Application of Model Based System Engineering (MBSE) methods in designing hybrid and electric propulsion system for aircraft

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List of abbreviations and symbols

Abbreviations

A4A	Airlines for America
ATA	Air Transport Association of America
BLI	Boundary Layer Ingestion
DEP	Distributed Electric Propulsion
DP	Distributed Propulsion
EASA	European Union Aviation Safety Agency
ECS	Environmental Control System
ESAR	Energy-specific air range
FAA	Federal Aviation Administration
GA	General aviation
HT	Horizontal tail
IATA	International Air Transport Association
ICE	Internal Combustion Engine
ISA	International Standard Atmosphere
MBD	Model-Based Design
MBSE	Model-Based Systems Engineering
MBSD	Model-Based Systems Design
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration
PDU	Power Distribution Unit
PEM	Polymer Electrolyte Membrane
SE	Systems Engineering
SOFC	Solid Oxide Fuel Cell
STOL	Short Take-Off and Landing
SysML	Systems Modeling Language
UAV	Unmanned Aerial Vehicle
UML	Unified Modeling Language
VSP	Vehicle Sketch Pad
VT	Vertical tail

Latin symbols

AR	Aspect Ratio
C_D	Drag coefficient
C_{D_0}	Drag coefficient at zero lift
C_{D_i}	Lift-induced drag
C_L	Lift coefficient
c_t	Thrust specific fuel consumption
D	Drag
E	Endurance
E^*	Battery specific energy capacity
e	Oswald span effciency factor
E_{Elec}	Total electrical energy
E_{Fuel}	Total chemical energy
g	Gravity constant
H_E	Degree of energy hybridisation
H_F	Hybridisation factor
H_P	Degree of power hybridisation
$hsfc$	Hydrogen specific fuel consumption
L	Lift
L/D	Lift-to-drag ratio
m	Aircraft mass
$m_{battery}$	Battery mass
P	Engine power
P_{EM}	Total power on the electric motor shaft
P_{ICE}	Total power on the engine shaft
R	Range
S	Wing area
T/W	Thrust-to-weight ratio
T	Thrust
v	Airspeed
W	Weight
W_{ini}	Initial weight
W_{fin}	Final weight
W/S	Wing loading

Greek symbols

η_{EC}	Energy conversion efficiency
η_P	Propeller efficiency
η_{PR}	Propulsive efficiency
η_{TR}	Transmission efficiency
η_{total}	Total propulsion efficiency
ρ	Air density

1. Introduction

Halting progressive climate change and the rise in global average temperature requires a reduction in the burning of fossil fuels. This also applies to aviation, which in 2022 accounted for between 3.8% and 4% of the European Union's total greenhouse gas emissions and is the second largest emitter in the transport sector. On the contrary, it is the only form of transport that emits pollutants at altitude. The gases produced by the aircraft engine create cirrus clouds, which limit the possibility of radiating excess heat from the earth's surface. Even the burning of alternative fuel by aircraft engines does not prevent the emission of greenhouse gases.

Changes towards reducing emissions in transport are currently particularly evident in the automotive industry. Electric or hybrid-electric vehicles are already an everyday sight on the streets. In the case of aviation, changes towards the use of alternative propulsion are moving slowly. In commercial aviation today, there is a particular focus on increasing the fuel efficiency of gas turbine engines, for example by using gears that allow the compressors and turbines in the engine to rotate at their optimum speed. In the case of general aviation, it is still widely based on engines whose first versions were developed in the 1950s and 1960s. However, in recent years there has been a small revolution in aircraft propulsion for GA aeroplanes. This was the introduction of engines produced by ROTAX, which run on automotive fuel and have low fuel consumption compared to classic aero piston engines.

In the case of alternative propulsion aviation, electric propulsion has been very successful so far and is used in some gliders as a take-off or sustainer motor, as well as in the Pipistrel Velis Electro, which is the first certified electric aircraft in the world designed for flight training. As for other alternatively powered aircraft, they belong to experimental aeroplanes, which are mostly retrofits of existing models. So far, the only aircraft built from scratch for the new propulsion system to take to the skies is the Eviation Alice.

Retrofitting an existing aircraft to an alternative propulsion system is easier and more reliable for fast introduction of the new technology to the market than designing a new one from scratch. This approach has its disadvantages, in terms of, among other things, a limited possibility of integrating the new propulsion into the airframe or a reduction in the number of passenger seats. For this reason, aircraft built in this way cannot fully exploit the potential of the new propulsion, analogously to the automotive industry.

Aircraft designed from the outset for the new propulsion system allow for better performance than retrofits. This is due to the adaptation of the aircraft structure to the requirements of the alternative propulsion system and the parameters of the aviation mission, including the securing of sufficient seats. The use of the new propulsion system may influence the design of an unusual airframe shape, which will use the propulsion system in a more efficient way than a retrofitted aircraft.

One of the problems associated with the use of alternative propulsion systems in aviation is the lack of historical data on which the aircraft design process is based and the need to integrate the new parameters that characterise alternative propulsion systems. For this reason, designing an aircraft from scratch for a new propulsion system is a lengthy and costly process. For hybrid propulsion, an additional aspect to analyse is the power strategy, which directly affects the aircraft's range and performance. This strategy defines how different energy sources contribute to driving the propellers, either at a constant rate or varying based on the flight phase and factors such as the available energy level.

For this reason, the work presented here aims to develop an appropriate adaptation of the aircraft design process to alternative propulsion. The conceptual and preliminary design phases, which rely more on historical data, require the most change. Appropriate models representing alternative propulsion systems and the aircraft are used to replace the historical data. The propulsion model enables the determination of the required parameters of its main subsystems based on the aviation mission for which the aircraft is designed. Knowing these parameters allows for estimating the size and weight of the subsystems, which in turn supports a more optimal airframe design using the parametric aircraft model. This approach makes it possible to analyse the propulsion parameters in a very short period of time, select an appropriate strategy for its operation when more than one energy storage is used, investigate various flight mission parameters and develop the most suitable airframe concept, taking into account from the outset the integration of the main subsystems of the alternative propulsion, which may be different from that of conventionally powered aircraft.

1.1. Relevance and objectives

More than 100 years of aviation history has made it possible to accumulate an extensive database of different aircraft models. The data[1] thus collected has made it possible to determine the relevant coefficients and parameters used in the design of new aircraft as described by Raymer and Gudmundsson [34, 79]. However, the knowledge and experience gained so far only applies to conventionally powered aircraft with a given design of the aircraft concept. For alternatively powered aircraft, we have a very small number of models that would allow us to develop suitable coefficients and design parameter ranges for aeroplanes representing different classes.

In view of this situation, the design of alternatively powered aircraft encounters the following problems:

- lack of sufficient historical data to properly estimate and select the parameters at the initial stage of the Conceptual Design phase,
- the need to consider new and additional parameters introduced by alternative propulsion systems and to understand how these parameters affect the aircraft design process,

[1] This data is called historical data in this thesis.

- determining which propulsion system best meets the required performance, along with identifying the necessary parameters for the associated subsystems,
- integration of the new propulsion system into the airframe and the associated changes to the architecture and geometry of the aircraft.

In order to address the issues regarding the design process, it is important to have a thorough understanding of the relationships between the systems[2] that comprise the aircraft and to identify the relevant design parameters. To achieve this, it is helpful to apply Model-Based System Design (MBSD) methods that use appropriate parameterised models of the alternative propulsion system and the airframe. With their help, model-based data are developed to replace missing historical data within the aircraft design process and to support also the airframe design process by determining the dimensions and weights of the main propulsion subsystems. Integrating models into the conceptual and preliminary design phases allows the new parameters of alternative propulsion systems to be taken into account and their impact on airframe characteristics to be assessed, thereby adapting the aircraft design process to the needs of the new propulsion systems.

Therefore, the aim of this dissertation is to develop an appropriate adaptation of the aircraft design process to alternative propulsion systems based on parameterised models. This objective is supported by the following major hypothesis:

The conceptual design as part of the classic design process of aircraft for general aviation initially focuses on the four main forces of lift, weight, drag and thrust and uses historical data to evaluate these forces in order to obtain first design decisions. However, for aircraft with alternative propulsion systems, the historical data are no longer valid or only to a limited extent. ***As an alternative to historical data, parameterised models can be used, provided that the design parameters of these models are directly related to the four main forces. The thorough identification of these design parameters therefore forms the basis for an appropriate model-based design process for aircraft with alternative propulsion systems.***

To validate this hypothesis, it is needed to find answers on the following scientific questions:

- Which design parameters of the subsystems comprising alternative propulsion systems exert the greatest influence on the relevant forces: thrust, weight, lift, and drag?
- What is the significance of these parameters in determining the overall aerodynamic behaviour and performance of the aircraft?
- In what ways does the integration of alternative propulsion systems, along with their corresponding energy storage components, affect the internal configuration, structural layout and operational characteristics of the aircraft as a whole?
- How does the implementation of an alternative propulsion system affect the parameters and profile of an aircraft's flight mission?

[2] In this work, the aircraft is also treated as a system of systems.

1.2. Literature survey

The idea of using alternative propulsion in an aircraft appeared as early as 1881 when the brothers Albert and Gaston Tissandier presented a dirigible with an attached electric motor. Two years after the presentation, the first flight of an electric airship took place [73, 97]. The further development of electric propulsion was stopped by the increasingly improved internal combustion engines. The return of electric propulsion to aviation occurred in 1973 with Fred Militky, who replaced an internal combustion engine with an electric motor in the HB-3 motor glider. This was the first manned electric aeroplane [97].

Since then, there has been an increase in the aviation industry's interest in electric drives, particularly among gliders with propulsion systems that allow for self-launch or sustained flight (e.g. Schempp-Hirth Arcus E, SZD-56 Diana 2 FES).

Electrification is also progressing in passenger aircraft. The Boeing 787 Dreamliner, Airbus A380 and A350 are all built using the More Electric Aircraft (MEA) concept, which involves changing the energy source used to operate some of the onboard systems from mechanical, pneumatic or hydraulic to electric. The advantages of this solution include a reduced workload on the propulsion unit, which is associated with lower fuel consumption, and greater freedom in the configuration of systems on board the aircraft [87, 107].

Current research work shows that alternative propulsion systems are opening up new possibilities in aircraft design [91]. By appropriately configuring the aeroplane, the optimum performance and benefits offered by the new propulsion systems can be achieved. To accomplish this, a detailed analysis must be carried out to find the best solution [52, 94, 110].

Aircraft as a system

Modern aircraft are characterised by a high degree of complexity. To better understand this complexity, the aircraft is seen as a system [16, 84]. Because an aircraft is constructed of numerous subsystems, components, and parts, representing different areas of expertise, which interact and interdepend on each other, it is often treated as a complex system [24, 41, 90]. In the aerospace industry, the word *system* also often refers to the assemblies of subsystems that allow flight operations to take place, such as pneumatic, electrical, and fuel systems [41]. For this reason, the aircraft can be referred to as a system of systems [18].

A system is described as an interconnected, hierarchically structured collection of elements, the purpose of which is to perform a defined task [16, 37, 62]. The basic division of systems is based on their origin [13, 41, 105]. A distinction is made between natural and man-made systems. The second type includes technical systems, an example of which is aircraft [38, 84]. Pahl [71] defines a technical system as a system in which technical processes related to the transformation of energy, material, and signals take place. Hubka [38] also points out that a technical system, in order to achieve its purpose, makes use of known natural phenomena that are combined in an appropriate chain of actions. A technical system is also characterised by the fact that it can only be created if each of its components can be produced with the appropriate properties and then assembled in the desired manner [38].

Taking into account the characteristics of the system mentioned above, the aircraft can be subdivided into different systems. The divisions can be general, which can be applied to any type of aeroplane, and specific, characterising a selected group, such as passenger aircraft. For example, [90] divided aircraft into four main (generic) systems: airframe/structure, vehicle systems, avionics systems and, in the case of military aircraft, mission systems. On the other hand, based on documents produced by Airlines for America (A4A, formerly known as the Air Transport Association of America- ATA), [41] divided the passenger aircraft into eight segments: environment, avionics, electrical, interiors, mechanical, propulsion, auxiliary, and airframe.

System modelling approaches

Systems are represented by *models* showing the connections between system elements and the interdependencies between its parameters. Among these are *computational models*, which describe a given system through the functions and relationships that occur between its elements. Mostly, models represent the system in an approximate way, tailored to the questions they are intended to answer. They allow simulation and evaluation of the system under analysis [18].

Related to the term *system* is Systems Engineering (SE), the aim of which is to arrange the subsystems of a system so that it works optimally [90]. This is particularly helpful for multidisciplinary systems with high complexity [24, 41, 84]. This is a holistic approach, taking into account different needs and requirements from the early stages of design through testing and manufacturing to the end of life to develop an effective system [24, 37, 63].

Model-Based Systems Engineering (MBSE) is indicated as a further development of Systems Engineering, which is characterised by the use of computational models in the development of systems rather than describing them through documentation [19, 104]. [14] indicates that this is the main approach used in the design of complex systems. MBSE combines three elements: system modelling, modelling language (SysML or UML) and modelling methods [48, 104, 106]. The advantages of using this approach include improved interoperability, communication between team members, earlier detection of errors and inaccuracies, and a better understanding of the system and its processes [8, 19, 112]. The use of MBSE can be particularly useful in the design of the early stages of the system (product, e.g., aircraft) due to the greater number of unknowns [9, 104].

A different approach that is also related to the term *model* is Model-Based Design (MBD), sometimes also called Model-Based Systems Design (MBSD) [100]. The idea behind this method is to use mathematical modelling to represent a dynamic system and its interactions [42, 44]. It combines the stages of design, model analysis (testing), and implementation into a single process, allowing a better understanding of the system and earlier elimination of errors [3, 100]. MBD focusses primarily on the design of the simulation model, while MBSE represents a more holistic approach to the development of requirements including cooperation with stakeholders and taking into account further life phases of the system (product) [44, 73, 93].

Alternative propulsion systems

The developments in alternative propulsion technology are very evident among UAVs. Drones are being built, for example, with electric propulsion powered by batteries that are simultaneously charged via solar panels [1, 55]. Compared to aircraft, UAVs are usually characterised by significantly lower weight, size and thus power requirements. An additional factor is the lack of people on board and thus the level of reliability and safety can be reduced.

Due to these differences, there are currently three types of alternative propulsion systems possible for aircraft, which coincide with those used also used in the automotive industry. These are:

- All-electric,
- Hybrid-electric,
- Fuel cells.

As such, this work focusses on analysing and adapting the aircraft design process to the alternative propulsion types listed above.

All-electric propulsion

In all-electric propulsion, batteries are the only source of energy. Electrical power from batteries flows through an inverter or converter to an electric motor, which, with or without a gearbox, turns the propeller [29, 64, 80]. The advantages of all-electric propulsion are its simple design, which contributes to higher reliability and efficiency (73%), no harmful emissions, lower operating costs and new possibilities in aircraft design [11, 29, 34]. The significant disadvantage of this propulsion system is the batteries due to their weight and low specific energy density (Wh/kg) [64, 73]. In Hepperle's [36] analysis of the current feasibility of using all-electric propulsion in aviation, he indicates that this type of drive can only be used for small aeroplanes and significantly reduces their performance compared to aircraft of the same class with a conventional engine.

Hybrid-electric propulsion

A characteristic feature of hybrid-electric propulsion is the combination of more than one energy source. Most often, it is a mix of the chemical energy created by burning fossil fuel with electricity from batteries. Although there are other possible combinations of energy sources, in this work the term *hybrid-electric* refers to a propulsion system that integrates ICE and batteries. It is equipped with an electric motor and a conventional motor or generator (internal combustion engine, gas turbine) [7, 64]. In its "Aircraft Technology Roadmap to 2050" [39] document, IATA lists three types of hybrid-electric propulsion:

- Series hybrid,
- Parallel hybrid,

- Series/Parallel partial hybrid.

The operating principle of the first two of these topologies is briefly characterised in [29]. In a series hybrid, the only component mechanically connected to the propeller is the electric motor, whereas the ICE acts as a generator and charges the battery or supplies electricity directly to the motor. In parallel architecture, both the electric motor and the conventional motor are mechanically connected to the propeller via a gearbox. In this arrangement, the electric and conventional parts of the propulsion system can operate together or separately [29]. The serial/parallel partial hybrid, on the other hand, is the result of combining the two previous topologies and allows for more flexible operation through a greater choice of modes [7, 80]. According to [5], the latter two topologies are best suited for use in the retrofitting of existing aircraft.

The hybrid propulsion system has more components, which increase its weight and complexity, and therefore those of the aircraft [29, 80]. Additionally, [23] points to the emergence of more challenges in the design process of a hybrid aircraft. Hybrid propulsion has the advantage of increasing efficiency, reducing fuel consumption and emissions [1, 80]. It is indicated to be used on regional aircraft operating short to medium flights [39].

Fuel cells

Fuel cells convert the chemical energy of a fuel (e.g. hydrogen, methanol, methane) into electrical energy [36, 77, 95]. Among the five main types of this kind of devices, the polymer electrolyte membrane (PEM, also known as proton exchange membrane) is of greatest interest to the automotive and aerospace industries [1, 10, 66]. PEM fuel cells use hydrogen as the fuel and oxygen as the oxidant, with the end by-products being water and heat [34, 82, 99]. The operating principle of PEMs has been described in [65] and [68].

In his work, Tong [99] lists the following advantages of this type of fuel cell: absence of emissions and noise, production of clean energy, high reliability and specific power, and operation at room temperature, which is associated with faster cell start and shutdown. They are characterised by efficiencies of 40-60% [1]. Like batteries, fuel cells are stacked to achieve adequate power, which results in increased system weight. They are not cheap and also require a complex heat and water management system [36, 77, 95]. An additional problem is the hydrogen tank and its integration into the aircraft structure [65]. Furthermore, PEM does not provide a fast response to dynamically changing loads. The solution to this problem is to add a battery or capacitors to the propulsion system, which provides additional power and allows the system to respond quickly to changing loads [1, 49, 53].

Using two types of energy, the fuel cell-based propulsion system can be included in the class of hybrid propulsion systems, but because of the significant differences between it and the previously described systems combining ICE and batteries, it is considered in this work as a separate type of propulsion system.

Airframe design

The design of airframe (aircraft structure) is determined by the requirements and missions. It consists of five main components: fuselage, wings, empennage, landing gears and nacelles. Each of them comes in several variants [34, 84].

The function of the fuselage is to provide sufficient space for the pilot(s), passengers, cargo and required systems. It must be designed in such a way that other components of the airframe can be attached and that it can carry the loads generated by them. Additionally, it should generate as little drag as possible [34, 84].

Considered the most important component, the wings are responsible for generating lift and the ailerons located on them are used for controlling the aircraft. The free space inside them also allows to accommodate fuel tanks. [84] lists 18 parameters that must be defined when designing wings, including the position relative to the fuselage height (low-, mid-, high-wing), shape, area, number of wings (monoplane, biplane). Wings can be cantilevered or braced with struts. The wing position affects the design of the fuel system [34].

Empennage consists of two components: the horizontal tail (HT) and the vertical tail (VT). Its main function is to provide control and stability to the aircraft. Its configuration most often depends on the positioning of the wings to avoid their negative impact on the airflow around it. The most common variation of empennage is to change the height of the HT relative to the VT (conventional: low-HT, cruciform: mid-HT and T-tail: high-HT). Other possible arrangements are as follows: V-tail (e.g. Beechcraft Bonanza), H-tail (e.g. PZL M28 Skytruck), boom-tail (e.g. Cessna 337 Skymaster). Special types of empennage are the canard, which is characterised by the placement of HTs in front of the aircraft wings near the cockpit, and the three-surface aircraft (e.g. Piaggio P.180 Avanti), which is a combination of the classic empennage and the canard (it has two pairs of HTs) [34, 47, 79].

The design of the landing gears depends on the ground on which the aircraft is operating (e.g., grass runway, water). They can be retractable or fixed, and the most common configurations are the tricycle and the taildragger [34].

Nacelles only occur when the aircraft engine is not located inside the fuselage. They allow the engine to be protected from external factors and reduce the aerodynamic drag of the aircraft [47].

A component that also greatly affects the aircraft's body shape is the engine and its placement. The propeller comes in two configurations- pusher and tractor. In aircraft with a conventional airframe design, the engine(s) together with the propeller(s) can be located in the nose of the aircraft, in or under the wings (multi-engine) and in the rear of the fuselage. In the case of a tail-boom aircraft, it may be located between the two, mounted in the rear of the fuselage. In addition, propellers can be open or in the form of a ducted fan [34, 84].

Aircraft design process

Design of a modern aircraft is an interdisciplinary process subject to many restrictions in terms of safety, market needs, costs, etc. Usually, this process uses a classical system approach (especially for aircraft under the EASA CS-25 regulation) [34, 47].

The aircraft design process consists of several basic phases:

1. Requirements and Conceptual Design. The first part involves defining the required capabilities of the aircraft in line with the needs of future users. The second part is the definition of constraints and includes preliminary sizing, aerodynamic aspects, performance, flight safety, and cost estimation. This stage is crucial and, if carried out correctly, enables the design of an aircraft that meets market requirements.

2. Preliminary Design. It includes detailed development of the aircraft geometry, accurate estimation of subsystems weights, aerodynamic properties and performance, assessment of certifiability, etc. Changes are made to the aircraft design until a decision is taken to 'freeze' the developed concept.

3. Detail Design. These phases include detailed design work (e.g. airframe, avionics, systems integration, ergonomics), discussing production, materials, preparing for testing (iron-bird) and beginning the construction of a demonstrator.

4. Validation and Certification. This is the final stage during which, among other things, the projected aircraft makes its maiden flight, followed by test flights. Relevant documents (e.g. Pilot's Operating Handbook, emergency procedures) are developed. This stage usually ends with the certification of the aircraft [34, 47, 98].

An aircraft with a new propulsion system can be a retrofit of an existing model or can be designed as a completely new aeroplane. Currently, the most common option is the first one – the use of an aircraft with an already defined configuration. However, this approach does not allow for the design of a new propulsion aircraft that uses its full capability [2, 103]. One factor influencing the decision to retrofit rather than build a new aircraft is the lack of adaptation of existing design methods to alternatively propelled aircraft, whose configuration may differ significantly from the airframes currently in existence.

The design process for conventionally powered aircraft uses historical data and analogy with existing models representing a particular class. For alternatively powered aircraft, such information is either not available or very limited [34, 81, 98]. The conceptual design methods used so far are not adapted to their use for aircraft that differ significantly from conventional models in terms of e.g. propulsion or structural solutions used. The basis for these process-mass fraction calculations has been identified in [81] and [98] as being unsuitable for use in the design of an aircraft with a new propulsion system and requires changes to the existing equations, which were developed on the basis of technology from 30-50 years ago and, even for aircraft with a conventional engine, require the use of appropriate coefficients during the calculations. Additional adjustment is also required for the aircraft sizing, allowing optimisation to take place. In the case of a conventional aircraft, it is mostly based on two parameters: thrust-to-weight ratio (T/W) and wing loading (W/S), which together determine the size of the engine and wing, which affects the weight of the aircraft [27, 34]. [27] indicates that a third parameter, which also affects the size of the propulsion system-the degree of hybridisation-should be taken into account for an aircraft using hybrid-electric propulsion. On the other hand, [103] points out that there is no systematic method for aircraft sizing using a new configuration, such as Distributed Propulsion (DP).

An additional difficulty is the lack of certification standards from which additional requirements for the airframe and the new propulsion system can be derived [27]. So far, only EASA has issued document SC E-19 on special requirements for the certification of electric and hybrid-electric propulsion systems.

1.3. Structure of work

In this thesis, an adaptation of the aircraft design process is developed to address the lack of historical data for alternatively powered aircraft. As an adaptation, it is proposed to use a model-based design process as an approach, which is in line with the main hypothesis introduced in the relevance and objectives section (1.1): *Parameterised models can be used as an alternative to historical data, provided that the design parameters of these models are directly related to the four main forces.* To achieve this, **Chapter 2** identifies and analyses the general relationships that exist between design requirements, the main forces: lift, drag, weight and thrust, the design parameters and the relevant aircraft systems and subsystems[3]. Then, the conventional aircraft design process and alternative propulsion aircraft design methods proposed in the recent years are analysed. With regards to this, the procedures, that need to be changed in relation to the alternative propulsion system, and the airframe modifications needed for this system, are identified. Based on these general considerations, an adaptation of the design process for aircraft with alternative propulsion systems is proposed, which involves the integration of the parametrised models of the new propulsion systems and the airframe in the conceptual and preliminary design phases. The cornerstone of this adapted design process is the identification of the relevant design parameters of the systems and subsystems, which are related to the main forces acting on the aircraft.

Chapter 3 analyses and categorises alternative propulsion systems with energy storage relevant for General Aviation (GA) and their subsystems in relation to their functions. These subsystems are divided into four categories: energy provision, energy conversion, thrust generation and auxiliaries. This analysis is essential to define key subsystems and their relevant design parameters. This identification is done in relation to the forces and is based on how they are affected by alternative propulsion systems, as proposed in Chapter 2. Based on this, parametric models of these subsystems are chosen from MATLAB/Simulink libraries and evaluated regarding the design parameters. The subsystem models are embedded in their real physical domains through the use of Simscape, which is part of Simulink. This forms the basis for the development of propulsion models for the adapted aircraft

[3] In this thesis, the following specifications are made in relation to systems and subsystems:
System of systems: entire aircraft
Systems: propulsion system with energy storage, airframe, avionics, flight control system
Subsystems: battery, electric motors, fuel cells, combustion engine etc.
Components: single elements of the subsystems

design process in Chapter 4. These models are also needed to develop the aircraft configuration when integrating the various propulsion systems and, in particular, their energy storage into the aircraft in Chapter 5. As energy storage, batteries, conventional fuel tanks and hydrogen vessels are analysed.

Based on the parameterised models of the subsystems generated previously, the models describing the entire propulsion systems are developed in Matlab/Simulink software in **Chapter 4**. To do so, this chapter analyses the configuration of selected examples of alternative propulsion systems: all-electric, hybrid-electric and hydrogen fuel cells. The main task is to determine the performance of the main propulsion subsystems based on the aircraft mission under consideration. Since the models of the propulsion systems have to capture different physical domains, energy-based modeling approaches are used, which allows to determine and track the energy flow between subsystems caused by the main forces acting on the aircraft. To achieve this, the propulsion system models are placed in the context of airframe characteristics, which in turn depend on the configuration of the propulsion system, the relevant environmental conditions such as altitude and temperature as well as the flight control module that defines the flight mission parameters.

Chapter 5 focusses on the impact of alternative propulsion systems on airframe geometry, possible configurations and weight distribution. For this purpose, parametrised aircraft models are developed using OpenVSP software. These models allow studying the relevant aerodynamic characteristics like lift and drag coefficient to evaluate the impact of the new propulsion system integration into the airframe, in particular, the impact of the energy storage integration because it can lead to an unconventional shape of the aircraft. The airframe model from Chapter 5 and the alternative propulsion system model developed in Chapter 4 are combined together in an iterative loop of the proposed design process in Chapter 2 and exchange information and changes in parameter values. The airframe parameters depend on the geometry of the propulsion and energy storage system, and the magnitude of the forces acting on the aircraft that affect energy consumption is related to the airframe characteristics.

On the basis of the new design process proposed in Chapter 2 and the subsystem models of Chapter 3 combined with the models of the entire propulsion system and the aircraft system (Chapters 4 and 5), **Chapter 6** showcases an example application of the proposed adaptation of the aircraft design process to the development of a hydrogen fuel cell aircraft concept. For this purpose, the requirement and conceptual design phases are carried out. On the basis of the results of the propulsion simulation, the commercially available main propulsion and hydrogen vessel subsystems are selected, which influence how the propulsion system is integrated into the airframe and its geometry.

2. Design process of aircraft with new propulsion system

With the use of alternative propulsion systems in aviation, new and additional subsystems as well as components are emerging, whose integration into the airframe should be mission-orientated. Each of the new propulsion systems has its own advantages and disadvantages, which have to be taken into account at the outset of requirements and flight mission development to enable the design of an aircraft that can meet market expectations. The weight and size of propulsion systems are directly influenced by the flight mission parameters and, in this way, affecting aircraft design.

Alternative propulsion systems also mean the introduction of different new parameters that describe the performance characteristics of individual subsystems and the relationships that exist between them and the entire system. The common denominator for these parameters are the forces acting on the aircraft. Their magnitude, which depends on the flight mission, influences the values of the parameters that the system should have.

New and additional alternative propulsion systems may sometimes require the airframe to be designed more unconventionally and individual subsystems to be arranged atypically due to their size and masses. Additionally, as a result of the lack of historical data and appropriate coefficients, the design process for conventionally powered aircraft requires changes. The solution to fill these gaps is to use suitable simulation models to create model-based data. Their use will make it possible to adapt the conventional design process to alternatively powered aircraft.

2.1. Relationship between forces and design parameters

In order to design a new aircraft, it is first necessary to define the flight mission(s), that the planned plane will perform. Depending on the role of the aircraft, the requirements are defined, including desired performance such as speeds, distance, payload, number of passengers, ceiling, take-off and landing distance [34, 78, 79]. The requirements defined in this step affect the design of the whole aircraft and its systems and thus the magnitude of the main forces acting on the entire plane. This is a starting point for determining the impact of a new propulsion system on an aircraft.

There are four basic forces acting on an aircraft during cruise flight with constant speed and maintaining a constant altitude (Fig. 2.1). This means that the forces are in equilibrium: the lift force balances the weight ($L = W$) and the drag is equal to the thrust force ($D = T$) [85].

The first force is weight W, which acts vertically downwards, and is the sum of the weights of all the systems $W_{systems}$ in the aircraft, airframe $W_{airframe}$, fuel W_{fuel}, oils W_{oils}, payload $W_{payload}$, passengers $W_{passengers}$ and crew W_{crew}:

$$W = W_{systems} + W_{airframe} + W_{fuel} + W_{oils} + W_{payload} + W_{passengers} + W_{crew}. \tag{2.1}$$

With the use of alternative propulsion in an aircraft, there are additional aspects that need to be analysed. The first is to ensure an adequate Static Margin value, which determines the stability level of the aircraft, through the appropriate arrangement of the propulsion subsystems. The second aspect relates to the energy source and its changes in weight during flight. When the energy source is only liquid or gaseous fuel, the weight of the aircraft will decrease during flight because of the combustion of the fuel. In the case of all-electric propulsion, where the only energy source is batteries, the weight of the aircraft will be constant or, for example, if lithium-air batteries are used, the weight may even increase [67]. In the case of hybrid propulsion, both cases should be taken into account due to the different degrees of hybridization, i.e. the percentage of electrical energy used by the propulsion system.

The next main force acting on the aircraft is related to the propulsion system. The thrust force T in the alternative propulsion systems analysed in this thesis (see Chapter 1) is produced by the propeller(s). This force acts in accordance with the aircraft's direction of flight. The basic formula for the thrust force in a propeller aircraft is as follows:

$$T = \frac{P\eta_P}{v}. \tag{2.2}$$

It is dependent on the power of the internal combustion engine or electric motor P, propeller efficiency η_P and flight speed v [34, 45].

The weight is balanced by the lift L, which is the aerodynamic force generated by the aircraft wings and directed vertically upwards:

$$L = \frac{1}{2}\rho v^2 S C_L. \tag{2.3}$$

The wing design and therefore the lift force can be affected by the integration of the energy storage system, for example by the integration of hydrogen tanks inside the wing.

The second aerodynamic force, which is more complex than lift and harder to estimate, is drag D. This force acts opposite to the direction of flight of the aircraft and in the cruise flight with the steady speed it is equal to the thrust. The drag formula is as follows:

$$D = \frac{1}{2}\rho v^2 S C_D. \tag{2.4}$$

The equations of the two aerodynamic forces– lift (Eq. 2.3) and drag (Eq. 2.4), consist of three components: the dynamic pressure $\frac{1}{2}\rho v^2$, which depends on the air density ρ and the speed v at which the aircraft is flying, the wing area S and the corresponding lift C_L or drag coefficient C_D. The lift coefficient C_L depends on the airfoil characteristics, which are selected based on the projected speeds and Maximum Take-Off Weight (MTOW) of the aircraft. The drag coefficient C_D, on the other hand, is formed by two main components:

the induced drag coefficient C_{D_i}, the value of which depends on the lift coefficient C_L, aspect ratio AR and efficiency factor e of the wing, and the drag coefficient at zero lift C_{D_0}, also called parasite drag:

$$C_D = C_{D_0} + C_{D_i} = C_{D_0} + \frac{C_L^2}{\pi ARe}. \tag{2.5}$$

Parasite drag refers to the drag generated by the shape of the aircraft, the friction of the airflow against the aircraft skin and the turbulence of the airflow created around various airframe components and interacting with each other. Integration of new alternative propulsion systems may require additional external components, such as, for example, under-wing hydrogen tanks, a pod under the fuselage belly for batteries, or an increase in fuselage cross-section. Such solutions will result in an increase in parasite drag and thus in the overall drag of the aircraft.

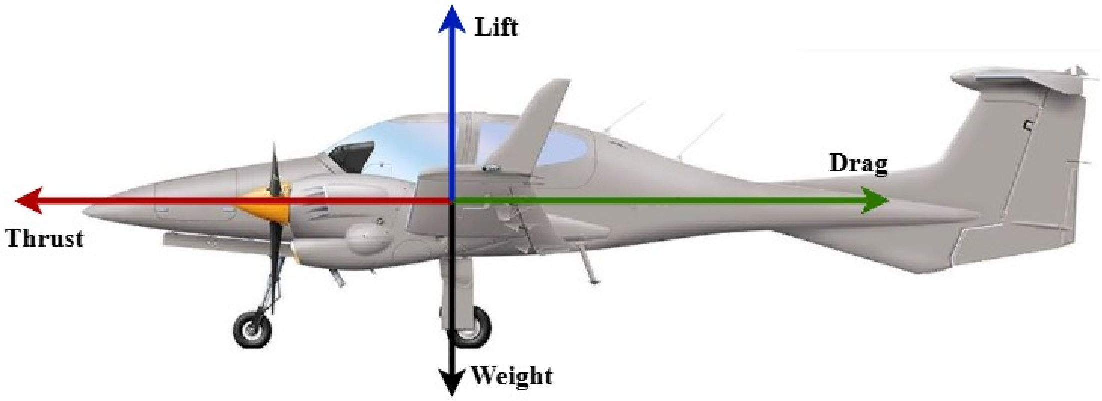


Figure 2.1.: Aircraft main forces in cruise flight with constant speed and at constant altitude

The requirements defined at the beginning of the aircraft design process affect the magnitude of the forces acting on the plane. They can be divided into several groups depending on what the requirements refer to. Among these, three groups are identified that have the greatest impact on the aircraft main forces and therefore also on the aircraft design parameters:

- flight mission and performance requirements,
- stability and control requirements,
- airworthiness requirements regarding safety and certification [34, 84].

