COLLABORATIVE PARAMETRIC OVERALL AIRCRAFT AND SYSTEMS DESIGN TO EVALUATE HYDROGEN-POWERED REGIONAL AIRCRAFT

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Abstract

In the collaborative aircraft design process, partners contribute to their respective area of focus, using, for example, established interfaces like the Common Parametric Aircraft Configuration Schema (CPACS). However, the design of on-board systems is typically considered only superficially in the aircraft design process, as no standard for including system design parameters has been defined within CPACS. In CPACS v3.5, however, system design parameters can now be incorporated, allowing for a more direct mapping of the overall systems design to the aircraft design process. To this end, this paper presents the first design iteration between the overall aircraft and systems design disciplines, demonstrating it on a hydrogen-powered regional concept aircraft with ten fuel cell-powered propulsion units. Based on the initial aircraft design conducted by the German Aerospace Center (DLR), the Hamburg University of Technology (TUHH) performs physical design of the on-board systems. The resulting design parameters are then used to update the initial aircraft design, analyzing how relevant parameters, such as geometric features and masses, are affected. For instance, the mass of the on-board systems increases by approximately $2426\,\mathrm{kg}$ compared to the mass estimate of the initial aircraft design, resulting in an increased maximum take-off mass of $3034\,\mathrm{kg}$. Despite the added mass, the redesigned aircraft remains a feasible concept.

Keywords

Collaborative Design, Hydrogen-Powered Aircraft, Overall Systems Design

NOMENCLATURE

Abbreviations

AMC	Aircraft Mission Calculator
CPACS	Common Parametric Aircraft Configuration Schema
DLR	German Aerospace Center
DSD	Detailed Systems Design
ECS	Environmental Control System
EPSS	Electric Power Supply System
FCS	Flight Controls System
FST	Institute of Aircraft Systems Engineering
HPP	Hydraulic Power Package
IPS	Ice Protection System
LH2	Liquid Hydrogen
LSP	Low-Speed Performance
OAD	Overall Aircraft Design
OBS	On-Board Systems
OSD	Overall Systems Design
SArA	Systems Architecting Assistant
TLAR	Top-Level Aircraft Requirement
TUHH	Hamburg University of Technology

1. INTRODUCTION

The aircraft design process involves numerous interfaces, making it a complex procedure [1]. These interfaces include areas such as aerodynamics, structures, or on-board systems (OBS). In research, collaborative approaches are used for aircraft design, allowing partners to contribute in their area of expertise by using a standard interface for the exchange of design parameters [1]. One such standard interface is the Common Parametric Aircraft Configuration Schema (CPACS), which is being developed by the German Aerospace Center (DLR) [2].

As an initial step in the aircraft design process, Top-Level Aircraft Requirements (TLARs) and the aircraft geometry are defined as part of Overall Aircraft Design (OAD). In this step, OBS are typically estimated using statistical methods such as regression functions. However, to achieve a higher level of accuracy, a physical approach to design OBS is necessary. Thus, this approach may lead to significant deviation of relevant parameters, such as mass, center-of-gravity, and installation space, compared to the initial estimates of OBS design. So far, however, the design of OBS has only been considered superficially in the aircraft design process, as no standard for including system design parameters has been defined within CPACS. In collaboration with partners working on OBS design, the DLR has updated the CPACS interface to CPACS v3.5, which supports the definition of OBS. This includes specifying the number of system components, their positions, masses, types of connections (e.g., electric, hydraulic) and their routing paths, as well as relevant static and dynamic load cases [3].

Hence, this paper presents the iterative loop between OAD and Overall Systems Design (OSD) using the design of a hydrogen-powered concept aircraft (cf. fig. 1) as use case,

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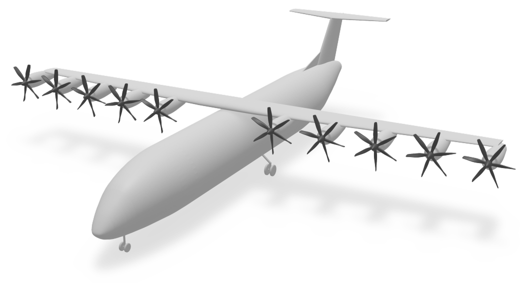


FIG 1. Hydrogen-powered concept aircraft *ESBEF-CP1*

with CPACS serving as the interface. Starting with an initial OAD concept, which is presented below, OBS are designed and fed back into OAD to redesign the aircraft. The resulting changes to geometry parameters and masses are then evaluated.

