optimization process begins by capturing system design requirements from multiple sources, including customer performance specifications, higher-level design disciplines (e.g., aerodynamics and structures), and regulatory standards. These requirements are linked to the main functionalities of the concept within a defined system boundary, distinguishing the subsystem from the rest of the aircraft and the external environment. Interactions between these regions are analyzed in later design stages. This decomposition generates a tree structure of potential functions and component solutions, representing the design space. A three-level function structure and its morphological matrix are illustrated in Fig. 2. The matrix links functional requirements to multiple component solutions, each of which may generate further functional or performance needs. The information is stored in a knowledge database, including component connectivity, composition, and appropriate sizing scenarios. A root-finding mechanism is applied to assign suitable parameters to achieve specified performance targets under given operational conditions.

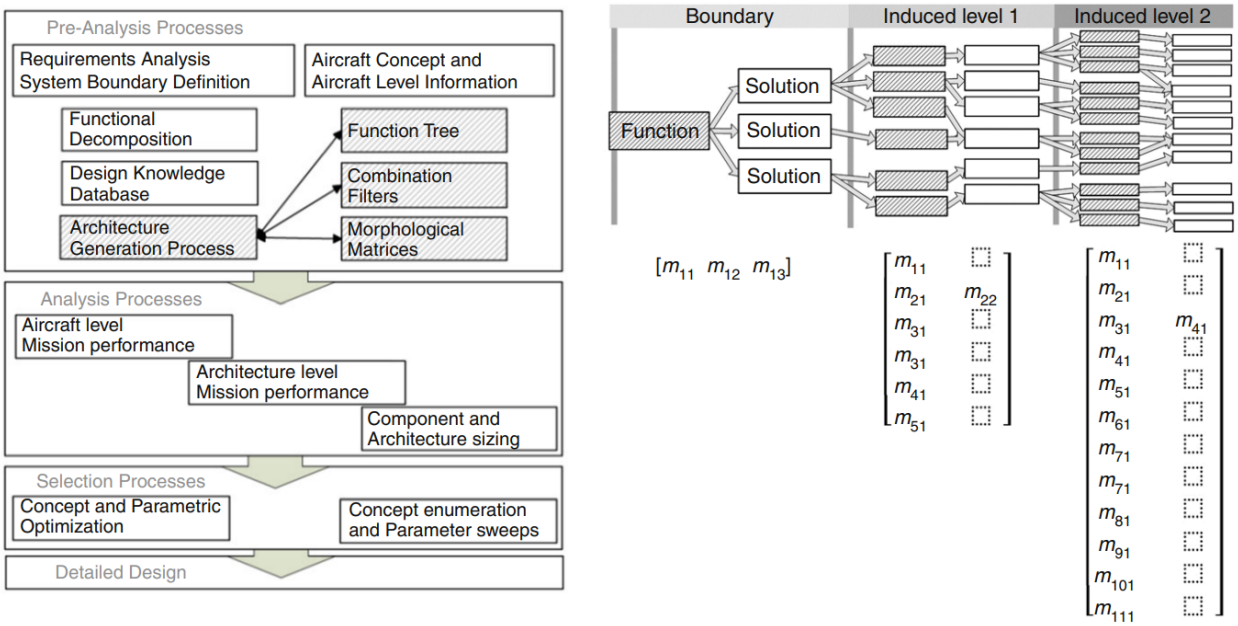


Fig. 2 Framework outline and function tree structure [6]

B. Enumeration procedure

Due to the potentially large number of component combinations, two strategies are employed: 1) down-selection of component solutions prior to analysis and 2) complete enumeration with user-defined optimization objectives and constraints to eliminate infeasible combinations. This enables complete tree traversal, with global architecture combinations formed from compositional solutions. This dynamic approach offers advantages over traditional single-matrix enumeration by reducing matrix dimensionality and memory usage. Furthermore, user-defined filters are applied during enumeration to discard infeasible architecture early in the process, thereby improving computational efficiency.