The first group mentioned above has the greatest influence on the operating forces and design of the aircraft. The requirements described therein are defined by designers and customer needs. The other two groups of requirements that must be taken into account in the design of the aircraft are derived from specifications set by the relevant aviation authorities and specify parameters such as maximum stall speed, minimum climb gradient, aircraft load limits [26, 34].

Two of the basic requirements regarding the flight mission and performance are range and endurance. The formulas used to calculate them were developed by French aviation pioneer and aircraft designer Louis Charles Breguet [34]. The formula used to calculate the range of a conventionally powered aircraft is called the Breguet Range Equation and is as follows:

$$R = \frac{v}{c_t} \int_{W_{fin}}^{W_{ini}} \frac{L}{D} \frac{1}{W} dW. \tag{2.6}$$

The range of the aircraft depends on airspeed v and thrust specific fuel consumption c_t, which for this equation are defined as constants, drag D and lift L forces as well weight W. As fuel is burned, the weight of the aircraft changes, resulting in a change in the magnitude of the lift and drag force. For this reason, this equation requires the determination of the dependence of v, c_t, L/D on the weight of the aircraft [34].

In case of the basic equation for aircraft endurance, which defines the maximum time an aircraft can stay in the air, the Breguet Endurance Equation formula is applied and it is the same as that of equation 2.6 with the omission of velocity and requires the definition of the dependence of c_t and L/D on W [34]:

$$E = \frac{1}{c_t} \int_{W_{fin}}^{W_{ini}} \frac{L}{D} \frac{1}{W} dW. \tag{2.7}$$

Both equations are directly related to the main forces acting on the aircraft during flight – lift, drag and weight, and indirectly in the case of thrust to airspeed and fuel consumption. The approximate range and endurance values for conventionally powered aircraft can be calculated in the initial design stage using historical data.

The magnitude of the main forces acting on the aircraft (Fig. 2.2) mainly depend on minimum, maximum and cruise speeds, MTOW, flight altitude, range, take-off distance and climb rate defined in the requirements. The most relevant of these parameters also appear in the formulas for the main forces described earlier (Equations 2.1-2.4). The magnitude of these forces depends not only on the requirements but also on the design of the individual aircraft systems and the way they are arranged in the airframe. For this reason, the mutual influence of the forces and the dependence on the system must be considered together.

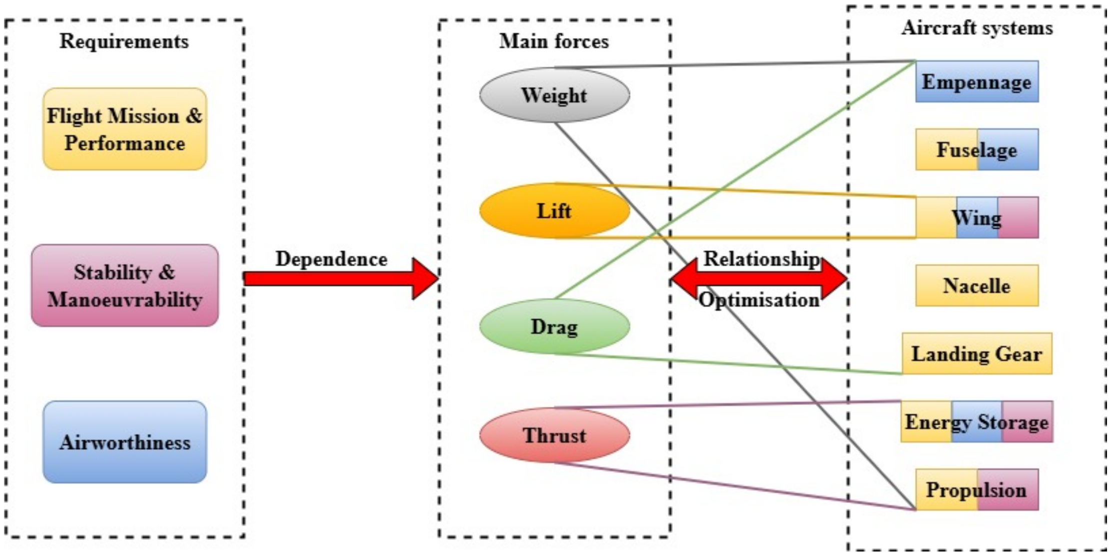


Figure 2.2.: Relationship between design requirements, forces and aircraft systems

As the main aircraft systems, wing, empennage, fuselage, propulsion, energy storage, nacelle(s) and landing gear can be distinguished (Fig. 2.3). The design parameters of the systems are not only related to the forces acting on the aircraft, but also partly depend on the requirements and task the systems have to perform. Figure 2.3 provides a general overview of the relevant parameters that should be considered independent of the propulsion system. The primary task of the wings is to generate enough lift to enable the aircraft to fly. Their design parameters, such as airfoil, chord and span, mainly depend on the weight of the whole aircraft, but also on the required stability and the speeds at which the aircraft will be flying and further characteristics of the mission. The wings are also the platform to which the ailerons are attached, to control the aircraft's roll and the place where the high-lift devices are mounted. The design of the wing involves not only ensuring enough lift force is generated, but also minimising its negative effect, which is induced drag. The empennage is responsible for the stability, yaw and pitch control of the aircraft. Its design and size are determined by other systems, mainly the wings and fuselage, as well as the weight of the aircraft and the associated inertia. The empennage is also a source of parasite drag. In case of the fuselage, its shape depends on the number of passengers or cargo taken on board, as well as on other systems and their integration, for example, the integration of energy storage within it, e.g. battery or hydrogen tank. This may lead to an increase in the drag force due to changes in the dimensions and shape of the fuselage. Furthermore, integrating additional systems into the fuselage will result in changes to the internal architecture and an increase in the weight of this airframe component. The fuselage is the aircraft system most likely to be affected by the changes brought about by alternative propulsion, but at the same time offering the greatest opportunity and flexibility for their introduction. The propulsion system with propeller and energy storage are responsible for providing thrust to the aircraft. Their configuration and arrangement in the aircraft affects the aircraft's manoeuvrability and stability. The energy sources such as batteries or hydrogen are problematic to integrate into the aircraft due to their larger size and weight. This results in changes to the design parameters of the aircraft's systems and, as described for the fuselage, the need for appropriate mass distribution and an increase in the required lift on the wing. Nacelles allow additional space outside the aircraft to house the engine, hydrogen tanks, batteries, or simply an additional luggage hold compartment. They are designed to protect anything placed inside it from external conditions and minimise drag. They are most often built into the wing, located under it or on the wingtip, and can also be installed under the fuselage. Their design depends on the subsystems they conceal within them. The landing gear provides the ability to move the aircraft when it is not in the air. This system can be fixed and during the flight constitute an additional drag source, or retractable and hidden inside the airframe improving the aircraft's lift-to-drag ratio, requiring however a sufficient amount of space in the fuselage, or wing, or an additional nacelle, which would have to be added for this purpose. Finding the sufficient amount of space can be especially challenging in combination with integrating an alternative propulsion system together with an energy source. Moreover, the retractable landing gear is characterised by greater weight than the fixed landing gear. In general, the landing gear design parameters depend on the weight of the aircraft and the surface on which it will operate.

The magnitude of the forces acting on an aircraft depends on the flight parameters and shapes of its individual systems, which are defined by their design parameters. This opens up the possibility of directly relating these parameters to the forces. This approach also enables to relate new parameters that arise from the use of alternative propulsion, without the need for historical data. This presents the possibility to change the approach in the design of an alternatively powered aircraft.

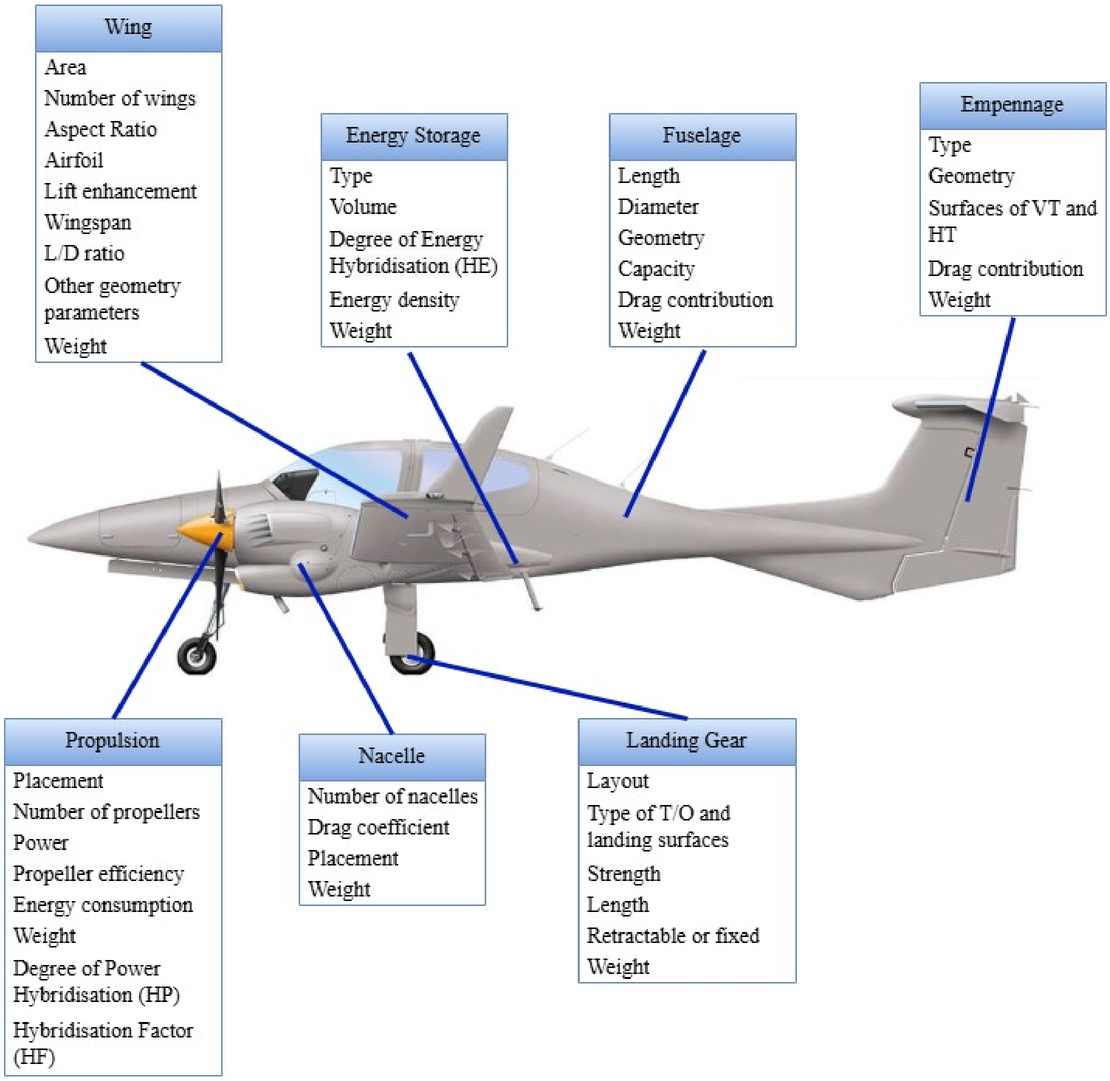


Figure 2.3.: Aircraft systems' general parameters

2.2. Conventional aircraft design process

Aircraft design processes differ depending on what type of different aircraft is being designed, such as commercial passenger, GA class or fighter jet. This is because they are designed for various flight missions and thus other design parameters are considered most important [34, 47, 84]. What this processes have in common is that they use historical data to estimate the value of the aircraft's design parameters. For this reason, Raymer [79] suggests performing an analysis of existing aircraft representing the class corresponding to the intended aircraft with the performance similar to that required for the project. The large number of iterations that occur in the process allow for a transition from general design parameter values, defined using historical data, to increasingly accurate values [78, 83, 96].

Aircraft are subject to very strict guidelines, defined by the aviation authorities, that they must meet in order to be approved for use. For this reason, it is important to carefully study and understand the standards, regulations and certification documents. In addition to the mission parameters, these mandatory documents define the requirements on which the design is based [34].

The overall aircraft design process consists of five phases and in the case of the GA aircraft design process, on which this thesis focuses, these phases actually overlap (Fig. 2.4) [34]:

1. Requirements Phase
2. Conceptual Design Phase
3. Preliminary Design Phase
4. Detail Design Phase
5. Prototype Construction and Testing.

The first phase of the aircraft design process, which defines the aircraft requirements, is to establish the design parameters based at first on the mission requirements received from the future customer or established internally anticipating what future potential users may require. In this phase, the technology used to build the aircraft is usually defined based on the company's manufacturing facilities, which must also be taken into account when developing requirements, since manufacturing technology affects production costs, aircraft performance and maintenance [34, 78].

The second phase is conceptual design that aims to establish the airplane's external configuration and perform the first calculations leading to the determination of the maximum take-off weight (MTOW) of the aircraft. Calculating this weight involves initially guessing it using historical data, which is then determined more and more accurately with successive iterations. The calculation of the maximum take-off weight of the aircraft allows to determine the other two key parameters: thrust-to-weight ratio (T/W) and wing loading (W/S), which in turn enable the constraint analysis to be performed [34, 78, 79]. This analysis graphically determines the optimum design point(s) of the aircraft, i.e., the points arising from the intersection of the T/W, W/S diagrams and those relating to other requirements, such as take-off speed or maximum flight altitude [84]. By determining the values of these three most important parameters of the conceptual design phase: MTOW, T/W and W/S, it is possible to start determining the geometrical parameters, such as wingspan, wing area, airfoil, fuselage length, and thus the size of the individual systems of the aircraft, the so-called sizing. The presence of a relationship between the weight of the aircraft and its geometry, which can be determined from historical data, is helpful here [34]. Raymer [79] suggests that to facilitate this phase, a sketch of the aircraft design concept should be made at the beginning of this phase, which can be used to approximate the aerodynamic parameters. The final results of the conceptual design phase are to establish the maximum take-off weight, layout and geometric parameters of the aircraft [78].

The third phase is called the preliminary design phase and begins after freezing the configuration of the aircraft, developed in the conceptual design phase. This part of the design process analyses the given configuration in detail, determines the feasibility of building such an airplane and refines the design of the aircraft systems. With more input than in the previous phase, a more thorough analysis of the weight, stability and the performance of the aircraft is carried out. The result of these analyses is a more precise definition of systems and their requirements [34, 78, 83].

The detail design phase comprises the design of the aircraft systems using CAD software, a more detailed definition of the manufacturing with regard to generating component specific process instructions as well as design of moulds and auxiliary equipment, and the validation of individual systems such as landing gear. In this phase, the final calculation of weight and associated fractions is carried out. All these activities lead to the final phase before the aircraft enters the market, that is, the building and assembly of the aircraft prototype and its testing [34, 78].

When developing aircraft with a completely new overall design or alternative major systems, the conceptual design phase becomes especially challenging. This is because the outcome of this phase will be a unique design, without any existing precedents. As a result, it is not possible to rely on historical data to the usual extent. Since not enough historical data is available, it is necessary to generate new data. This can be done using analytical modelling.

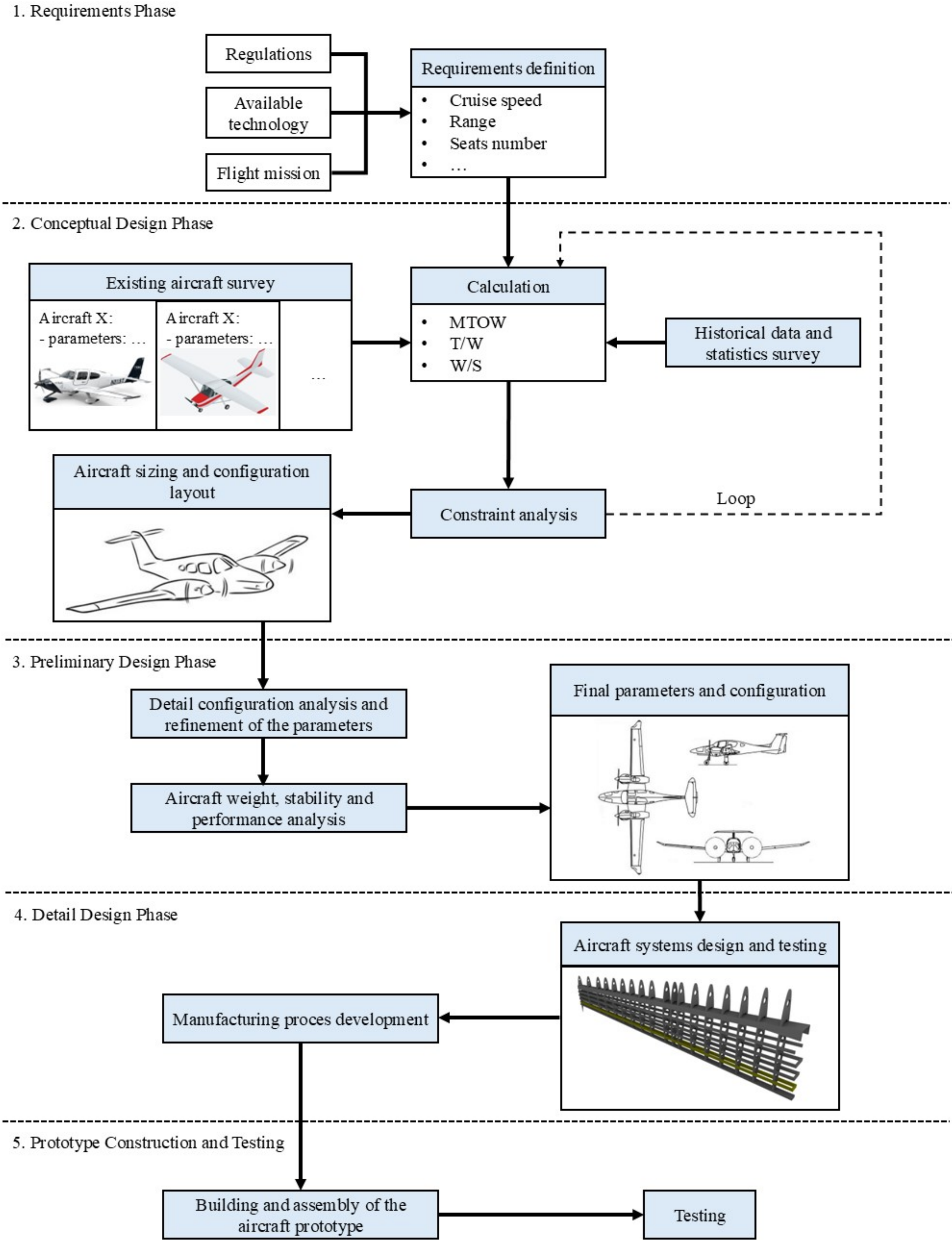


Figure 2.4.: Conventional aircraft design process

2.3. Overview of available design methods for alternatively powered aircraft

As designing aircraft with alternative propulsion systems involves only a limited amount of applicable historical data, estimating the maximum take-off weight, which determines the other parameters of the airplane during the conceptual design process, poses a particular challenge. An aircraft with a new propulsion system may also require changes to the external and internal configuration. The design process for the aircraft with the new propulsion system therefore needs to be adapted accordingly to allow the development of an airplane that will optimally use the opportunities offered by the alternative propulsion system and also consider the limitations caused by the new propulsion system, e.g. due to the integration of the tank.

Designing an aircraft with a new propulsion system can be carried out in two ways: retrofitting of a given aircraft design or designing a fully new aircraft concept. In the case of the former method, the conceptual design phase is the most important, allowing the selection of appropriate propulsion parameters for the already defined geometry of the aircraft. The subsequent preliminary design refers primarily to adapting the available space inside the aircraft for the new propulsion system and ensuring adequate flight stability through correct weight distribution of the propulsion subsystems. Retrofitting will not lead to optimum use of the capabilities of alternative propulsion systems. In case of designing a fully new aircraft concept, both phases are very important and require all the steps described for them to be carried out.

The use of alternative propulsion systems in aircraft requires changes to the existing design process regarding the need to integrate new parameters into it (see Fig. 2.4). In general, the approach to designing aircraft with new propulsion systems can be devided into two types of methods: 1) analytic based on mathematical calculation with formulas adapted to the new drive; 2) numerical based on software and simulation models. The analytical method, which is also the most common analysis method, is mainly applied to hybrid electric and pure electric propulsions. On the contrary, the latter is primarily used for aircraft with fuel cells. With the increase in the number of alternatively powered aircraft, there will also be the opportunity to again base the aircraft design process on historical data.

Analytical method

The design of a hybrid-electric aircraft is most often based on analytical methods. Due to the use of more than one energy source by this type of propulsion and the possibility to separate them from the subsystems responsible for thrust generation, hybrid aircraft require additional parameters to be defined in the design process: Degree of Power Hybridisation (H_P), Degree of Energy Hybridisation (H_E) and Hybridisation Factor (H_F) [23, 28, 74].

The H_P parameter is defined as the ratio of the total power on the electric motor shaft (P_{EM}) to the total useable power ($P_{EM} + P_{ICE}$):

$$H_P = \frac{P_{EM}}{P_{EM} + P_{ICE}}. \tag{2.8}$$

If the value of H_P is 0 it means that the aircraft only has a conventional engine, while when $H_P = 1$ the propeller(s) of the aircraft under consideration are driven solely by an electric motor [75, 76, 102]. In this case we are dealing with one of the listed propulsion topologies: series hybrid, turbo-electric (i.e. series hybrid without batteries) and all-electric [31, 77]. For other cases (e.g. parallel hybrid), the ratio may be constant throughout the flight or vary depending on the phase of flight [40, 101].

The H_E parameter is used to describe the ratio of total electrical energy (E_{Elec}) to all energy available in the aircraft in different forms, for example, chemical energy as fuel (E_{Elec} + E_{Fuel}) [28, 31, 102]:

$$H_E = \frac{E_{Elec}}{E_{Elec} + E_{Fuel}}. \tag{2.9}$$

The H_F parameter is individually defined for serial and parallel/complex hybrid:

$$H_{F,series} = \frac{P_{EM,max} - P_{ICE,max}}{P_{EM,max}}, \tag{2.10}$$

$$H_{F,parallel} = \frac{P_{EM,max}}{P_{EM,max} + P_{ICE,max}}. \tag{2.11}$$

The H_F value depends on the maximum power of the internal combustion engine and the electric motor [23, 75].

The next two basic parameters that need to be defined are the power-to-weight ratio (P/W), which is equivalent to T/W for conventionally powered aircraft, and wing-loading (W/S), which, together with H_P, allow to build a matching diagram and determine the optimal design point of the aircraft [50, 103]. For hybrid-electric aircraft, [28] recommends using higher P/W and W/S values than for conventional propulsion, which shifts the optimal design point for hybrids (for pure-electric propulsion, the point will be shifted even further towards higher P/W and W/S values due to higher power and efficiency and lower weight of electric motors). Further calculations proceed as for conventional propulsion: using the maximum power, a sizing of the propulsion subsystems is carried out, and by calculating the power requirements for the different stages of flight taking into account the hybridisation factor, the fuel and battery masses are calculated. From this, the MTOW is obtained, and these calculations are based on the formulae presented by Raymer [78] and Roskam [83].

The aircraft's use of two energy sources also requires an adaptation of the range equation, which is used in the traditional design process to assess aircraft performance and the amount of fuel required. For hybrid, but also for pure-electric aircraft, the energy-specific air range (ESAR) is used, which is a development of the commonly used Breguet-Coffin

Specific Air Equation Range. The general form of this equation has been presented in [40]:

$$ESAR = \frac{\eta_{EC}\eta_{TR}\eta_{PR}(L/D)}{W}. \tag{2.12}$$

The equation is based on the energy conversion efficiency (η_{EC}), transmission (η_{TR}) and propulsive (η_{PR}) in combination with the lift-to-drag ratio of the aircraft (L/D) and instantaneous gross weight (W). The result is obtained in units of NM/kWh.

The equations presented above (2.8, 2.9, 2.10, 2.11, 2.12) allow the conceptual design phase for the hybrid-electric aircraft to be carried out in the same way as for conventional propulsion.

Despite using only one energy source, part of the equation for hybrid-electric propulsion also applies to all-electric aircraft [46, 102]. Unlike fuel-burning propulsion systems, an all-electric aircraft retains the same mass, which means that the MTOW equals the maximum landing weight (MLW). With the development of batteries using oxidation (e.g.Li-air), the MLW will even have a higher value than the MTOW, due to the fact that batteries of this type increase their mass during discharge [97]. As with hybrid aircraft, the ESAR equation is also dedicated to calculate the range [36, 97]. Hepperle [36] proposed an adaptation of the general form of this formula (Equation 2.12) for pure electric propulsion:

$$ESAR = \eta_{total}\frac{1}{g}(L/D)\frac{m_{battery}}{m}E^{*}, \tag{2.13}$$

in which: E^{*} stands for battery specific energy capacity, η_{total} is the total propulsion efficiency and $\frac{m_{battery}}{m}$ is the ratio of the battery mass to the total aircraft mass.

For the range equation for hydogen fuel cell aircraft, [47] proposes to use the following development of the Breguet-Coffin Specific Air Equation Range formula:

$$R = \int_{W_{ini}}^{W_{fin}} ds = \frac{375\eta_{total}}{hsfc\sqrt{\frac{0.5WC_D^2}{\rho SC_L^3}}}\int_{W_{ini}}^{W_{fin}}\frac{dW}{W}, \tag{2.14}$$

in which the limits of the integrals W_{ini} and W_{fin} are the initial weight of the aircraft and the final weight for the cruise phase of flight, hsfc is hydrogen specific fuel consumption, η_{total} is the efficiency of the propulsion system, W is the weight of the aircraft, S is the wing area, C_D and C_L are the drag and lift coefficients respectively. The equation gives the range in miles.

Numerical method

The second type of approach uses software and simulation models to supplement or extend the computational method with new capabilities. There are three possibilities: adapting dedicated software for conventionally powered aircraft, integrating several different software in the design process and creating a suitable simulation or calculation tool using a single software.

The first option was applied by [5], which used adapted MICADO (Multidisciplinary Integrated Conceptual Aircraft Design and Optimisation environment) software to carry out sizing and evaluation of the hybrid Airbus A320-200. The principle of this software developed by RWTH Aachen was presented in [89]. On the other hand, [30] integrated several commercially available software in his approach to analyse and optimise fuel and energy consumption for a 1-hour flight of the hybrid microlight aircraft demonstrator SOUL: X-Plane (to simulate the aircraft model), Java-Prop (to model the propeller performance) and MATLAB/Simulink (which is the central element, connecting all software and allowing to control the aircraft). MATLAB has also been used in [72, 92]. The former uses THEA-CODE to carry out the conceptual design of a hybrid aircraft with conventional and unconventional configurations. The latter uses the Aircraft Propulsion System Simulation (APSS) framework developed by Bauhaus Luftfahrt (BHL) to design and configure the new propulsion system and adapt the engine to new operating parameters. In contrast, another framework prepared by BHL, 'aircraft-integrated propulsion system analysis' (APA), was used to further evaluate the performance of the hybrid propulsion system integrated into the aircraft, the results of which allow sizing of the aircraft and propulsion system. AMESim is another programme used to carry out aircraft conceptual design that is commercially available. After calculating the HF parameter for the aircraft under development, [32] uses AMESim to perform a hybrid propulsion performance analysis for the planned mission using a numerical model. On the basis of the obtained simulation results, sizing was performed and the propulsion subsystems were selected from ones commercially available.

In addition to the approach based on the mathematical calculations and formulas for the preliminary design of an electric aircraft, [6] again uses MICADO software, which also allows the design of an electric aircraft to be carried out together with its optimisation. Its current capabilities allow the retrofitting of an existing conventional aircraft to electric propulsion, while it can be used for GA aircraft and large passenger aircraft. The possibility of using simulation models developed in MATLAB/Simulink in this phase of aircraft design to determine the performance of the most important subsystems of the propulsion system was presented in [73]. Knowing these parameters allows the weight and dimensions of a subsystem to be determined, e.g. by selecting them from commercially available ones. This is similar to the approach presented in [32] for hybrid aircraft.

In the case of hydrogen-powered fuel cell aircraft (e.g. PEM), in addition to the need to carry out its sizing together with the propulsion subsystems, there is the additional difficulty of the hydrogen tank, which needs to be properly designed and integrated into the airframe. For this reason, [109] recommends modelling the hydrogen tank in a simulation model to consider its working parameters in relation to the entire propulsion system and, in case of the whole aircraft, to analyse its impact on other subsystems due to, for example, very low hydrogen storage temperatures.

To analyse fuel cell propulsion, simulation models are mostly used. [53] uses Simcenter software for the performance analysis of a GA-class aircraft with a PEM cell, while [108] has developed a system-level model of propulsion consisting of SOFC and gas turbine (SOFC-GT) using ProMax. Analysis and optimisation of PEM fuel cell and battery propulsion can also be carried out using a stochastic computational model and Monte Carlo method, as presented in [43] for two of the world's most popular passenger aircraft types (Airbus A320 and Boeing 737).

[65] took a different approach to the design of a fuel cell aircraft, which focused on the design and optimisation of the airframe. He chose as the propulsion system the one used in the Toyota Mirai, and determined the basic P/W and W/S parameters of the aircraft based on a comparison of aircraft of a similar class to the one being designed. This approach was chosen because of the lack of data for aircraft with this propulsion. Subsequently, the aircraft was designed using SUAVE software with which aerodynamic analysis and MTOW estimation were also carried out.

The use of limited historical data

With more aircraft (commercially available and demonstrators), motorgliders and powered UAVs with alternative propulsion, there is an opportunity to create a database with historical data for use in the design process (as with conventionally powered aircraft). This opportunity has been exploited in [81] for designing an electric aircraft, who then combines it with the Sizing Matrix Plot (SMP) and the mission profile analysis to create a new integrated preliminary sizing, a task which required an adaptation of the equations used for conventionally powered aircraft.

The Conceptual Design phase and the sizing of the aircraft for hybrid-electric and electric-powered airplanes is mostly done in the same way as for conventionally powered aircraft with the equations adjusted accordingly. The situation is different for the design of fuel cell aircraft. For this case, the use of simulation models is preferred, due to the larger number of parameters that affect aircraft performance and less experience.

Preliminary design of aircraft with alternative propulsion system

The use of the new propulsion system involves not only the need to define new parameters during the conceptual design phase but also the consideration of new aspects in the preliminary design. Due to the new propulsion subsystems and their different dimensions compared to the conventional ones, they will have an impact on the airframe design. Also their arrangement in the aircraft needs to be analysed in order to get the centre of gravity in the right position and to ensure functionality (e.g., providing enough space for passengers or cargo in the case of a commuter aircraft). Safety issues will influence the outcome of this design phase [2, 33, 74].

The current level of technology used in new propulsion systems results in an increase of its weight or reduction of performance compared to conventional ones. For this reason, it is important to develop the airframe itself in the direction of reducing its weight and increasing its efficiency (using a propeller with higher efficiency, improving the L/D ratio of the aircraft), thus reducing the energy consumption during flight and therefore increasing the range or altogether reducing the weight of the propulsion system. To achieve this, new aircraft concepts are being proposed: Distributed Propulsion (DP), Boundary Layer Ingestion (BLI) [2, 33, 74].

Attempts to design alternatively powered aircraft are being pursued through various routes and methods. The most common approach is retrofitting existing aircraft designs, which primarily involves specifying the parameters of the propulsion system and its subsystems, as well as determining their arrangement within the airframe. However, when designing an aircraft with a new propulsion system from scratch, the lack of historical data poses a challenge in determining key parameters such as maximum take-off weight, thrust-to-weight (T/W) ratio and wing loading (W/S). Additionally, the use of a new propulsion system alters the subsystem weight ratio. For propulsion systems that rely on multiple energy sources, it becomes difficult to estimate the percentage contribution of each energy source to the overall power needed for flight, due to the absence of relevant historical data.

2.4. Adaptation of aircraft design process to new propulsion system

The introduction of a new propulsion system significantly impacts the aircraft in two key ways, which are not fully covered by the available methods described in section 2.3. First, it can alter both the internal and the external configurations. This includes changes to the wing profile to ensure sufficient thickness, allowing the integration of alternative propulsion subsystems within the wings. Additionally, modifications to the fuselage may be necessary to accommodate these subsystems, along with the integration of external components, such as pods under the fuselage or external hydrogen tanks, which contribute to increased drag. The second major impact of the alternative propulsion system is the overall increase in aircraft weight and changes in mass distribution. This results, for example, in stronger landing gear and reduces payload capacity, such as cargo weight or number of passengers, leading to a different payload-to-MTOW ratio compared to conventionally powered aircraft. The increase in weight also increases the energy demand, reducing the range and speed, at the same time, increasing inertia. This, in turn, requires larger control surfaces and greater engine power or torque. To compensate the heavier weight of the aircraft and therefore the change in T/W and W/S parameters, an increase in wing area or improved airfoil designs are needed to generate additional lift. Furthermore, the new propulsion system affects flight characteristics, such as the use of electric motors to drive propellers, which have a different torque-speed relationship compared to piston engines.