TAB 1. TLARs of the reference aircraft model

Characteristic	Value
Design range [NM]	1000
Cruise speed [-]	0.55
Cruise altitude [ft]	27000
Max. PAX number [-]	70

To showcase the first iteration loop between OAD and OSD, the hydrogen-powered regional concept aircraft *ESBEF* (german acronym for *Development of Systems and Components for Electrified Flight*) *Concept Plane 1 (CP1)* is used. As the primary focus of the *ESBEF* project was on system design rather than overall aircraft modeling, the aircraft model was derived from existing models used in other projects. Consequently, the *ESBEF-CP1* is derived from an *ATR 72*-like aircraft model and was developed by the DLR Institute of System Architectures in Aeronautics during the preliminary design stage within the DLR internal project *EXACT* [4, 5].
As visualized in fig. 1, the *ESBEF-CP1* has ten propulsion units (pods), each containing a hybrid fuel cell system, necessary peripheral systems, such as air supply and cooling, as well as an electric power train [5,6]. Two cryogenic hydrogen tanks are positioned in the aft section of the fuselage, behind the cabin deck. Relevant TLARs for the *ESBEF-CP1* are listed in table 1.

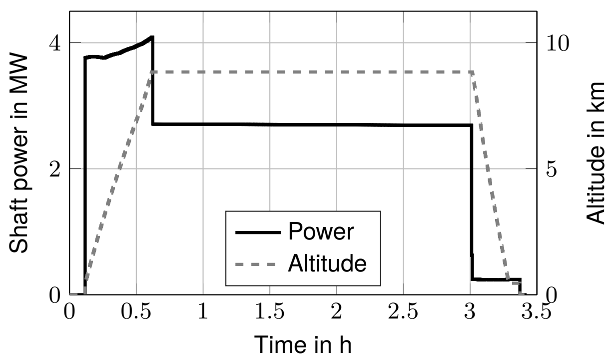


FIG 2. Total shaft power of all pods

Figure 2 displays the flight mission according to the TLARs listed in table 1, along with the shaft power calculated by OAD based on the designed aircraft. The peak shaft power is approximately $4\,\mathrm{MW}$ and is reached at the top of climb. Additionally, the relevant aircraft masses of the initial design of the *ESBEF-CP1* are listed in table 2. Relevant to the interface presented in this paper are the masses for *Propulsion systems* and *Systems* as they are recalculated during OSD. The category *Systems* includes conventional OBS, such as the environmental control system (ECS) and the electric power supply system (EPSS), as well as the hydrogen storage and supply system. The category *Propulsion Systems* comprises the systems within each pod, including the electric power train and the fuel cell system.

TAB 2. Parameters from Overall Aircraft Design

Component Breakdown	Mass in kg
Wing	2113
Fuselage structure	3950
Horizontal tail plane	186
Vertical tail plane	184
Landing gear	698
Propulsion (structure & systems)	3244
Systems	2634
Furnishings	1400
Manuf. empty mass	**14409**
Operating items	1400
Operating empty mass	**15809**
Max. payload	7500
Max. fuel	695
Max. zero-fuel mass	**23309**
Max. landing mass	**23518**
Max. take-off mass	**24004**

The paper is further structured as follows. The methods for OAD and OSD are described in more detail in section 2. In section 3, the collaborative design method between the OAD and OSD, using the CPACS interface, is explained. After introducing the initial OAD design in this section, the system design based on the initial OAD design is presented in section 4. Finally, section 5 presents the redesign of the aircraft by OAD, which is based on the recalculated OBS masses, power requirements, and center-of-gravity parameters.

2. METHODOLOGICAL APPROACH

The methods used to conduct OAD and OSD during the aircraft design process are described accordingly below.