C. Analysis process

The generated architectures are evaluated for feasibility and performance via performance modelling and component-level sizing. Component models of low to medium fidelity are used to maintain acceptable computation time. Connectivity between models is continuously reviewed to reflect evolving design constraints. The analysis operates across three hierarchical levels: aircraft, architecture, and components. The aircraft-level model receives a

mission profile (e.g., taxi, take-off, climb, cruise, descent, landing), which serves as an input for evaluating subsystem performance.

At the architecture level, models are built by connecting individual components based on interface conditions. These are evaluated using a fixed-point iteration method, where a design structure matrix (DSM) tracks the current state of inputs and outputs. Convergence is achieved when DSM changes fall below a predefined threshold. The process is repeated for different mission conditions to generate a time-dependent performance profile. Sizing is then performed by adjusting parameters to meet target outputs using a root-finding algorithm.

D. Ranking process

After enumeration, all feasible architectures are known, and no further performance evaluations are necessary. The solutions are then ranked using weighted objective functions, combining multiple design metrics based on user-defined weighting factors [7]. This approach allows visual inspection via trade-off diagrams or composite score calculation. Once ranked, a reduced concept set is selected for deeper analysis. These architectures are re-evaluated across various parameters to explore performance variation and sensitivity to future technological changes. Parameter sweeps help assess long-term competitiveness and identify promising configurations.

E. Optimization method

In addition to enumeration and ranking, a direct optimization approach is used to identify the most competitive architecture. This includes discrete component choices and continuous variables (e.g., mission profiles and component characteristics), resulting in a mixed-integer optimization problem. A hybrid algorithm combining Ant Colony Optimization (ACO) and a Genetic Algorithm (GA) is applied to solve this. The functional tree is graph-based, analogous to the Travelling Salesman Problem (TSP). Each component choice affects the path and resulting architecture quality, minimizing energy consumption and satisfying performance constraints.

III. System Requirements Definition

To apply the AS-MAGO tool, system components, their behaviors, interfaces, and interactions must be clearly defined to satisfy the specified requirements and remain fully traceable [8,9]. This process involves analyzing the functional design requirements, mission objectives, and aircraft-level functions.

A. Functional design requirements

The functional design requirements for the baseline, SAF, and LH2 platforms are based on a narrow-body, single-aisle commercial jet airliner optimized for short- to medium-haul routes, with twin engines mounted under the wings. These are summarized as follows:

Baseline platform:

- Aerodynamic efficiency: High lift-to-drag ratio and optimized wing and fuselage design
- Propulsion System: High-thrust turbofan engine
- Fuel Storage: Large onboard tanks
- Operational Versatility: Ability to perform across diverse conditions
- Weight Considerations: Lightweight materials

SAF platform:

- Fuel Compatibility: Certification to ensure seamless switching between SAF and Jet fuel
- Energy management: Allocate power electric propulsion and gas turbine depending on phases
- Emissions Optimization: Reduced carbon footprint and particulate matter emissions
- System Optimization: Allocating and switching power between turbines and electric systems smoothly
- Performance Efficiency: Minimal impact on range, payload, and speed while using SAF

LH2 platform:

- Fuel Storage and Handling: Cryogenic tank performance; lightweight, insulated
- Airframe Redesign: Change the center of mass because of the LH2 tank position
- Safety Systems: Robust designs to handle cryogenic temperature and pressure changes

These high-level functional requirements will be translated into detailed, measurable system specifications in future work.

B. Mission analysis

Mission analysis provides the foundation for system design by establishing high-level objectives, operational scenarios, and environmental conditions. It supports the development of system architecture and functional hierarchies aligned with stakeholder priorities [8,9].

In addition to platform-specific requirements, common functional needs related to ground operations are considered, particularly taxiing performance.

- Taxiing: Safe, efficient, and controlled movement between gates, taxiways, and runways.
- Towing: Capability to be towed by airport ground vehicles when needed.
- Maneuverability: Effective navigation in constrained airport environments.
- Ground Support Integration: Seamless interfacing with ground services.
- Power Efficiency: Reduce fuel consumption during ground operations.

The following mission phases are analyzed in greater detail:

Landing phase [10,11]:

- Approach: guiding the descent of the aircraft towards the runway.
- Touchdown: reducing the speed and altitude of the aircraft until the wheels make contact with the ground.
- Deceleration: slowing down the aircraft after touchdown.