The design process for a conventionally powered aircraft (Fig. 2.4) needs to be adapted to the current state of knowledge regarding the entire design of an alternatively powered aircraft. This approach takes into account more parameters regarding new propulsion system and flight mission than the metods descibed in section 2.3. Due to the lack or very small number of aircraft with alternative propulsion, which mostly belong to the experimental class, a review of existing aircraft of this type cannot be performed. This also implies the impossibility of generating historical data of sufficient quality to allow their use in the design process, which are the basis of the Conceptual Design Phase. Alternative propulsion systems may also affect the internal configuration of the aircraft, potentially requiring modifications to the airframe structure. As a result, the drag coefficient of the aircraft can change. This means that it is almost impossible to use the drag coefficient values developed for conventional aircraft as a starting point for calculating the drag force and the required power that the propulsion system should produce.

The problems mentioned in the preceding paragraph and the shortcomings that must be faced in the design of an alternative propulsion aircraft can be solved by adapting the design process accordingly. The adaptation of the aircraft design process for alternative propulsion proposed in this thesis is done by using the Model-Based Systems Design (MBSD) method to develop parametric models of the new propulsion system and modified airframe, which allow to generate model-based data and thus replace missing historical data. It also allows new parameters associated with alternative propulsion systems to be effectively incorporated into the design process.

As with the design process for a conventionally powered aircraft, the developed adaptation consists of five phases (Fig. 2.5). The Requirements (1), Detail Design (4), Prototype and Testing (5) Phases are the same as for the conventionally powered aircraft. In the first phase, the Requirements Phase, additional specifications defining the new propulsion system and its desired work sequence must also be included, which is particularly important for hybrid-electric propulsion systems.

The second phase, the Conceptual Design Phase, has undergone the most modification compared to the design process of a conventionally powered aircraft. It is a phase that relies on a large number of iterations to define the geometric and mass parameters of the aircraft and the propulsion parameters. The first step is to estimate the MTOW based on the requirements defined in the earlier phase. The MTOW and flight mission requirements define the arrangement and design of the aircraft wings, which are then designed and analysed. Given that this is the early phase of aircraft design, it is reasonable to use an appropriate modelling approach that allows for the rapid design of the entire aircraft model or its systems, ensuring the appropriate quality of the analysis output. In this thesis both aspects – design and analysis, are performed using the open source OpenVSP software for parametric modelling of airframe components as well as the whole aircraft. OpenVSP provides information on aspect ratio, wing area, lift and drag coefficients, which are the input parameters for the propulsion system simulation model. The number and position of propellers is then estimated. The parameters and requirements developed in both the Requirement Phase and the initial steps of the Conceptual Design Phase allow the simulation of the propulsion system and the initial analysis of the aircraft's performance. Each of the alternative propulsion systems has its corresponding simulation model developed in Matlab/Simulink software. These are key elements of the adapted alternatively powered aircraft design process, allowing missing historical data to be replaced by model-based data. Based on the simulation results, the required parameters of the subsystems of the new propulsion system are calculated, and based on these, their weight and geometric dimensions are determined. Defining these parameters enables to design the entire aircraft in OpenVSP and analyse it. In this way, more accurate aircraft parameters are obtained. This step is followed by iterating and repeating the previous steps again, i.e. determining the MTOW, using the data obtained from the previously performed steps. This loop is repeated until the correct MTOW, propulsion and aircraft parameters are achieved. It is similar to the iteration that takes place in the design process of a conventionally powered aircraft for the MTOW calculation. Once the correct MTOW is obtained, the final step in the Conceptual Design Phase is the aircraft sizing and configuration layout.

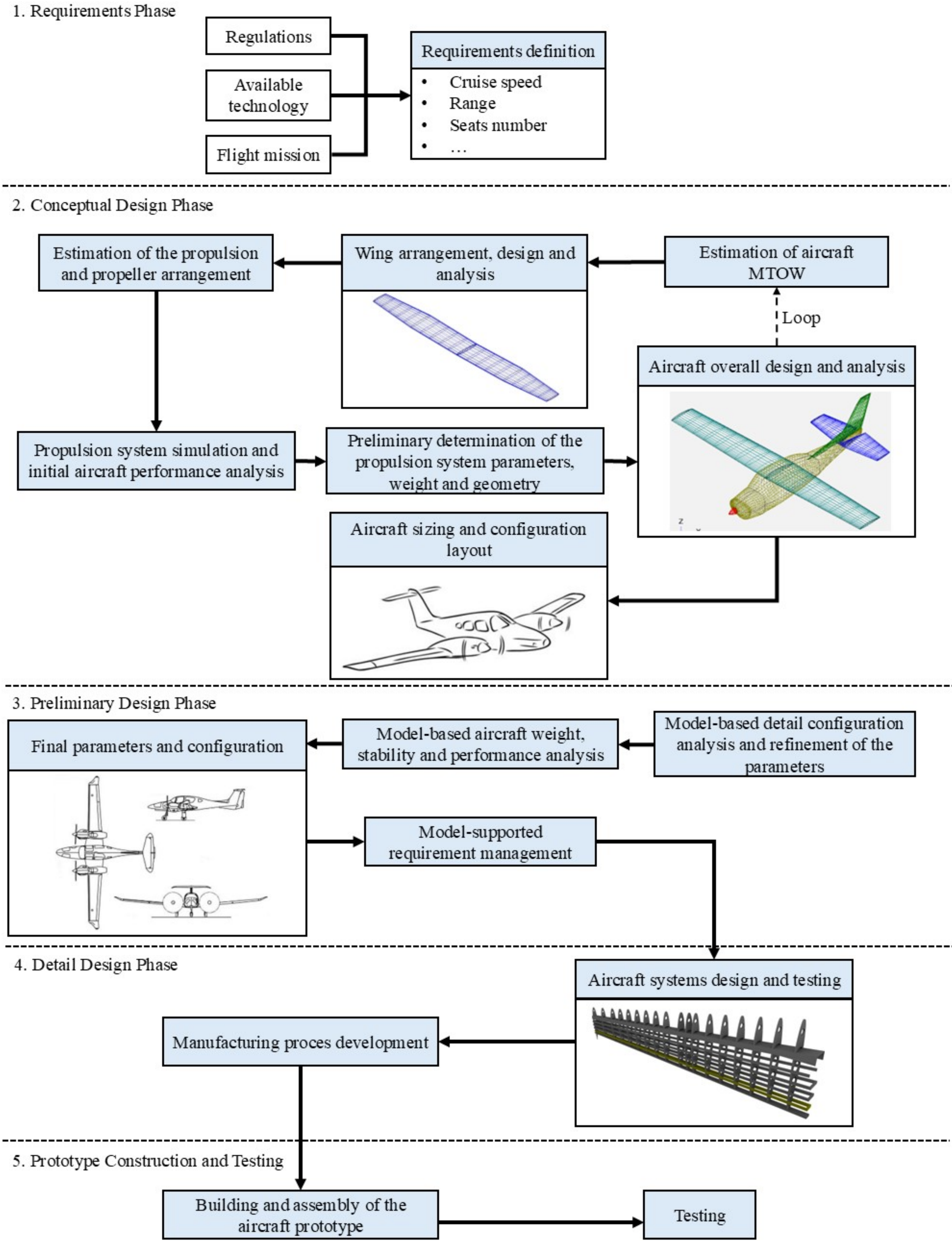


Figure 2.5.: Proposed adaptation of the aircraft design process for alternative propulsion

The third phase, Preliminary Design Phase, consists of similar steps to the design process for a conventionally powered aircraft. The changes affected the first three steps, that are now based on a model-based data. As a result of this phase, the final parameters and configuration of the aircraft are developed together with model-supported requirement management. A significant outcome of the Conceptual and Preliminary Design Phases of the model-based design process of the aircraft with an alternative propulsion system is more exact and better-structured data of the aircraft and propulsion system. Also, high quality system data requirements can be generated with this approach.

By basing the aircraft design process on parametric simulation models, it is possible to easily and efficiently estimate the performance characteristics and geometric dimensions of the propulsion system along with the weights of its subsystems. This, in turn, makes it possible to design the airframe more optimally and to achieve full capabilities of the aircraft with the new propulsion system. The proposed adaptation of the design process is characterised by placing the propulsion system as the most important element of the aircraft and building the airframe around it.

3. Parametrised models of the subystems

Alternative propulsion systems are characterised by a greater degree of, or complete, electrification compared to conventional systems used in aviation. These features of new propulsion systems allow for greater design flexibility, enabling optimisation of both the internal and external aircraft design.

The use of parameterised models of alternative propulsion systems with energy storage in the aircraft design process requires the proper identification and description of their main subsystems and their most relevant design and performance parameters. The advantage of using parameterised models instead of historical data is that they provide more realistic data based on physical models in combination with explicit data, e.g. from subsystem suppliers. This is particularly important if new technologies, such as batteries, are to be used in the subsystems. Parameterised models of the subsystems for alternative propulsion system also allow the analysis of different types of subsystems, such as various battery technologies or electric motors, which have distinct characteristics and operating principles.

In this chapter, parameterised subsystem models are selected and/or developed from blocks available in MATLAB/Simulink libraries according to the working concept of the parameterised models of the entire propulsion system. This ensures that the models of the propulsion systems developed in Chapter 4 provide the information needed for the adapted aircraft design process (Figure 2.5). It is also essential to develop models for subsystems that are not part of the propulsion system and energy storage, but consume energy from the energy source(s) and thus contribute to the aircraft's range reduction.

3.1. Categorisation of the propulsion system subsystems

The basis for the development of parametrised models of the main subsystems of the alternative propulsions is their categorisation. This can be accomplished in different ways. In this thesis the categorisation is done with regard to the main functions of the subsystems. The first function considered is energy provision. This can be approached in two ways: firstly, as energy stored in the fuel or hydrogen tanks and in the battery, secondly, as the energy production e.g. photovoltaic modules[1] [55]. The second relevant main function is the change of the energy type, for example chemical into electric by a hydrogen fuel cell or into mechanical by a combustion engine. The third main function is thrust production, which is mainly done by propellers in the case of GA aircraft. The rest of the subsystems,

[1] Applied in experimental airplanes and drones.

that have different functions and are not directly affected by the main forces, are categorised as auxiliary subsystems.

3.2. Characteristics of energy provision in alternative propulsion systems

The three types of alternative propulsion systems analysed in this thesis – all-electric, hybrid-electric and hydrogen fuel cell – each rely on one of two energy sources: electricity from batteries or chemical energy from a fuel tank or hydrogen vessel. Notably, batteries are present in all three systems, either as the sole energy source or in combination with another source. In hybrid-electric propulsion, they work alongside conventional or alternative fuel, while in hydrogen fuel cell systems, they operate in tandem with hydrogen. The size and weight of the energy storage, which is related to the amount of energy accumulated, affects both the range and the entire aircraft design.

The amount of energy stored on board must be sufficient to complete the flight, taxi and provide the reserve required by regulations, which for hybrid-electric aircraft will require the development of new specifications due to the use of two energy sources. A certain amount of fuel in the tanks is called 'non-usable fuel', which will not be used by the engine [78].

Battery

Battery technology is currently undergoing intensive development because of its key role in green mobility. Despite intensive research, so far batteries have achieved the energy density and life cycle length that allows electrification of smaller aircraft only, whose range and flight time are significantly lower compared to conventionally powered aircraft [2]. Currently, the battery technologies most commonly used in aviation, as well as in automotive, are nickel-cadmium (Ni-Cd), nickel-metal hybride (Ni-MH) and lithium-ion (Li-ion) batteries [80, 102]. Ongoing research into other battery types indicates as of today that lithium-sulphur (Li-S), lithium-air (Li-air), lithium-metal (Li-metal) and solid-state batteries have the greatest potential for future use in aircraft, and also in road transport [36, 67, 86]. A comparison of the specific energy of the mentioned battery technologies is presented in Table 3.1.

A feature of the battery is its modularity. Cells and modules can be connected in series and in parallel manner. The first way allows for an increase in the voltage of the entire battery subsystem, while the second way leads to an increase in capacity [86, 102]. As a result of the heat generated by the batteries, an efficient thermal management subsystem is required to ensure that the batteries are not only cooled but also heated in colder conditions, allowing the temperature of the battery to be maintained to ensure the best performance of the entire system. Safety issues, weight and size of batteries resulting from low gravimetric and volumetric energy density make their integration in the airframe a complex task forcing the use of less optimal solutions in terms of aerodynamics, and therefore aircraft performance. [86].

Table 3.1.: Specific energy of the different battery technologies [80, 86, 102]

Battery technology	Specific energy (Wh/kg)	Comment
Ni-Cd	50-60	
Ni-MH	60-70	
Li-ion	200-300	
Li-S	471	testing, theoretically up to 2,700
Li-air	200	testing, theoretically up to 11,140
Li-metal	300-350	testing
Solid state	390-500	testing

The basic units of a battery are the cells which, when connected together, form a battery pack. Depending on how the individual cells or battery packs are connected, the voltage or amperage can be boosted. A series connection allows the voltage to be increased by adding up the voltages of the connected cells: $U = U_1 + U_2 + ... + U_n$. Parallel connection is used when it is necessary to increase the amperage of the entire module by adding the amperages of the cells comprising it: $I = I_1 + I_2 + ... + I_n$.

Battery power (P) can be calculated using one of the following basic equations:

$$P = UI, \tag{3.1}$$

$$P = I^2 R, \tag{3.2}$$

where: U - voltage, I- current and R- resistance of a battery.

The basic parameters describing the battery subsystem are as follows:

- **Nominal voltage $\mathbf{U_{nom}}$** (in V) representing the average output voltage of the battery when its state of charge is 100%,
- **Capacity Ah** (in Ah) indicating the total amount of energy stored in the battery,
- **Gravimetric energy density $\mathbf{E_g}$** (in Wh/kg) and **volumetric energy density $\mathbf{E_v}$** (in Wh/L) describing the amount of stored energy in relation to the mass and size of the battery,
- **Internal resistance $\mathbf{R_{int}}$** (in Ω) indicating the energy loss as the current flows through the battery,
- **Maximum output power $\mathbf{P_{max}}$** (in W) determining from Ohm's law in three ways: as the product of voltage and current, the ratio of the square of voltage to resistance or as the product of resistance to the square of current.

Various off-the-shelf battery models are available in MATLAB/Simulink library that differ in their modelling approaches and the level of detail. As the battery block[2] for the alternative propulsion simulation models developed in this work, a simple behavioural battery model

[2] A block in MATLAB/Simulink represents a single component of various physical systems or can also represent a subsystem such as a gearbox.

was chosen (Fig. 3.1). It was selected because of its best compatibility with simulation models and flexibility in changing parameters. This battery model makes it possible to analyse battery behaviour and its interaction with other subsystems.

The voltage source in the behavioural battery block, which is modelled as a series resistor, is dependent on the state of charge. The battery voltage is described by the following equation [56]:

$$U = U_{nom}\left(\frac{\mathrm{SOC}}{1-\beta(1-\mathrm{SOC})}\right), \tag{3.3}$$

where: U_{nom}- nominal voltage, SOC- state of charge, β- constant.

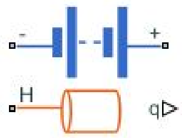


Figure 3.1.: Battery behavioural model from MATLAB/Simulink

In addition to the ports that connect it to the electrical circuit (- and +), it also has a port for the battery thermal mass (H) that allows the battery behaviour to be simulated, taking into account temperature changes and choosing parameters for the Thermal Management Subsystem. This model also has an output port that provides information on battery charge level (q).

Temperature affects the battery voltage and its internal series resistance, as shown in Equations (3.4) and (3.5) [56]:

$$U = U_{nom_T}\left(\frac{\mathrm{SOC}}{1-\beta_T(1-\mathrm{SOC})}\right), \tag{3.4}$$

$$R_T = R(1+\lambda_R(T-T_1)), \tag{3.5}$$

where:

- T- battery temperature
- T_1- nominal measurement temperature
- U_{nom_T}- nominal voltage dependent on battery temperature calculated as: $U_{nom_T} = U_{nom}(1+\lambda_V(T-T_1))$ and λ_V- temperature dependence coefficient for U_{nom}
- β_T- variable calculated as follows: $\beta_T = \beta(1+\lambda_\beta(T-T_1))$ and λ_β- temperature dependence coefficient for β
- λ_R- temperature dependence coefficient for battery resistance [56].

The selected block calculates the temperature of the battery based on the ohmic losses present according to the following equation [56]:

$$M_{th}\dot{T} = \sum_{i} \frac{U_{T,i}^2}{R_{T,i}}, \tag{3.6}$$

where: M_{th}- battery thermal mass, $U_{T,i}$- voltage drop across resistor i and $R_{T,i}$- resistor i [56].

Tanks for conventional and alternative fuels

Several types of fuel can be used in aviation depending on the type of engine:

1. aviation gasoline (Avgas): classic fuel for aviation piston engines,
2. automotive gasoline (sometimes called Mogas): used primarily in the ROTAX engines,
3. diesel: this fuel has recently gained increasing recognition,
4. kerosene: used in turbo prop and jet engines,
5. drop-in sustainable aviation fuel (SAF) and syntetic fuel: currently very expensive kerosine substitute.

The gravimetric energy density of the mentioned fuels is approximately 12,000 Wh/kg [86].

Avgas is the fuel most commonly used in small GA piston-engine aircraft. It comes in several types depending on the fuel grade, and the most popular are: 100LL- the most widely used, mainly in North America and western Europe, 91/96UL- contains no lead and is suitable for almost all aviation piston engines. When flying Mogas, it is important to be aware of the different values of the vapour pressure parameters between this fuel and Avgas and its impact on aircraft safety when flying at higher altitudes. Diesel fuel has an advantage over Avgas and Mogas in terms of price, and diesel aircraft engines can also burn kerosene. It is a fuel that is currently gaining popularity. Kerosene, like Avgas, comes in several types. For civil aviation, Jet A-1 and Jet A are used primarily. The type of jet fuel used depends on the temperature at the airports from which the aircraft operate, due to the different freezing points of the fuel [34].

In recent years, drop-in SAF has been gradually used as an additive to kerosene or as a 100% substitute for traditional fuel and does not require changes to the fuel subsystem and engines. EASA distinguishes between two basic types of drop-in SAF: biofuels and synthetic aviation fuels. The former is produced from biomass. The latter type of SAF is also referred to as Power-to-Liquid or e-fuel. In the e-fuel production process, renewable energy sources are used to produce hydrogen, which is then combined with CO_2 to produce syngas, which undergoes further processes until fuel is obtained. There is also a second type of SAF called non-drop-in SAF, for example hydrogen or methanol, and requires changes to the propulsion system. The use of drop-in and non-drop-in SAF allows for a reduction in cumulative global CO_2 emissions. Another of its advantages is the reduction of contrails due to lower particle emission [20, 54, 86].

Each of the aforementioned fuels, except non-drop-in SAF, uses traditional aircraft tanks, allowing for easy integration into the airframe as they do not require specially shaped tanks. This makes it possible to adapt such tanks to the free spaces inside the airframe. Due to safety requirements, the fuel tanks in general and civil aviation are currently located inside the wings. If the tank is installed in the fuselage, additional aircraft certification is required, which needs to be taken into account when designing an aircraft in which the arrangement of the propulsion subsystems will be different from the classical layout [86].

The basic parameters that define a conventional fuel and, at the same time, its tank(s) are:

- **Fuel quantity L** (in litres) defining the maximum fuel amount in the tank(s),
- **Fuel density** ρ (in kg/m^3) allowing to determine the mass of the fuel in the tank(s).

In the hybrid-electric propulsion model in Matlab/Simulink, the fuel tanks were described only by the amount and weight of fuel on board, without using a block from the Matlab/Simulink library. In this way, the amount of fuel remaining and the changes in the weight of the aircraft due to the operation of the conventional engine are controlled.

Hydrogen vessel

Hydrogen, with a specific energy of 33,330 Wh/kg, is recognized as the fuel with the largest potential to replace traditional kerosene. However, the use of hydrogen as aviation fuel raises several issues, including safety problems - high permeability, which leads to the occurrence of hydrogen leaks from the tank, and flammability.

Hydrogen can be stored on board an aircraft in three ways: as liquid, compressed gas or cryo compressed. Liquid hydrogen is used for combustion in engines in a conventional manner, while gaseous hydrogen powers fuel cells, which generate electricity and form part of the propulsion system analysed in this work.

However, hydrogen is challenging to store due to its low density. As a result, gaseous hydrogen tanks must be designed currently to withstand pressures of up to 700 bar or higher, under which hydrogen is compressed [111].

So far, five types of hydrogen pressure tanks related to the structure have been developed (Types I-V) [111]. Depending on the type, hydrogen vessels differ in terms of the materials used, the cost and the parameters under which the hydrogen can be stored. Type I is an all-metal vessel. Type II is a metal tank, whose cylindrical part is reinforced with composite. Both types are not intended for use in aviation or road transport. Type III consists of a metal liner completely wrapped in composite. The most advanced type of hydrogen tank used commercially by the automotive industry, apart from Type III, is Type IV. It is constructed with a polymer liner and, as in Type III, a carbon- or glass-fibre-reinforced epoxy composite wrapped around it. Currently under development is Type V hydrogen tank, which is entirely made of composite, without a liner. Type V is designed for use in the aerospace industry [15, 88, 111].

Due to the high pressures that hydrogen vessels must endure, it is not possible to use tanks shaped to conform to the internal structure of the airframe, as is common with conventional fuels. Compressed hydrogen requires the cross-section of the tank to be circular. Consequently, the possible shapes of such a vessel are cylindrical, eliptical, sherical and conical. These tanks, because of their predetermined shape, can be integrated into the airframe in unconventional ways, such as inside the fuselage or under the wings.

The parameters of the stored hydrogen depend on the type of tank used, differentiating hydrogen from conventional fuels, which do not require a specially shaped tank. The most important parameters describing hydrogen vessels and the hydrogen stored in them are:

- **Hydrogen pressure $\mathbf{P_{H2}}$** (in bar) defining the maximum value of which is determined by the type of vessel,
- **Volumetric mass density $\rho_{\mathbf{H2}}$** (in kg/m^3) depending also on the pressure,
- **Hydrogen vessel volume $\mathbf{V_{H2}}$** (in m^3),
- The **mass of stored hydrogen $\mathbf{m_{H2}}$** (in kg) deriving from the previous parameters,
- The **weight of the vessel $\mathbf{m_{vessel}}$** (in kg) and **its dimensions and shape** determining how it is integrated into the airframe.

As with the fuel tank, the hydrogen vessel was only described in the simulation model of the propulsion system by the mass of hydrogen stored.

3.3. Specification of energy conversion subsystems

The most important subsystems of the propulsion system are those responsible for converting the chemical energy of the fuel into electrical energy: the combustion engine combined with a generator or fuel cells, as well as for converting electrical energy into mechanical energy, as in the case of the electric motor.

Electric motor and generator

Electric motors are integral to all alternative propulsion systems, driving aircraft propellers either independently or in conjunction with combustion engines, as seen in parallel hybrid systems. In a series hybrid system, a generator is used to convert the mechanical energy of the combustion engine into electrical energy. The reverse occurs in an electric motor, which converts electrical energy into mechanical energy [64]. Collectively, electric motors and generators are known as electric machines. Both generators and electric motors can operate using direct current (DC) or alternating current (AC) [11]. The output power ($\mathrm{P_{out}}$) of the electric motor is calculated as follows:

$$P_{out} = Q\omega, \tag{3.7}$$

where: Q- torque and ω- angular velocity, which is calculated as $\omega = RPM\frac{2\pi}{60}$ and RPM-rotational velocity.

Compared to combustion engines, electric motors are more efficient and reliable due to their fewer moving parts, and they are also lighter and cheaper to maintain. Additionally, there is no need to warm up the motor before increasing its rotational speed. Electric motors also offer the added benefit of producing less noise and vibration. They are characterized by high power density, with specific power ratings reaching up to 5.2 kW/kg, a feature that remains consistent even as their size decreases, unlike combustion engines. The maximum torque of an electric motor is available almost immediately [29, 77, 80].

Electric machines come in various types, with the fundamental distinction being between synchronous and asynchronous machines [11]. The most commonly used machines for vehicle propulsion are the brushless DC electric motor (BLDC) and the permanent magnet synchronous motor (PMSM) [23, 80]. PMSMs are also commonly employed as generators and are regarded as the best type of electric motor for aircraft propulsion due to their high efficiency and power density [35, 80]. Additionally, they generate less heat in the rotor during operation compared to other electric motors [23, 35, 80].

An electric motor must be designed to operate continuously at cruising power, making the maximum continuous power one of the most critical selection criteria [36]. If the motor operates at higher rotational speeds (RPM), a gearbox is required to adjust the motor's RPM to the values needed by the propeller(s) [35].

The basic parameters defining electric motors and generators are as follows:

- **Efficiency** η (in %) indicating the amount of energy loss during the work of an electrical machine,
- **Maximum rotational speed $\mathbf{RPM_{max}}$** (in RPM),
- **Maximum torque $\mathbf{Q_{max}}$** and **maximum continuous torque $\mathbf{Q_{con}}$** (in Nm),
- **Maximum power $\mathbf{P_{EM_{max}}}$** and **maximum continuous power $\mathbf{P_{EM_{con}}}$** (in kW),
- **Mass** of the electric machine m_{EM} (in kg) and its **dimensions**,
- **Operating voltage $\mathbf{U_{op}}$** (in V) indicating the voltage range within which the machine operates,
- **Rotor inertia $\mathbf{I_{rotor}}$(in kg·m^2)** defining how easily the machine can change its rotational speed.

Maximum power, torque, and speed are parameters at which the machine can operate only for a short duration. In contrast, maximum continuous power, torque, and speed can be sustained indefinitely without negatively affecting the machine's longevity. The motor's performance is selected based on the aircraft's required performance, while the generator's performance must be compatible with that of the combustion engine.

In simulation models developed within this thesis, the motor and the generator are represented by a pre-configured block from the Matlab/Simulink library called Motor&Drive (System Level) (Fig. 3.2). This block represents a generic model of an electric motor, such as a PMSM, with closed-loop torque control. The block was chosen for its versatility and ease of parameter definition. It features four physical connection ports: two (blue) for electrical circuit connections (+ and -), and two (green) for mechanical rotational connections: R for the motor rotor and C for the motor casing. Additionally, it includes input and output ports, where the input passes reference torque demand (Tr) to the motor, and the output measures the motor's mechanical speed (W).

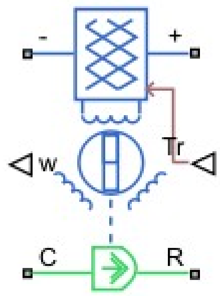
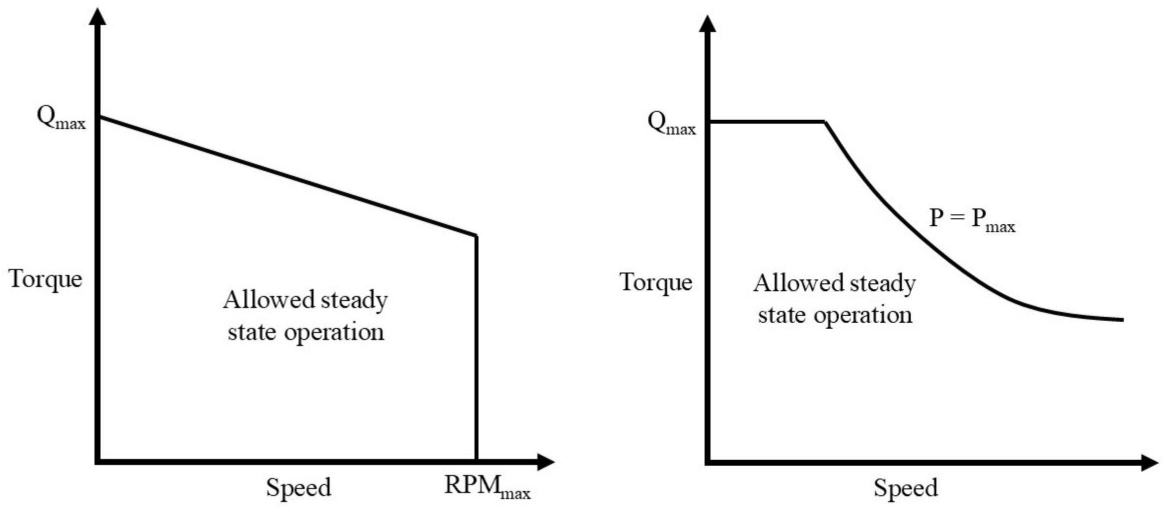


Figure 3.2.: MOTOR&DRIVE (SYSTEM LEVEL) block from MATLAB/Simulink library

The torque-speed envelope can take one of the two forms shown in Figure 3.3, depending on which parameters are chosen to be defined in the block:



(a) A torque-controlled electric motor **(b)** Specification of maximum torque and power

Figure 3.3.: Torque-speed envelope depending on the selected parameterisation method [60]

Combustion engine

The output power of a reciprocating engine is described by the same formula as for an electric motor (3.7): $P_{out} = Q\omega$. Since it is classified as a heat engine, which converts heat from the combustion of fuel into mechanical power, its thermal efficiency is calculated in addition to mechanical efficiency:

$$\eta_{thermal} = \frac{P_{out}}{H_{fuel}}, \tag{3.8}$$

where: P_{out}- output power and H_{fuel}- thermal energy of the burnt fuel.

In addition to the efficiency of the internal combustion engine, its important parameters are the specific fuel consumption SFC (3.9) and the total engine volume V_{tot} (3.10), both of which affect the amount of fuel an aircraft has to carry during flight:

$$SFC = \frac{\dot{m}_{fuel}}{P_{out}}, \tag{3.9}$$

$$V_{tot} = n\frac{\pi}{4}D^2 S, \tag{3.10}$$

where: $\dot{m}_{fuel}$- weight of fuel consumed per unit time, n- number of cylinders, D- cylinder diameter and S- stroke length.

An internal combustion engine is also characterised by its compression ratio η, which is the ratio of the total volume of the cylinder V_{bottom} to the combustion chamber V_{top}: $\eta = \frac{V_{bottom}}{V_{top}}$.

The combustion engine is used in hybrid propulsion systems, and depending on the configuration, it either drives a generator in a series hybrid setup or works together with an electric motor to rotate the propeller, as in a parallel hybrid system. Combustion engines are divided into two types: piston engines, which include Wankel and diesel engines, and gas turbines [1].

Piston engines are characterized by power outputs of up to 2,000 kW and better performance at speeds up to Mach 0.3. However, their power decreases at higher altitudes, which is why piston engines are often equipped with compressors [1, 23, 34].

In recent years, ROTAX engines, which are a new type of the aviation piston engine and run on automotive gasoline, have become very popular in general aviation (GA). These engines operate at much higher RPMs compared to traditional aircraft piston engines, requiring the use of a gearbox between the engine and the propeller. They are also known for their very low fuel consumption [34].

Table 3.2 compares the main parameters of four aircraft engine technologies with similar maximum power. Three piston engines are juxtaposed: a Rotax engine, a classic aircraft piston engine from Lycoming and a diesel engine manufactured by Austro Engine, with an electric motor from Emrax.

Table 3.2.: Comparison of the electric motor and three different piston engine technologies [21, 22, 25, 51]

	Emrax 228	Rotax 916 iS	Lycoming O-320-D2G	AE 300
Type	electric motor	piston engine with turbocharger	aviation piston engine	Diesel engine
Maximum power	124 kW at 5500 rpm	117 kW at 5800 rpm	119 kW at 2700 rpm	123.5 kW a 3880 rpm
Engine displacement	N/A	1,352 cm^3	5,241 cm^3	1,991 cm^3
Weight	13.2 kg	85.8 kg	127.5 kg	186 kg

Gas turbines typically produce between 100 and 400 MW and offer a significantly better power-to-weight ratio compared to piston engines. However, one major drawback of gas turbines is their high fuel consumption [1, 23]. The gas turbine is not considered further in this work.

The hybrid-electric propulsion simulation models analysed in this thesis for GA aircraft utilize a piston engine. This choice is based not only on the lower power requirements of smaller aircraft but also on leveraging the knowledge and experience from the automotive industry and the potential to integrate hybrid propulsion subsystems already developed for cars into the later stages of aircraft design.

The key parameters describing combustion engines include:

- **Maximum power $\mathbf{P_{max}}$** (in kW) and the corresponding engine rotational speed,
- **Maximum rotational speed $\omega_{\mathbf{max}}$** (in RPM),
- **Engine mass $\mathbf{m_{eng}}$** (in kg) and its **dimensions**,
- **Specific fuel consumption SFC** (in g/kWh) determining the amount of fuel needed to produce one unit of energy by the engine,
- **Engine inertia $\mathbf{I_{eng}}$** (in kg·m^2) defining how easily the engine can change its rotational speed,
- **Efficiency $\eta_{\mathbf{eng}}$** (in %) indicating the amount of energy loss during the work of a combustion engine,
- **Maximum torque $\mathbf{Q_{max}}$** (in Nm),
- **Engine displacement L** (in litres) describing total volume of all cylinders in the engine.

For the piston engine model, the Generic Engine block (Fig. 3.4) from the Matlab/Simulink library was selected. This model provides enough versatility for simulation models while allowing easy parameterization of the engine. The block can operate in three modes: generic, spark ignition, and diesel. It is controlled via the throttle (Thr) using a signal that ranges from 0 to 1, indicating the throttle's opening level. Two mechanical rotational ports are available: one (B) for the engine block and the other (F) representing the engine crankshaft, which transmits the power generated by the pistons. Additionally, the block has two output ports that provide physical signals: one (P) for instantaneous power in watts and the other (FC) for fuel consumption in kg/s, both depending on the throttle setting.

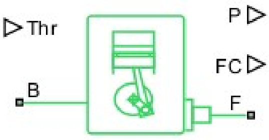


Figure 3.4.: Generic Engine model from Matlab/Simulink library

This block can be parameterised by:

- tabulated torque data
- tabulated power data
- normalised 3rd-order polynomial [58].

The first two parameterisation methods use a speed-torque table and a speed-power table, respectively [60].