2.1. Overall Aircraft Design

As mentioned above, the *ESBEF-CP1* aircraft model was developed using the overall aircraft design capabilities of the DLR Institute of System Architectures in Aeronautics. This aircraft design process is integrated into the workflow-driven environment RCE [7], which enables collaborative and distributed work between various DLR institutes and external partners. The tools used within the RCE workflow are based on CPACS [8]. The preliminary model provided for *ESBEF*, which is the initial aircraft design described in section 1, was developed using three tools, all created by the Institute of System Architectures in Aeronautics:

- ***openAD***: A tool for OAD, using a conceptual-level, semi-empirical sizing methodology and providing a complete aircraft sizing based on input constraints [9]. *openAD* generates a 3D aircraft model in CPACS format as an output, along with a semi-empirical component mass breakdown (including center-of-gravity estimates), handbook-level aerodynamic polars, and propulsion characteristic maps, all stored in CPACS format. A key feature of *openAD* is its flexibility: it allows results from higher-fidelity tools, such as detailed propulsion systems and OBS sizing results from OSD (cf. section 2.2), to be fed back into the aircraft sizing process. Once integrated, *openAD* recalculates the full set of aircraft properties, including geometry, mass, aerodynamics, and power requirements, making it an essential synthesizer for complex modeling workflows.
- ***AMC* (Aircraft Mission Calculator)**: A tool for mission performance calculation. Using the aircraft data generated by *openAD* (mass, aerodynamic polars, propulsion maps), *AMC* calculates detailed mission trajectories. While there is no dedicated publication on *AMC* yet, it has been used in several projects and studies [10–12], which provide general descriptions of its capabilities. An example of a trajectory generated by *AMC* is shown in fig. 2, illustrating the altitude and power profile of the design mission trajectory for the preliminary *ESBEF-CP1* aircraft model. Such trajectories are typically used to determine the fuel required for the mission. Detailed profiles of flight conditions, such as altitude, speed, and propeller power over time, are used to resize the aircraft's propulsion systems and OBS.
- ***LSP* (Low-Speed Performance)**: A tool for analyzing take-off and landing performance [13]. Similar to *AMC*, *LSP* calculates detailed low-speed flight trajectories. These trajectories help determine the aircraft's power requirements for meeting TLARs, which are then fed back into the *openAD* sizing process.

These three tools are executed sequentially within a convergence loop, where the design mission fuel and take-off power requirements are fed back into *openAD* at the beginning of each iteration. The process is repeated until convergence is achieved.

2.2. Overall Systems Design Framework

From the perspective of aircraft OBS design, different levels of abstractions and disciplines need to be considered to enable a seamless process chain [14]. These levels include OAD, systems architecting, OSD, and Detailed Systems Design (DSD) as illustrated in fig. 3.
After receiving the initial aircraft design from OAD, including the aircraft geometry, TLARs, and the design mission trajectory, the OBS are designed. As shown in fig. 3, the first step at the OSD-level is the definition and evaluation of functional-logical systems architecture variants using the *Systems Architecting Assistant* (*SArA*) methodology developed by the Institute of Aircraft Systems Engineering (FST) at Hamburg University of Technology (TUHH) [14, 15]. The next step is to generate the systems topology (positioning of components and routing of connections, cf. fig. 5) for the selected architectures and perform system sizing based on high-fidelity, physics-based methods using the *GeneSys* software framework, also developed by FST [1, 5, 6, 16–18]. The final step in the pyramid shown in fig. 3 is DSD, which includes, for instance, transient simulation models. This abstraction level, however, is not discussed further within the scope of this paper.

For topology generation, a knowledge-based approach is used to position system components within the aircraft, while an automated routing method is employed to route the connections, such as cables, pipes, and ducts, according to the aircraft's geometry. These connections link the system components to one another [18]. This method is applied to all supply systems in the aircraft, taking into account relevant boundary conditions, such as the required segregation between and within systems [6, 18]. For example, the EPSS is influenced by the integration of the hydrogen supply system within the aircraft. A minimum distance between hydrogen pipes and electrical cables is required, or alternatively, additional housing must be applied to electrical cables that do not meet this criterion, particular in areas such as inside the wing or the pylon connecting the wing with the pods [6].