Take-off phase [10. 11]:

- Acceleration: increasing the speed of the aircraft along the runway to achieve lift-off.
- Lift-off: reach the necessary speed for the aircraft to become airborne and start the initial climb.
- Climb: Continue to ascend and adjust speed and altitude until reaching cruising altitude.

Taxiing phase [10,11]:

- Taxiing after landing: After touchdown, the aircraft decelerates and exits the runway, guided by nose wheel steering and engine thrust control.
- Taxiing before take-off: Movement from the gate to the runway threshold before acceleration.

C. Aircraft functions

Functions describe what the aircraft must do to fulfil its mission. Aircraft Functions (AFs) define operational capabilities across various flight conditions and are derived directly from mission analysis. A function-centric approach ensures system responsiveness to mission demands while enabling flexibility in design adaptation [10,11].

The following AFs are established:

1) AF1: the ability to move forward (accelerate and decelerate)
2) AF2: the ability to change direction
3) AF3: the ability to stop
4) AF4: the ability to control lift (take-off and descend)
5) AF5: the ability to manage (reduce and increase) aerodynamic drag
6) AF6: the ability to convert/recover energy (through regenerative components)

These functions form the foundation of the functional tree and are essential for translating mission-level requirements into subsystem-level design strategies.

IV. Advanced Component Technologies

This section outlines the core component technologies relevant to next-generation aircraft. The focus is on systems critical for achieving increased efficiency, sustainability, and compliance with future aviation regulations.

A. Primary power systems

The evolution of aircraft power systems reflects the shift of the aviation industry toward more efficient and environmentally sustainable propulsion methods. In response to increasing environmental concerns and regulatory pressures, particularly the goal of achieving net-zero carbon emissions by 2050, new technologies such as parallel hybrids, series hybrids, hydrogen jet engines, and hydrogen fuel cells are being actively explored.

Jet engines have traditionally dominated aviation due to their high-power output and long-range performance. However, they contribute significantly to greenhouse gas emissions. Hybrid systems—parallel and series configurations—offer transitional solutions with improved fuel efficiency and reduced emissions. Nevertheless, their complexity and dependence on battery technologies pose challenges. Hydrogen-based propulsion, including hydrogen jet engines and fuel cells, presents a longer-term solution with the potential for zero-emission flight. These technologies, however, demand substantial advancements in energy storage, thermal management, and supporting infrastructure [12–17].

B. Actuator technologies

Actuators are essential for manipulating aircraft control surfaces. The most common types are hydraulic actuators (HAs), electro-hydraulic actuators (EHAs), and EMAs. Although all serve the same purpose—controlled movement—they differ in efficiency, complexity, and application suitability:

1) HAs excel in high-force, rugged applications but require complex infrastructure and regular maintenance.
2) EHAs balance force and precision, making them ideal for aviation and high-performance systems, though they come with increased complexity and weight.
3) EMAs are the lightest and most efficient option, preferred in applications prioritizing simplicity and low maintenance, though they lack the force capabilities of hydraulic systems.

In recent years, the adoption of EMAs has increased due to their energy efficiency and reduced environmental impact, aligning with the aviation industry's broader sustainability goals [18–20].

C. Flap system

Flaps are critical aerodynamic surfaces that enhance lift during take-off and landing, enabling safe and efficient operations at lower speeds. Among the various designs, Fowler flaps have historically been preferred for superior lift generation with minimal drag penalty. These flaps extend rearward and downward, increasing both surface area and camber. However, Fowler flaps are mechanically complex and heavier due to their drive mechanisms. In contrast, hinged flaps, as seen in aircraft such as the Boeing 787, offer a lighter and simpler alternative. Hinged flaps pivot on a fixed hinge at the wing's trailing edge and have recently gained favor in next-generation aircraft due to their reduced weight and sufficient lift capabilities [21–23].