For the third parameterisation method, it uses the normalised angular velocity ω_N of the motor to calculate its RPM and torque. ω_N is defined as a function of the current angular velocity of the motor ω to the angular velocity at which it reaches peak power ω_{PP} [58]:

$$\omega_N(\omega) = \frac{\omega}{\omega_{PP}}. \tag{3.11}$$

This parameterisation method uses 3rd-degree polynomials to calculate motor power and torque:

$$P(\omega(\omega_N)) = P_P(s_1\omega_N + s_2\omega_N^2 + s_3\omega_N^3), \tag{3.12}$$

$$T(\omega(\omega_N)) = p_1 + p_2\omega_N + p_3\omega_N^2, \tag{3.13}$$

where: P_P- peak power, s_1, s_2 and s_3- polynomial coefficient constants select according to the type of motor, $p_1 = \frac{s_1 P_P}{\omega_{PP}}$, $p_2 = \frac{s_2 P_P}{\omega_{PP}}$, $p_3 = \frac{s_3 P_P}{\omega_{PP}}$

Hydrogen fuel cell

The fuel cell that converts the chemical energy of hydrogen into electricity is the proton exchange membrane (PEM) fuel cell. It features a low operating temperature, between 60 and 90 degrees Celsius, compared to other fuel cell types like SOFC. Its disadvantage is the low power density, which can be improved by adding a battery to the system, further reducing hydrogen consumption and improving powertrain performance. The efficiency of PEM fuel cells is 40-60% and they are capable of producing between 100 W and several kW of power. For this reason, single cells are combined in stacks to achieve the required power output [1, 36]. A single PEM cell produces direct current (DC) with a low voltage of 0.6-0.7 V and thus a DC-DC boost converter is required to increase the voltage [12, 68]. The chemical reaction that takes place in a hydrogen fuel cell is as follows [17]:

$$2\,H_2O + O_2 \longrightarrow 2\,H_2O + \text{heat}$$

$$\text{anode: } 2\,H_2 \longrightarrow 4\,H^+ + 4\,e^-$$

$$\text{cathode: } O_2 + 4\,e^- + 4\,H^+ \longrightarrow 2\,H_2O$$

The by-products of the PEM fuel cell's electricity generation are heat and water. Consequently, a hydrogen fuel cell requires suitably efficient thermal and water management subsystems to avoid overheating and flooding the cell [68, 86].

The power (P) produced by a hydrogen fuel cell is calculated as the product of the voltage (U) and the current (I) produced by the cell: $P = IU$ [68].

In the case of fuel cells, an important concept is the current density j, which is defined as the intensity I divided by the interfacial area $j = \frac{I}{A}$. The size of the interfacial area A determines the total current that a given cell can generate [68].

The basic equation used to calculate the voltage produced by a fuel cell is the Nernst equation. This equation represents the relationship between the voltage of the cell and its temperature and the pressure of the gases supplied to and produced by the cell. In the case of a hydrogen fuel cell, the Nernst equation comes in two versions depending on the temperature of the cell, which affects the state of matter of the water produced during the process [68]:

$$E_{thermo} = \begin{cases} E_OC - \frac{RT}{zF} \ln \frac{p_{H_2O}}{p_{H_2} p_{O_2}^{\frac{1}{2}}}, & T \geq 100\,°\mathrm{C} \\ E_OC - \frac{RT}{zF} \ln \frac{1}{p_{H_2} p_{O_2}^{\frac{1}{2}}}, & T < 100\,°\mathrm{C} \end{cases} \tag{3.14}$$

where: E_{OC}- open circuit voltage, which at 25°C for a fuel cell is 1.229, R- universal gas constant, T- temperature, p_{H_2O}, p_{H_2} and p_{O_2}- partial pressure of water, hydrogen and oxygen respectively, F- Faraday's constant, E_{thermo}- ideal (thermodynamic) voltage calculated using the Nernst equation [68].

The true value of the voltage U_{FC} produced by a fuel cell depends on the magnitude of three types of losses: activation η_{act} related to reaction kinetics, ohmic η_{ohmic} caused by the resistance of materials during ion and electron conduction, and concentration η_{conc} related to mass transport inside the cell (Fig. 3.5) [68]:

$$U_{FC} = E_{thermo} - \eta_{act} - \eta_{ohmic} - \eta_{conc}. \tag{3.15}$$

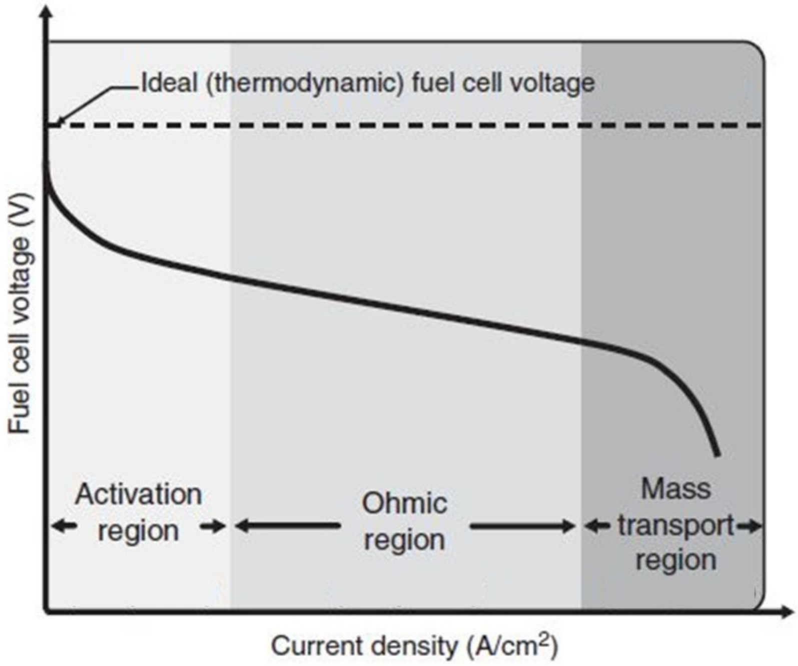


Figure 3.5.: Effect of activation, ohmic and concentration losses on the I-U curve of a fuel cell with reference to ideal (thermodynamic) voltage [68]

The most important parameters to model a generic PEM fuel cell model are:

- **Open-circuit voltage $\mathbf{E_{oc}}$** (in V) denoting the no-load voltage present in the cell,
- **Tafel slope A (in V)** relating the overpotential to the rate of electrochemical reaction,
- **Internal resistance $\mathbf{R_{int}}$** (in Ohm) characterising the relationship between voltage and current in a fuel cell,
- **Nominal exchange current $\mathbf{I_{nom}}$** (in A) indicating the current value at which the polarisation area changes from active to ohmic,
- **Collapse current $\mathbf{I_{coll}}$** (in A) defining the value of the current at which the cell voltage is 0,
- **Fuel cell system weight $\mathbf{m_{FC}}$** (in kg) and its **dimensions**,
- **Cell number per module**,
- **Module units**.

The amount of electricity generated by a hydrogen fuel cell depends on the quantity of hydrogen and oxygen taken in. For this reason, it is also required to determine the parameters of the fuel and air taken in:

- Hydrogen and air flow (in l/min),
- Absolute hydrogen pressure (in bar),
- Gauge air pressure (in bar).

The Fuel Cell block available in the Matlab/Simulink library was selected as the model for the PEM fuel cell (Fig. 3.6). This block focusses primarily on simulating the amount of electricity generated by the cell at given fuel flow parameters, which is in line with the objective of the alternative propulsion simulation models developed. In addition to this, the model allows for flexible parameter changes and does not require detailed parameterisation, thus facilitating its use. The mathematical description of this block is presented in A.4.

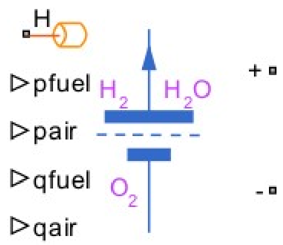


Figure 3.6.: PEM fuel cell block from Matlab/Simulink library

The Fuel Cell block has seven ports. Two of these (+ and -) allow the generated electricity to be transferred to subsequent propulsion system subsystems. Due to the heat generated during cell operation, this model also has a port (H) to connect the cell to the Thermal Management Subsystem. The other four ports are input ports representing the hydrogen and oxygen supply to the fuel cell in the form of a physical signal: pfuel and pair represent the absolute supply pressures of hydrogen and manometric pressures of oxygen, respectively, qfuel and qair- the flow rate of hydrogen and oxygen, respectively.

3.4. Characteristics of the thrust generation subsystem

Among GA aircraft, the conversion of torque generated by an internal combustion engine and/or electric motor into thrust is most often performed by a propeller. This can come in a variety of types and configurations. The two basic types of propeller are fixed pitch, meaning that the angle of the propeller blades cannot be changed, and variable pitch, in which the angle of the blades is adjusted by the pilot or automatically. In addition, propellers come in different configurations as pusher, in which the engine is in front of the propeller, the most common tractor, which is the opposite of the previous configuration (engine behind the propeller). A special type of propeller configuration is where the propellers are located in the nacelle, which allows them to be moved from the fuselage to another location on the aircraft, for example on the wings. With this configuration, the propellers can operate as a pusher or tractor [34].

The basic parameters that characterise propellers are:

- **Number of blades**,
- **Diameter**,
- **Weight**,
- **Type**, i.e. fixed or variable pitch,
- **Efficiency**,
- **Configuration**, e.g. pusher or tractor.

The propeller parameters are selected according to the characteristics of the internal combustion engine and/or electric motor with which they are to operate [34].

The simulation models developed do not take into account the propeller block, which is available in the Matlab/Simulink library, due to its incompatibility with the working principle of the models. The only propeller parameter considered in the developed models is its percentage efficiency, which was assumed to be constant, i.e. similar to that of a variable pitch propeller, which also allows the generation of negative thrust to enable recuperation in the propulsion system.

3.5. Auxiliary subsystems of the alternative propulsion systems

The other subsystems that comprise the propulsion system are: converters, thermal management subsystem (TMS), power distribution unit (PDU), gearbox and propeller. Their operating parameters, as well as their type, are defined by the main propulsion and energy storage system, which are described in Sections 3.2 and 3.3. They determine not only the required performance of such a subsystem, but also its type, as in the case of the converter. Each of these subsystems constituting the propulsion system is characterised by specific energy losses, which affect the overall performance of the propulsion system and thus the amount of energy that must be stored on board the aircraft to provide the required amount for flight.

The aircraft is also equipped with additional mandatory systems such as avionics, lighting and radio, which also place an additional load on the energy storage. This also affects the amount of energy required on board. As with conventionally powered aircraft, these systems must be able to operate when the propulsion system is switched off, using battery power from the energy storage system or from its own accumulator. This means additional weight added to the aircraft and the need to locate an extra battery inside the airframe.

Power electronics

Their function is to adjust the voltage between the various subsystems of the circuit and/or to change the type of current (AC or DC). Power electronics are divided into: rectifiers to convert AC to DC, inverters to convert current in the reverse direction from DC into AC and converters to change the voltage value of the current [11, 102]. There are three types of converters:

- buck converter decreasing the output voltage,
- boost converter increasing the voltage at the output,
- buck-boost converter combining both functions [102].

In the simulation models developed in this thesis, the main subsystems of the propulsion system use direct current for their operation. For this reason, the DC-DC Converter (Fig. 3.7) block from the MATLAB/Simulink library was selected. It represents a behavioural model of the power converter. Each model has two such blocks - one for the high voltage between the power source(s) and the electric motor, the other for the low voltage adjusting its value between the battery and onboard systems such as avionics and lighting. It is a versatile model that also allows electricity to flow in both directions, which is important when the battery is charged by a generator, fuel cells, or as a result of recuperation by the propeller.

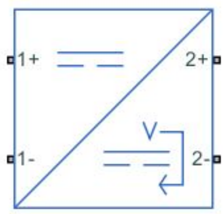


Figure 3.7.: DC-DC Converter block from MATLAB/Simulink library

The most important parameters that describe a DC-DC converter are as follow:

- **Rated output power P_{out}** (in kW) indicating the output power value, for which the efficiency of the converter is given,
- **Output voltage reference demand U_{out}** (in V) defining the value of the output voltage in the absence of output current, this is also the reference value for the voltage regulator,
- **Efficiency $\eta_{converter}$** (in %) indicating the amount of energy loss when flowing through the device, efficiency of converters reaches up to 97%,
- **Weight $m_{converter}$** (in kg) and its **dimensions**.

Thermal management subsystem (TMS)

It is an important subsystem in propulsion and energy storage systems that is responsible for keeping the subsystems of both systems within their thermal limits. There are three types of TMS: Air or Liquid Cooling, and Cryocooling. The first two are used for the cooling of power electronics and batteries, with Liquid Cooling being heavier but also more efficient than Air Cooling, while the last type is for subsystems that need to be kept below 80 K [102].

For the simulation models, a simplified Liquid Cooling TMS (Fig. 3.8) was developed to regulate the battery temperature. For the other subsystems, the heat they generate and its transfer were neglected. The TMS was modelled as a simplified hydraulic circuit in which the amount of coolant flow is controlled by a pump based on the measurement of battery temperature. The circuit also defined the type of coolant and its tank.

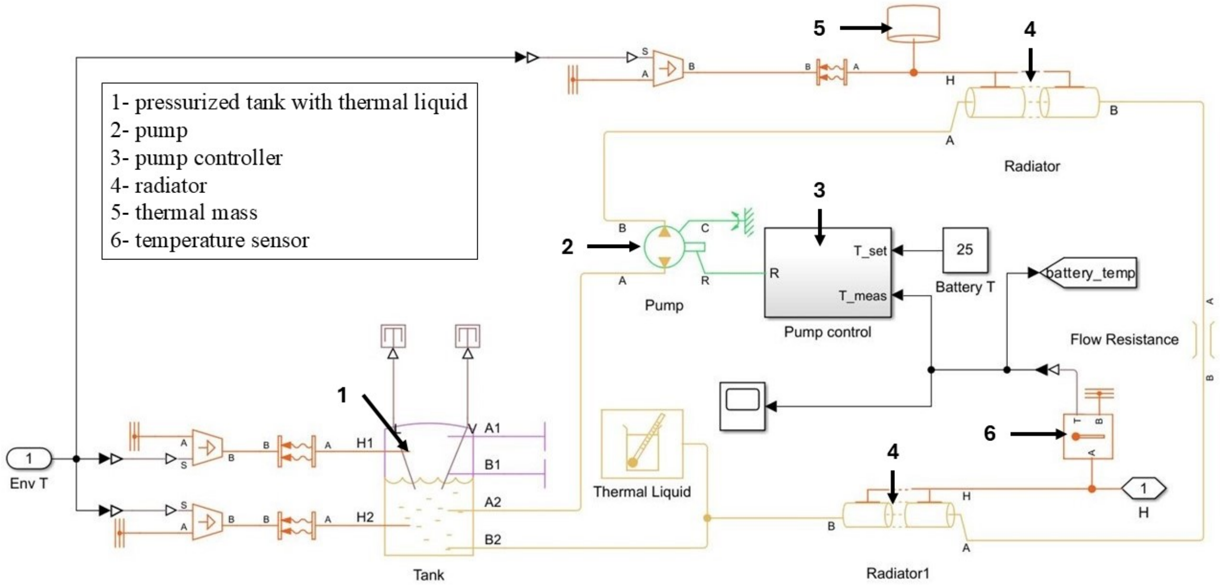


Figure 3.8.: Simplified thermal management subsystem (TMS) modelled for the battery in simulation models

The basic parameters to define a simple liquid-cooling TMS are as follows:

- **Volume of the coolant reservoir $\mathbf{V_{cool}}$** (in L),
- **Type of coolant**,
- **Total length of the radiators $\mathbf{L_{cool}}$** (in m),
- **The displacement of the pump $\mathbf{L_{pump}}$** (in cm^3), its **maximum speed $\omega_{\mathbf{pump}}$** (in RPM) and the **Power demand $\mathbf{E_{pump}}$** (in kW),
- **Cooling efficiency $\eta_{\mathbf{TMS}}$** (in %).

Power distribution unit (PDU)

Its task is to distribute electrical energy to the various subsystems of the aircraft. In addition, it is responsible for protecting the subsystems of the propulsion system and energy storage from overload, as well as monitoring the parameters of the flowing current. It is a complex device that consists of cables, circuit breakers, converters, rectifiers and inverters. At the same time, it allows for a more optimal and organised arrangement of cables in the aircraft [77].

The simulation models developed in this thesis represent the PDU in a very simplified way: for the high voltage by implementing a DC-DC Converter block with circuit breaker between the battery and the electric motor, for the low voltage, which supplies the on-board subsystems, the PDU is represented as a DC-DC Converter block with a self-developed MATLAB/Simulink subsystem[3] (Fig.3.9) that distributes the power flow based on demand by the on-board subsystems.

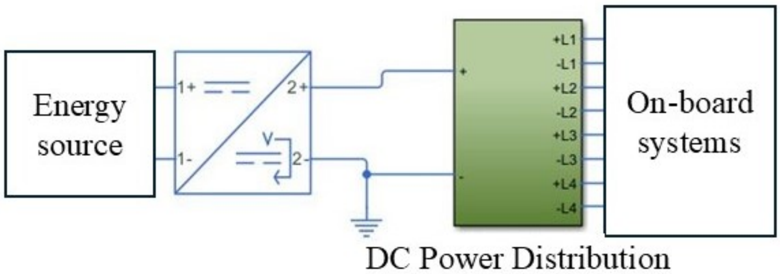


Figure 3.9.: Developed simplified Power Distribution Unit model for low voltage

The most important parameters that characterise a PDU are:

- **The maximum current parameters**, such as current I_{max} and voltage U_{max}, that can flow through this device without damaging it,
- **The efficiency of the η_{PDU}** (in %), which determines the losses during the transmission of electrical energy through the PDU,
- **The weight of the m_{PDU}** (in kg) and **the dimensions** depending on the PDU's operating parameters.

On-board systems

Aircraft are also equipped with other systems such as avionics, lighting and radio, which also place an additional load on the propulsion system and energy storage. Some of these

[3] A MATLAB/Simulink custom subsystem is a user-created subsystem that consists of selected blocks from the library.

systems, which are important from the point of view of flight safety, should, as in conventionally powered aircraft, also have their own battery to allow them to be used when the propulsion system is inoperative or the energy storage is damaged.

In the simulation models developed, the on-board systems (Fig. 3.10) were represented as an additional load for energy storage. The avionics with radio, the environmental control system that maintains cabin temperature, the lighting and, if there is an internal combustion engine or hydrogen fuel cells, also the fuel pump are modelled symbolically.

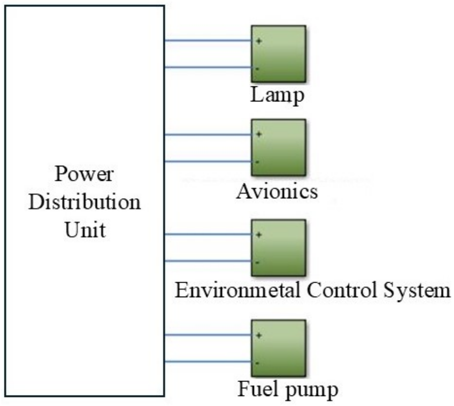


Figure 3.10.: Simplified on-board systems modelled in MATLAB/Simulink

The basic parameters relevant to the propulsion system and energy storage to characterise the on-board systems are:

- **Mass $\mathbf{m_{subs}}$** (in kg) affecting the weight of the whole aircraft,
- **Energy consumption $\mathbf{E_{subs}}$** (in kW) defining the amount of additional electrical energy that must be supplied by the energy storage and thus affecting the range of the aircraft.

Gearbox

Its primary function is to change the speed, for example between the electric motor and the propeller. The ROTAX internal combustion engine, due to its high rpm, requires a fixed gearbox between it and the propeller so that the propeller blade tips do not achieve the speed of sound. The parallel hybrid uses a planetary gearbox, with which both engines can drive the propeller or be decoupled [102].

The gearbox was implemented only for the parallel hybrid simulation model. Simple Gear was selected as a block from the MATLAB/Simulink library (Fig. 3.11).

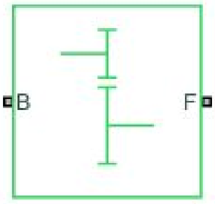


Figure 3.11.: Simple Gear block from the MATLAB/Simulink library

Port B is used to connect the gearbox to the base shaft, while F is for connecting the follower shaft.

A gearbox can be described in a basic way by the following parameters:

- **Gear ratio GR** defined as the ratio of the speed of the incoming shaft, e.g. from the engine, to the speed of the outgoing shaft leading to the propeller. This is the only parameter defined in the Simple Gear block,
- **Efficiency** $\eta_{\mathbf{gear}}$ (in %),
- Its **mass** $\mathbf{m_{gear}}$ (in kg) and **dimensions**.

4. Analysis and modelling of the alternative propulsion systems

System models for propulsion provide a deeper understanding of both existing and newly designed systems. Their application in the system design process improves decision-making by enabling virtual testing and evaluation across various operational scenarios, reducing potential errors in the system and, in turn, minimising the need for physical prototypes and experiments. This results in a more efficient development process, along with reduced project costs. The efficiency and effectiveness of models depends on their configuration, e.g. model boundaries, scaling, boundary conditions and physical models, whereby the model parameters must be adapted to the objectives of the relevant simulation in the development process. The generation of simulation models has, therefore, the advantage that the model can be specifically tailored to the relevant objectives within the development process of new alternatively powered aircraft. This fundamentally distinguishes models from empirical knowledge such as historical data, the accuracy of which is difficult to assess.

In this thesis, simulation models of alternative propulsion systems are key elements in developing a new approach for the aircraft design process. System models are combination of subsystem and component modelds described in Chapter 3. Due to the different physical domains represented by the subsystems and components, the basis of the analysis of the system is the energy flow, which is driven by forces acting on the aircraft, between the different subsystems. This enables the identification of relevant propulsion parameters needed to meet the defined performance requirements. These simulation models incorporate reasonable simplifications based on design assumptions and model functionality. This approach enables the creation of a versatile simulation model with computational efficiency, permitting multiple iterations within a relatively short timeframe and enabling high modularity. These modular models allow them to be extended according to current demand, starting with a generic representation of the system under analysis and progressing to a more detailed models in later design phases.

4.1. Configuration of alternative propulsion systems

Developing a simulation model of an alternative propulsion requires analysing the modelled system and identifying the relationships that exist between its subsystems. How the system is modelled depends on what answers are sought. For this work, the electrical, mechanical and thermal energy flows shaped by the aircraft's mission are analysed to determine the required parameters of the alternative propulsion system subsystems. Based on the required parameters of the subsystems, their size and weight are determined in the next step.

In this work, three types of propulsion system are modelled: all-electric, hybrid-electric and hydrogen fuel cell. For the hybrid-electric propulsion system, two configurations have been chosen for the analysis: series and parallel. Each of these propulsion systems has different advantages and disadvantages that affect how and whether they can be used in the designed aircraft and its planned mission profile. Their impact on airframe design and the possibility of changing the internal configuration of the aircraft must also be considered.

All-electric

This is the simplest type of propulsion system (Fig. 4.1), whose only energy source is the battery. The flow of electrical energy from the battery to the electric motor is bidirectional and goes through the power electronics and/or power distribution unit, which regulates the voltage and/or also changes the type of current between both main subsystems. The electric motor then converts the electrical into mechanical energy and, through a shaft-mounted propeller, into thrust. When the electric motor operates at a higher speed than needed for the propeller, a gearbox is mounted between the two, which reduces the speed of the electric motor shaft and then transmits it to the propeller shaft. One-way power flow occurs between the battery and the on-board systems via a power electronics or power distribution unit, which protects, adjusts current parameters and/or distributes power between the systems. During operation, the battery also emits thermal energy, which is transferred to a heat exchanger-part of the thermal management subsystem, whose task is to keep the battery within the appropriate thermal window for optimal performance.

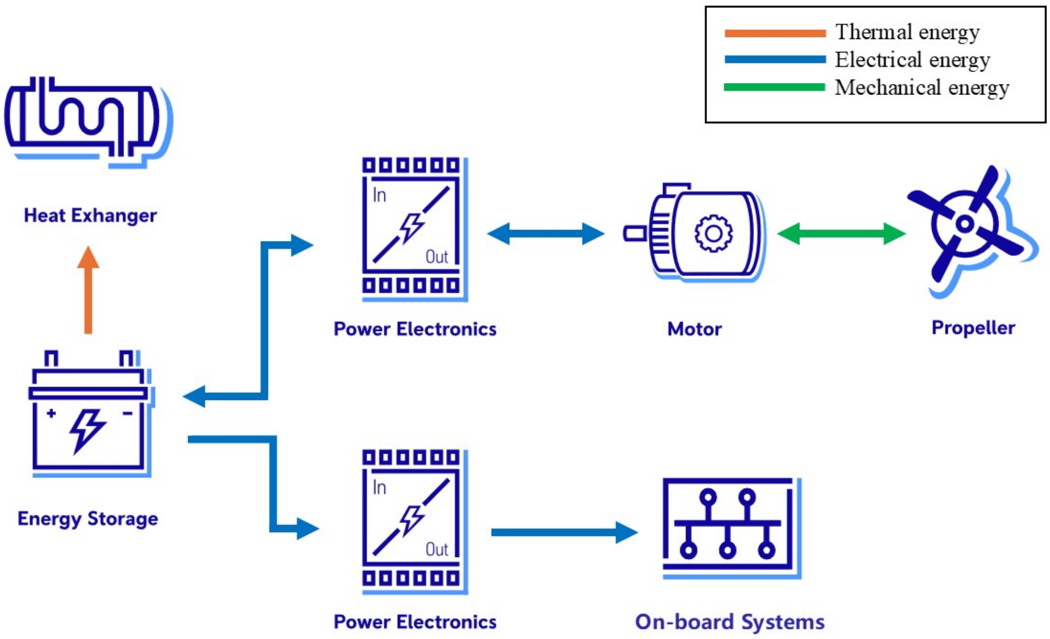


Figure 4.1.: All-electric propulsion system

Hybrid-electric

This type of propulsion is characterised by greater complexity than all-electric owing to the use of two energy sources. Hybrid-electric propulsion systems come in several topologies, two of which are analysed and modelled in this thesis: series and parallel.

The main feature of the series hybrid-electric (Fig. 4.2) is that there is no mechanical connection between the internal combustion engine and the propeller. Chemical energy in the form of fuel feeds the engine, which produces mechanical energy by burning it. The engine is connected to a generator that converts the mechanical into electrical energy. The electricity generated by the generator is then regulated by a power distribution unit and/or power electronics, which can be transmitted simultaneously to the electric motor and battery or directly to one of these two propulsion subsystems. The way the electricity is distributed depends on the designed operating strategy of the propulsion system. Bidirectional electrical flow only occurs between the battery and the electric motor connected to the propeller. As with all-electric propulsion, unidirectional power flow occurs between the battery and the on-board systems through the power distribution unit and/or power electronics. Also, between the electric motor and the propeller, a gearbox can be mounted. The battery transfers excess thermal energy to the heat exchanger in the thermal management subsystem, just as in the all-electric.

An aircraft with such propulsion can operate in three modes: using energy from the battery without the engine running, generating the electrical energy by the combustion engine-generator system, or jointly by both energy sources. The three ways of driving the propeller depend on the maximum amount of electricity the battery can produce and its level of charge. The internal combustion engine in such a system operates at the most optimal parameters for the vast majority of the time.

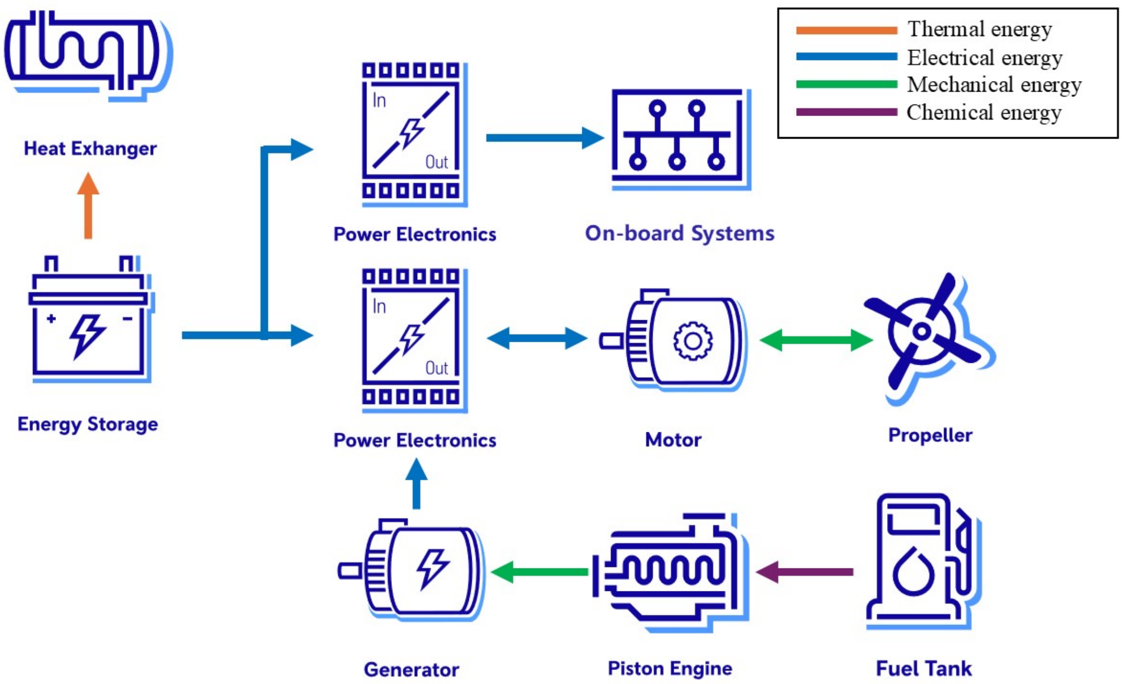


Figure 4.2.: Series hybrid-electric propulsion system

Parallel hybrid-electric propulsion can be briefly characterised as a combination of all-electric and conventional propulsion through a gearbox to drive a common propeller, as shown in Fig. 4.3. A second possible version of this topology is when the aircraft has two or more propellers that are driven separately by a conventional engine or an electric motor.

In the case of the parallel hybrid-electric configuration shown in Fig. 4.3, chemical energy in the form of fuel supplies the internal combustion engine, which generates mechanical energy by burning it. The rotating shaft of the engine is connected to the gearbox. For the electrical part of the drive, the mechanical energy of the electric motor has the same flow as that in the all-electric drive. The shaft of the electric motor is also connected to the gearbox, which allows the propeller to be driven jointly or separately to generate the aircraft's thrust. Between the propeller and the battery, the current flow is bi-directional, allowing the batteries to be charged by the propeller recuperation or by the internal combustion engine. Batteries also power the on-board systems and emit thermal energy that is transferred to the heat exchanger.

This topology allows the use of smaller, and therefore lighter, electric and combustion engines than a series hybrid. On the other hand, does not always operate at its most optimal performance. In addition, the mechanical connection between the combustion engine and the propeller via gearboxes limits the possible engine's location inside the airframe. The amount of mechanical energy generated by the electric motor is determined by the degree of hybridisation and depends on the strategy developed. The aircraft can operate in pure electric mode.

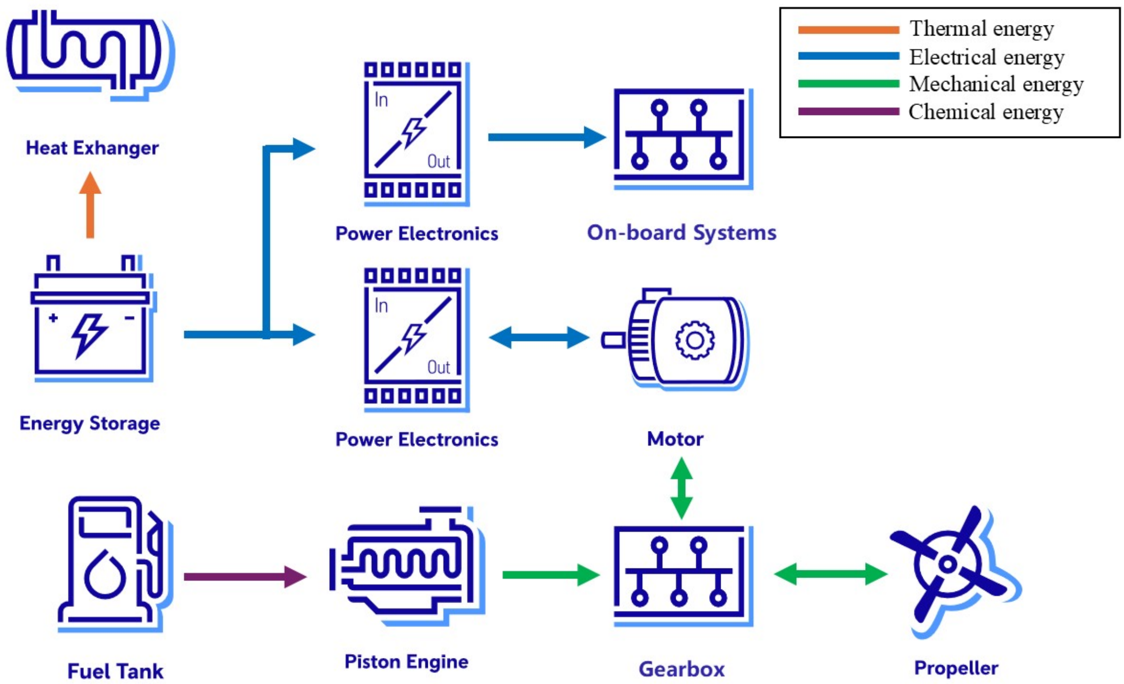


Figure 4.3.: Parallel hybrid-electric propulsion system

In order to be able to maximise the potential of hybrid-electric propulsion, it seems reasonable to include in each of the analysed topologies a subsystem that allows batteries to be recharged from the grid (as in an automotive plug-in hybrid), rather than rely solely on the operation of the internal combustion engine and generator or propeller recuperation, which, unlike in cars, the conditions are not often available during flight to implement.

Hydrogen fuel cell

This propulsion system (Fig. 4.4) usually uses two energy sources, hydrogen and batteries. Electricity is supplied to the electric motor mainly by hydrogen fuel cells. The chemical energy contained in hydrogen is converted by these fuel cells into direct current (DC), which has a low voltage and thus requires the use of a power electronics and/or power distribution unit to raise it before it reaches the electric motor. Fuel cells also power on-board systems. The flow of electricity between fuel cells and the electric motor and on-board systems is unidirectional.

