CONCEPTUAL DESIGN OF A HYDROGEN-POWERED 9-SEATER COMMUTER AIRCRAFT

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ABSTRACT

New propulsion technologies are an important factor in enabling the transformation of the aviation sector to a sustainable future. In this paper, the feasibility of a 9-seater small aircraft with a hydrogen powertrain is evaluated. One focus is on the development of tools and methods for the preliminary design of this aircraft. Based on an existing framework, a design process is created which consolidates various disciplinary tools. This process is designed to cover a comparably wide range of TLARs and configurations and to quickly model and evaluate new designs. The second focus is on the actual design of the aircraft. Starting with a market analysis, a set of TLARs and the overall configuration are defined. With these, the design process is executed. The result is an aircraft with air-cooled fuel cells and a distributed electric propulsion system. It has the capability to transport a payload of 855 kg over 600 km. For this mission, 78 kg of pressurized hydrogen is required. In the future, the design process will be expanded and improved in various ways in order to increase the accuracy of the results and to consider more aspects in greater detail.

Keywords
Aircraft Design; Hydrogen Propulsion; Fuel Cell; Small Air Transport

NOMENCLATURE

Symbols

c_D	Drag coefficient	[-]
c_{D0}	Zero-lift drag coefficient	[-]
c_{Di}	Induced drag coefficient	[-]
c_L	Lift coefficient	[-]
L/D	Lift-to-drag ratio	[-]

Acronyms

AMC	Aircraft Mission Calculator
CAS	Calibrated Air Speed
CPACS	Common Parametric Aircraft Configuration Schema
CoG	Center of gravity
CS	Certification specification
DEP	Distributed electric propulsion
DLR	German Aerospace Center
DMU	Digital mock-up
EIS	Entry into service
FAA	Federal Aviation Administration
FC	Fuel cell
HTP	Horizontal tailplane
IFR	Instrument flight rules
ISA	Standard atmosphere conditions
LFL	Landing field length
MTOM	Maximum take-off mass
OEM	Operating empty mass
OIM	Operator items mass
PEM	Proton exchange membrane
RCE	Remote Component Environment
SAT	Small air transport
SL	Sea level
TAS	True Air Speed
TOFL	Take-off field length
TLAR	Top-level aircraft requirement
VTP	Vertical tailplane

1. MOTIVATION

As the consequences of global warming become increasingly apparent, it is necessary to significantly reduce the climate impact of the largest contributors, one of which is aviation.
Within the aviation sector, large CS-25 aircraft generate most of the climate effect [1]. However, because of prohibitive risks and high costs, it is unlikely that revolutionary technology will first be introduced in this segment.
In contrast, the development of small aircraft in the CS-23 category [2] generally is less complex and risky, and consequently more suitable for less investment-intensive proof-of-concept development projects. Furthermore, most existing small aircraft designs originated at least 30 years ago and thus

rarely use state-of-the-art technology.
Therefore, aircraft with up to 19 seats pose the opportunity to pave the way for sustainable aviation by establishing new concepts, while significantly improving the technology level and thus the efficiency of the small aircraft segment itself.
To advance the development in this segment, the German Aerospace Center (DLR) launched the Project "Digital Climate-neutral Light Aircraft" (D-Light). Its goal is to develop methods and tools for the digital design of advanced small aircraft and to apply these to design a concept of a 9-seater commuter aircraft with hydrogen-electric propulsion.

2. PROJECT-IMPOSED DESIGN BOUNDARY CONDITIONS

The aircraft design needs to facilitate the successful work on the D-Light project with the following goals:

- Develop methods and tools for the design of advanced small aircraft.
- Generate a design of a 9-seater commuter aircraft with hydrogen-driven propulsion based on low temperature fuel cells (PEM technology).
- Generate a digital mock-up of the aircraft.

These goals impose design constraints on top of the conventional product-driven approach.

2.1. CS-23

The project requires a 9-seater design as a commuter airliner. This binds the design rules to the CS-23 requirements. Since Amendment 5, the CS-23 rule set has become more suitable for unconventional technologies and designs [3, 4]. Previous rules at system level, bound to the combustion engine technology with liquid fuel, have been removed and replaced with objective-oriented requirements. The objectives, bound to aircraft level safety, enable unconventional solutions as long as the safety requirements can be demonstrated.
Based on this, the aircraft of the project needs to be compliant with the conventional safety objectives, ensuring the extreme unlikeliness of catastrophic failure of the aircraft and sufficient redundancy allowing the mitigation of single component failure through emergency procedures. E.g. one engine inoperative case is considered for take-off calculations and controllability assessment. The initial assumption at this preliminary stage is that the component failure rate is sufficiently low for considering the failure of two components. This assumption will be revisited at later stages of the project.

2.2. Technology Constraints

The propulsion system type is predetermined. The primary power provider is a fuel cell. The primary energy storage is hydrogen based. Since the aircraft design targets the commuter market segment, it needs to be practical in terms of small airport infrastructure and manufacturing costs. Pressurized hydrogen was preferred for the initial design, as it is less demanding in terms of airport infrastructure than liquid hydrogen storage. The fuel cell type was set to air-cooled fuel cells, which feature a far less complex overall system, making them the potentially cheaper solution. However, both choices are costly in terms of propulsion system mass. This was mitigated by choosing TLARs at the lower-end spectrum of the market requirements in terms of aircraft speed and range, which will be discussed in section 3.