D. Actuation control connection system

Modern flight control systems have evolved from purely mechanical linkages to fly-by-wire (FBW) systems, which use electronic signal transmission. FBW technology is widely adopted in commercial and military aircraft—such as the Airbus A320, Boeing 777, and F-35—due to its reliability and advanced control capabilities. However, as electronic subsystems become more prevalent, the associated wire harness mass has increased significantly, with estimates of 6,400 kg in aircraft such as the A320/B737 and up to 23,000 kg in newer aircraft like the A350/B787. This weight imposes a significant performance and cost penalty. To address this, Fly-by-Wireless (FBWLS) systems are being proposed. These systems could reduce wire mass, leading to significant cost savings (estimated at $2,200 per kilogram saved) and fuel efficiency improvements [24,25]. Despite its potential, FBWLS faces technical challenges, including cybersecurity, system redundancy, and fail-safe operation. Continued research and development are required before it can be widely adopted in commercial aviation [24–26].

E. Regenerative system

Regenerative technologies are increasingly important in sustainable aircraft design. These systems aim to recover and reuse energy that would otherwise be wasted, thus improving overall efficiency and reducing environmental impact.

Key regenerative systems include:

- Regenerative Braking Systems: Capture kinetic energy during landing and deceleration. For instance, case studies on the A320 show that up to 47.8 MJ can be recovered during idle mode and 24.2 MJ in full reverse thrust. This energy could be used to power taxiing systems, reducing fuel use on the ground [27].
- Piezoelectric Generators: Convert mechanical stress from aircraft structures—such as landing gear and control surface hinges—into electrical energy. These are being explored to power onboard sensors and monitoring systems.

Typical power densities for piezoelectric devices range from a few microwatts to several milliwatts per cubic centimeter. Some experimental designs have demonstrated up to 60 $\mu W/cm^3$ outputs under specific vibration conditions [28]. Ongoing research aims to enhance the efficiency of piezoelectric materials and to optimize their structural integration for improved energy harvesting. Advancements in this area could support low-power electronic systems and contribute to developing more electric aircraft [29]. Accordingly, regenerative systems—such as braking energy recovery and piezoelectric harvesting—represent promising avenues for improving energy efficiency in aviation. However, widespread adoption depends on continued progress in material science and system integration. The future of aviation is expected to increasingly rely on technologies such as electric propulsion, hydrogen fuel, advanced materials, and digital control systems to enable a more sustainable industry [30,31].

V. System Design Process

The methodology employed in this study utilizes function trees to develop system architectures, ensuring that all components and behaviors are accurately defined and interconnected. This structured approach improves traceability, consistency, and design precision throughout the engineering process [5]. Functional requirements derived from mission analysis form the basis of the function tree, from which corresponding system architectures are generated. These architectures consider component interactions, interfaces, and logical and physical system organization.

A. Function tree definition

The function tree establishes design space for exploring aircraft architecture; however, viable concepts require integrating quantitative performance requirements, validated through modeling and analysis. The resulting system architecture defines structural and functional relationships, supporting a modular and scalable design process with early simulation capabilities. Aircraft architecture must accommodate multiple subsystems responsible for ground movement, propulsion, and aerodynamic control. While fundamental design principles apply across various aircraft types, specific implementations vary depending on platform requirements. Individual components often fulfil multiple functions, necessitating the integration of corresponding sub-components. To validate the proposed methodology, three configurations are analyzed: a baseline aircraft, a SAF-powered parallel hybrid concept, and an LH2-based architecture, with a focus on the ground movement mission phase. Fig. 3 presents the function tree developed for these case studies.