The main function of batteries is to provide additional electricity for the electric motor at times of increased and/or dynamically changing load. They can be charged by hydrogen fuel cells or by propeller recuperation. The flow of electricity between the battery and the electric motor is bidirectional.

Both the battery and the hydrogen fuel cells transfer the excess heat generated to a heat exchanger that is part of the thermal management subsystem. Depending on the operating parameters of the electric motor, a gearbox can be mounted between it and the propeller to adapt the rotational speed to the propeller's limits.

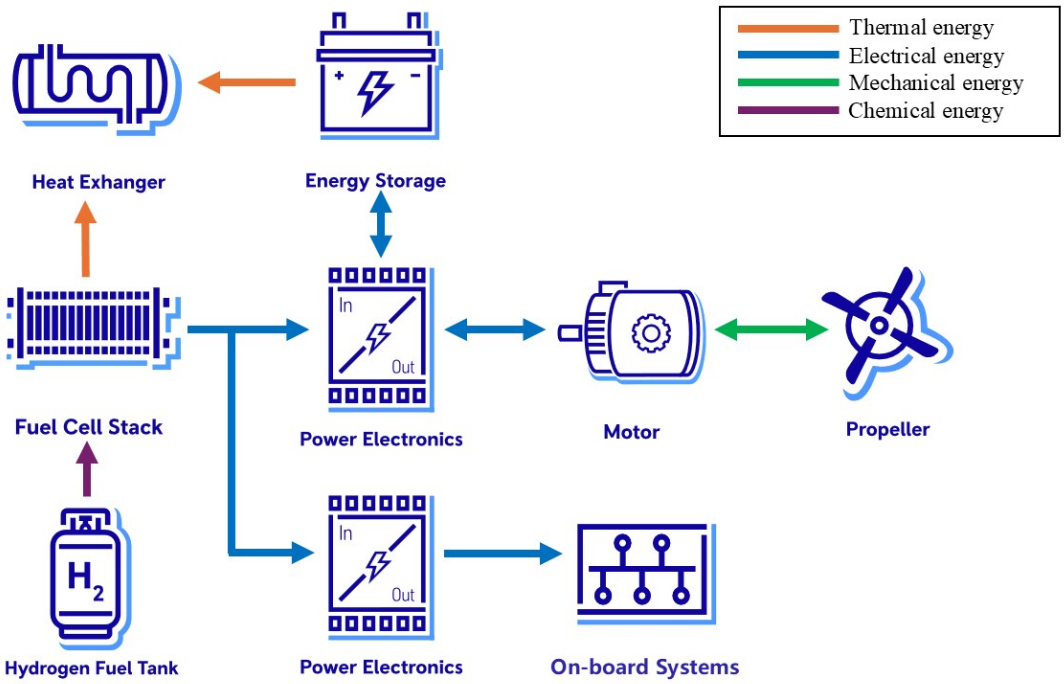


Figure 4.4.: Hydrogen fuel cell propulsion system

4.2. Modelling of the propulsion systems

MATLAB/Simulink software was chosen to develop the simulation models of the propulsion systems analysed in Section 4.1. This is a tool developed by MathWorks and used, among other things, for programming, simulating, and analysing dynamic systems. MATLAB is an environment that uses its own programming language for numerical analysis. The basic file used by MATLAB is a script in which the user creates the code for their programme. Simulink is part of MATLAB and allows the graphical designing of multi-domain dynamic simulation models using blocks available in the library- some of them are presented in Chapter 3, or created by the user.

Each of the alternative propulsion models developed consists of three files: two scripts in MATLAB containing simulation parameters and functions for calculating flight parameters, and one with a simulation model in Simulink. The developed models were built as an extension of the “Electrical Component Analysis for Hybrid and Electric Aircraft” model created by the MathWorks team[1].

The approach to modelling the analysed system depends on the assumptions and requirements that must be defined at the beginning of the model design. They determine the level of complexity and accuracy of the model, and thus the choice of modelling approach. The simulation models of alternative propulsion systems in this thesis have been developed to determine the parameters of the main propulsion subsystems depending on the flight mission. To achieve this goal, the developed models need to answer the question of energy demand at each stage of flight. The next assumption was to use forces as a common denominator for the parameters of the aircraft systems and subsystems that represent the different physical domains (see Section 2.1). An additional requirement was the ability to simulate different flight missions. The range of simulation capabilities of the developed models was limited to aircraft with MTOWs compliant with the EASA CS-23 document.

Based on assumptions and requirements, the backward approach and system-level simulation were chosen as methods for modelling the propulsion system. The backward approach requires a pre-planned flight mission, whose parameters such as flight speed and climb determine the energy requirements. This method does not require precise parameterisation of the subsystems of the system under analysis, and the simulation time is very short. System-level simulation, on the other hand, is an approach that allows the simulation of the entire system, and the level of accuracy of the representation of the subsystems that make it up is adapted to the requirements for the model. This allows the model to be simplified and modelled in such a way that only the questions asked, such as energy demand, are answered.

Each of the simulation models developed consists of four main modules: flight control module, environment, airframe and propulsion (Fig. 4.5).

[1] Available online at: https://www.mathworks.com/help/aeroblks/Electrical-Component-Analysis-Hybrid-and-Electric-Aircraft.html.

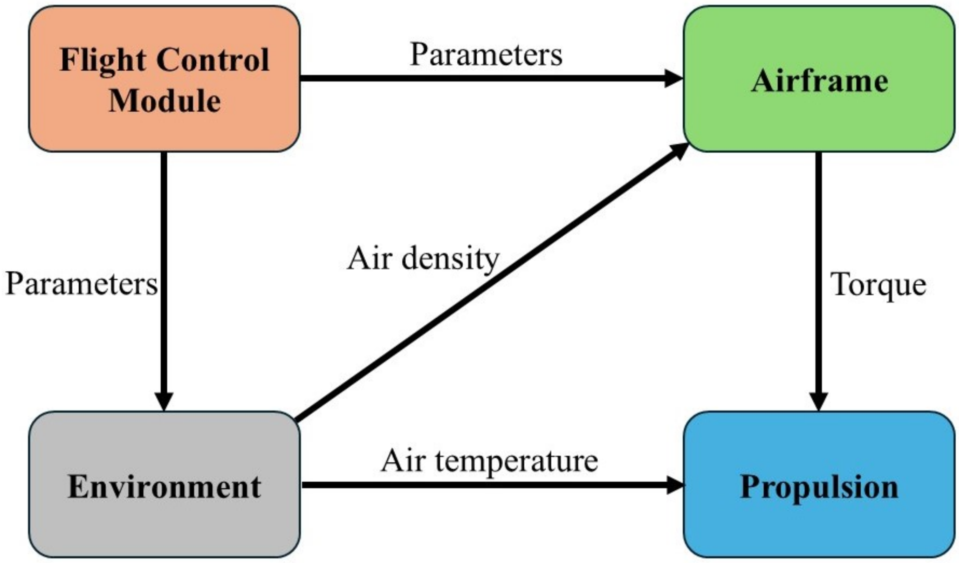


Figure 4.5.: Four main blocks of the simulation model along with the parameter flow

The flight control module was created using Stateflow[2]. It contains all the parameters of a planned flight mission such as electric motor rotational speed, aircraft airspeed and flight altitude. Five types of aviation missions are defined: simple and complex cross-country flight, traffic pattern flight, glider towing and skydiving flight. The additional procedures to be followed for the simulated aircraft are also defined in the event that the battery charge or fuel quantity falls below the user-defined safety minimums. The flight control module plays the role of the pilot in the model and manages the flight mission parameters during the simulation. For each propulsion model, the flight control module is adjusted accordingly due to the different or additional parameters that characterise the propulsion system. Parameters from the flight control module are passed to the environment and airframe modules.

The environment module is used to calculate the parameters of the Earth's atmosphere in which the aircraft is moving. For the simulation models developed, it provides values for temperature and air density as a function of flight altitude. For this purpose, the flight control module passes information to environment about the airspeed and rate of climb of the aircraft. The environment uses the International Standard Atmosphere (ISA) model for the calculations. Information on air density is passed to the airframe module and on air temperature to the propulsion module.

The task of the airframe module is to calculate the required torque that should be produced by the propulsion system. To determine it, the airframe module uses flight data from the flight control module, the aerodynamic characteristics of the aircraft defined in the parameter script and the air density depending on the altitude at which the aircraft is at any given time during the simulation from the environment module. From these, the four main forces acting on the aircraft are calculated: weight, thrust, lift and drag. These are then used to calculate the net forces acting in the x, y and z axes of the aircraft using a

[2] A tool that is part of Simulink and is used to create control logic for a simulation model.

block available in the Simulink library called "6th Order Point Mass Forces (Coordinated Flight)" (Fig. 4.6).

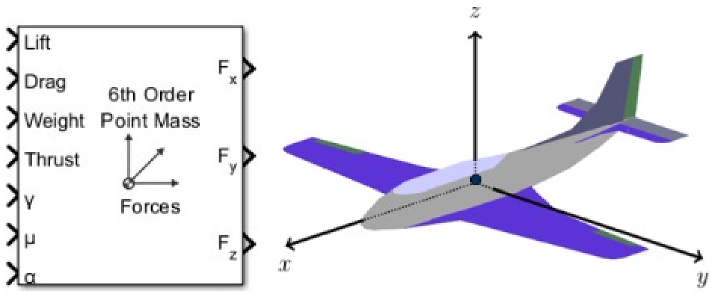


Figure 4.6.: 6th Order Point Mass Forces (Coordinated Flight) block and aircraft's axes

This block calculates the resultant forces using the following equations:

$$F_x = T\cos\alpha - D - W\sin\gamma, \tag{4.1}$$

$$F_y = (L + T\sin\alpha)\sin\mu, \tag{4.2}$$

$$F_z = (L + T\sin\alpha)\cos\mu - W\cos\gamma, \tag{4.3}$$

where: F_x, F_y, F_z- net forces acting on the aircraft in the axes, x, y, z respectively, T-thrust force, D- drag force, W- aircraft weight, α- angle of attack, μ- bank angle, γ- flight path angle.

The net force F_x is then used to calculate the actual speed of the aircraft. The product of this speed and the thrust force is the power. The ratio of the power to the RPM of the propeller gives the torque that must be produced by the propulsion system.

The last module in the simulation model developed is propulsion, which represents both the propulsion system and energy storage. It was developed using Simscape[3]. It is used to determine the relevant operating parameters of the main subsystems of the propulsion and energy storage system. This is achieved by using a backward approach that causes the propulsion module to be "forced" by the airframe module to produce the required torque, affecting the energy consumption of the electric motor and/or combustion engine. The propulsion module comes in two versions for each of the alternative propulsion systems analysed: with one or multiple propellers. The air temperature, which is reported from the environment module, is used by the thermal management subsystem to control the battery temperature. The simulation models of each propulsion system analysed in this are described in more detail in Section 4.3.

The following simplifications have been applied to the simulation models developed:

1. Propeller(s) are represented only by their efficiency expressed as a percentage,
2. The aircraft is considered as a point mass,

[3] Simscape is an add-on programme that is part of Simulink, allowing the modelling and simulation of multidomain physical systems.

3. Use of direct current (DC) for all subsystems, including the electric motor,
4. Omitted aspect of heat generation by propulsion and energy storage subsystems, except for batteries and hydrogen fuel cells,
5. Assumption that flight takes place in ideal conditions- windless and non-thermal.

The first three simplifications are related to the use of a backward approach and allow subsystems to be omitted or selected from the Simulink library that do not require precise parameterisation. The fourth simplification is to simplify the model and apply the thermal management subsystem only to batteries and hydrogen fuel cells, whose performance degrades significantly when they do not operate at their optimum temperatures. For the battery in particular, this is a key aspect because of its thermal sensitivity and thus impact on the aircraft's range. The last assumption also aims to simplify the design of the simulation model. The simplifications adopted made it possible to create a generic simulation model for the category of aircraft defined in document CS-23. Simulated aircraft are characterised only by basic parameters.

4.3. Simulation models of the alternative propulsion systems

The main task of the simulation model described in Section 4.2 is to determine the parameters of the main propulsion subsystems. The four variants of the propulsion module are considered: all-electric, series and parallel hybrid-electric, hydrogen fuel cell. In this module, the propulsion system has been modelled together with the energy storage and, in addition, the thermal management subsystem and the on-board systems, which provide additional load to the propulsion system.

All-electric propulsion model

This model (Fig. 4.7) was developed first and became the basis for the design of the other propulsion simulation models. It is divided into four basic subsystems: battery, electric motor, thermal management and on-board systems. As an additional load for propulsion and energy storage on-board systems lamps, avionics and environmental control system (ECS) are modelled. The ECS activates when the aircraft exceeds a predetermined flight altitude, e.g., 500 m above sea level, during climb, and switches off when the aircraft descends below this predetermined altitude. This is due to the fact that as the flight altitude increases, the outside air temperature decreases.

Batteries can be recharged via propeller recuperation. In the flight control module, the user defines the discharge level of the batteries, which, when reached during the simulation, results in the aircraft starting a descent and then landing. For example, for the simulations performed as part of this work, this level was set at 30%. This is done to ensure that there is sufficient reserve to carry out a safe landing and to ensure that the battery is protected from being discharged too deeply.

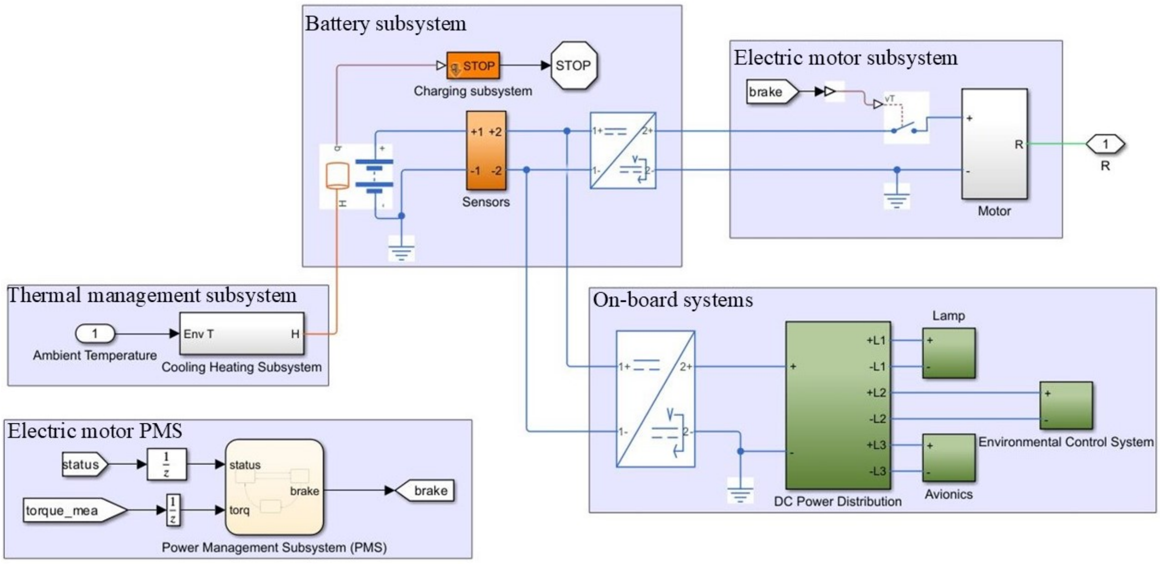


Figure 4.7.: All-electric propulsion block in simulation model

Series hybrid-electric propulsion model

The simulation model of a series hybrid-electric (Fig. 4.8) differs from the all-electric model by the addition of an engine&generator subsystem and an additional load in the on-boards systems in the form of a fuel pump. The electric motor can be powered by electrical energy: directly produced by the generator, coming only from the battery or jointly by both subsystems.

As in the all-electric model, when the battery discharge level set by the user is reached, the flight control module initiates the descent and subsequent landing of the aircraft. The operating parameters of the internal combustion engine and generator are controlled by the engine management subsystem, which was designed using Stateflow, just like the flight control module. Three states of the internal combustion engine and generator are defined: off, normal mode and power mode. The engine and generator are off when: the battery charge level is sufficiently high, part of the flight is to take place in electric mode only, such as the initial take-off phase to reduce noise, and when there is no fuel. Normal mode means running the engine at the most optimal parameters. The engine and generator operate in this mode when the battery discharge level is within user-defined limits; e.g. in this work the following limits have been defined: 80%- switching on the subsystem and operating in normal mode, and 50%, which is the lower limit, and a drop in battery charge to this level results in the engine and generator entering power mode. This mode means operating at higher and less optimal parameters. This is done to generate enough electricity to cover the demand of the electric motor and charge the battery at the same time. The fuel pump only runs when the combustion engine is running.

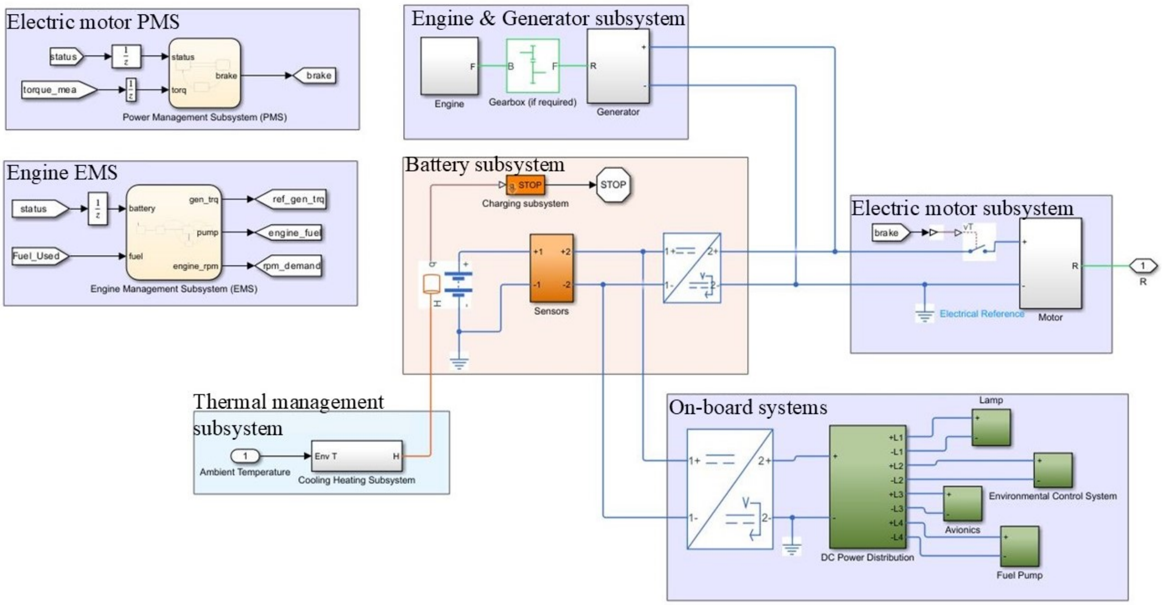


Figure 4.8.: Series hybrid-electric propulsion block in simulation model

Parallel hybrid-electric propulsion model

In a parallel hybrid-electric, the propeller is driven jointly or separately by an electric motor as well as by an internal combustion engine. Compared to the simulation model of the series hybrid-electric developed in this work, the parallel hybrid-electric model (Fig. 4.9) is equipped with an alternator, which is mainly used to generate electrical power to balance the amount of energy drawn by the on-board systems. Connecting the alternator as used in this model allows it to be simplified by not having to model an additional battery. At the same time, the alternator can be adapted to perform the function of charging the battery of an electric motor.

The separation of the electric motor and the combustion engine, and the lack of a common gearbox, are due to the use of variable percentages of propulsion to generate the aircraft's thrust. For example, during level flight, the internal combustion engine is responsible for generating 70% of the required power, and the electric motor 30%.

In the flight control module developed for this simulation model, three in-flight scenarios have been prepared: joint operation of the electric and combustion engines, battery discharge below a predetermined level and flight using the combustion engine only, battery discharge and reaching fuel reserve resulting in the aircraft proceeding to descent and then landing. Additional propulsion operation scenarios can be developed and implemented in the flight control module.

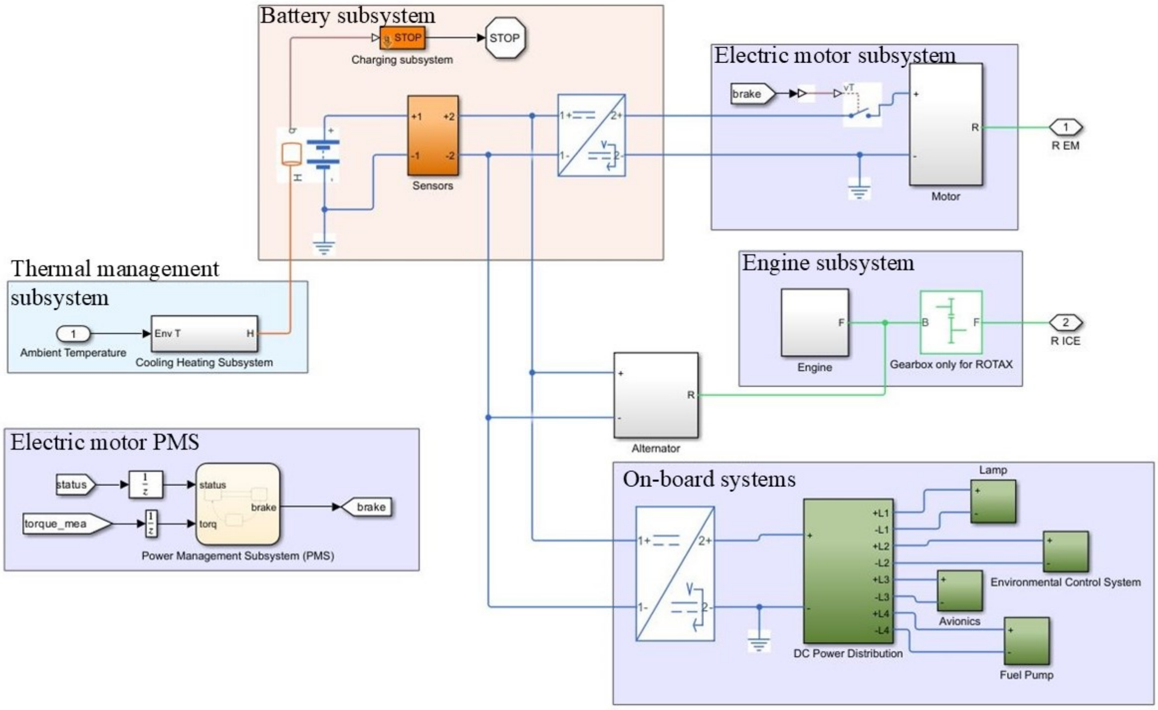


Figure 4.9.: Parallel hybrid-electric propulsion block in simulation model

Hydrogen fuel cell propulsion model

This simulation model (Fig. 4.10) features the same layout as a series hybrid-electric- in place of the engine&generator subsystem is the fuel cell subsystem. The main source of electricity is the hydrogen fuel cell, which runs all the time, and therefore the fuel pump operates all the time drawing electricity. The battery, on the other hand, provides support for the fuel cells at times of increased power demand by the aircraft. When the battery discharge level reaches a user-defined value, the aircraft proceeds to descent and landing. The amount of hydrogen is not defined, as one of the tasks of the developed simulation model is to determine the required amount of hydrogen that the aircraft needs to take on a simulated flight. This is to appropriately select the hydrogen tanks for the designed aircraft, ensuring that the aircraft achieves the required range.

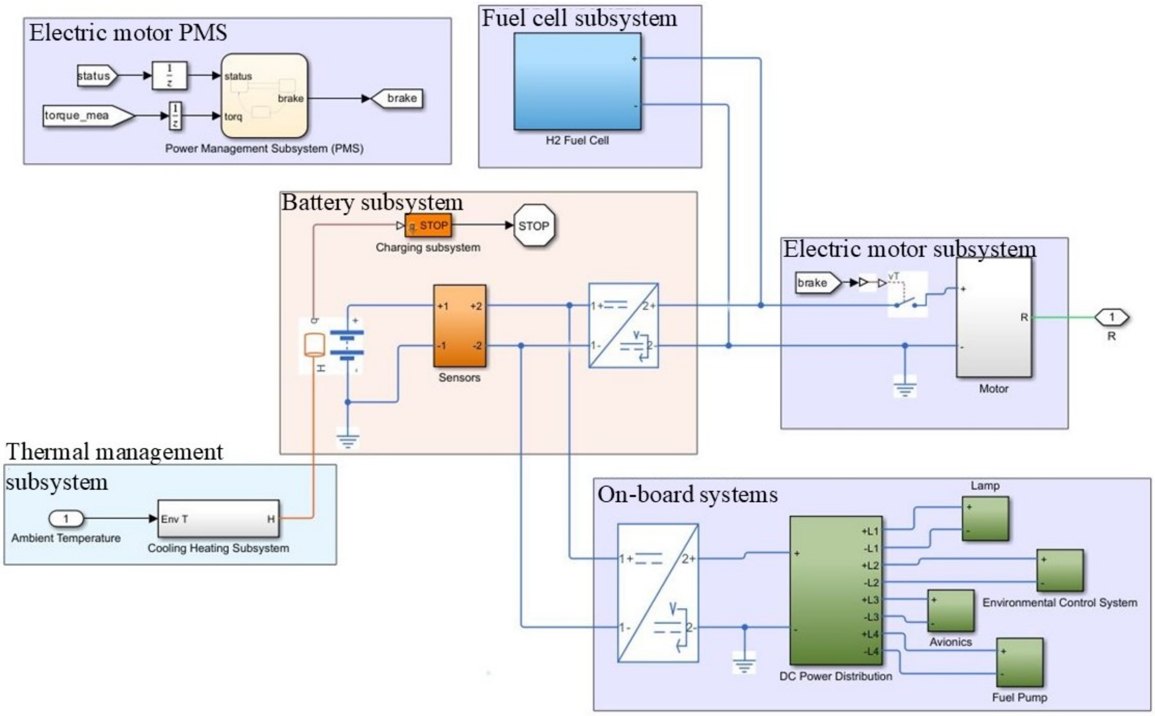


Figure 4.10.: Hydrogen fuel cell propulsion block in simulation model

5. Alternative propulsion system arrangement

The use of alternative propulsion systems influences the design of the entire aircraft and its internal configuration. The models of the propulsion system developed in Chapter 4 allow the required parameters of the propulsion subsystems and components to be defined and specified regardless of their final design. The identification of these parameters, which essentially represent the requirements of subsystems and components, means that the new systems design approach developed in this thesis enables a modified, more cooperative design process between aircraft manufacturers and suppliers. This more intensive collaboration enables the development of an appropriate, optimised arrangement of propulsion subsystems in the airframe, which will maintain the proper mass and balance of the aircraft. Also, when arranging propulsion subsystems in the airframe, it is important to take into account safety requirements that may prevent the chosen configuration from being used in the aircraft.

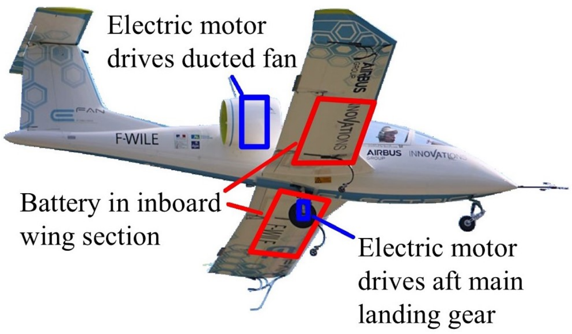
A suitable modelling tool which allows the consideration of the integration of an alternative propulsion system and takes into account the impact on airframe design is OpenVSP. In addition, it allows aerodynamic analyses to be carried out to determine the drag and lift coefficients that affect the magnitude of these forces acting on the aircraft and, thus, the required thrust. The values of these coefficients obtained from the aerodynamic analysis are used in the propulsion model within the iterative design process. OpenVSP is used in this work to analyse the wing parameters in the initial design phase of the aircraft, and then to develop the entire aircraft model including the layout of the propulsion subsystems and their significant effects on the airframe.

5.1. Analysis of the airframe modelling and propulsion subsystems configuration

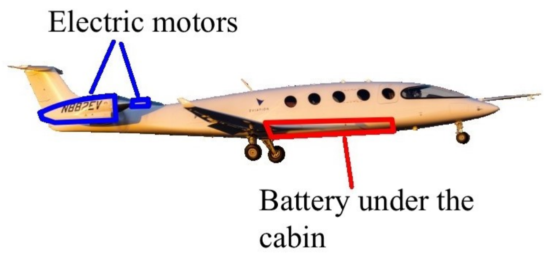
Interest in the use of alternative propulsion in aviation is mainly shown by the development of various new designs and the building of technology demonstrators by retrofitting a conventionally powered aircraft. In the case of all-electric aircraft, which represent the largest number among alternative propulsion aircraft, there are already aircraft built from the outset as electric, among them the Airbus E-Fan (Fig. 5.1a) and Eviation Alice (Fig. 5.1b). The former is a technology demonstrator in the form of a two-seater aircraft designed to train pilots with tandem seats to reduce the fuselage cross-section and thus the drag force. Batteries are integrated inside the wings and provide an electrical energy supply for a 45-minute flight. The Airbus E-Fan has three electric motors: one driving the rear main landing gear to help accelerate the aircraft during take-off or when it is taxiing and two in the ducted fans located in the rear of the fuselage. Meanwhile, the Eviation Alice is a prototype aircraft designed to transport up to nine passengers or cargo. The fuselage of this aircraft has been designed in such a way that batteries are placed under the cabin floor. Two electric motors were placed at the rear of the fuselage that drive traditional propellers.

The retrofitted aircraft represent the largest number among all-electric powered aircraft. Prominent in this group is the Pipistrel Velis Electro (Fig. 5.1c), which is the world's first certified alternative-powered aircraft. It is an electric version of the Pipistrel Virus SW 121 designed for pilot training and provides an electrical power reserve for up to 50 minutes of flight. It is an ultralight class aircraft with a MTOW of 600 kg. The Velis Electro has two batteries - behind the cockpit and behind the electric motor, which is located in the front of the fuselage. Both the Airbus E-Fan, Eviation Alice and Pipistrel Velis Electro are aircraft that have proven their capabilities in flight tests. Among them, the Airbus E-Fan was the first to do so back in 2014.

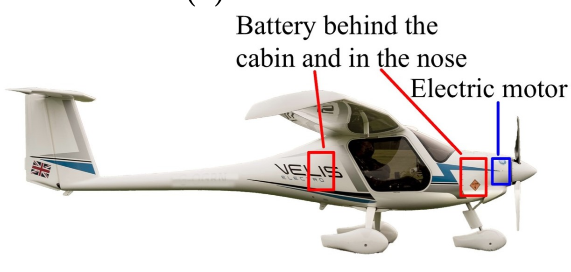
The Tecnam P-Volt (Fig. 5.1d), which is the design of the electric version of the Tecnam P2012 Traveller, presents a different approach to the retrofitting of the aircraft with the alternative propulsion. It is intended to take up to nine passengers and two pilots on board. In order to provide enough space in the passenger compartment, the batteries are placed in the pod underneath the fuselage, which increases the drag force generated during the aircraft's flight. The electric motors are placed at the original location of the internal combustion engines. The Tecnam P-Volt aircraft project is currently not being continued.



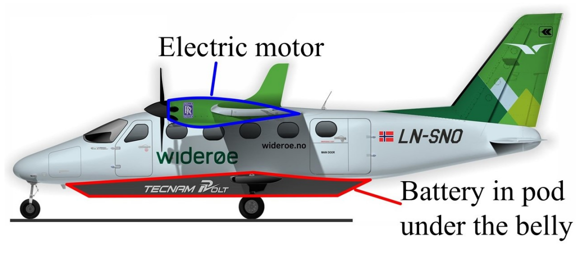
(a) Airbus E-Fan



(b) Eviation Alice



(c) Pipistrel Velis Electro



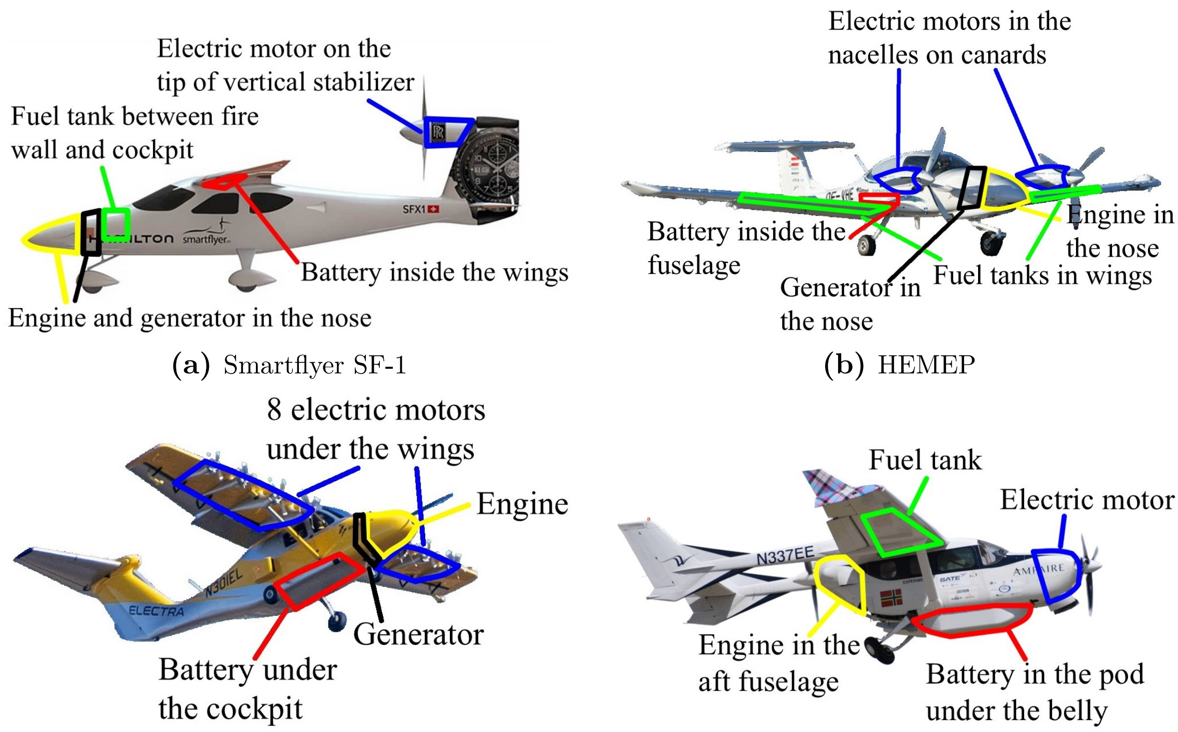
(d) Tecnam P-Volt

Figure 5.1.: Examples of electrically-powered aircraft

The second alternative propulsion system most commonly used in the design of various aircraft is hybrid-electric propulsion. The Smartflyer SF-1, HEMEP, Electra EL-2 Goldfinch and Ampaire Electric EEL aircraft represent different approaches to integrating hybrid-electric propulsion into the airframe. The Smartflyer SF-1 (Fig. 5.2a) is an aircraft built from scratch as a hybrid-electric aircraft, currently at the design stage. The Smartflyer SF-1 is designed for recreational flying for three passengers and one pilot with a hybrid-electric propulsion in a series configuration. The internal combustion engine and generator are integrated into the nose of the fuselage with the airframe. The fuel tank is placed between the cockpit and the fire wall, which separates it from the internal combustion engine and the generator. The batteries are located inside the wings. The electric motor is located in the nacelle at the top of the vertical tail. The second aircraft that also uses series hybrid-electric propulsion is the HEMEP (Hybrid Electric Multi Engine Plane) (Fig. 5.2b), built as a retrofit of the Diamond DA40 aircraft. Compared to the conventionally powered DA40, the HEMEP was equipped with two propellers, each driven by a single electric motor, which are located in the nacelles and connected to the front of the fuselage via canards. The internal combustion engine, together with the generator, is located in the nose of the fuselage and is powered by fuel stored in tanks integrated inside the wings. The position of the internal combustion engine is the same as in the DA40, which is driven by a single propeller. The batteries in the HEMEP are located inside the fuselage behind the pilots' seats.