2.3. Design Targets

The design needs to be sufficiently generic to be a suitable platform for tool development. The following disciplinary tools will be developed for the project:

- Fuel Cell Sizing: The tool "Airfox" provides the design and performance of the fuel cell system. The fuel cell stacks and various subsystems, e.g. air cooling system and batteries, are modeled. These models are validated with data from testing of commercial components to improve accuracy.
- Aerodynamics: The aerodynamics tool provides aerodynamic properties of the main components, such as wings, fuselage, or engine pods. It further determines the propeller-wing interaction, especially the change in lift and drag due to the propeller wake. The tool consists of a metamodel created with data from high-fidelity numeric simulations performed with TAU [5], combined with data from low-fidelity calculations from Lifting Line [6].
- Wing structure: This tool supplies the structural composition of the main wing, which is determined by a metamodel of high-level numeric simulations and optimizations using the structural solver Nastran [7]. The main focus is on aeroelasticity, driven by the DEP (distributed electric propulsion) system and propeller effects, such as gyroscopic and 1P forces.
- System design: The tool provides sizing and packaging of aircraft systems, such as flight control and powertrain components. Further aspects are considered, such as power management, including efficiency and allowable temperature range for each component, as well as safety, reliability, and failure analysis. It is based on SysArc [8].
- Tank sizing: The tank sizing tool "TankTool" provides geometric and gravimetric data of the H_2 pressure tanks. It contains a metamodel based on high-fidelity winding simulations of the tank structure [9] and assumptions for the tank support structure and systems mass. Its outputs are main properties of the tank, such as tank arrangement, dimensions and gravimetric efficiency. This tool is already in use within the main design workflow, see section 5.1.1

Since the project aircraft will be used as a base for the development of some of these tools and capabilities, a conventional tube and wing configuration was chosen for the project, see section 4.1.

3. DESIGN REQUIREMENTS

To obtain relevant Top Level Aircraft Requirements (TLARs), an analysis of the projected market segment and comparable aircraft was performed. Based on these results, the TLARs and a design mission were defined.

3.1. Market Analysis

CS-23 aircraft are used in a wide range of applications, such as:

- feeder flights from small airfields to large hubs
- service to remote regions
- pilot training
- medical flights
- wildfire suppression
- private-owned aircraft

The first two scenarios are deemed the most relevant, therefore the market analysis was focused on the required range, cruise altitude, cruise speed and take-off/landing distance in these cases.

3.2. TLARs

Based on the market analysis, the following Top-Level Aircraft Requirements (TLARs) were defined.

TLAR	Value	Unit	Comment
Pax	9	-	project req.
Ref. payload	855	kg	95 kg per pax
Ref. range	600	km	see 3.2.1
Cruise altitude	10000	ft	see 3.2.2
Cruise speed (TAS)	160	kts	see 3.2.3
TOFL (sea level, ISA)	$\leq$800	m	see 3.2.4
TOFL (6600ft, ISA+15)	$\leq$1200	m	assumption
LFL (sea level, ISA)	$\leq$800	m	see 3.2.4
MTOM[1]	$\leq$ 8618	kg	CS-23
Wing span	$\leq$ 24	m	airport size
EIS	2030	-	project req.

TAB 1. TLARs

3.2.1. Range

Comparable aircraft, such as Cessna 402, Piper PA-31 or Tecnam P2012, typically have a design range of about 1500-1900 km [11]. The flight distance in actual operations, however, is generally lower. In 2014, turboprop aircraft with less than 19 seats averaged 137 km [12]. This shows that the maximum range of such aircraft is rarely used. Considering the overall SAT (Small air transport) demand in Europe modeled for 2022, the required distance to cover 95% of the SAT market is 525 km [13]. With an added margin, the design range was hence set to 600 km.

3.2.2. Cruise Altitude

For a fuel cell aircraft, the cruise altitude significantly effects the propulsion system complexity and performance. Since the fuel cell requires a defined condition and mass flow of air for operation, a large compressor is required in higher altitudes to compensate the reduced air density. Due to the specific case of an air-cooled fuel cell, a higher cruise altitude further requires a larger heat exchanger to sufficiently cool the fuel cell. Because these increase mass and aerodynamic drag, a comparably low cruise altitude of 10000 ft was chosen. Furthermore, defining a service ceiling of 10000 ft eliminates the need for an oxygen system for crew and passengers, otherwise required by CS-23 regulations [2]. Additionally, the cabin can remain unpressurized, reducing weight and manufacturing costs.

3.2.3. Cruise Speed

In cruise, comparable aircraft reach a true airspeed (TAS) between 139 and 190 kts [11]. This can be confirmed by the analysis of actual flight data by twin piston aircraft. During roughly 75% of the regarded flights, a maximum ground speed of less than 190 kts is reached [14]. As these are short-term maximum values, the design cruise speed can be assumed to be even lower. Consequently, the TAS in cruise for the design mission was set to 160 kts (300 km/h). This comparably low speed further benefits fuel cell and tank mass, as less power and energy is required during cruise.

3.2.4. Runway Length

In order to serve smaller airports, the aircraft must be able to take-off and land from comparably short runways. The minimum take-off and landing distances of comparable aircraft are between 400 and 800 m [11]. However, in Europe and the USA, 84% of the runways with a length below 900 m are unpaved [15] and therefore less relevant for the projected missions. In order to be able to use all code 2 aerodromes, i.e. airports whose longest runway is between 800 and 1200 m [16], the required take-off and landing distance was thus set to 800 m.

3.3. Design Mission

Based on these TLARs, a design mission was defined, see Tab. 2. It consists of the block mission with a climb, cruise, and descend phase, as well as a reserve mission with a diversion and a holding phase.
The diversion distance was derived from an analysis of suitable airports in Europe and the USA [17]. The holding time was adopted from FAA IFR regulations [18].

[1] Due to runway strength limitations on many small airports [10], it is aimed to achieve MTOM $\leq$ 5700 kg

	Cruise	Diversion	Holding
Distance, km	600	70	-
Time, min	-	-	45
Altitude, ft	10000	8000	optimized[2]
Speed, kts	160	150	-

TAB 2. Design mission phases, speed in TAS

4. CONCEPT DEFINITION

Prior to the full design process, the aircraft configuration needs to be defined. Due to the unconventional propulsion system, the powertrain architecture and tank arrangement strongly influence the design. Therefore, these aspects have to be considered early in the design phase.

4.1. Configuration

Initially, the most suitable overall configuration is to be determined. However, performing complete analysis of all potential options is not feasible due to the large amount of possible combinations, therefore each configuration was evaluated qualitatively following handbook guidelines [19] [20].