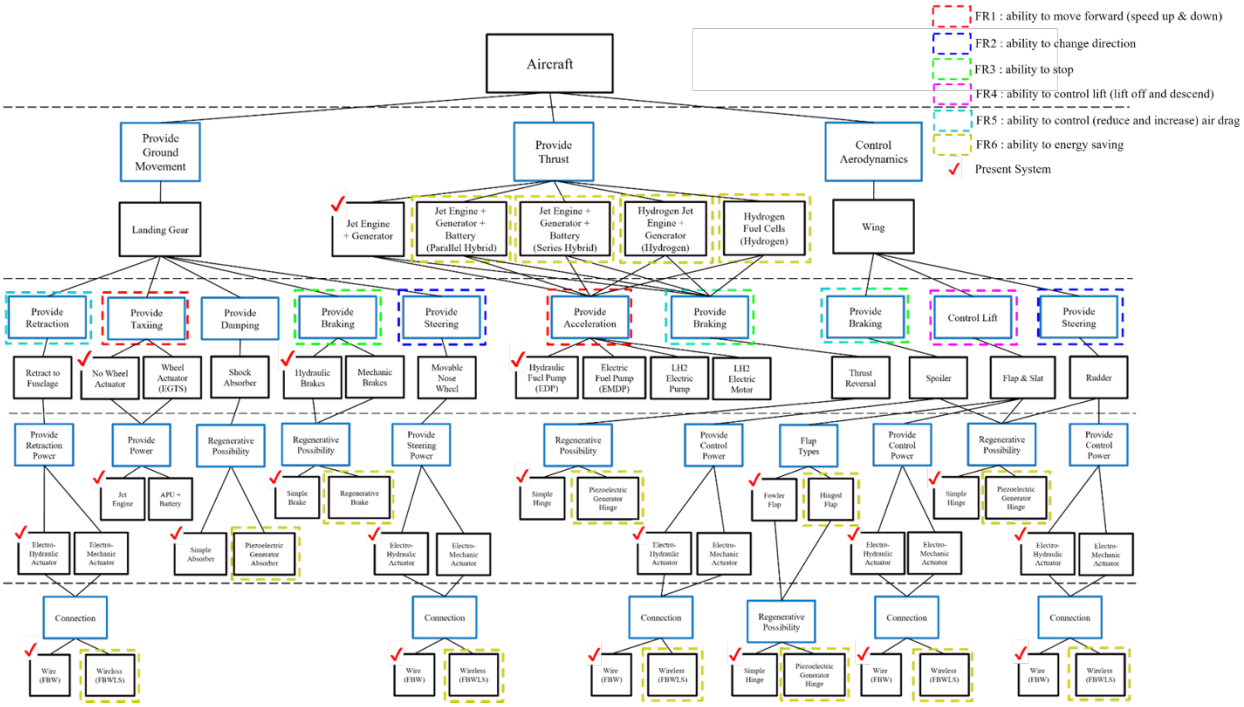


Fig. 3 Function tree for aircraft system

B. Baseline aircraft system architecture

Using the function tree methodology, the system architecture of the baseline aircraft was constructed. The baseline aircraft is a conventional single-aisle jetliner that does not include additional electric actuators or motors for autonomous ground movement. Its power system comprises two turbofan engines mounted on the wing pylons and an APU. All actuators are electrically controlled and powered by a centralized system of three hydraulic circuits.

The baseline system provides the reference for evaluating advanced architectural modifications. Fig. 4 illustrates the system architecture of the baseline configuration.