In contrast, the Electra EL-2 Goldfinch aircraft (Fig. 5.2c) is the only hybrid-electric propulsion aircraft developed from scratch that has been flown to date. The aircraft uses distributed electric propulsion (DEP)-four electric motors under each wing-and incorporates blown-lift wing technology allowing for short take-off and landing (STOL). The aircraft use a series hybrid-electric propulsion system. The batteries are located under the cockpit and the internal combustion engine together with the generator are in the fuselage nose.

The Ampaire Electric EEL (Fig. 5.2d) presents a different approach to integrating a new propulsion system into an existing airframe, which uses a parallel hybrid-electric propulsion system. The Ampaire Electric EEL is a modified Cessna 337 whose front internal combustion engine is replaced with an electric motor. However, the rear engine remained as an internal combustion engine. To provide space for three passengers, the batteries powering the electric engine are located in the pod under the fuselage. The fuel tanks are inside the wings. The internal combustion engine and the electric motor work together during take-off and climb. During level flight, the percentage of the electric motor powering the Ampaire Electric EEL depends on the flight parameters and battery charge level.



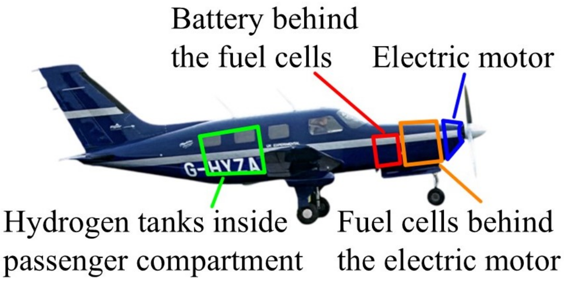
(a) Smartflyer SF-1 **(b)** HEMEP

(c) Electra EL-2 Goldfinch **(d)** Ampaire Electric EEL

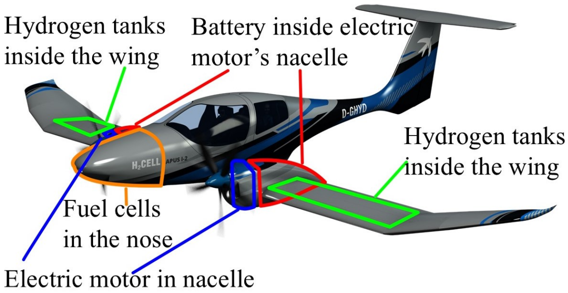
Figure 5.2.: Examples of aircraft with hybrid-electric propulsion systems

The third type of alternative propulsion system analysed in this thesis is hydrogen fuel cells. The number of hydrogen fuel cell aircraft designs developed is lower than for the other two alternative propulsion systems investigated. In contrast to other alternative propulsion systems, hydrogen fuel cell aircraft, which have been developed as a result of retrofitting, have been flown. One of these is the ZeroAvia HyFlyer (Fig. 5.3a) based on the Piper Malibu. The electric motor, hydrogen fuel cells and batteries are located in the nose of the aircraft, while the hydrogen tanks are inside the fuselage, behind the cockpit, resulting in a lack of space for passengers. The ZeroAvia HyFlyer serves as a testbed.

An aircraft concept built from scratch for hydrogen fuel cells is the APUS i-2 (Fig. 5.3b). It is a twin engine aircraft where the electric motor and batteries are placed in nacelles integrated into the wings. The hydrogen fuel cells are located in the nose of the fuselage. A distinctive element of this design is the integration of hydrogen tanks inside the wings, which allows the fuselage to remain fully functional and provide adequate space for passengers. Batteries serve as a booster for the fuel cells in power-intensive moments during flight.



(a) ZeroAvia HyFlyer



(b) APUS i-2

Figure 5.3.: Examples of aircraft with hydrogen fuel cells

Most often, alternative propulsion systems are integrated into existing airframes, requiring additional external components such as nacelles and pods. This results in the an additional increase in drag force and power requirements of the aircraft. On the contrary, the advantage is that there are no or limited changes to the internal space in the fuselage for passengers or cargo. The aircraft used as testbeds most often have subsystems of the new propulsion system located in the passenger compartment, as this is the easiest integration and does not require significant changes to the structure of the airframe. Building an aircraft from scratch for an alternative propulsion system allows greater freedom in the arrangement of the new propulsion subsystems and the required functionality of the aircraft.

5.2. Characteristics matrix for alternatively powered aircraft

The integration of alternative propulsion in an aircraft can introduce changes within the airframe structure, affect the values of the forces acting on it during flight, the amount of free space inside the fuselage and thus the parameters of the flight mission. The effect that a new propulsion system can have also depends on the approach to the development of such an aircraft: as a retrofit of an existing conventionally powered model or as a new design. Whichever approach is chosen, it is important to ensure that the aircraft has adequate, safe mass distribution.

In the first case, the aircraft already has a defined shape and dimensions, which imposes limitations on the integration of the new propulsion system into the airframe. For this reason, nacelles or pods are most commonly used, forming additional space for the new propulsion subsystems and allowing for more freedom in the way they are integrated. As an additional external component of the airframe, they cause an increase in drag force. When nacelles with internal combustion engines from conventional propulsion are mounted on the wings, if electric motors are used instead, the drag force will decrease due to their smaller size of the motors and thus the nacelle. Integration of the new propulsion system into the airframe is also more often achieved by installing some of the propulsion subsystems in the passenger compartment of the aircraft, thus reducing the number of available seats. Some propulsion subsystems require their own air intake for cooling or for combustion, resulting in the need for additional intakes in the fuselage. This leads to an increase in the drag force. If some subsystems are integrated into the nose section of the fuselage, this can result in a change in its dimensions and shape. The interior of the wing allows for the integration of such subsystems of the new propulsion system, whose shape can be adapted to the free space. Most often, wings have an integral fuel tank, whereas the free space in the wing can be adapted to integrate batteries by removing or reducing the capacity of the fuel tank.

The most relevant ways of integrating the new propulsion system into the existing airframe, summarised in Tables 5.1 and 5.2, not only result in an increase in drag force and a reduction in available space inside the airframe, but also affect the balance of the aircraft and its inertia. This has an impact on the aircraft's behaviour and energy consumption. Poor aircraft balance is a major threat to flight safety. An additional aspect is the MTOW of the aircraft, which was determined for the conventional propulsion system originally used in the aircraft. The structural components of the airframe, including the landing gears, were designed for this value and for this reason such an aircraft with a new propulsion system cannot exceed the MTOW.

Table 5.1.: Characteristics matrix for integration of new propulsion systems in retrofitted aircraft: electric motor, combustion engine, generator, fuel cells and hydrogen tank

	Nacelle		Fuselage	
Propulsion subsystem	Integration	Effect	Integration	Effect
Combustion engine	In the wing, under the wing, at the tip of the VT or wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft	Nose shape, air inlets, drag coefficient, space inside, weight, mass distribution, inertia
Generator	In the wing, under the wing, at the tip of the VT or wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft	Space inside, nose shape, drag coefficient, weight, mass distribution, inertia
Fuel cells	In the wing, under the wing, as a pod under the fuselage	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft, in passenger compartment	Space inside, nose shape, drag coefficient, weight, mass distribution, inertia
Electric motor	In the wing, at the tip of the VT or wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft	Space inside, weight, mass distribution, inertia
Hydrogen tank	Under the wing, as a pod under the fuselage	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft, in passenger compartment	Space inside, nose shape, drag coefficient, weight, mass distribution, inertia

Table 5.2.: Characteristics matrix for integration of new propulsion systems in retrofitted aircraft: battery and fuel tank

	Nacelle		Fuselage		Wing	
Propulsion subsystem	Integration	Effect	Integration	Effect	Integration	Effect
Battery	As a pod under the fuselage	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft, in passenger compartment	Space inside, weight, mass distribution, inertia	Inside the wing	Internal configuration, weight, mass distribution, inertia
Fuel tank	Under the wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles, weight, inertia	In the nose, in the aft, in passenger compartment	Space inside, weight, mass distribution, inertia	Inside the wing	Internal tank volume, weight, mass distribution, inertia

Designing an alternatively powered aircraft from scratch allows all or most subsystems of the new propulsion system to be “hidden” inside the airframe, thus reducing the number of nacelles and the drag associated with their use. The designer has more freedom to develop the most optimal configuration in terms of the space to be used inside the aircraft and its lift-to-drag ratio. Unlike retrofitting, the airframe geometry is tailored to the needs of the subsystems of the new propulsion system and the missions for which the new aircraft is designed.

The biggest changes are taking place in the design of the fuselage, which may feature a more unusual shape than conventionally powered aircraft. This is due to the integration of the subsystems of the new propulsion system and to ensure that the usable space inside the fuselage is large enough to accommodate the required number of passengers or cargo. The redesigned wings allow for optimal integration of the propulsion energy sources used: hydrogen tanks, batteries alone or together with conventional fuel tanks. In addition, they can be designed for distributed electric propulsion (DEP) and integrate nacelles housing electric motors, which have a smaller size than nacelles with conventional engines, in order to reduce aerodynamic drag. The wing profile can be adjusted to have the right lift and drag coefficients to better match aircraft speeds such as cruise and stall. Nacelles can still be applied not only to the electric or internal combustion engine, but also in the case of a retrofitted aircraft. The possible integration of the new propulsion subsystems into a new aircraft designed from scratch is summarised in Tables 5.3 and 5.4.

An additional advantage of designing a new alternative-propulsion aircraft from scratch is that it is possible to ensure from the outset that the aircraft is properly balanced and the other airframe components such as landing gears are adjusted to the designed MTOW. In the case of a new design aircraft, the size of the control surfaces is also selected to suit the inertia of the aircraft and its required time reaction to the controls.

Table 5.3.: Characteristics matrix for integration of new propulsion systems in new designed aircraft: combustion engine, generator and fuel cells

Propulsion subsystem	Nacelle		Fuselage	
	Integration	Effect	Integration	Effect
Combustion engine	In the wing, under the wing, at the tip of the VT or wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles	In the nose, in the aft	Shape, dimensions, drag coefficient, inside configuration
Generator	In the wing, under the wing, at the tip of the VT or wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles	In the nose, in the aft	Shape, dimensions, drag coefficient, inside configuration
Fuel cells	In the wing, under the wing, as a pod under the fuselage	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles	In the nose, in the aft, central section	Shape, dimensions, drag coefficient, inside configuration

Table 5.4.: Characteristics matrix for integration of new propulsion systems in new designed aircraft: electric motor, hydrogen tank battery and fuel tank

	Nacelle		Fuselage		Wing	
Propulsion subsystem	Integration	Effect	Integration	Effect	Integration	Effect
Electric motor	In the wing, at the tip of the VT or wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles	In the nose, in the aft	Shape, dimensions, drag coefficient, inside configuration	as distributed electric propulsion (DEP), pusher or tractor configuration	Drag coefficient, lift coefficient, shape
Hydrogen tank	Under the wing, as a pod under the fuselage	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles	Under or above the passenger compartment, in the nose, in the aft	Shape, dimensions, drag coefficient, inside configuration	Inside the wing	Internal structure, design, lift and drag coefficient
Battery	As a pod under the fuselage	Length, cross-sectional dimensions, shape, drag coefficient	in the nose, in the aft, under the passenger compartment	Shape, dimensions, drag coefficient, inside configuration	Inside the wing	Internal structure
Fuel tank	Under the wing	Length, cross-sectional dimensions, shape, drag coefficient, number of nacelles	In the nose, in the aft	Shape, dimensions, drag coefficient, inside configuration	Inside the wing	Internal tank volume

5.3. Aircraft modelling with OpenVSP software

OpenVSP (VSP- Vehicle Sketch Pad) is open-source software that is used to create parametric geometric 3D models. It is intended for use in the conceptual phase of the aircraft design process. OpenVSP was created by NASA and later made available and further developed by users. Furthermore, the “OpenVSP Airshow” (up to 08.2024 appearing as “The Hangar”) was created as a platform to allow users to share their models [4, 61, 69].

During modelling, the user first selects the airframe component available in the OpenVSP, e.g. wings, fuselage, which they then customise by changing its parameters (Fig. 5.4).

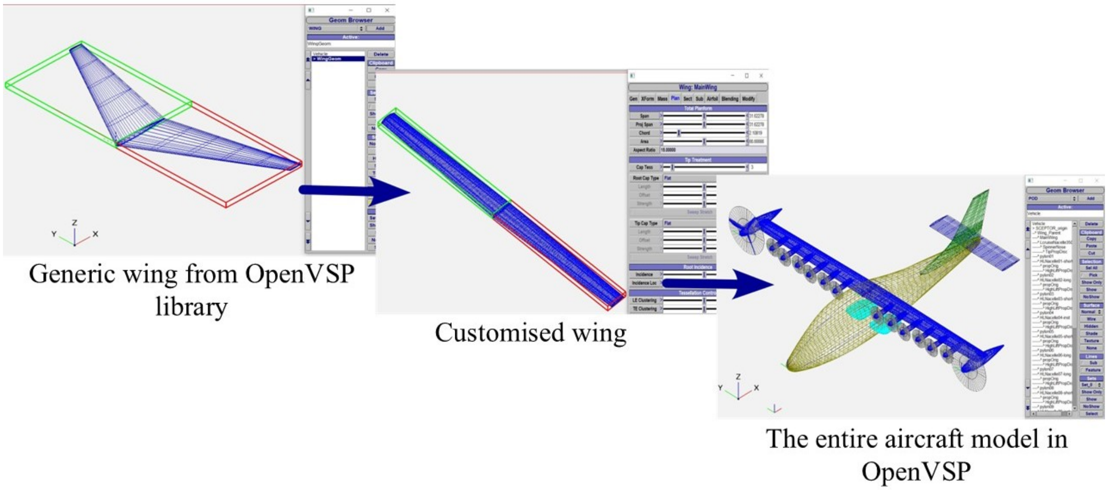


Figure 5.4.: OpenVSP modelling environment

OpenVSP makes it possible to relate the various parameters that shape a given model component by defining the mathematical relationships that occur between them, for example, the correlation between wingspan and fuselage length [61]. In addition to modelling the external geometry of the aircraft, OpenVSP also allows its internal configuration to be represented (Fig. 5.5).

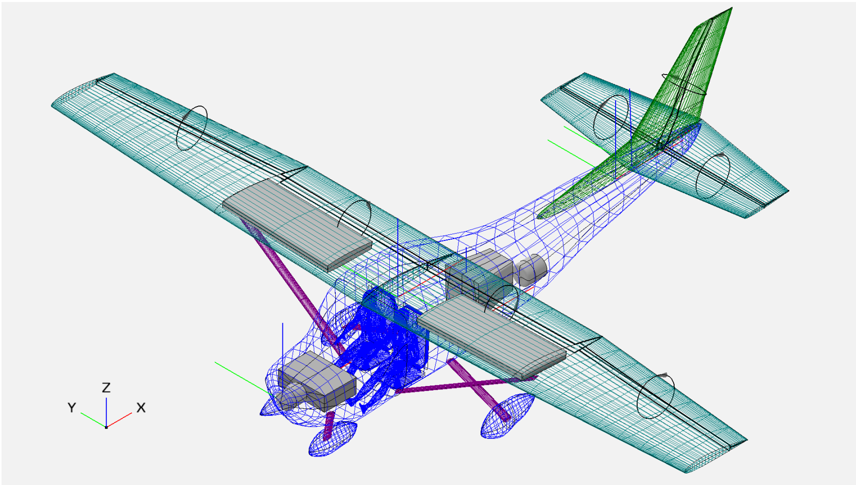


Figure 5.5.: Model of the aircraft with its internal configuration of the main propulsion system subsystems

OpenVSP also has a module to perform aero analysis in three options: Parasite Drag, Wave Drag and VSPAERO. The first two focus only on the analysis of a selected drag force, with Wave Drag being designed for aircraft developed for velocities above the speed of sound [61]. VSPAERO, on the other hand, is a tool that allows an extensive analysis of the modelled aircraft and defining parameters such as lift and drag coefficient or pitching moment, for example.

6. Conceptual design of a hydrogen fuel cell aircraft

The adaptation of the aircraft design process to alternative propulsion systems presented in Section 2.4 is used to develop the hydrogen fuel cell aircraft concept. For this purpose, the steps included in the first and second phases of the aforementioned process were followed: requirements and conceptual design (Fig. 6.1).

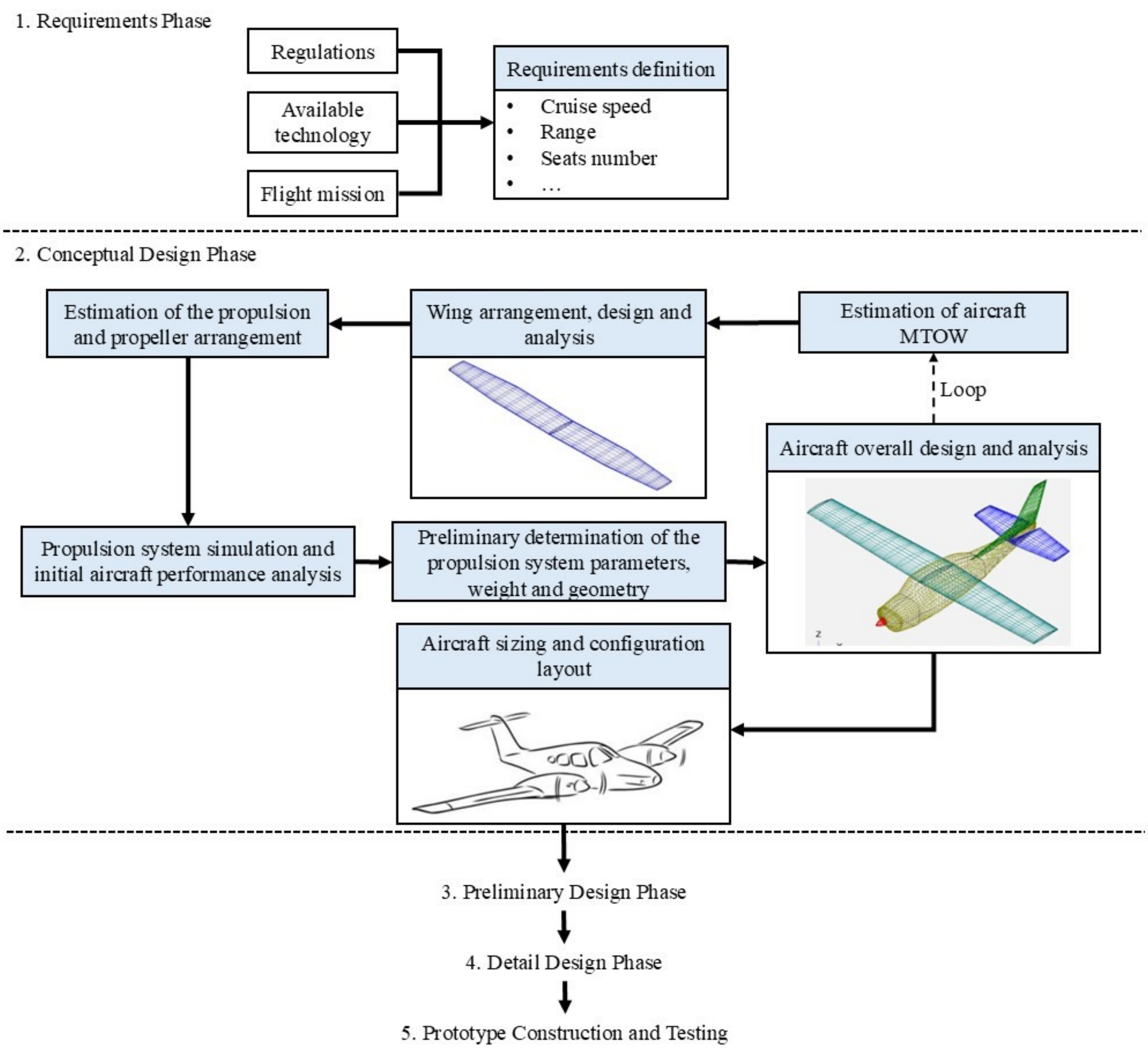


Figure 6.1.: Requirements and conceptual design phases of the adapted aircraft design process to alternative propulsion systems, with an indication of the steps taken during the development of the hydrogen fuel cell aircraft concept

The first phase is the same as in the classic aircraft design process, and has the task of creating a list of requirements for the aircraft from potential customers in terms of mission parameters, regulations from the Civil Aviation Authority and available technology. The conceptual design phase in the adapted aircraft design process, on the other hand, is adapted to address the lack of or insufficient historical data used in the development of conventionally powered aircraft. This phase is based on the use of a simulation models to define the propulsion parameters and a parametric airframe model to define its parameters and develop the arrangement of propulsion subsystems including energy storage in the aircraft.

6.1. Requirements phase

This phase consists of only one step, the requirements definition, which the designed aircraft should fulfil. The requirements defined in this step affect the aircraft's performance and design. In addition, the requirements defined should be consistent with the requirements specified in the relevant documents relating to the airworthiness of the aircraft, e.g., CS-23 issued by EASA or Part 23 published by the FAA.

This work addresses a concept for a 4-seat hydrogen fuel cell aircraft based on document CS-23, which refers to aircraft with an MTOW of 8,618 kg (19,000 lbs) and a maximum number of passengers of 19 or less. On the contrary, this document does not address the requirements for alternative propulsion aircraft. In addition, flight speed and never exceed speed, maximum flight altitude and range are specified in the first step. The aircraft is designed as a twin-engine with retractable landing gear. The requirements developed in the first step are shown in Table 6.1. Due to the unknown integration of the propulsion subsystems into the airframe and their dimensions at this stage, the position of the wings has not been defined in the requirements. The MTOW of the designed aircraft was also not defined due to the lack of a suitable method to estimate the weight of the propulsion system and energy storage.

Table 6.1.: Requirements for a hydrogen fuel cell aircraft concept under development

Number of seats	4
Number of propellers	2
Propulsion system	Hydrogen fuel cell
Range	500 km
Cruise speed	150 kt
Never exceed speed	180 kt
Maximum altitude	3048 m
Landing gears	Retractable

6.2. Conceptual design phase

This phase in the adapted aircraft design process for alternative propulsion consists of seven steps. Its purpose is to determine the MTOW and dimensions of the aircraft, as well as to select appropriate propulsion and energy storage parameters. Steps 2 to 7 form an iterative loop that allows for more accurate results. The iterative process is also used in the classic aircraft design process.

Step 2 in the adapted design process (Fig. 6.1) is the estimation of the MTOW of the aircraft. As in the classical process, the first MTOW value of the aircraft is estimated. In the case of the aircraft designed in this thesis, the first guess was based on a comparison with an aircraft with a conventional propulsion system for 5 to 9 seats and was estimated at 2,000 kg. After running the iteration loop several times, the MTOW was found to be 2,600.3 kg.

All subsequent results obtained in each step are presented for a final MTOW of 2,600.3 kg.

Step 3 involves the deployment, design and analysis of the wings. Due to the use of retractable landing gear and the use of hydrogen fuel cells with the required performance, whose size and weight do not allow them to be placed inside the fuselage and forced them to be moved to the nacelle of the electric motors, the wings were placed in the lower part of the fuselage so that they were above the hydrogen tanks integrated into the fuselage.

The wings (Fig. 6.2) are designed similarly to those of the Tecnam P2012 Traveller aircraft. The choice of such wing parameters is dictated by the Tecnam aircraft's MTOW of 3,680 kg, which gives a large margin of error when estimating the weight of the designed aircraft. The wings were designed and analysed in OpenVSP software. Their parameters and analysis results are shown in Table 6.2.

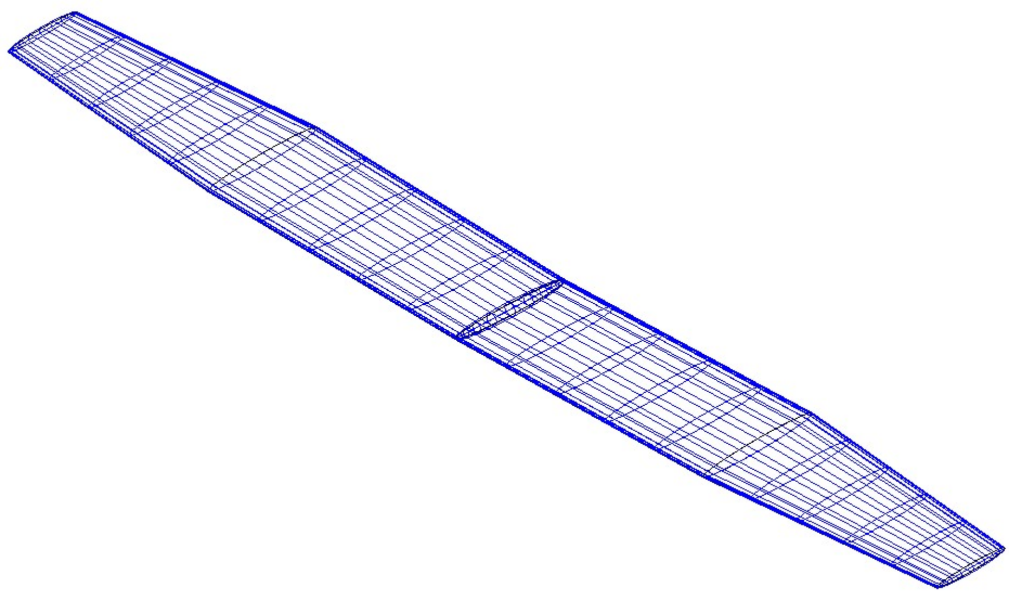


Figure 6.2.: Designed wing in step 3 using OpenVSP

Table 6.2.: Parameters of the designed wing

Wingspan	13.5 m
Surface area	19.71 m2
Aspect Ratio	9.24376
Airfoil	NACA 63-412
C_L at alpha=0 deg	0.0507
$\Delta C_L/\Delta$alpha	5.2569
C_{D_0} for v=150 kt at 3,048 m	0.00557

In step 4, an estimate of the location of the propulsion system and propellers is made, which influences the shape of the fuselage and the use of additional external components such as under-wing tanks. In the case of the designed aircraft, the location of the electric motors together with the wings propellers in the nacelles is determined by the requirements described in Table 6.1. During the first iteration, both the fuel cell and hydrogen tanks were placed inside the fuselage and the batteries inside the wings. After the final iteration, the results of the simulation of the propulsion parameters were received and the main subsystems were selected, the location of the hydrogen fuel cell was changed and moved from the fuselage to the nacelle of the electric motor in the wing. This was also due to the need to use two fuel cells to achieve the required power. During the first iteration, the dimensions and weight of the hydrogen tanks, which will hold the amount of compressed gas required to achieve a range of 500 km, were also underestimated.

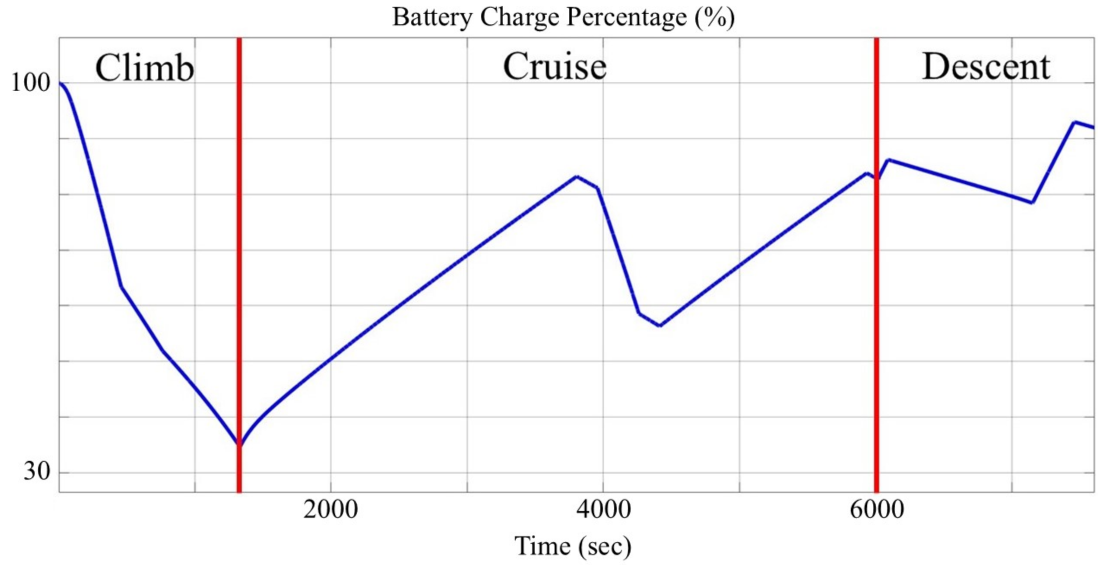
Step 5 is a crucial part of the alternative propulsion aircraft design process. In this step, an alternative propulsion simulation model developed using MATLAB/Simulink software is used to perform a preliminary analysis of the aircraft's performance (the simulation models and their operating principle are described in Chapter 4). As part of the simulation, the parameter values of the main propulsion and energy storage subsystems required for the aircraft to perform the planned flight mission are obtained. In addition, in the case of hybrid propulsion, which also includes hydrogen fuel cells, since they operate in conjunction with a battery, the simulation model used at this stage allows the different power tactics of electric motors to be easily tested. Each iteration allows more and more accurate data to be fed into the model, thus producing more accurate results.

As part of this phase, a reference flight mission was developed for the designed aircraft with the parameters shown in Table 6.3.

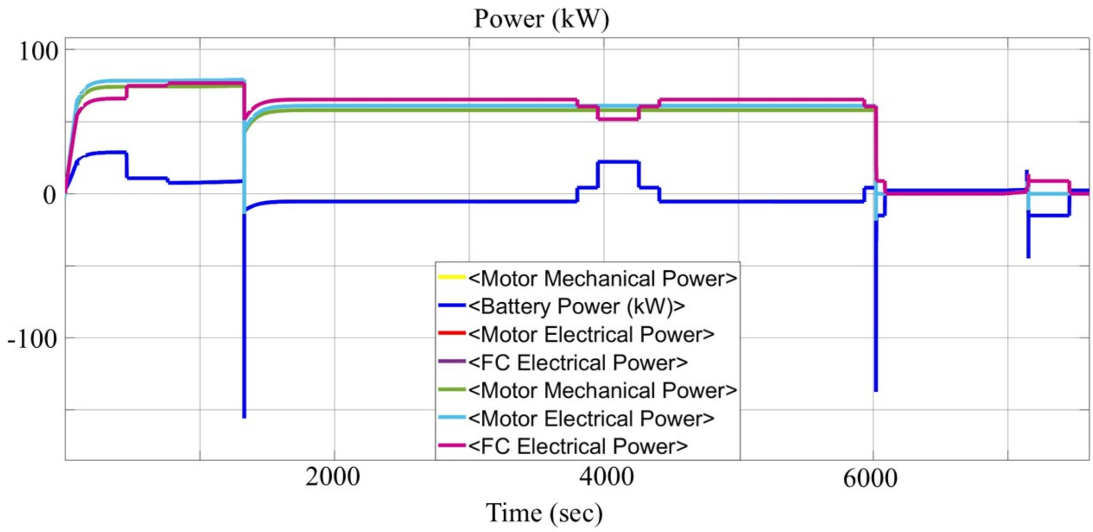
Table 6.3.: Reference flight mission parameters

Take-off speed	90 kt	167 km/h
Climb speed	110 kt	204 km/h
Rate of climb	500 ft/min	2.5 m/s
Cruise speed	150 kt	277.8 km/h
Descent speed	110 kt	204 km/h
Landing speed	95 kt	176 km/h
Rate of descent	500 ft/min	2.5 m/s
Flight distance	270 NM	500 km
Flight altitude	10,000 ft	3,048 m

The results shown in Table 6.4 and the selected graphs (Fig. 6.3) generated from MATLAB/Simulink were obtained for an aircraft with a final mass of 2,600.3 kg. The power strategy developed is to charge the battery through the hydrogen fuel cell by increasing the power generated by 9 kW when the battery charge level falls below 80%, and when this level reaches 60%, the cell starts generating an additional 14 kW of power.