Overall Configuration
For the overall configuration, a conventional layout was selected, i.e. tube-and-wing with the empennage at the aft fuselage. As a widely-used configuration in the CS-23 segment, it fits all project needs without adding much complexity.
Alternatively, a canard and a three-surface configuration were evaluated qualitatively. These configurations could possibly achieve higher aerodynamic efficiency. However, due to the inherently higher complexity and problematic stall behaviour in low-speed flight [19], the potential advantages are likely to be outweighed. Therefore, these configurations were rejected.

Propulsion
For the propulsion system, several preconditions were defined for the project. Specifically, the aircraft is powered by an air-cooled fuel cell and is fueled by gaseous hydrogen stored in pressure tanks.
Subsequently, a DEP concept was selected. While the complexity of such a system increases significantly, it can offer aerodynamic advantages. The interaction of the propeller wake with the wing leads to increased lift coefficients during powered flight. This effect significantly improves take-off performance and, especially in high-temperature conditions, benefits the fuel cell system by reducing the power requirement.
To maximize the powered-lift effect, the propellers are located in front of the wing and are distributed across the entire wing span, including the wing tips. The propellers on each wing half are rotating inboard up to allow partial swirl energy recovery, which benefits the induced drag [21].
Additional considerations regarding the tank arrangement and the powertrain architecture are discussed in sections 4.2 and 4.3.

Wing
Configurations with the wing below or above the fuselage were evaluated[3]. A low wing configuration benefits landing gear integration and improves accessibility and maintainability. A high wing configuration improves the ground clearance but, at the same time, increases structural mass and raises the vertical position of the center of gravity (CoG). As a consequence of the higher CoG, the ground stability is reduced and the aircraft requires a wider landing gear, leading to an even more complex integration.
Because of the DEP configuration, the propellers are comparably small, enabling a low wing arrangement with sufficient ground clearance.

Empennage
While a conventional fuselage-mounted tail is more structurally efficient, a T-tail was selected for the project configuration. This is primarily due to the specific fuselage geometry, which will cause the wing wake to blanket a fuselage-mounted horizontal tailplane (HTP) at high angles of attack. This reduces longitudinal controllability, and could, in the worst case, cause an irrecoverable stall. Additionally, the strong wake of the DEP propellers could lead to increased fatigue on a fuselage-mounted HTP [19]. Although these risks could be reduced with a V-tail, the potential aerodynamic advantage of such a configuration was considered too small compared to its inherent complexity, which would ultimately lead to increased manufacturing and maintenance costs.

Landing Gear
As found on virtually all similar aircraft, a conventional tricycle landing gear was selected, which consists of two main gears and one nose gear. Compared to a tailwheel configuration, this offers improved controllability during landing, a better visibility from the cockpit, and allows the cabin being horizontal when on ground. In order to reduce drag during cruise, the landing gear is retractable. Because of the low wing configuration, the main landing gear is attached to the wing and retracts into the fuselage.

4.2. Tank Arrangement

The hydrogen tank placement is a crucial design consideration, because of its high mass and safety impact. The tank pressure is an important design parameter, as it acts as tradeoff between tank mass and fuel volume. As a first assumption, the pressure was set to a comparably high value of 700 bar in order to minimize the required volume.

[2] Holding altitude is optimized for minimum energy consumption by the mission simulation tool AMC

[3] a mid wing severely obstructs the fuselage volume and/or increases complexity and is therefore not considered

Fig. 1 shows the considered installation locations, specifically:

1) Behind the cabin
2) Above the cabin
3) Below the cabin
4) Between cabin and cockpit
5) Inside the engine pods
6) Alongside the fuselage

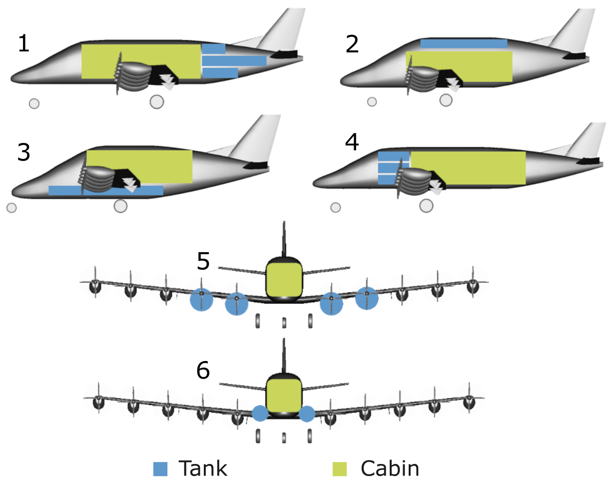

FIG 1. Overview of evaluated tank configurations (not to scale)

All options were analysed and compared qualitatively regarding various criteria such as safety, structural mass, and accessibility. Additionally, the tank mass in each case was estimated with the tank sizing tool, see section 2.3.
The result of this consideration is that the most promising arrangement is the installation of the tanks above the cabin (option 2). While it requires a heavy support structure to protect the cabin in crash cases and increases fuselage diameter, this option provides easy accessibility of the tanks, high safety in case of leakage, and is uncritical in terms of weight and balance.
The specific advantages and drawbacks of the other potential configurations are briefly discussed hereafter.

- Option 1 has favourable aerodynamics and safety characteristics, but limits the available space in the fuselage and suffers from the wide range and extremely aft position of the CoG, which requires large stabilizers.
- Option 3 is structurally advantageous, but has significant safety issues in crash cases. Due to the hydrogen tanks being located in the impact zone below the cabin, a crash may damage the tanks, possibly leading to a fire or an explosion.
- Option 4 enables reducing the fuel line length compared to the selected configuration. However, it increases the risk of tank damage in case of propeller failure, and its volume is limited due to the connection between cabin and cockpit required for certification. Furthermore, the storage of hydrogen within the cabin poses a significant safety risk.
- Option 5 benefits from improved safety, accessibility, and weight and balance compared to the selected configuration, but is severely penalized by the massive pods, which increase drag and lead to significant aeroelastic issues.
- Option 6 improves fuel routing compared to the selected configuration and is uncritical in terms of weight and balance, but has safety issues in case of propeller failure, and requires large fairings, which could have a negative aerodynamic impact.