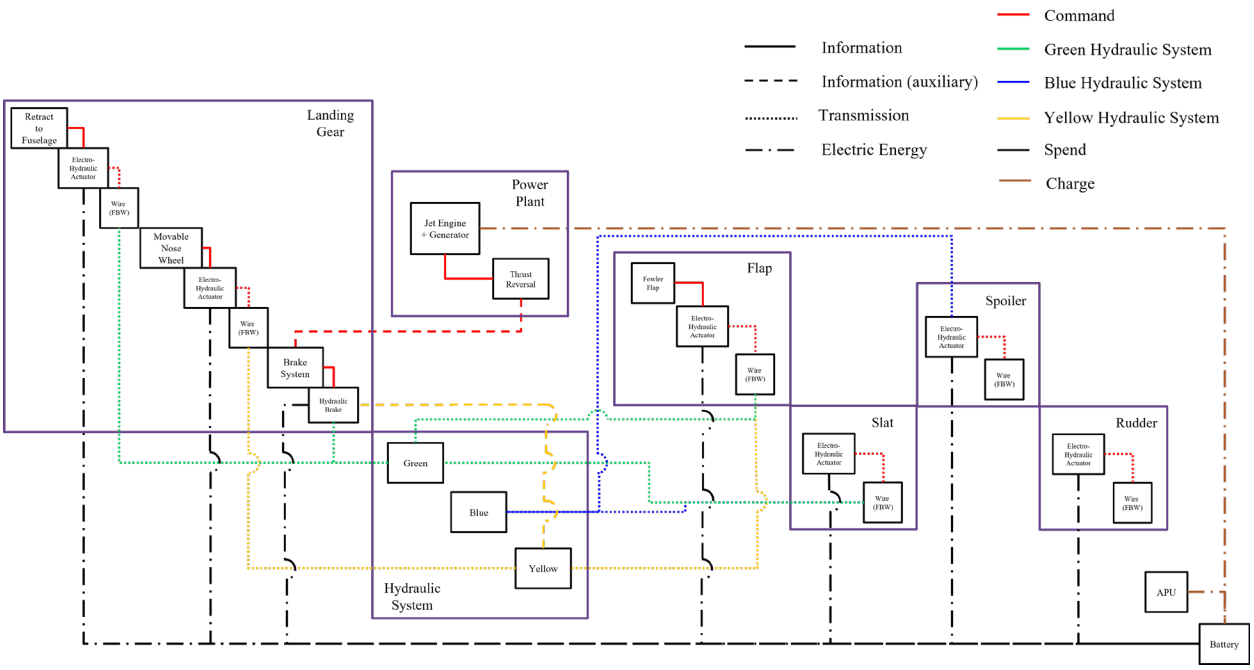


Fig. 4 System architecture for the baseline system

C. SAF aircraft concept system architecture

In alignment with the roadmap of the Airbus (Fig. 5), a parallel hybrid system is selected over a series hybrid alternative. A series hybrid configuration, which relies entirely on electric motors powered by batteries and turbine-generated electricity, does not meet the operational goals outlined in the Airbus plan. The parallel hybrid model allows phase-specific utilization of jet and electric power sources, making it a more suitable solution.

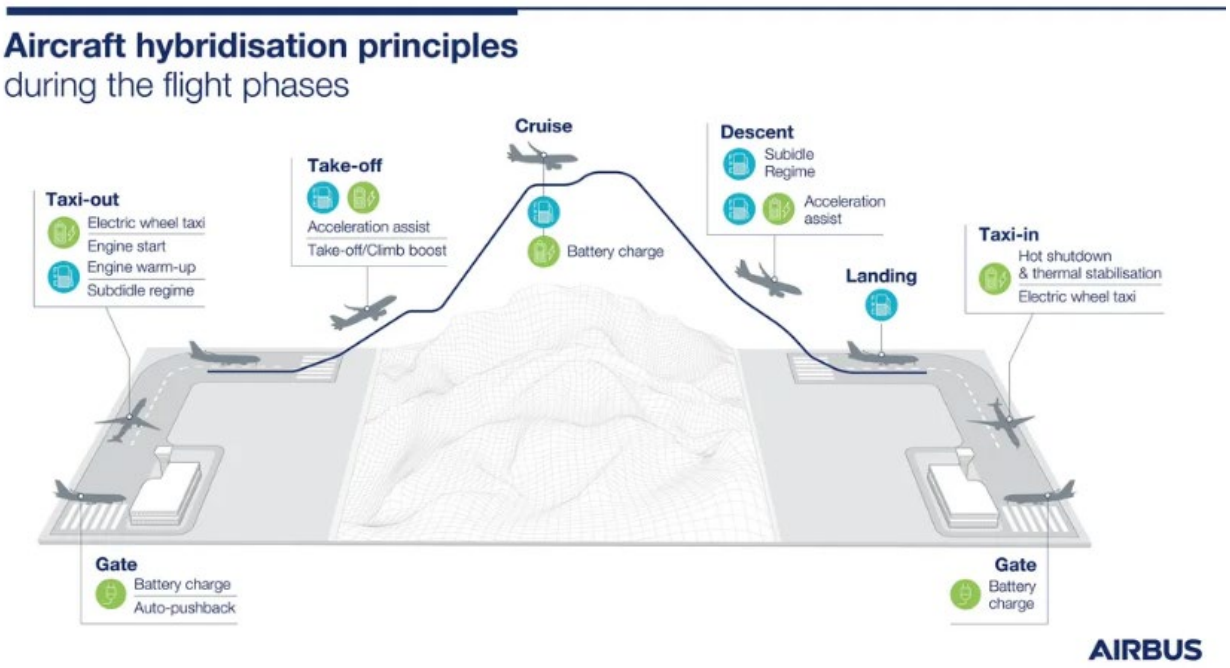


Fig. 5 Aircraft hybridization principles during the flight phases [3]