(a) Battery charging level during reference flight mission simulation



(b) Power generated by electric motors, battery, hydrogen fuel cells during reference flight mission simulation

Figure 6.3.: The results obtained in the final flight mission simulation in MATLAB/Simulink software of the designed aircraft concept with MTOW of 2,600.3 kg

Table 6.4.: Final results obtained with the propulsion simulation model

Distance	500 km
Duration	2 h 7 min
Used hydrogen	23.12 kg
Maximum power of:	
Hydrogen fuel cell	76.7 kW
Battery	22 kW
Electric motor	75.25 kW
Continuous power during cruise:	
Hydrogen fuel cell	63.4 kW
Electric motor	58.8 kW

In step 6 a preliminary selection of the main propulsion subsystems is made, in the case of the aircraft designed these are batteries, fuel cells, electric motors and hydrogen tanks. The selection of subsystems is based on the results of the simulations carried out in step 5. For the aircraft concept developed in this thesis, commercially available subsystems were selected. Their parameters are shown in Tables 6.5-6.8.

Table 6.5.: Hydrogen tank parameters

Manufacturer	NPROXX
Model	AH620-70
Storage capacity of hydrogen	12.4 kg
Volume	350 L
Weight	211 kg
Outer diameter	610 mm
Length incl. valve	1917 mm
Working pressure	700 bar

Table 6.6.: Hydrogen fuel cell parameters

Manufacturer	PowerCell Group
Model	P System 100
Dimensions	606 x 696 x 674 mm
Weight	212 kg
Net power output	15 - 100 kW
Gross output (rated power)	300 V / 380 A
Voltage output	250 - 500 V
Current output	50 - 450 A
System efficiency (peak)	55 %
System efficiency (rated power)	45 %

Table 6.7.: Electric motor parameters

Manufacturer	EMRAX
Model	268
Diameter	268 mm
Length	94 mm
Peak power (max 2 min)	210 kW
Continuous power	117 kW
Peak torque (max 2 min)	500 Nm
Continuous torque	250 Nm
Max speed	4,500 rpm
Operating voltage	100 - 830 V
Efficiency	96 %
Weight	22.3 kg

Table 6.8.: Battery parameters

Manufacturer	EaglePicher Technologies
Model	LP33081
Nominal cell weight	950 g
Cell dimensions	9.58 x 2.81 x 15.20 cm
Nominal cell voltage	3.6 V
Nominal cell capacity	30 Ah at C/5 at 20°C
Cell energy density	335 Wh/L
Cell specific energy	141 Wh/kg
No. of cells in a series	84
No. of cell in a parallel	1
Voltage of the storage system	302 V
Current of the storage system	150 A
Capacity of the storage system	30 Ah = 9.072 kWh
Storage system weight	79.8 kg

The information on the dimensions of the subsystems selected in step 6 makes it possible in step 7 to adjust the airframe accordingly and thus to obtain more realistic values for the aerodynamic coefficients that affect the power and energy requirements of the designed aircraft in flight. In addition, the weight of the propulsion and energy storage system, and thus the MTOW of the aircraft, are more realistic.

The overall analysis of the aircraft design is carried out using OpenVSP. Figure 6.4 shows the final concept of the hydrogen fuel cell-powered aircraft. Both hydrogen tanks are located in the lower part of the fuselage, which forced the fuselage to increase in height and width, and its shape is inspired by the PW-5 Smyk glider and the PZL TS-11 Iskra aircraft. The location of the fuel cells in the nacelles of the electric motors forced an increase in their dimensions. The batteries were divided into 2 packs and individually placed in the inner part of the wing to ensure easy access and a smooth wing structure.

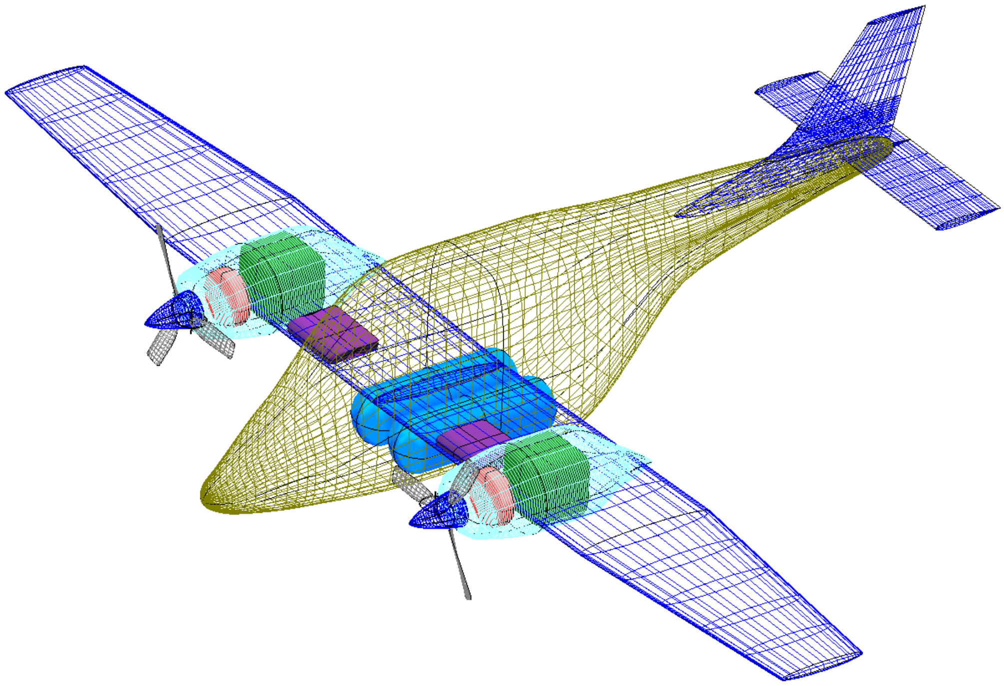
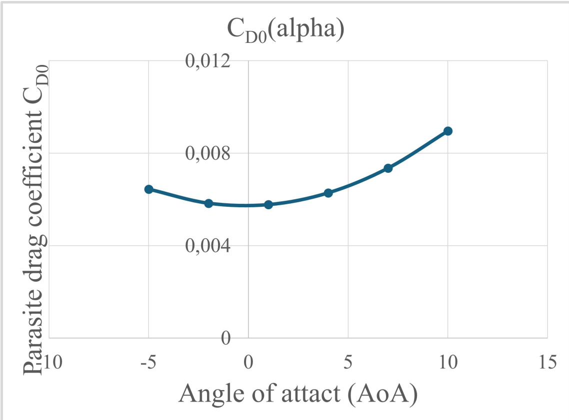
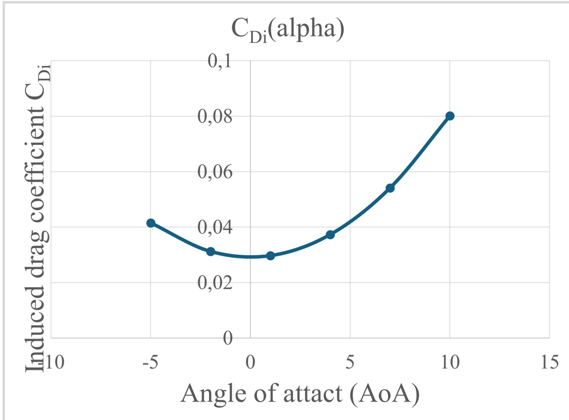


Figure 6.4.: Final integration of major propulsion subsystems into the designed aircraft concept

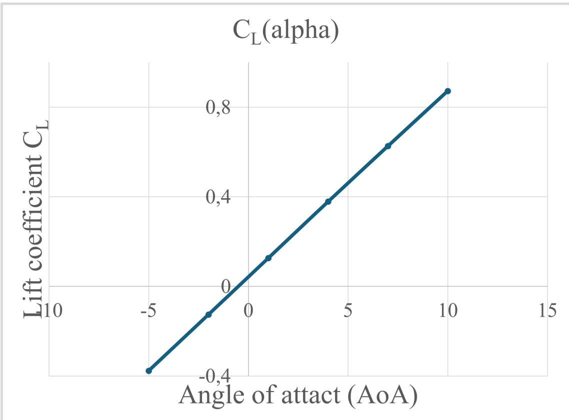
After making changes to the airframe structure, an aerodynamic analysis of the aircraft is performed using VSPAERO module in OpenVSP, the results of which feed into the iterative loop. The final results of the analysis are shown in Fig. 6.5. The parasitic drag coefficient for flight at 150 kt at an altitude of 3,048 m is 0.01760 for the final aircraft concept.



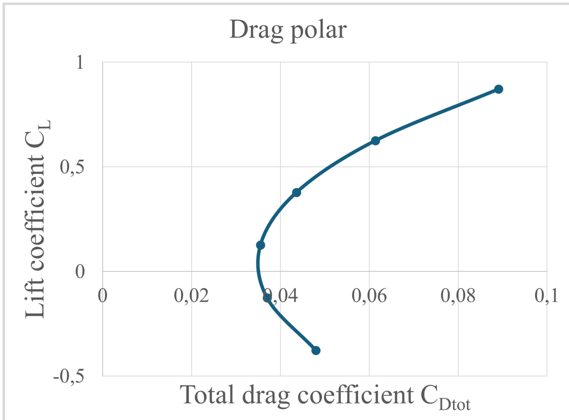
(a) Parasite drag coefficient



(b) Induced drag coefficient



(c) Lift coefficient



(d) Drag polar

Figure 6.5.: Results of aerodynamic analysis of the final aircraft concept performed in OpenVSP using VSPAERO module

Using the mass information of the main propulsion system and energy storage subsystems, as well as adjusting the airframe and determining the dimensions of its individual components, it is possible to calculate the final MTOW of the aircraft. The mass of the airframe was calculated using an Excel file received from Queen's University Belfast, while the mass of the other propulsion subsystems was estimated. The MTOW of the designed aircraft, broken down into the individual parts that make it up, is shown in Table 6.9.

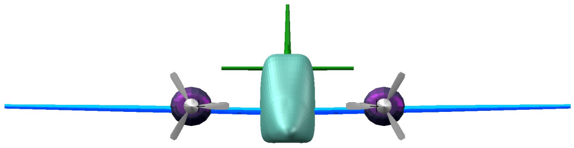
Table 6.9.: Mass of individual subsystems comprising the MTOW of the aircraft

Hydrogen fuel cells	424 kg
Battery	79.5 kg
Hydrogen tanks	422 kg
Electric motors	50 kg
Other propulsion system subsystems	380 kg
Propellers	80 kg
Airframe	800 kg
Hydrogen	24.8 kg
Payload (4 people)	340 kg
Total	2,600.3 kg

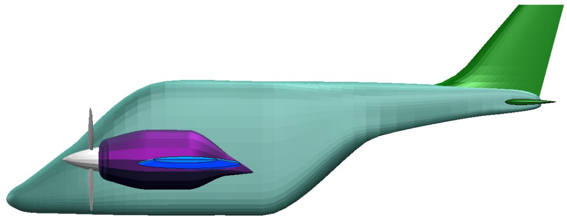
Step 8 is the last step in the conceptual design phase and does not belong to the iteration loop. It is the final sizing and configuration layout of the aircraft (Fig. 6.4 and 6.6), the configuration layout here being the overall aircraft design obtained in the previous step after all necessary iterations have been performed. The final dimensions of the aircraft are shown in Table 6.10.

Table 6.10.: Basic aircraft dimensions

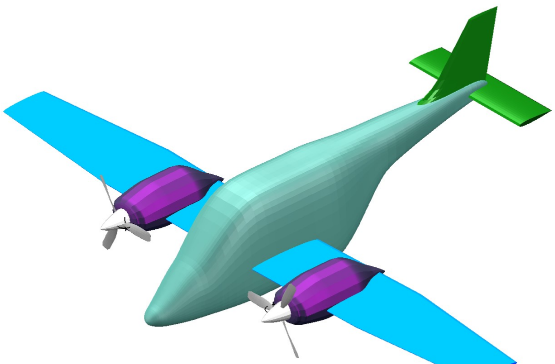
Fuselage length	8.35 m
Wingspan	13.5 m
Maximum fuselage height	2.09 m
Maximum fuselage width	1.31 m
Aircraft height (without landing gears)	3.30 m



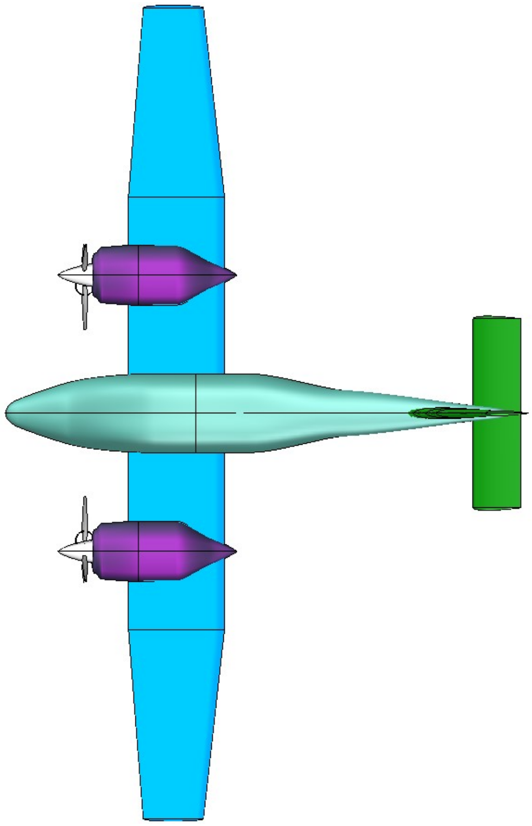
(a) Front projection



(b) Left projection



(c) Isometric projection



(d) Top projection

Figure 6.6.: Hydrogen fuel cell aircraft concept developed using adapted aircraft design process for alternative propulsion systems

After the 'freeze' configuration of the developed aircraft, the next stage is the preliminary design. It consists of refining the parameters of the airframe and its systems, conducting a more detailed analysis of the aircraft. This is possible due to the development of the necessary data in the previous stage, and therefore, there is no need to guess them as in conceptual design. Additionally, in the adaptation of the aircraft design process to alternative propulsion proposed in this thesis, one of the final steps of the preliminary design phase is the development of requirements management for the systems that form the aircraft, which is carried out based on models describing these systems and the relationships between them. The detail design and prototype construction and testing phases consist of the same steps as in the classic aircraft design process.

7. Conclusion

The design of General Aviation aircraft with alternative propulsion systems requires significant changes compared to conventional designs. Alternative propulsion systems introduce different propulsion design characteristics, configurations, and demand new integration approaches, especially regarding different energy storage, which strongly affects aircraft structure, weight distribution, geometry, and aerodynamics. Traditional historical data used in conventional design are unsuitable, risking incorrect parameter selection in early design phases. Thus, the design process must adopt advanced methods for defining and integrating alternative propulsion systems to achieve optimal aircraft configuration, particularly during the conceptual and preliminary design phases.

In this thesis, the adapted design process is based on the use of Model-Based Systems Design (MBSD) methods, combined with a deep understanding of the relationships between the main forces acting on the aircraft – weight, drag, lift, and thrust – as well as a clear definition of the key design parameters of both the airframe and the new propulsion system. The approach proposed in this thesis supports the determination of crucial design parameters for the propulsion system's subsystems and enables the analysis of their impact on the airframe's design parameters.

The application of the MBSD method to adapt the aircraft design process to alternative propulsion and to integrate parametric models of the propulsion system with the energy storage and airframe allows the replacement of historical with model-based data.The use of parametric models allows the parameters of systems, subsystems and components to be directly related to the main forces acting on the aircraft. The parameters of the flight mission for which the aircraft is being designed affect the magnitude of the forces acting and thus the value of the design parameters. The results from the modelling obtained for the parameters of the subsystems and components that comprise the aircraft's propulsion system enable the determination of their dimensions and masses, which have an impact on the airframe structure.

Alternative propulsion system models are an essential element in the proposed adaptation of the GA aircraft design process. They consist of subsystems and components that have one of the following functions to perform in the propulsion system: energy provision, energy conversion and thrust generation. In addition, the models also consist of auxiliary subsystems that are not directly part of the propulsion system and energy storage but draw power from the energy source and thus affect the performance of the aircraft.

The adaptation of the alternative propulsion aircraft design approach proposed in this thesis primarily changes the second phase of the conventional design process — the conceptual design phase. As in the case of the design of a conventionally powered aircraft, this phase is preceded by the definition of requirements, mainly with respect to the flight mission parameters to be met by the aircraft under study. These parameters are then used in the second phase in the propulsion system model, as well as in the airframe model. The former is generated in MATLAB/Simulink software and its purpose is to define the required parameters of the subsystems and components that comprise the propulsion system under consideration. The objective of this is to determine the size and weights of the propulsion subsystems and components, which are then used as inputs to design the airframe. The airframe model is developed using OpenVSP software, the main purpose of which is to develop the airframe according to the requirements and the way to integrate and arrange the propulsion system with the energy storage. Using the OpenVSP model, the drag and lift coefficients for the designed aircraft are defined. The values of these coefficients are then used as input to the propulsion system model. Both models are in an iterative loop that allows the transition from approximate values of propulsion and airframe parameters to exact data.

The application of OpenVSP in this approach provides a wide range of freedom in the modelling of the aircraft and thus allows a more creative quantified approach to new airframe concept allowing greater flexibility in the way the propulsion system is integrated and, thus, allows the design of an aircraft with an unconventional shape. This approach makes it possible to base the design process of an alternatively powered aircraft on model-based data and replace missing historical data with it. It also enables the capabilities of the alternative propulsion system to be virtually tested during the initial phase of the aircraft design process. Therefore, the number of potential errors in the system is also reduced, minimising the need for physical prototyping and testing. This results in a more efficient development process, along with reduced project costs.

The proposed adaptation of the aircraft design process can also change the relationship and collaboration between aircraft manufacturers and suppliers of propulsion system subsystems and storage systems. They can be more closely integrated into the design process because they can best assess the relevance of the parameters of their subsystems to be considered in the aircraft design process. Parameter identification is therefore crucial to the entire design process and determines the success of the design, especially the conceptual design.

This approach is universal and can also be applied to drones or other types of aeroplanes also with conventional propulsion system. In addition, it allows the use of various modelling tools or surrogate models based on detailed high-fidelity models provided, for example, by suppliers of propulsion and energy storage subsystems. The aircraft manufacturer can also provide an airframe model developed in OpenVSP to the propulsion system supplier for integration and applicable design changes.

Bibliography

[1] Abdul Sathar Eqbal, M.; Fernando, N.; Marino, M.; Wild, G.: Hybrid Propulsion Systems for Remotely Piloted Aircraft Systems. *Aerospace* 5 (2018), Nr. 2, S. 34. – DOI 10.3390/aerospace5020034

[2] Adu-Gyamfi, B. A.; Good, C.: Electric aviation: A review of concepts and enabling technologies. *Transportation Engineering* 9 (2022), S. 100134. – DOI 10.1016/j.treng.2022.100134. – ISSN 2666691X

[3] Ahmadian, M.; Nazari, Z. J.; Nakhaee, N.; Kostic, Z.: Model based design and SDR. *Proceedings of the 2005 The 2nd IEE/EURASIP Conference on DSPenabledRadio (Ref. No. 2005/11086)* (2005). – DOI 10.1049/ic:20050389

[4] Ahuja, V.; Litherland, B. L.: Comparison of Aerodynamic Analysis Tools Applied to a Propeller-Blown Wing. *Proceedings of the AIAA SCITECH 2023 Forum* (2023). – DOI 10.2514/6.2023–1753

[5] Aigner, B.; Nollmann, M.; Stumpf, E.: Design of a Hybrid Electric Propulsion System within a Preliminary Aircraft Design Software Environment. *Proceedings of the Deutscher Luft- und Raumfahrtkongress 2018* (2018). – DOI 10.25967/480153

[6] Aigner, B.; Strathoff, P.; Stumpf, E.: MICADO: Recent Developments of Models for Design and Evaluation of Electric Aircraft Propulsion Systems. *Proceedings of the Deutscher Luft- und Raumfahrtkongress 2020* (2021). – DOI 10.25967/530051

[7] Alrashed, M.; Nikolaidis, T.; Pilidis, P.; Jafari, S.: Utilisation of turboelectric distribution propulsion in commercial aviation: A review on NASA's TeDP concept. *Chinese Journal of Aeronautics* 34 (2021), Nr. 11, S. 48–65. – DOI 10.1016/j.cja.2021.03.014. – ISSN 10009361

[8] Basnet, S.; Bahootoroody, A.; Chaal, M.; Valdez Banda, O. A.; Lahtinen, J.; Kujala, P.: A decision-making framework for selecting an MBSE language–A case study to ship pilotage. *Expert Systems with Applications* 193 (2022), S. 116451. – DOI 10.1016/j.eswa.2021.116451. – ISSN 09574174

[9] Beery, P.; Paulo, E.: Application of Model-Based Systems Engineering Concepts to Support Mission Engineering. *Systems* 7 (2019), Nr. 3, S. 44. – DOI 10.3390/systems7030044

[10] Bradley, T. H.; Moffitt, B. A.; Parekh, D. E.; Fuller, T. F.; Mavris, D. N.: Energy Management for Fuel Cell Powered Hybrid-Electric Aircraft. *Proceedings of the 7th International Energy Conversion Engineering Conference* (2009)

[11] Brelje, B. J.; Martins, J. R.: Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches. *Progress in Aerospace Sciences* 104 (2019), S. 1–19. – DOI 10.1016/j.paerosci.2018.06.004. – ISSN 03760421

[12] Brinson, T. E.; Ren, W.; Ordonez, J. C.; Luongo, C. A.; Baldwin, T.: Fuel Cell-Based Powertrain System Modeling and Simulation for Small Aircraft Propulsion Applications. *Journal of Fuel Cell Science and Technology* 6 (2009). – DOI 10.1115/1.3006303

[13] Buede, D. M.: *The engineering design of systems: Models and methods*. 2nd ed. Hoboken N.J.: John Wiley & Sons, 2009 Wiley series in systems engineering and management

[14] Cao, Y.; Liu, Y.; Paredis, C. J.: System-level model integration of design and simulation for mechatronic systems based on SysML. *Mechatronics* 21 (2011), Nr. 6, S. 1063–1075. – DOI 10.1016/j.mechatronics.2011.05.003. – ISSN 09574158

[15] Cheng, Q.; Zhang, R.; Shi, Z.; Lin, J.: Review of common hydrogen storage tanks and current manufacturing methods for aluminium alloy tank liners. *International Journal of Lightweight Materials and Manufacture* 7 (2024), Nr. 2, S. 269–284. – DOI 10.1016/j.ijlmm.2023.08.002. – ISSN 25888404

[16] Chiesa, S.; Fioriti, M.; Viol, N.: Methodology for an Integrated Definition of a System and Its Subsystems: The Case-Study of an Airplane and Its Subsystems. *Systems Engineering – Practice and Theory* (2012). – DOI 10.5772/34453

[17] Dicks, A.; Rand, D. A. J.: *Fuel cell systems explained*. 3. Hoboken NJ USA: Wiley, 2018

[18] Diston, D. J.: *Computational modelling and simulation of aircraft and the environment*. Chichester U.K.: Wiley, 2009 Aerospace series

[19] Do, Q.; Cook, S.; Lay, M.: An Investigation of MBSE Practices across the Contractual Boundary. *Procedia Computer Science* 28 (2014), S. 692–701. – DOI 10.1016/j.procs.2014.03.083. – ISSN 18770509

[20] EASA: *European Aviation Environmental Report 2022*. http://dx.doi.org/10.2822/04357

[21] EASA: *Type-Certificate Data Sheet E.200 for Austro Engine E4 series engines: TCDS No.: E.200 Issue: 12*. 2020

[22] EASA: *Type-Certificate for Piston Engine Rotax 912 series: TCDS No.: E.121 Issue:17*. 2023

[23] Economou, J. T.; Tsourdos, A.; Wang, S.: Design of a Distributed Hybrid Electric Propulsion System for a Light Aircraft based on genetic algorithm. *Proceedings of the AIAA Propulsion and Energy 2019 Forum* (2019). – DOI 10.2514/6.2019–4305

[24] Elgezabal, O.; Schumann, H.: Creating Synergies for Systems Engineering: Bridging Cross-Disciplinary Standards. *Systems Engineering – Practice and Theory* (2012). – DOI 10.5772/34571

[25] EMRAX: *EMRAX 228: Data Sheet.* `https://emrax.com/e-motors/emrax-228/#1482059435741-232ed37a-accc`

[26] European Union Aviation Safety Agency: *Certification Specification for Normal-Catergory Aeroplanes (CS-23).* `https://www.easa.europa.eu/en/document-library/certification-specifications/cs-23-amendment-6-and-amc-gm-cs-23-issue-4`. Version: 2023

[27] Finger, D. F.; Braun, C.; Bil, C.: Impact of Engine Failure Constraints on the Initial Sizing of Hybrid-Electric GA Aircraft. `http://dx.doi.org/10.2514/6.2019-1812`. In: *AIAA Scitech 2019 Forum.* – DOI 10.2514/6.2019–1812

[28] Finger, D. F.; Braun, C.; Bil, C.: An Initial Sizing Methodology for Hybrid-Electric Light Aircraft. *Proceedings of the 2018 Aviation Technology, Integration, and Operations Conference* (2018). – DOI 10.2514/6.2018–4229

[29] Finger, D. F.; Götten, F.; Braun, C.; Bil, C.: On Aircraft Design under the Consideration of Hybrid-Electric Propulsion Systems. *Proceedings of the 2018 Asia-Pacific International Symposium on Aerospace Technology (APISAT2018)* (2018)

[30] Friedrich, C.; Robertson, P. A.: Hybrid-electric propulsion for automotive and aviation applications. *CEAS Aeronautical Journal* 6 (2015), Nr. 2, S. 279–290. – DOI 10.1007/s13272–014–0144–x. – ISSN 1869–5582

[31] Frosina, E.; Caputo, C.; Marinaro, G.; Senatore, A.; Pascarella, C.; Di Lorenzo, G.: Modelling of a Hybrid-Electric Light Aircraft. *Energy Procedia* 126 (2017), S. 1155–1162. – DOI 10.1016/j.egypro.2017.08.315. – ISSN 18766102

[32] Frosina, E.; Senatore, A.; Palumbo, L.; Di Lorenzo, G.; Pascarella, C.: Development of a Lumped Parameter Model for an Aeronautic Hybrid Electric Propulsion System. *Aerospace* 5 (2018), Nr. 4, S. 105. – DOI 10.3390/aerospace5040105

[33] Geiss, I.; Voit-Nitschmann, R.: Sizing of fuel-based energy systems for electric aircraft. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 231 (2017), Nr. 12, S. 2295–2304. – DOI 10.1177/0954410017721254. – ISSN 0954–4100

[34] Gudmundsson, S.: *General Aviation Aircraft Design: Applied Methods and Procedures.* Oxford, UK and Butterworth-Heinemann: Elsevier, 2014

[35] Henke, M.; Narjes, G.; Hoffmann, J.; Wohlers, C.; Urbanek, S.; Heister, C.; Steinbrink, J.; Canders, W.-R.; Ponick, B.: Challenges and Opportunities of Very Light High-Performance Electric Drives for Aviation. *Energies* 11 (2018), Nr. 2, S. 344. – DOI 10.3390/en11020344

[36] Hepperle, M.: Electric Flight- Potential and Limitations. *Proceedings of the Energy Efficient Technologies and Concepts of Operation* (2012)

[37] Hitchins, D. K.: *Systems engineering: A 21st century systems methodology.* Chichester West Sussex England and Hoboken NJ: John Wiley, 2007 Wiley series in systems engineering and management

[38] Hubka, V.; Eder, W. E.: *Theory of Technical Systems: A Total Concept Theory for Engineering Design*. 2. Berlin Heidelberg: Springer-Verlag, 1988

[39] IATA: *Aircraft Technology Roadmap to 2050*. https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf

[40] Isikveren, A. T.; Kaiser, S.; Pornet, C.; Vratny, P. C.: Pre-design strategies and sizing techniques for dual-energy aircraft. *Aircraft Engineering and Aerospace Technology* 86 (2014), Nr. 6, S. 525–542. – DOI 10.1108/AEAT–08–2014–0122. – ISSN 0002–2667

[41] Jackson, S.: *Systems Engineering for Commercial Aircraft: A Domain-Specific Adaptation*. 2. Surrey: Ashgate, 2015

[42] Jensen, J. C.: *Elements of Model-Based Design*. https://www2.eecs.berkeley.edu/Pubs/TechRpts/2010/EECS-2010-19.pdf

[43] Kadyk, T.; Schenkendorf, R.; Hawner, S.; Yildiz, B.; Römer, U.: Design of Fuel Cell Systems for Aviation: Representative Mission Profiles and Sensitivity Analyses. *Frontiers in Energy Research* 7 (2019). – DOI 10.3389/fenrg.2019.00035

[44] Kelemenová, T.; Kelemen, M.; Miková, Ľ.; Maxim, V.; Prada, E.; Lipták, T.; Menda, F.: Model Based Design and HIL Simulations. *American Journal of Mechanical Engineering* 1 (2013), Nr. 7, 276–281. – DOI 10.12691/ajme–1–7–25

[45] Kermode, A. C.; Barnard, R. H.; Philpott, D. R.: *Mechanics of flight*. 11th ed. Harlow England and New York: Pearson Prentice Hall, 2006

[46] Köhler, J.; Jeschke, P.: Conceptual design and comparison of hybrid electric propulsion systems for small aircraft. *CEAS Aeronautical Journal* 12 (2021), Nr. 4, S. 907–922. – DOI 10.1007/s13272–021–00536–4. – ISSN 1869–5582

[47] Kundu, A. K.; Price, M. A.; Riordan, D.: *Conceptual Aircraft Design: An Industrial Approach*. Hoboken, NJ: JohnWiley & Sons, 2019

[48] Laukotka, F.; Hanna, M.; Krause, D.: Digital twins of product families in aviation based on an MBSE-assisted approach. *Procedia CIRP* 100 (2021), S. 684–689. – DOI 10.1016/j.procir.2021.05.144. – ISSN 22128271

[49] Loskutov, A.; Kurkin, A.; Shalukho, A.; Lipuzhin, I.; Bedretdinov, R.: Investigation of PEM Fuel Cell Characteristics in Steady and Dynamic Operation Modes. *Energies* 15 (2022), Nr. 19, S. 6863. – DOI 10.3390/en15196863

[50] Ludowicy, J.; Rings, R.; Finger, D. F.; Braun, C.: Sizing Studies of Light Aircraft with Serial Hybrid Propulsion Systems. *Proceedings of the Deutscher Luft- und Raumfahrtkongress 2018* (2018). – DOI 10.25967/480226

[51] Lycoming: *Operator's Manual Lycoming: O-320 Series*. 3. Williamsport, PA. 17701 U.S.A.,

[52] Marciello, V.; Di Stasio, M.; Ruocco, M.; Trifari, V.; Nicolosi, F.; Meindl, M.; Lemoine, B.; Caliandro, P.: Design Exploration for Sustainable Regional Hybrid-Electric Aircraft: A Study Based on Technology Forecasts. *Aerospace* 10 (2023), Nr. 2, S. 165. – DOI 10.3390/aerospace10020165

[53] Marinaro, G.; Di Lorenzo, G.; Pagano, A.: From a Battery-Based to a PEM Fuel Cell-Based Propulsion Architecture on a Lightweight Full Electric Aircraft: A Comparative Numerical Study. *Aerospace* 9 (2022), Nr. 8, S. 408. – DOI 10.3390/aerospace9080408

[54] Märkl, R. S.; Voigt, C.; Sauer, D.; Dischl, R. K.; Kaufmann, S.; Harlass, T.; Hahn, V.; Roiger, A.; Weiss-Rehm, C.; Burkhardt, U.; Schumann, U.; Marsing, A.; Scheibe, M.; Dörnbrack, A.; Renard, C.; Gauthier, M.; Swann, P.; Madden, P.; Luff, D.; Sallinen, R.; Schripp, T.; Le Clercq, P.: Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails. *Atmospheric Chemistry and Physics* 24 (2024), Nr. 6, S. 3813–3837. – DOI 10.5194/acp–24–3813–2024

[55] Mateja, K.; Skarka, W.; Peciak, M.; Niestrój, R.; Gude, M.: Energy Autonomy Simulation Model of Solar Powered UAV. *Energies* 16 (2023), Nr. 1, S. 479. – DOI 10.3390/en16010479

[56] MathWorks: *Battery: Behavioral battery model*. https://de.mathworks.com/help/sps/ref/battery.html?searchHighlight=battery&s_tid=srchtitle_support_results_1_battery. Version: 2025

[57] MathWorks: *Fuel Cell: Fuel cell electrical system*. https://de.mathworks.com/help/sps/ref/fuelcell.html?searchHighlight=fuel+cell&s_tid=srchtitle_support_results_2_fuel+cell. Version: 2025

[58] MathWorks: *Generic Engine: Generic internal combustion engine*. https://de.mathworks.com/help/sdl/ref/genericengine.html?searchHighlight=engine&s_tid=srchtitle_support_results_3_engine. Version: 2025

[59] MathWorks: *ISA Atmosphere Model*. https://www.mathworks.com/help/aeroblks/isaatmospheremodel.html. Version: 2025

[60] MathWorks: *Motor & Drive (System Level): Generic motor and drive with closed-loop torque control*. https://de.mathworks.com/help/sps/ref/motordrivesystemlevel.html?searchHighlight=electric+motor&s_tid=srchtitle_support_results_7_electric+motor. Version: 2025

[61] McDonald, R. A.; Gloudemans, J. R.: Open Vehicle Sketch Pad: An Open Source Parametric Geometry and Analysis Tool for Conceptual Aircraft Design. *Proceedings of the AIAA SCITECH 2022 Forum* (2022). – DOI 10.2514/6.2022–0004

[62] Micouin, P.: *Model-based systems engineering: Fundamentals and methods*. London UK and Hoboken NJ USA: iSTE and Wiley, 2014 Control, systems and industrial engineering series

[63] NASA: *NASA Systems Engineering Handbook*. 2007

[64] National Academies of Science, Engineering, and Medicine: *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, D.C.: National Academies Press, 2016. http://dx.doi.org/10.17226/23490