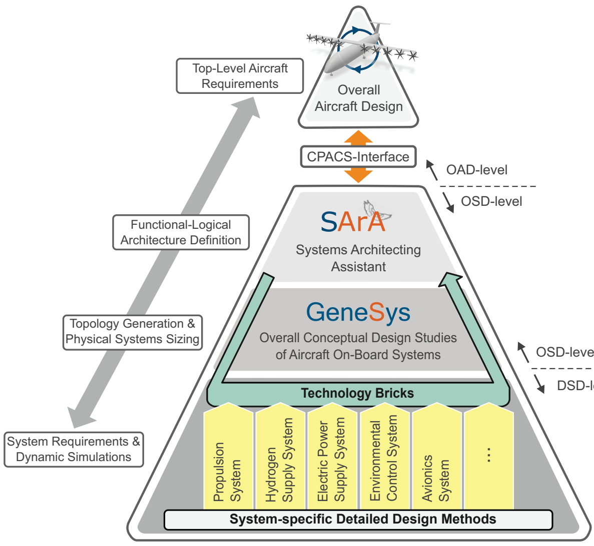


FIG 3. Overall Systems Design Framework

The sizing of OBS in *GeneSys* is performed in two steps. First, consumer systems, such as the ECS, flight control system (FCS), and ice protection system (IPS), are sized based on physical sizing laws at the component or subsystem level [16, 17]. Second, the supply systems are sized according to the connected consumer systems. Relevant system parameters for sizing are propagated through the supply network, which is a graph-based representation of information from both the systems architecture and the geometrical data from the systems topology. During this step, the connections are sized to minimize mass while maximizing the potential over the connection (e.g., voltage drop, pressure loss), using maximum allowable values for flow variables (e.g., current, volume flow) as boundary condition. These boundary conditions are typically derived from aviation authority regulations. The final step is sizing the power sources (e.g., pumps, generators), using physical sizing laws at the component level [16, 17].
In this paper, the focus lies on generating the systems topology and performing the sizing of OBS and propulsion systems for a baseline architecture of the *ESBEF-CP1*, based on the initial aircraft design parameters [5].

3. COLLABORATIVE DESIGN METHOD

Preliminary aircraft design can be described as a multi-disciplinary and multi-fidelity process, where specialized teams collaborate. Collaborative design comes along with the exchange of information and the definition and interpretation of interfaces. In this study, the disciplines of OAD and OSD work together to create a common aircraft concept. For the design of the *ESBEF-CP1*, information regarding the propulsion system and OBS needs to be shared. Therefore, a common understanding of system boundaries and the bookkeeping of the components have to be found. As mentioned in section 1, the OAD relies on statistical methods to derive an initial estimate of OBS. This top-down approach does not necessarily reflect the same system boundaries as the physics-based, component-centered calculation in OSD. For clarification, the bookkeeping of the landing gear masses serves as an example: while the statistical method [19] used in OAD only calculates the structural mass without including the actuators, the system boundaries for landing gear calculation in OSD follow the sorting approach established by the Air Industries Association, referred to as ATA chapters [20], and include the actuators. Therefore, a standardized interface is necessary to address such challenges in collaborative design.

The data schema CPACS [2] is used to exchange information between the two disciplines. As mentioned above, it has recently been extended to define OBS in a higher level of detail [3]. The schema offers the possibility to pre-define recurring system elements as a list of explicit components. These components are specified by their mass, geometry, and optionally performance indicators. For an aircraft model, these components can be instantiated as systems and connected to each other to define a system architecture. This implementation provides different perspectives on the OBS: a geometrical view and a functional-logical view. In addition, based on the connections within the systems architecture, the exchange of mass flows and power can be stored as an analysis result for static and transient conditions. This newly defined interface enables a seamless exchange of information and supports the collaborate design process.