This architecture adds an electric wheel motor to enable autonomous taxiing. As a result, the system incorporates an electric actuator and supports the following operational modes:

- Taxiing (ground movement): Propelled by an electric motor.
- Take-off: Primarily powered by the jet engine, with auxiliary support from the electric actuator
- Cruise: The jet engine operates normally while charging the onboard batteries.
- Landing: Regenerative braking is activated, and the electric motor is re-engaged for taxi-in.

Other systems, such as actuators and control connections, are consistent with the baseline configuration, except for including an electric drive system for ground movement and regenerative braking capabilities. The architecture for the SAF aircraft is shown in Fig. 6.

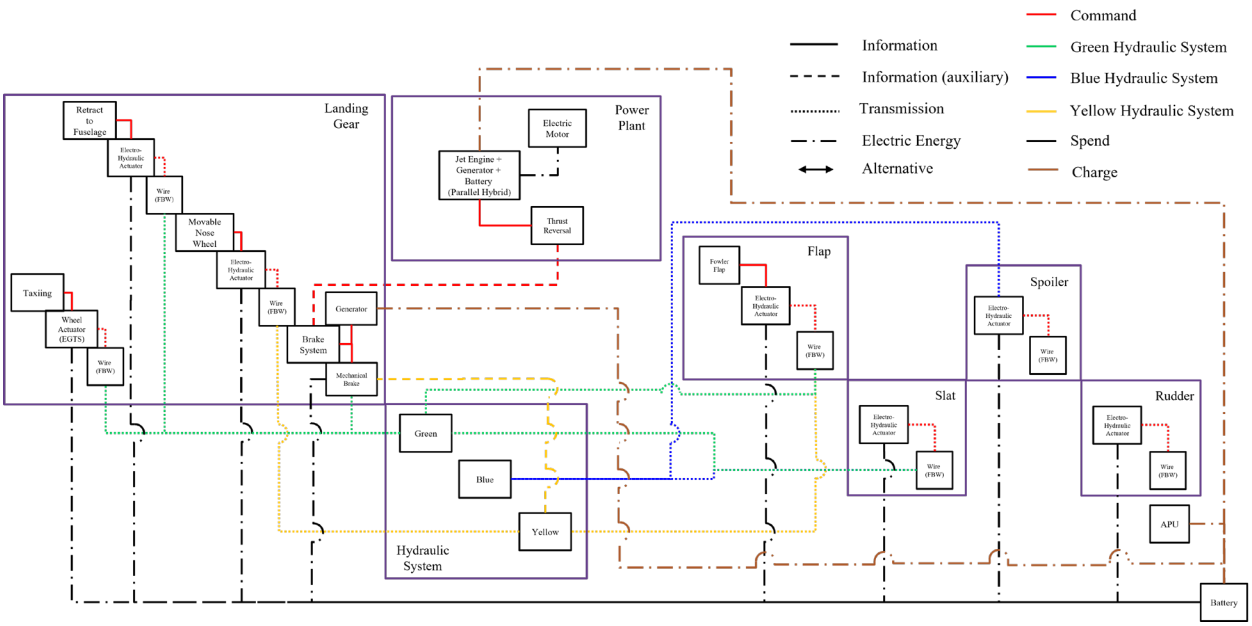


Fig. 6 System architecture for a SAF system

D. LH2 aircraft concept system architectures

The LH2 aircraft system introduces several fundamental changes to support a zero-emissions future. All actuators are replaced with EMAs, eliminating the need for central hydraulic systems, and they are aligned to create a fully electrical control architecture. Given that FBWLS systems are still undergoing validation, they are implemented only within secondary control systems, where failure is less critical to safety. This incremental adoption strategy reduces risk while providing opportunities to mature the technology. The implementation of FBWLS in primary control systems is deferred until sufficient reliability is achieved. The power sources of the system consist of either hydrogen jet engines or hydrogen fuel cells, depending on thrust and power requirements during various mission phases. Control connections include both FBW and FBWLS architectures, chosen based on the criticality of each subsystem. This configuration also incorporates hinged flaps for simplicity and reduced maintenance compared to Fowler flaps. Furthermore, regenerative systems—such as piezoelectric generators—are integrated to harvest energy from structural vibrations and surface deflections. These generators supplement low-power systems by providing sustainable onboard energy. The LH2 system architecture is depicted in Fig. 7.