4.3. Powertrain Architecture

The placement of the propulsion system and its subsystems has a strong effect on the overall configuration. The fuel cell, in particular, is heavy and requires a large cooling system. Furthermore, the entire system needs to be designed redundantly to provide safe operation even in case of a component failure.
A detailed design and safety analysis of the powertrain architecture will be performed at a later point in the project. As a first approximation, a preliminary architecture was assumed based on conceptual studies and discussions within the project team, and the effect on the overall design was estimated.
A DEP architecture with 10 propellers was selected. As shown in Fig. 2, the fuel cells and power electronics are distributed among the engine pods, resulting in identical and self-sufficient units which include all required electrical, thermal, and mechanical subsystems. The hydrogen fuel is routed through the fuselage and wing to each pod. Furthermore, a common buffer battery is located in each wing which compensates transient load changes. This is necessary, because quick load changes accelerate the degradation of the fuel cells [22].

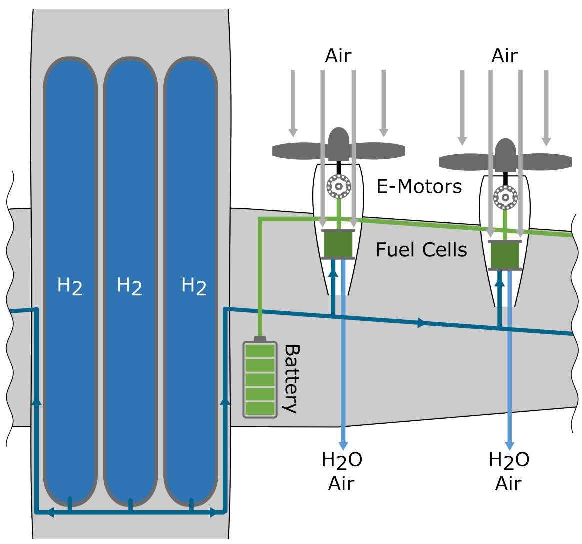

FIG 2. Section of preliminary powertrain architecture

5. METHODS AND TOOLS

The previously discussed TLARs and overall configuration are used as input for the digital design process, which generates a comprehensive design capable of fulfilling these requirements. The design process consists of various tools, including those developed within the D-Light project. For calibration and evaluation of the results, a reference aircraft is introduced.

5.1. Digital Design Process

The aim of the D-Light project is to create a digital and preferably entirely automated design process to enable quick and comprehensive evaluation of different aircraft concepts. This is achieved by modeling various disciplines with specialized tools. These tools are combined in a single workflow which runs iteratively and consolidates each result into a consistent design.

5.1.1. Design Workflow

The design workflow is implemented in the software RCE [23]. As shown in Fig. 3, the input containing TLARs, mission profiles and other data is provided externally and used for a basic initial design with OpenAD. This design is used for further design and analysis by the other tools.
First, the propulsion system is sized, particularly fuel cell and propellers, using the tools FCtool and OpenProp respectively. The output is used for mission analysis, where simultaneous calculations of the low speed and high speed segments is performed by the tools LSperfo and AMC, respectively. Separately, the hydrogen tanks is sized by the project-developed tankTool. After all the previous steps are completed, the results are merged and used as updated input data for synthesis by another OpenAD run. This procedure is repeated until convergence is reached.
The tools and workflow components use CPACS (Common Parametric Aircraft Configuration Schema) as universal file format for exchanging data between each other [24]. By using the same file format, the number of connections between tools is reduced significantly and the implementation of additional tools can be simplified.