[65] Nicolay, S.; Liu, Y.; Elham, A.: Conceptual Design and Optimization of a General Aviation Aircraft with Fuel Cells and Hydrogen. *Proceedings of the Aerospace Europe Conference 2020* (2020)

[66] Nishizawa, A.; Kallo, J.; Garrot, O.; Weiss-Ungethüm, J.: Fuel cell and Li-ion battery direct hybridization system for aircraft applications. *Journal of Power Sources* 222 (2013), S. 294–300. – DOI 10.1016/j.jpowsour.2012.09.011. – ISSN 03787753

[67] Nomura, A.; Ito, K.; Yu, D. Y.; Kubo, Y.: Gravimetric analysis of lithium-air batteries during discharge/charge cycles. *Journal of Power Sources* 592 (2024), S. 233924. – DOI 10.1016/j.jpowsour.2023.233924. – ISSN 03787753

[68] O'Hayre, R. P.; Cha, S.-W.; Colella, W. G.; Prinz, F. B.: *Fuel cell fundamentals*. Third edition. Hoboken New Jersey: Wiley, 2016

[69] Olson, E. D.: Three-Dimensional Modeling of Aircraft High-Lift Components with Vehicle Sketch Pad. *Proceedings of the 2016 AIAA Science and Technology Forum and Exposition (SciTech 2016)* (2016)

[70] OpenVSP: *Parasite Drag*. https://openvsp.org/wiki/doku.php?id=parasitedrag. Version: 2025

[71] Pahl, G.; Beitz, W.; Feldhusen, J.; Grote, K.-H.: *Engineering design: A systematic approach*. 3rd ed. London: Springer, 2007

[72] Palaia, G.; Zanetti, D.; Abu Salem, K.; Cipolla, V.; Binante, V.: THEA-CODE: a design tool for the conceptual design of hybrid-electric aircraft with conventional or unconventional airframe configurations. *Mechanics & Industry* 22 (2021), S. 19. – DOI 10.1051/meca/2021012. – ISSN 2257–7777

[73] Peciak, M.; Skarka, W.: Assessment of the Potential of Electric Propulsion for General Aviation Using Model-Based System Engineering (MBSE) Methodology. *Aerospace* 9 (2022), Nr. 2, S. 74. – DOI 10.3390/aerospace9020074

[74] Pelz, P. F.; Leise, P.; Meck, M.: Sustainable aircraft design — A review on optimization methods for electric propulsion with derived optimal number of propulsors. *Progress in Aerospace Sciences* 123 (2021), S. 100714. – DOI 10.1016/j.paerosci.2021.100714. – ISSN 03760421

[75] Pornet, C.; Gologan, C.; Vratny, P. C.; Seitz, A.; Schmitz, O.; Isikveren, A. T.; Hornung, M.: Methodology for Sizing and Performance Assessment of Hybrid Energy Aircraft. *Journal of Aircraft* 52 (2015), Nr. 1, S. 341–352. – DOI 10.2514/1.C032716. – ISSN 0021–8669

[76] Pornet, C.; Isikveren, A. T.: Conceptual design of hybrid-electric transport aircraft. *Progress in Aerospace Sciences* 79 (2015), S. 114–135. – ISSN 03760421

[77] Pornet, C.: *Conceptual Design Methods for Sizing and Performance of Hybrid-Electric Transport Aircraft.* Technische Universität München, Dissertation, 2017

[78] Raymer, D. P.: *Aircraft Design: A Conceptual Approach.* Washington, D.C.: American Institute of Aeronautics and Astronautics, 1992

[79] Raymer, D. P.: *Dan Raymer's simplified aircraft design for homebuilders.* Los Angeles, CA: Design Dimension Press, 2012

[80] Rendón, M. A.; Sánchez R., C. D.; Gallo M., J.; Anzai, A. H.: Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities. *Journal of Control, Automation and Electrical Systems* 32 (2021), Nr. 5, S. 1244–1268. – DOI 10.1007/s40313–021–00740–x. – ISSN 2195–3880

[81] Riboldi, C.; Gualdoni, F.: An integrated approach to the preliminary weight sizing of small electric aircraft. *Aerospace Science and Technology* 58 (2016), S. 134–149. – DOI 10.1016/j.ast.2016.07.014. – ISSN 12709638

[82] Romeo, G.; Cestino, E.; Pacino, M.; Borello, F.; Correa, G.: Design and testing of a propeller for a two-seater aircraft powered by fuel cells. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 226 (2012), Nr. 7, S. 804–816. – DOI 10.1177/0954410011415476. – ISSN 0954–4100

[83] Roskam, J.: *Airplane Design Part I: Preliminary Sizing of Airplanes.* Lawrence, Kansas: DARcorporation, 1997

[84] Sadraey, M. H.: *Aircraft design: A systems engineering approach.* Chichestet West Sussex: Wiley, 2013 Aerospace series

[85] Sadraey, M. H.: *Aircraft performance: An engineering approach.* Boca Raton: CRC Press/Taylor & Franics Group, 2017

[86] Sain, C.; Kazula, S.; Enghardt, L.: Electric Propulsion for Regional Aircraft - Critical Components and Challenges. *Proceedings of the DLRK2022* (2022)

[87] Sarlioglu, B.; Morris, C. T.: More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft. *IEEE Transactions on Transportation Electrification* 1 (2015), Nr. 1, S. 54–64. – DOI 10.1109/TTE.2015.2426499

[88] Schmidt, F.; Richter, J.; König, R.; Birke, M.; Schlegel, D.; Spitzer, S.; Gude, M.: Conception, Design and Manufacture of Type IV Hydrogen Pressure Vessels for General Aviation. *Proceedings of the DLRK2023* (2023). – DOI 10.25967/610462

[89] Schültke, F.; Aigner, B.; Effing, T.; Strathoff, P.; Stumpf, E.: MICADO: Overview of Recent Developments within the Conceptual Aircraft Design and Optimization Environment. *Proceedings of the Deutscher Luft- und Raumfahrtkongress 2020* (2021). – DOI 10.25967/530093

[90] Seabridge, A. G.; Moir, I.: *Design and Development of Aircraft Systems.* Second Edition. Hoboken: John Wiley & Sons Inc, 2013

[91] Seitz, A.: *Advanced Methods for Propulsion System Integration in Aircraft Conceptual Design*. München. Technische Universität München, Dissertation, 2012

[92] Seitz, A.; Nickl, M.; Stroh, A.; Vratny, P. C.: Conceptual study of a mechanically integrated parallel hybrid electric turbofan. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 232 (2018), Nr. 14, S. 2688–2712. – DOI 10.1177/0954410018790141. – ISSN 0954–4100

[93] Skarka, W.: Model-Based Design and Optimization of Electric Vehicles. `http://dx.doi.org/10.3233/978-1-61499-898-3-566`. In: *Peruzzini et al. (Red.) 2018 – Transdisciplinary Engineering Methods for Social*. – DOI 10.3233/978–1–61499–898–3–566

[94] Soleymani, M.; Mostafavi, V.; Hebert, M.; Kelouwani, S.; Boulon, L.: Hydrogen propulsion systems for aircraft, a review on recent advances and ongoing challenges. *International Journal of Hydrogen Energy* 91 (2024), S. 137–171. – DOI 10.1016/j.ijhydene.2024.10.131. – ISSN 03603199

[95] Spencer, K. M.; Martin, C. A.: *Investigation of Potential Fuel Cell Use in Aircraft*. `https://www.ida.org/-/media/feature/publications/i/in/investigation-of-potential-fuel-cell-use-in-aircraft/d-5043.ashx`

[96] Stinton, D.: *The design of the aeroplane*. 2. Oxford, UK: Blackwell Science, 2001

[97] Stückl, S.: *Methods for the Design and Evaluation of Future Aircraft Concepts Utilizing Electric Propulsion Systems*. Technische Universität München, Dissertation, 2016

[98] Sziroczak, D.; Jankovics, I.; Gal, I.; Rohacs, D.: Conceptual design of small aircraft with hybrid-electric propulsion systems. *Energy* 204 (2020). – DOI 10.1016/j.energy.2020.117937. – ISSN 03605442

[99] Tong, S.; Qian, D.; Huo, C.: *Hydrogen-air PEM fuel cell integration, modeling and control*. Berlin and Boston: Walter de Gruyter GmbH, 2018

[100] Tripakis, S.: Compositional Model-Based System Design and Other Foundations for Mastering Change. Version: 2016. `http://dx.doi.org/10.1007/978-3-319-46508-1{_}7`. In: Steffen, B. (Hrsg.): *Transactions on Foundations for Mastering Change I*. Cham: Springer International Publishing, 2016. – DOI 10.1007/978–3–319–46508–1_7. – ISBN 978–3–319–46508–1, S. 113–129

[101] Voskuijl, M.; van Bogaert, J.; Rao, A. G.: Analysis and design of hybrid electric regional turboprop aircraft. *CEAS Aeronautical Journal* 9 (2018), Nr. 1, S. 15–25. – DOI 10.1007/s13272–017–0272–1. – ISSN 1869–5582

[102] Vratny, P. C.: *Conceptual Design Methods of Electric Power Architectures for Hybrid Energy Aircraft*. Technische Universität München, Dissertation, 2018

[103] Vries, R. de; Brown, M.; Vos, R.: Preliminary Sizing Method for Hybrid-Electric Distributed-Propulsion Aircraft. *Journal of Aircraft* 56 (2019), Nr. 6. – DOI 10.2514/1.C035388. – ISSN 0021–8669

[104] Wang, Y.; Steinbach, T.; Klein, J.; Anderl, R.: Integration of model based system engineering into the digital twin concept. *Procedia CIRP* 100 (2021), S. 19–24. – DOI 10.1016/j.procir.2021.05.003. – ISSN 22128271

[105] Wasson, C. S.: *System Analysis, Design, and Development : Concepts, Principles, and Practices*. Hoboken, New Jersey: John Wiley & Sons, 2006

[106] Weilkiens, T.: *Systems Engineering mit SysML/UML : Anforderungen, Analyse, Architektur. Mit einem Geleitwort von Richard Mark Soley*. 3. Heidelberg, GERMANY: dpunkt.verlag, 2014

[107] Wheeler, P.; Bozhko, S.: The More Electric Aircraft: Technology and challenges. *IEEE Electrification Magazine* 2 (2014), Nr. 4, S. 6–12. – DOI 10.1109/MELE.2014.2360720. – ISSN 2325–5897

[108] Wilson, J. A.; Wang, Y.; Carroll, J.; Raush, J.; Arkenberg, G.; Dogdibegovic, E.; Swartz, S.; Daggett, D.; Singhal, S.; Zhou, X.-D.: Hybrid Solid Oxide Fuel Cell/Gas Turbine Model Development for Electric Aviation. *Energies* 15 (2022), Nr. 8, S. 2885. – DOI 10.3390/en15082885

[109] Winnefeld, C.; Kadyk, T.; Bensmann, B.; Krewer, U.; Hanke-Rauschenbach, R.: Modelling and Designing Cryogenic Hydrogen Tanks for Future Aircraft Applications. *Energies* 11 (2018), Nr. 1, S. 105. – DOI 10.3390/en11010105

[110] Xie, Y.; Savvarisal, A.; Tsourdos, A.; Zhang, D.; GU, J.: Review of hybrid electric powered aircraft, its conceptual design and energy management methodologies. *Chinese Journal of Aeronautics* 34 (2021), Nr. 4, S. 432–450. – DOI 10.1016/j.cja.2020.07.017. – ISSN 10009361

[111] Xie, Z.; Jin, Q.; Su, G.; Lu, W.: A Review of Hydrogen Storage and Transportation: Progresses and Challenges. *Energies* 17 (2024), Nr. 16, S. 4070. – DOI 10.3390/en17164070

[112] Younse, P. J.; Cameron, J. E.; Bradley, T. H.: Comparative Analysis of Model-Based and Traditional Systems Engineering Approaches for Architecting a Robotic Space System Through Automatic Information Transfer. *IEEE Access* 9 (2021), S. 107476–107492. – DOI 10.1109/ACCESS.2021.3096468

A. Appendix

A.1. Parasite drag calculation in OpenVSP

Parasite Drag module in OpenVSP is used to estimate a traditional form factor based skin friction based on the wise wetted areas of the components that comprise the analysed aircraft model. The following equations are extracted from the OpenVSP documentation [70].

A.1.1. General Overview

The following parameters were used for the basic calculations presented below:

$$\begin{aligned}
c_i &\equiv \text{Chord length at span station} \\
b_i &\equiv \text{Section span} \\
S_i &\equiv \text{Section area} \\
S_{total} &\equiv \text{Total Area} \\
\bar{c} &\equiv \text{Weighted chord sum} \\
L_{ref} &\equiv \text{Reference length} \\
D &\equiv \text{Diameter} \\
X_{area} &\equiv \text{Max cross sectional area} \\
FR &\equiv \text{Fineness ratio} \\
Re &\equiv \text{Reynolds number} \\
\rho &\equiv \text{Air density} \\
V_{\inf} &\equiv \text{Freestream velocity} \\
\nu &\equiv \text{Kinematic viscosity} \\
C_f &\equiv \text{Friction coefficient} \\
f &\equiv \text{Flat plate drag} \\
S_{wet} &\equiv \text{Wetted area} \\
S_{ref} &\equiv \text{Reference area} \\
C_D &\equiv \text{Coefficient of drag}
\end{aligned}$$

Wing reference length and total area are calculated based on the width of the wing section:

$$\Delta x = |x_{le}(1) - x_{le}(\text{end})| \tag{A.1}$$

$$\Delta y = |y_{le}(1) - y_{le}(\text{end})| \tag{A.2}$$

$$\Delta z = |z_{le}(1) - z_{le}(\text{end})| \tag{A.3}$$

$$b_i = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \tag{A.4}$$

$$S_i = b_i \cdot \frac{c_i + c_{i+1}}{2} \tag{A.5}$$

$$S_{total} = \sum S_i \tag{A.6}$$

$$\bar{c} = \sum \left(\frac{c_i + c_{i+1}}{2} \right) \tag{A.7}$$

$$L_{ref} = \frac{\bar{c}}{S_{total}} \tag{A.8}$$

Body geometry reference length is calculated the width of the body section:

$$\Delta x = |x_{le}(1) - x_{le}(\text{end})| \tag{A.9}$$

$$\Delta y = |y_{le}(1) - y_{le}(\text{end})| \tag{A.10}$$

$$\Delta z = |z_{le}(1) - z_{le}(\text{end})| \tag{A.11}$$

$$L_{ref} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \tag{A.12}$$

Fineness ratio is used to describe the body proportions and it is calculated as a ratio of body length to its maximum diameter:

$$D = 2 \cdot \sqrt{\frac{X_{area}}{\pi}} \tag{A.13}$$

$$FR = \frac{D}{L_{ref}} \tag{A.14}$$

In case of a wing its refers to ratio of maximum thickness of the wing to its chord.

Air flow around the body can be laminar (generating the least resistance), transient and turbulent. To determine which type of flow can occur, the Reynolds number is used, which is calculated with the following formula:

$$Re = \frac{\rho \cdot V_{\text{inf}} \cdot L_{ref}}{\nu} \tag{A.15}$$

Coefficient of friction equations

The parasite drag analysis in OpenVSP is only concerned with the average surface friction coefficient of a flat plate- C_{f}. There are several methods to calculate it, which can be selected in OpenVSP to perform a parasite drag analysis of the developed aircraft model.

$$\begin{aligned}
x &\equiv \text{distance along chord} \\
k &\equiv \text{roughness height} \\
\gamma &\equiv \text{specific heat ratio} \\
r &\equiv \text{recovery factor} = 0.89 \\
n &\equiv \text{viscosity power-law exponent} = 0.67 \\
l &\equiv \text{length of component} \\
d &\equiv \text{diameter of component} \\
w &\equiv \text{width at maximum cross sectional area} \\
h &\equiv \text{height at maximum cross sectional area} \\
FR &\equiv \text{covert Fineness ratio} \\
l_r &\equiv \text{length of fuselage} \\
A_x &\equiv \text{cross sectional area of fuselage} \\
Q &\equiv \text{interference factor}
\end{aligned}$$

where:

$$FR = \frac{l}{\sqrt{wh}} \tag{A.16}$$

The type of airflow around the body determines how the coefficient of friction is calculated. The Blasius equation is used to calculate the friction coefficient for laminar flow, while for turbulent flow there are several possible formulas to choose from in OpenVSP.

Laminar

Blasius:

$$C_f = \frac{1.32824}{\sqrt{Re}} \tag{A.17}$$

Turbulent

Explicit Fit of Spalding:

$$C_f = \frac{0.523}{ln^2\sqrt{0.06Re}} \tag{A.18}$$

Explicit Fit of Spalding and Chi:

$$C_f = \frac{0.430}{log(Re)^{2.32}} \tag{A.19}$$

Explicit Fit of Schoenherr:

$$\frac{1}{\sqrt{C_f}} = 3.46log(Re) - 5.6 \tag{A.20}$$

Implicit Schoenherr:

$$log(ReC_f) = \frac{0.242}{\sqrt{C_f}} \tag{A.21}$$

Implicit Karman-Schoenherr:

$$\frac{1}{\sqrt{C_f}} = 4.13log(ReC_f) \tag{A.22}$$

Power Law Blasius:

$$C_f = \frac{0.072}{Re^{1/5}} \tag{A.23}$$

Power Law Prandtl Low Re:

$$C_f = \frac{0.074}{Re^{1/5}} \tag{A.24}$$

Power Law Prandtl Medium Re:

$$C_f = \frac{0.0315}{Re^{1/7}} \tag{A.25}$$

Power Law Prandtl High Re:

$$C_f = \frac{0.0725}{Re^{1/5}} \tag{A.26}$$

Schlichting Compressible:

$$C_f = \frac{0.455}{log(Re)^{2.58}} \tag{A.27}$$

Schlutz-Grunow Estimate of Schoenherr:

$$C_f = \frac{0.427}{(log(Re) - 0.407)^{2.64}} \tag{A.28}$$

Roughness Schlichting Avg:

$$C_f = \left(1.89 + 1.62 \log\left(\frac{l}{k}\right)\right)^{-2.5} \tag{A.29}$$

Schlichting Avg Compressible:

$$C_f = \frac{\left(1.89 + 1.62 \log\left(\frac{l}{k}\right)\right)^{-2.5}}{\left(1 + \frac{\gamma-1}{2} M_\infty^2\right)^{0.467}} \tag{A.30}$$

Heat transfer White-Christoph:

$$f = \frac{\left(1 + 0.22 r \frac{\gamma-1}{2} M_e^2 \frac{T_e}{T_w}\right)}{\left(1 + 0.3\left(\frac{T_{aw}}{T_w} - 1\right)\right)} \tag{A.31}$$

$$C_f = \frac{0.451 f^2 \frac{T_e}{T_w}}{\ln^2\left(0.056 f \frac{T_e}{T_w}^{1+n} Re\right)} \tag{A.32}$$

Form Factor Equations

The shape factor is a coefficient used to transform the skin friction drag for a flat plate to account for the effect of the object's shape.

Wing Equations

The form factor of bodies whose shape is based on an airfoil (wings, tail) can be calculated using several available formulas in OpenVSP:

EDET Conventional Airfoil

$$FF = 1 + \frac{t}{c}\left(2.94206 + \frac{t}{c}\left(7.16974 + \frac{t}{c}\left(48.8876 + \frac{t}{c}\left(-1403.02 + \frac{t}{c}\left(8598.76 + \frac{t}{c}\left(-15834.3\right)\right)\right)\right)\right)\right) \tag{A.33}$$

EDET Advanced Airfoil:

$$FF = 1 + 4.275\,\frac{t}{c} \tag{A.34}$$

DATCOM:

$$FF = \left[1 + L\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right] * R_{L.S.} \tag{A.35}$$

Hoerner:

$$FF = 1 + 2\left(\frac{t}{c}\right) + 60\left(\frac{t}{c}\right)^4 \tag{A.36}$$

Shevell:

$$FF = 1 + Z\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4 \tag{A.37}$$

$$Z = \frac{(2 - M^2)\cos\left(\Lambda_{\frac{c}{4}}\right)}{\sqrt{1 - M^2\cos^2\left(\Lambda_{\frac{c}{4}}\right)}} \tag{A.38}$$

Kroo:

$$FF = 1 + \frac{2.2\cos^2\left(\Lambda_{\frac{c}{4}}\right)}{\sqrt{1 - M^2\cos^2\left(\Lambda_{\frac{c}{4}}\right)}}\left(\frac{t}{c}\right) + \frac{4.84\cos^2\left(\Lambda_{\frac{c}{4}}\right)\left(1 + 5\cos^2\left(\Lambda_{\frac{c}{4}}\right)\right)}{2\left(1 - M^2\cos^2\left(\Lambda_{\frac{c}{4}}\right)\right)}\left(\frac{t}{c}\right)^2 \tag{A.39}$$

Torenbeek:

$$FF = 1 + 2.7\ \left(\frac{t}{c}\right) + 100\ \left(\frac{t}{c}\right)^4 \tag{A.40}$$

Covert:

$$FF = 1 + 1.8\ \left(\frac{t}{c}\right) + 50\ \left(\frac{t}{c}\right)^4 \tag{A.41}$$

Schemensky 6 Series Airfoil:

$$FF = 1 + 1.44\left(\frac{t}{c}\right) + 2\left(\frac{t}{c}\right)^2 v \tag{A.42}$$

Schemensky 4 Series Airfoil:

$$FF = 1 + 1.68\left(\frac{t}{c}\right) + 3\left(\frac{t}{c}\right)^2 \tag{A.43}$$

Jenkinson Wing:

$$F^* = 1 + 3.3\left(\frac{t}{c}\right) - 0.008\left(\frac{t}{c}\right)^2 + 27.0\left(\frac{t}{c}\right)^3 \tag{A.44}$$

$$FF = (F^* - 1)\left(cos^2\left(\Lambda_{\frac{c}{2}}\right)\right) + 1 \tag{A.45}$$

Jenkinson Tail:

$$F^* = 1 + 3.52\left(\frac{t}{c}\right) \tag{A.46}$$

$$FF = (F^* - 1)\left(cos^2\left(\Lambda_{\frac{c}{2}}\right)\right) + 1 \tag{A.47}$$

$$Q = 1.2 \tag{A.48}$$

Body Equations

The equations of the form factor of the slender body are usually given in terms of the fineness ratio (FR):

$$FR = \frac{l}{d} \tag{A.49}$$

Diameter of bodies of arbitrary cross section:

$$d = 2 * \sqrt{\frac{A_{xsec}}{\pi}} \tag{A.50}$$

Schemensky Fuselage:

$$FF = 1 + \frac{60}{FR^3} + 0.0025\ FR \tag{A.51}$$

Schemensky Nacelle:

$$FF = 1 + \frac{0.35}{FR} \tag{A.52}$$

Hoerner Streamlined Body:

$$FF = 1 + \frac{1.5}{(FR)^{1.5}} + \frac{7}{(FR)^3} \tag{A.53}$$

Torenbeek:

$$FF = 1 + \frac{2.2}{(FR)^{1.5}} + \frac{3.8}{(FR)^3} \tag{A.54}$$

Shevell:

$$FF = 1 + \frac{2.8}{(FR)^{1.5}} + \frac{3.8}{(FR)^3} \tag{A.55}$$

Covert:

$$FF = 1.02\left(1.0 + \frac{1.5}{(FR)^{1.5}} + \frac{7.0}{(FR)^3 (1.0 - M^3)^{0.6}}\right) \tag{A.56}$$

Jenkinson Fuselage:

$$\Lambda = \left(\frac{l_r}{\frac{4}{\pi}A_x}\right)^{0.5} \tag{A.57}$$

$$FF = 1 + \frac{2.2}{\Lambda^{1.5}} - \frac{0.9}{\Lambda^3} \tag{A.58}$$

Jenkinson Wing Nacelle:

$$FF = 1.25 \tag{A.59}$$

Jenkinson Aft Fuselage Nacelle:

$$FF = 1.50 \tag{A.60}$$

The above calculations are then used to modify the flat plate drag formula to take into account the shape of the object (FF) and the effect of other aircraft components on airflow interference between them, such as the fuselage on the wing flow (Q):

$$f = S_{wet} \cdot Q \cdot C_f \cdot FF \tag{A.61}$$

The drag coefficient is calculated as a ratio of the above plate drag formula and the reference area:

$$C_D = \frac{f}{S_{ref}} \tag{A.62}$$

Flow Condition

OpenVSP provides two atmospheric models for parasite drag analysis: US Standard Atmosphere 1976 and USAF 1966, which describe in different ways the variation of air temperature in relation to altitude.

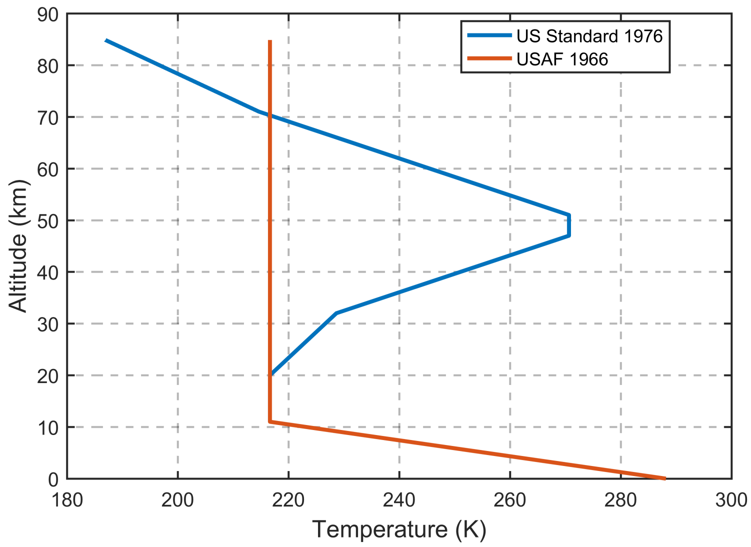


Figure A.1.: Comparison of the two atmospheric models available in OpenVSP

Changes in air temperature affect its **dynamic viscosity** and thus the magnitude of the shear forces acting on a body in the airstream.

$$\beta \equiv 1.458E10^{-6} \frac{kg}{(s * m * K^{1/2})}$$

$$\mu \equiv \text{Dynamic Viscosity}$$

$$S \equiv \text{Sutherland's Constant} = 100.4 \text{ K}$$

$$\mu = \frac{\beta \cdot T^{3/2}}{T + S} \tag{A.63}$$

A.2. Parameters of the ISA atmosphere model

Table A.1.: Parameters of the ISA atmosphere model using in propulsion models [59]

Sutherland temperature (K)	110.4
Reference temperature (K)	273.15
Reference dynamic viscosity (kg/ms)	1.716e-5
Acceleration from gravity (m/s^2)	9.80665
Ratio of specific heats	1.4
Characteristic gas constant (J/kg/K)	287.0531
Lapse rate of the troposphere (K/m)	0.0065
Height of troposphere (m)	11000
Height of tropopause (m)	20000
Air density at mean sea level (kg/m^3)	1.225
Ambient pressure at mean sea level (N/m^2)	101325
Ambient temperature at mean sea level (K)	288.15

A.3. Aircraft airframe weight calculation

Equations used to calculate fuselage, wing and tail masses provided by Queen's University Belfast School of Mechanical & Aerospace Engineering:

$$\begin{aligned}
AR &\equiv \text{Aspect Ratio} \\
S &\equiv \text{Wing Area (m}^2\text{)} \\
\varphi &\equiv \text{Effective Sweep (deg)} \\
c_{\mathrm{t/c}} &\equiv \text{Ratio of Tip to Centreline chords} \\
W &\equiv \text{Maximum Take Off Weight} \\
a &\equiv \text{Maximum maneouvre acceleration factor} \\
v &\equiv \text{Design maximum speed (m/s)} \\
t_{\mathrm{c/c}} &\equiv \text{Thickness-chord ratio at wing centreline} \\
C1 &\equiv \text{Wing constant} \\
C2 &\equiv \text{Fuselage constant} \\
l &\equiv \text{Overall fuselage length (m)} \\
d_{\max} &\equiv \text{Maximum width of the fuselage (m)} \\
h_{\max} &\equiv \text{Maximum height of the fuselage (m)} \\
m_{\mathrm{fuselage}} &\equiv \text{Fuselage mass (kg)} \\
m_{\mathrm{wing}} &\equiv \text{Wing mass (kg)} \\
m_{\mathrm{tail}} &\equiv \text{Tail mass (kg)}
\end{aligned}$$

Fuselage mass:

$$m_{fuselage} = C2 \cdot (l \cdot (d_{\max} \cdot h_{\max}) \cdot 0.5v \cdot 1.5) \tag{A.64}$$

Wing mass:

$$m_{\text{wing}} = (\frac{AR}{2} \cdot 1.5S \cdot \frac{1}{cos(\varphi)}) \cdot (\frac{1+2c_{\text{t/c}}}{3+3c_{\text{t/c}}}) \cdot \frac{W}{S} \cdot (1.65 \cdot 0.3a) \cdot ((\frac{v}{t_{\text{c/c}}} \cdot 0.5) \cdot 0.9) \cdot C1 \quad \text{(A.65)}$$

Tail mass:

$$m_{\text{tail}} = 0.4 \cdot m_{\text{fuselage}} \quad \text{(A.66)}$$

A.4. Fuel cell block – mathematical description

The Fuel Cell block allows for the selection of one of two levels of simulation fidelity: simplified and detailed. In this work, the latter level of accuracy is chosen. This block uses two equations to calculate the Nernst voltage E in relation to the temperature of the hydrogen fuel cell [57]:

$$E = \begin{cases} K_c N \left(1.229 + K_z \frac{RT}{zF} \ln \left(p_{H_2} p_{O_2}^{1/2}\right)\right) - E_{\text{Tafel}} - E_{\text{conc}}, & T < 373.15\,\text{K} \\ K_c N \left(1.229 + K_z \frac{RT}{zF} \ln \left(\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}}\right)\right) - E_{\text{Tafel}} - E_{\text{conc}}, & T \geq 373.15\,\text{K} \end{cases} \quad \text{(A.67)}$$

where:

$K_c \equiv$ voltage constant at nominal condition operation
$N \equiv$ number of cells per module
$R \equiv$ universal gas constant
$T \equiv$ fuel cell operating temperature
$z \equiv$ number of moving electrons per second
$F \equiv$ Faraday's constant
$p_{H_2}, p_{O_2}, p_{H_2O} \equiv$ partial pressure of hydrogen, oxygen and vapor
$E_{Tafel} \equiv$ activation losses
$E_{conc} \equiv$ concentration losses

The variable K_z used in the equation A.67 is calculated as follows [57]:

$$K_z = \frac{\frac{E_{oc\_adm}}{K_c N} - 1.229}{(T_{nom} - 298)\frac{-44.43}{z_0 F} + \frac{RT_{nom}}{z_0 F} \ln \left(P_{nH_2} P_{nO_2}^{\frac{1}{2}}\right)} \quad \text{(A.68)}$$

where:

$T_{nom} \equiv$ nominal temperature
$z_0 \equiv$ number of electrons moving per second at nominal exchange current i_0
$p_{nH_2} \equiv$ nominal hydrogen pressure (in bar)
$p_{nO_2} \equiv$ nominal oxygen pressure (in bar)

The following formula is used to calculate the E_{oc_adm} variable [57]:

$$E_{oc\_adm} = \max\left(E_{oc},\ N\left(1.229 + \frac{RT_{nom}}{2F}\ln\left(p_{nH_2}p_{nO_2}^{\frac{1}{2}}\right)\right)\right) \tag{A.69}$$

The magnitude of activation and concentration losses is calculated using the following formulas [57]:

$$E_{\text{Tafel}} = N\frac{AT}{\ln(10) * 298}\ln\left(\frac{i_{\text{FC}}}{i_0}\right) \tag{A.70}$$

$$E_{\text{conc}} = V_e\frac{T}{298}\ln\left(\frac{i_{lim}}{i_{lim} - i_{FC}}\right) \tag{A.71}$$

where:

$A \equiv$ Tafel slope (in V)
$i_{FC} \equiv$ current generated by the fuel cell
$i_0 \equiv$ nominal exchange current
$V_e \equiv$ thermal voltage at room temperature

The partial pressures of hydrogen, oxygen and vapour are defined as follows [57]:

$$p_{H_2} = p_{fuel}x_{H_2} - \frac{60000Ni_{FC}V_e}{p_{fuel}q_{fuel}x_{H_2}} \tag{A.72}$$

$$p_{O_2} = p_{air}x_{O_2} - \frac{60000Ni_{FC}V_e}{2p_{air}q_{air}x_{O_2}} \tag{A.73}$$

$$p_{H_2O} = p_{air}x_{H_2O} - 2 \cdot \frac{60000Ni_{FC}V_e}{2p_{air}q_{air}x_{O_2}} \tag{A.74}$$

where:

$p_{\text{fuel}}, p_{\text{air}} \equiv$ supply pressure of fuel and air respectively (in bar)
$x_{H_2}, x_{O_2} \equiv$ concentration of hydrogen in the fuel and oxygen in the air (in percentage)
$x_{H_2O} \equiv$ concentration of vapor in air (in percentage)
$q_{\text{fuel}}, q_{\text{air}} \equiv$ fuel and air flow rates respectively

The block calculates the heat generated by the fuel cell during electricity production as follows [57]:

$$P_{heat} = Z_{e\_agg}(T\Delta S) + R_i i_{FC} + v_d^2 \frac{1}{R_d} \tag{A.75}$$

$$Z_{e\_agg} = \frac{(N_{unit}E - R_i i_{FC} v_d) i_{FC}}{2\Delta G} \tag{A.76}$$

where:

$Z_{e\_agg} \equiv$ total electron circulation rate (in mol/s)
$T\Delta S \equiv$ change in entropy of the fuel cell reaction regarding its operating temperature
$R_i \equiv$ internal resistance
$v_d \equiv$ voltage drop
$R_d \equiv$ total resistance of activation and concentration
$N_{\mathrm{unit}} \equiv$ number of modules in series
$E \equiv$ Nernst voltage
$\Delta G \equiv$ the Gibbs free energy change of the full fuel cell reaction