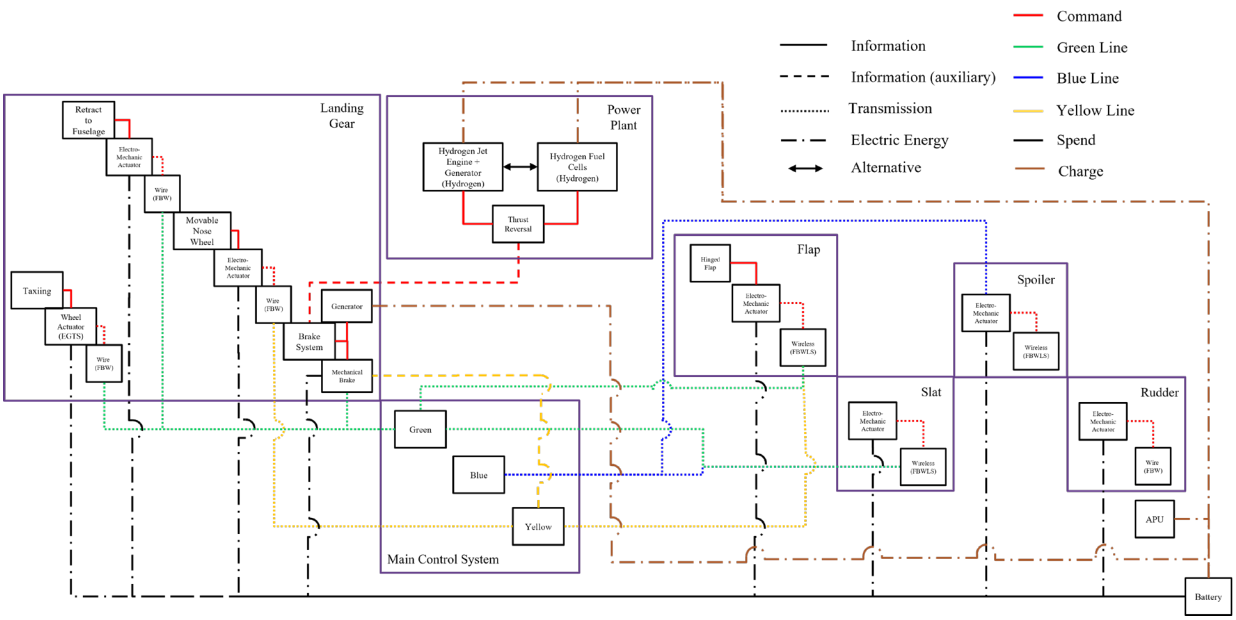


Fig. 7 System architecture for the LH2 system

VI. Conclusion

This study investigated the functional decomposition and system architecture of various aircraft configurations for baseline, SAF and LH2 platforms, focusing on a narrow-bodied, single-aisle commercial airliner. A structured design methodology was applied—combining functional tree development and system architecture synthesis—through mission analysis of key operational phases: landing, take-off, and taxiing. This approach improved the traceability, accuracy, and efficiency of the system design process by explicitly modelling system components and their functions.

For the baseline, the functional tree and architecture were developed using a selective integration of conventional components. For the SAF and LH2 variants, both standard technologies (e.g., power systems, actuator types, flap mechanisms) and advanced design considerations (e.g., control connection types, regenerative capabilities) were evaluated. In alignment with the Airbus technology roadmap, platform-specific components were identified, and tailored system architectures were constructed.

Future work will focus on refining component models with consideration for emerging technologies and innovations. This will be followed by a system-level optimization phase to determine the most efficient architecture for each platform configuration.

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