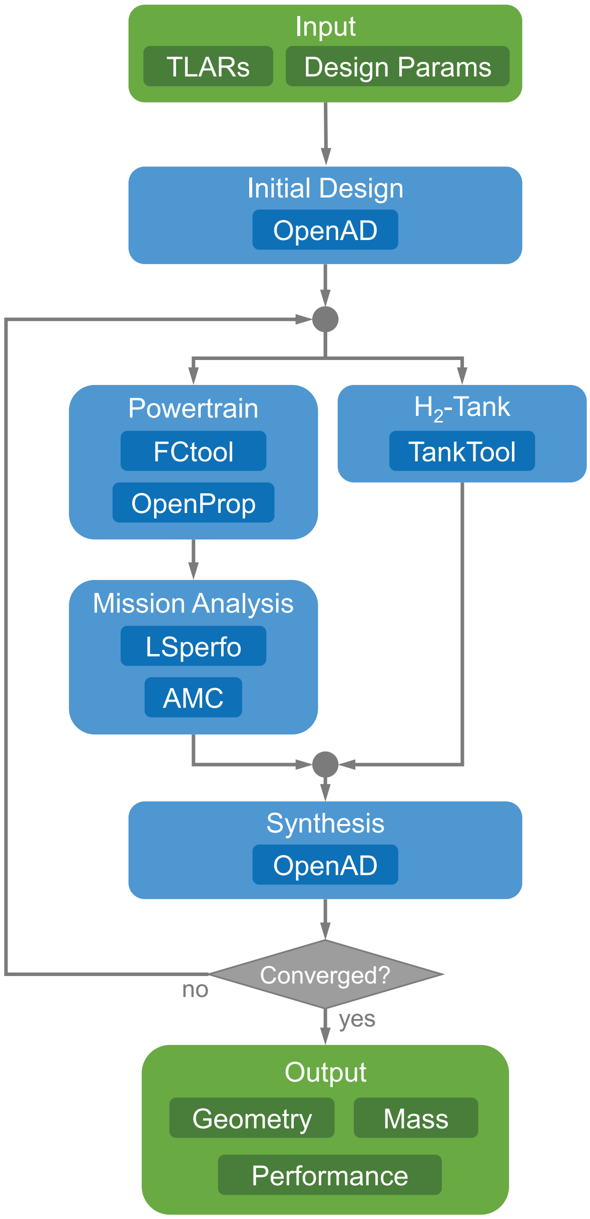

FIG 3. Workflow structure

5.1.2. OpenAD

OpenAD is a conceptual aircraft design tool developed by DLR [25]. From the initial input, an iterative calculation process is triggered, the result of which is a parametric representation of the aircraft, including geometry, engine performance, and aerodynamics. The calculation methods are based on both physical and empirical models. The tool structure is designed to be highly modular to enable the capability to easily add or modify functionalities required for the specified application.
For the commuter aircraft designs of the D-Light project, OpenAD was modified to the regime of CS-23 aircraft. In particular, suitable empirical models for small aircraft were implemented, such as mass estimation models. Specific certification requirements, such as stall speed limitations, were introduced as well. Furthermore, capabilities regarding the hydrogen propulsion were added, such as the integration and initial sizing of the pressure tanks and fuel cells.

5.1.3. Additional Tools

For various disciplines, separate tools are used, which provide higher fidelity results. In particular:

AMC (Aircraft Mission Calculator) [25] simulates the design mission and provides the trajectory and required fuel mass for this mission. The focus is on high-speed mission phases, such as climb, cruise, and descent.

LSperfo [26] simulates the low-speed phases of the design mission, such as ground roll, take-off, and landing. It provides the trajectory and required amount of fuel for these segments.

OpenProp [27, 28] provides the propeller design. Based on the blade momentum theory, the propeller is sized to the propulsion requirements and the geometry is defined. As a result, the properties and performance parameters, such as propeller efficiency are calculated for each operating point.

FCtool is used for fuel cell design. Taking into account all relevant powertrain components, the fuel cell is sized and its properties, such as mass or efficiency, are calculated. Furthermore, the tool includes a simple model for altitude dependency and cooling requirement of the fuel cell.
FCtool will be replaced by the project-developed fuel cell sizing tool "Airfox" once ready, see section 2.3.

TankTool was created within the project and is used for the design of the hydrogen tank. It is described in section 2.3

5.2. Assumptions and Simplifications

As many important parameters, such as fuel cell mass or powertrain efficiency are unknown in the initial design phase, these values have to be assumed. To ensure that the assumptions are as precise as possible, various experts from within the project and from DLR in general were consulted to assess the expected values, taking into account the EIS in 2030. Where possible, the assumptions will be replaced by simulations or other design methods once they are available.
The assumptions are shown in Tab. 3.

Parameter	Value	Unit	Comment
FC power/weight	1.0	kW/kg	system-level
FC power fraction[4]	0.8	-	
FC efficiency	0.4	-	at max. power
H_2 tank pressure	700	bar	see 4.2
E-motor power/weight	5	kW/kg	incl. inverter
E-motor efficiency	0.975	-	incl. inverter
Cooling drag	5	%	relative to c_{D0}
Δ Fuel system mass	+ 50	kg	compared to ref.
Δ Fuselage mass	+ 65	kg	compared to ref.

TAB 3. Assumptions

5.3. Calibration

Most of the design methods used in the workflow are empirical, i.e. fitted to a range of existing aircraft. Consequently, the results might be distorted by differences between the aircraft or implicit assumptions of the models. To mitigate this, the design methods were calibrated on a similar reference aircraft, of which detailed data, such as component masses or engine performance, are available.
The calibration was performed by using the TLARs and design parameters of the reference aircraft as the input for the design process. The results were compared to the actual reference data. If significant deviations were observed, it is likely that any aircraft designed with the design methods contains the same relative error. Thus, these deviations were accounted for in the design methods by applying factors to achieve the reference values.

Reference Aircraft
The reference aircraft chosen for calibration is the Cessna 441 Conquest II, a twin-engine turboprop capable of transporting 9 passengers. Although not all properties match the TLARs defined in Tab. 1, such as reference payload or cruise speed, the Cessna 441 was used as reference, because of the similar dimensions and mass.
For the Cessna 441, detailed mass and performance data are available [19, 29], see appendix A.

Baseline Aircraft
To evaluate the effect of the hydrogen propulsion system on an aircraft level, a baseline aircraft will be developed at a later point in the project. This aircraft will be based on TLARs comparable to those defined in section 3.2 and powered by a conventional turboprop engine. To preserve reproducibility, it will be designed with the same workflow, excluding hydrogen-specific steps, such as fuel cell sizing.

6. RESULTS

The output of the design process is a consistent representation of the hydrogen-electric aircraft, including geometry, mass data, performance data, and various other parameters. The resulting aircraft and detailed properties are shown in this chapter. Further, by comparing it with the reference aircraft, the effects of the hydrogen propulsion system are evaluated.
The threeview of the D-Light aircraft showing outer geometry and important dimensions is shown in Fig. 4. Detailed parameters of the designed aircraft are listed in Tab. 4. Mass and drag breakdowns distributed among components are shown in Fig. 5. The payload-range diagram is shown in Fig. 6.

Analysing the results, the OEM is noticeably dominated by the mass of the hydrogen powertrain components, specifically engine, including the fuel cells, and H_2 tank. In contrast, the fuel mass directly accounts only for a small fraction of the MTOM, although it strongly influences the tank mass via the gravimetric efficiency of the tank. This also effects the payload-range diagram in Fig. 6, since it limits the flexibility to trade payload for additional range.

[4] Fuel cell design power related to its maximum power. The fuel cell is oversized to improve efficiency in the design point.

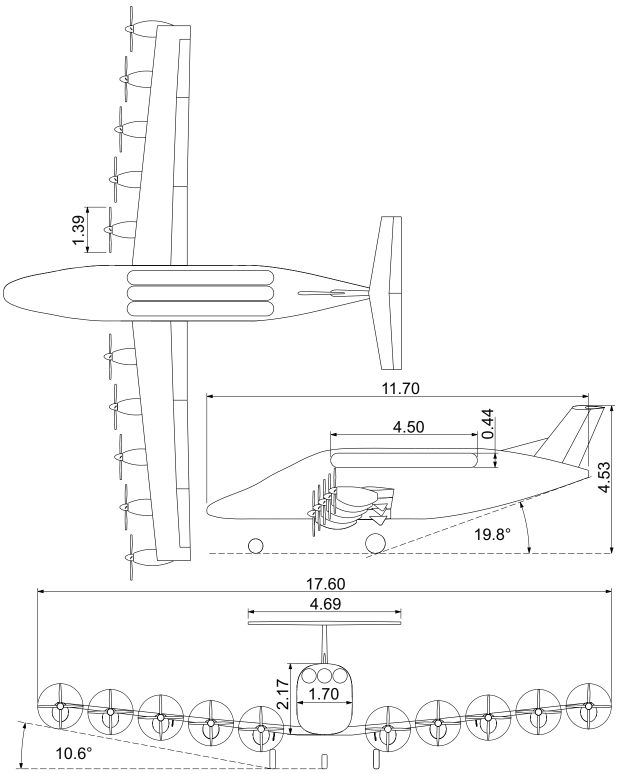

FIG 4. Threeview of D-Light aircraft, dimensions in [m]

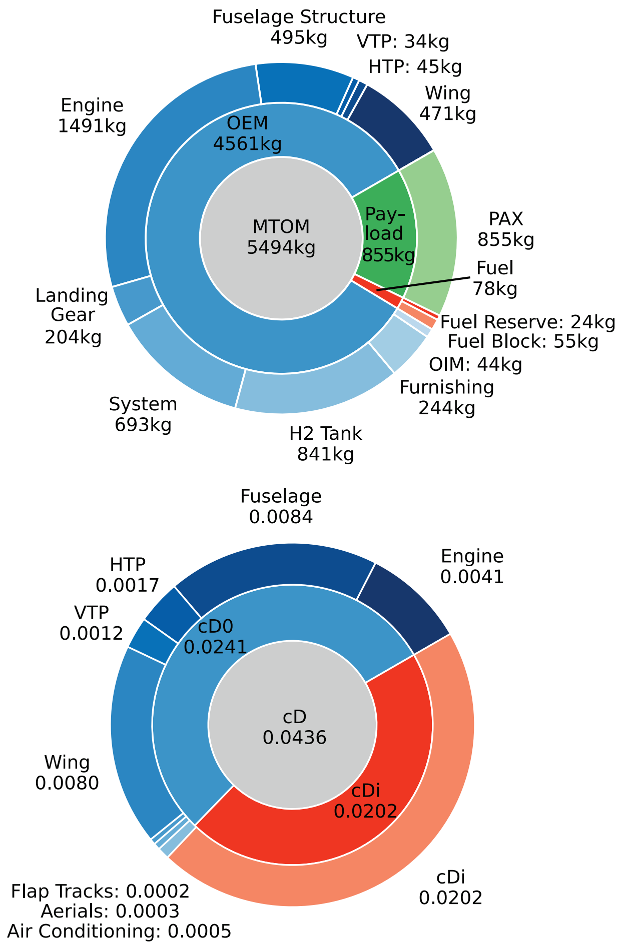

FIG 5. MTOM breakdown (top) and drag breakdown in cruise (bottom) of the D-Light aircraft

Parameter	Value	Unit	Comment
Mach Cruise	0.25	-	at cruise alt.
Total power	663	kW	shaft power
Takeoff power	663	kW	ISA, SL
Takeoff power	627	kW	ISA+15, 6600ft TOFL = 1200m
Cruise power	271	kW	at mid cruise
Powertrain efficiency[5]	0.42	-	at mid cruise
MTOM	5494	kg	
OEM	4561	kg	
Fuel mass	78	kg	incl. reserves
H_2-tank mass	841	kg	
Fuel cell mass	1066	kg	
Systems mass	693	kg	
L/D max	18.1	-	
$c_{L,max}$ takeoff	3.0	-	assumption
$c_{L,max}$ landing	3.0	-	assumption
c_L cruise	0.78	-	at mid cruise
c_D cruise	0.044	-	at mid cruise
c_{D0} cruise	0.024	-	
Wing aspect ratio	12.0	-	assumption
Wing reference area	22.4	m^2	
Wing loading	245	kg/m^2	
Power loading	0.121	kW/kg	

TAB 4. Properties of D-Light aircraft

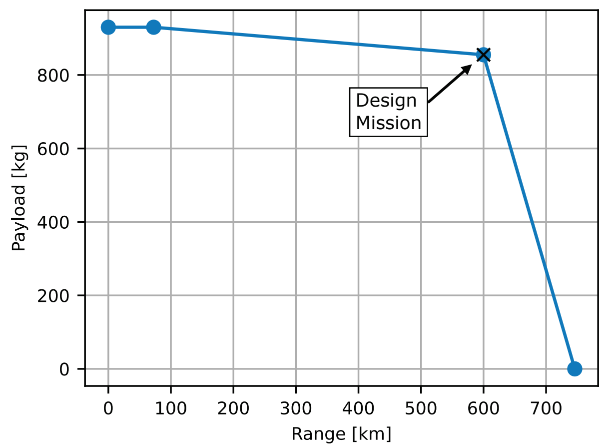

FIG 6. Payload-range performance of D-Light aircraft

In comparison with the reference aircraft Cessna 441 Conquest II (see appendix B), MTOM and OEM are significantly increased by 23% and 73%, respectively, while the fuel mass is massively reduced. Comparing the performance of both aircraft on an identical evaluation mission with the Cessna's reference payload of 358 kg and a range of 600 km, the D-Light aircraft requires 47% less energy per passenger-km. Although, due to different performance figures, e.g. cruise altitude and speed, this comparison is not fully signifi-

[5] not including propeller efficiency

cant. Overlaying both payload-range diagrams, as in fig. 8 in appendix B, further illustrates the differences, as the Cessna 441 covers a significantly larger range of missions in both flight distance and payload. The design mission also differs considerably. While the design mission of the D-Light aircraft is suited to commuter flights, the Cessna 441's design mission has less payload and a much higher range, indicating a VIP transport mission. Nevertheless, most flights don't use the full mission envelope, as discussed in section 3.2.1, therefore the D-Light aircraft still delivers the relevant mission performance for commuter flights. In the further course of the project, a baseline aircraft will be used to enable a more meaningful comparison and evaluation of the propulsion efficiency.

7. DISCUSSION AND OUTLOOK

In order to reduce the climate impact of aviation, new concepts and technologies have to be developed. For CS-23 aircraft, a promising option is a hydrogen fuel cell propulsion system with DEP. In this paper, the conceptual design of a 9-seater commuter aircraft was performed using various digital tools and models. First, the TLARs were identified and the design mission was defined as 9 passengers or 855 kg over 600 km. Cruise speed and cruise altitude were set to 160 kts (300 km/h) and 10000 ft (3048 m), respectively.
As a result, a low wing aircraft with a MTOM of 5494 kg was designed, which, in standard conditions, can take off and land from runways of at least 800 m. For the design range of 600 km including reserves, 78 kg of hydrogen are required, which is stored at 700 bar in three pressure tanks located above the cabin. The total mass of all tanks is 841 kg, including valves and mounting structure, but excluding structural reinforcement of the fuselage.
The powertrain components, specifically fuel cells, power electronics, motors and propeller are integrated in each engine pod and account for a combined mass of 1491 kg.
Compared to the reference aircraft Cessna 441 Conquest II, the MTOM increases by 23%, mainly due to the heavy tank and fuel cells. At the same time, the required energy per passenger-km can be significantly reduced by 47%, however, this value is not entirely suitable for comparison due to the different mission performance. Nevertheless, these preliminary results indicate improved efficiency of the hydrogen power train.

In the further course of the D-Light project, various aspects will be addressed in greater detail. For instance, the power train architecture and packaging currently is chosen based on qualitative assessment. In the next phase, it will be defined by developing a tool modeling the power train, and performing tradeoffs between possible options. Other aspects that will be considered include the aerodynamic and structural assessment of the main components, and an efficient and flexible cabin layout. This will enable a more detailed aircraft design process and thus the optimization of the current design.
The comparison of the D-Light concept to a conventional turboprop baseline aircraft will allow a more significant evaluation of the effect of the novel propulsion system on the overall performance. The baseline aircraft will be designed with the same methodology.
An additional goal of the D-Light project is the development of a digital mock-up (DMU). The DMU is intended to digitally represent the entire aircraft and enable further analysis and evaluation. It will contain detailed geometric information of all regarded components and components, combined with other properties, such as masses or power.

The preliminary results presented previously indicate an increased efficiency of the hydrogen powertrain compared to conventional combustion engines. Despite the additional mass from the tank and fuel cells, and the drag penalty due to the fuselage and DEP system, the required energy for the intended mission is significantly reduced. Although the results are not yet final, and several aspects will be evaluated more detailed in the further course of the project, a hydrogen propulsion concept might enable sustainable operation of small aircraft and could potentially pave the way for widespread usage in larger aircraft as well.

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A. REFERENCE AIRCRAFT

Parameter	Value	Unit
Pax	9	-
Ref. payload	358	kg
Ref. range	2278	km
Max. payload	1188	kg
Cruise altitude	35000	ft
Cruise speed	480	km/h
TOFL (SL, ISA)	752	m
LFL (SL, ISA)	572	m
MTOM	4468	kg
OEM	2631	kg
Total power	948	kW
Max. fuel mass	1444	kg
Fuselage length	11.89	m
Prop diameter	2.29	m
Wing span	15.0	m
Wing aspect ratio	9.5	-
Wing loading	189.4	kg/m^2
Power loading	0.21	kW/kg
EIS	1977	-

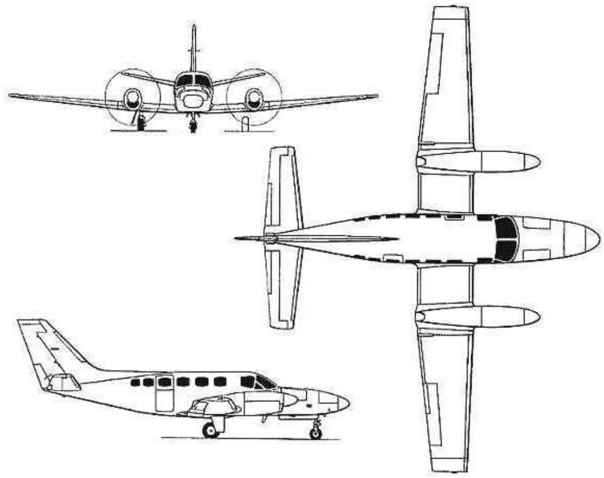

FIG 7. Main properties and threeview of Cessna 441 Conquest II [19]

B. COMPARISON

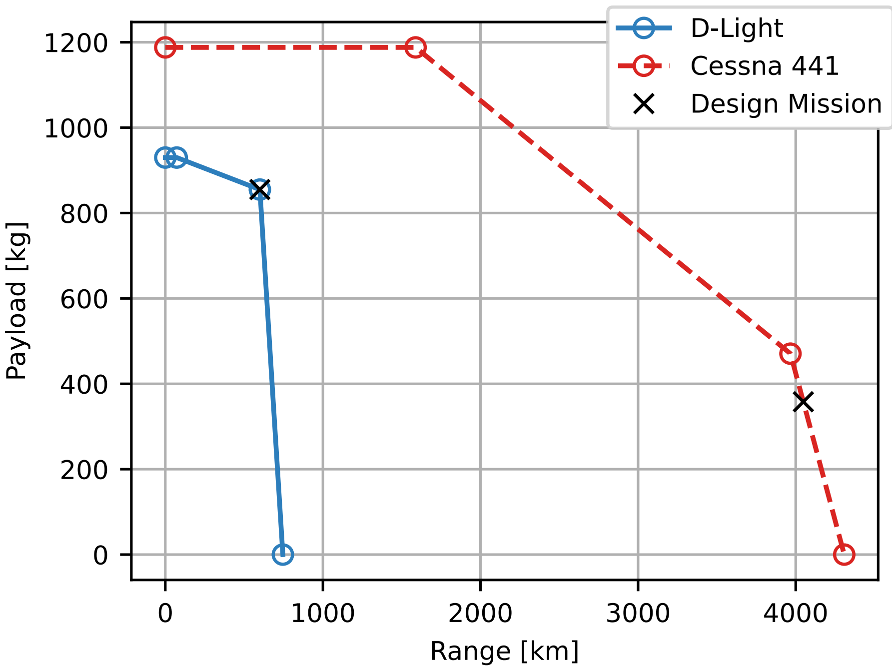

FIG 8. Payload-range diagram of D-Light and the Cessna 441

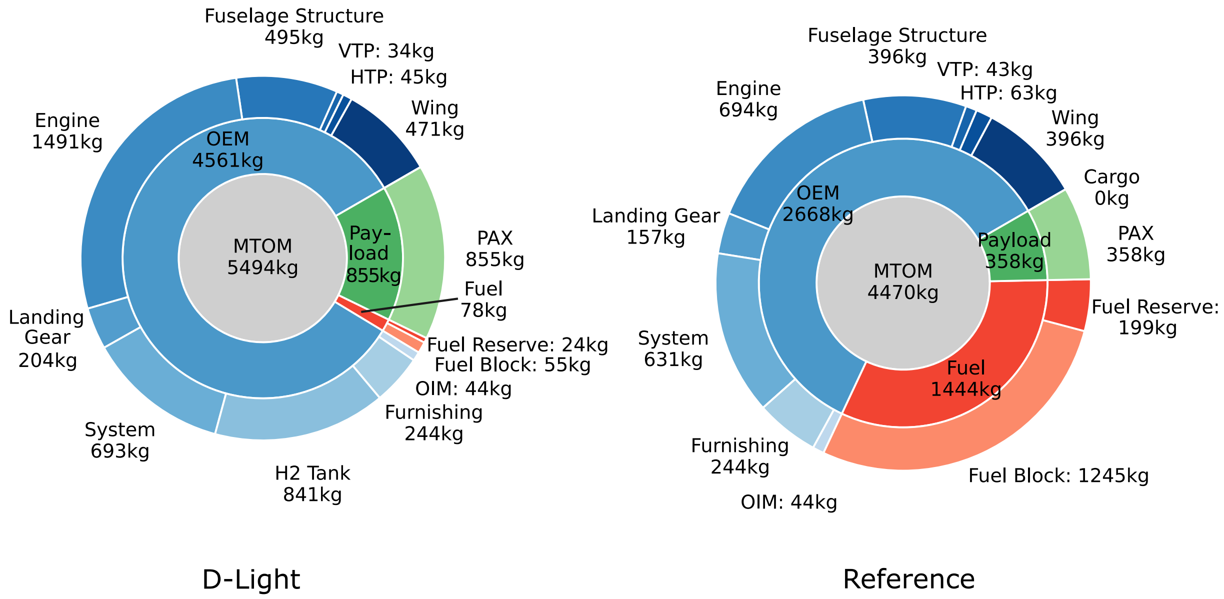

FIG 9. Mass breakdown of D-Light (left) and Cessna 441 [19] (right)

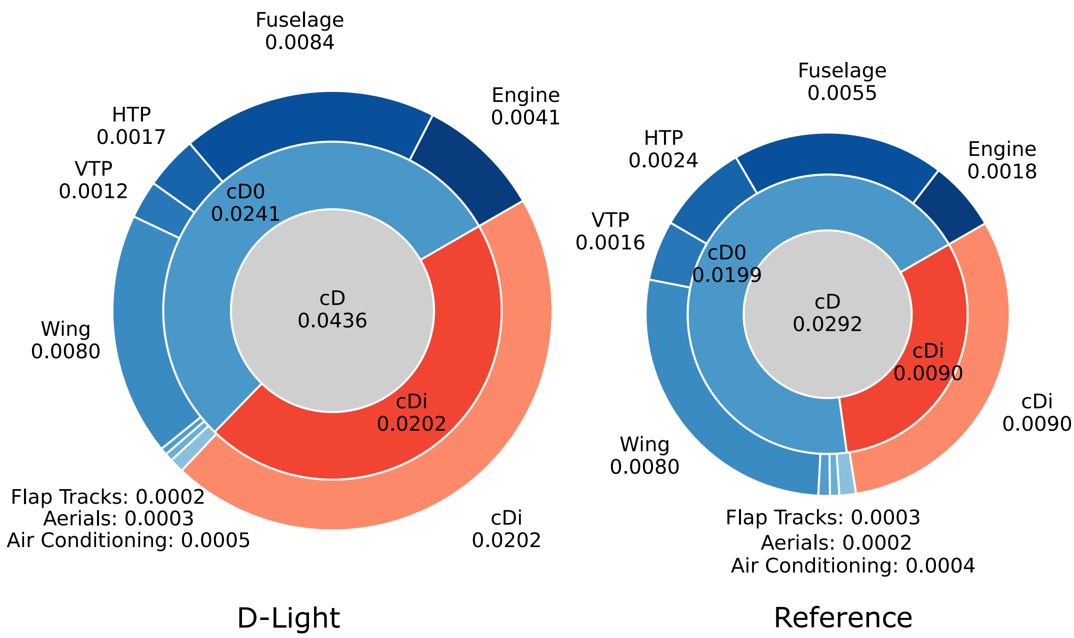

FIG 10. Drag breakdown of D-Light (left) and Cessna 441 [19] (right)