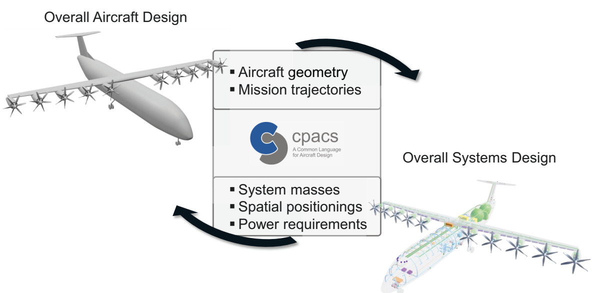


FIG 4. Visualization of the collaborative design process including the relevant required parameters

The method for collaborative design described above is illustrated in fig. 4, referring to the use case example. First, OAD generates an initial design of the aircraft as described in the example of the *ESBEF-CP1* in section 1. For OSD, the following is required from the initial OAD: aircraft geometry, masses and their bookkeeping, and mission trajectories. A design mission trajectory is necessary, while additional mission trajectories, such as for different mission ranges or emergency scenarios, can enhance the accuracy of the OSD results. Second, the masses and power requirements of the OBS are calculated during OSD. Along with the number of components, their positions for calculating the OBS center-of-gravity, and the types of connections, these parameters are written in the CPACS interface. In addition, static and dynamic power breakdowns based on the flight trajectory are generated and included in the CPACS interface. Finally, OAD uses the OBS information from the CPACS file to redesign the aircraft. Consequently, relevant parameters of the aircraft, such as masses and geometry parameters like wing surface area, may change during the redesign. However, in case the OBS design significantly impacts the aircraft, such as a shift in the OBS center-of-gravity, the redesigned aircraft may fail to converge or be feasible. In such cases, further adaptions to the aircraft design are necessary, such as shifting the position of the wing or changing the number of propulsion units.

This iteration between OAD and OSD needs to be performed multiple times until the results from both disciplines converge. However, after the first iteration loop, significant changes in either discipline are not typically expected (cf. section 5).

4. OVERALL AND PARAMETRIC ON-BAORD SYSTEMS DESIGN

With the initial design of the aircraft as presented in section 1, the OBS are designed according to the methods described in section 2.2. Compared to earlier publications about designing OBS for the *ESBEF-CP1* [5, 18], assumptions and requirements for the design have been adapted, partly due to an updated mission trajectory provided by OAD (cf. fig. 2). A primary goal for defining the systems architecture is to reduce the electrical loads of the OBS, thus reducing the mass of the fuel cells and batteries in the pods. Additionally, further consumer systems, such as required electrification due to the unavailability of bleed air and the electrical requirements for hydrogen conditioning, are taken into account.

First, the consumer systems are designed based on the assumptions outlined below. The resulting calculated masses are listed in table 3.

- **Environmental Control:** An electric ECS is integrated due to the unavilability of bleed air. Additional ram air channels are used to provide air to the cabin air compressors. Furthermore, a turbocharger is integrated into the ECS extraction network, reducing the power required for the cabin air compressors by up to $66.2\,\%$ [21].
- **Equipment & Furnishing:** The mass of the cabin and cargo equipment & furnishing is calculated by OAD. However, components like galleys, lavatories and other cabin loads (e.g., passenger service units) are designed by OSD to account for their electric power requirements.
- **Flight Controls:** The FCS is partly electrified. Actuators for the ailerons, elevators, and rudders are either electrically supplied electro-hydrostatic actuators (EHA) or hydraulically supplied electro-hydraulic servo actuators (EHSA). The spoilers are powered by electro-mechanic actuators (EMA). For secondary flight controls, the *ESBEF-CP1* uses a single drive flap system powered by EHSA [5].
- **Landing Gear:** Within the scope of OSD, only the mass and power requirements of the actuators for the landing gear, including doors, the steering cylinder, and brakes, are calculated. The structure of the landing gear is designed by OAD (cf. section 3).
- **Ice Protection:** A hybrid wing IPS is integrated. The wing stagnation point is constantly heated, while the ice protection for the wing surfaces is provided by piezo-electric servo actuators. This hybrid IPS is used as it can reduce the power requirements by up to $91\,\%$ compared to a fully electric IPS [22].
- **Lights:** The lights are primarily considered in terms of their power requirements. This includes lights for the

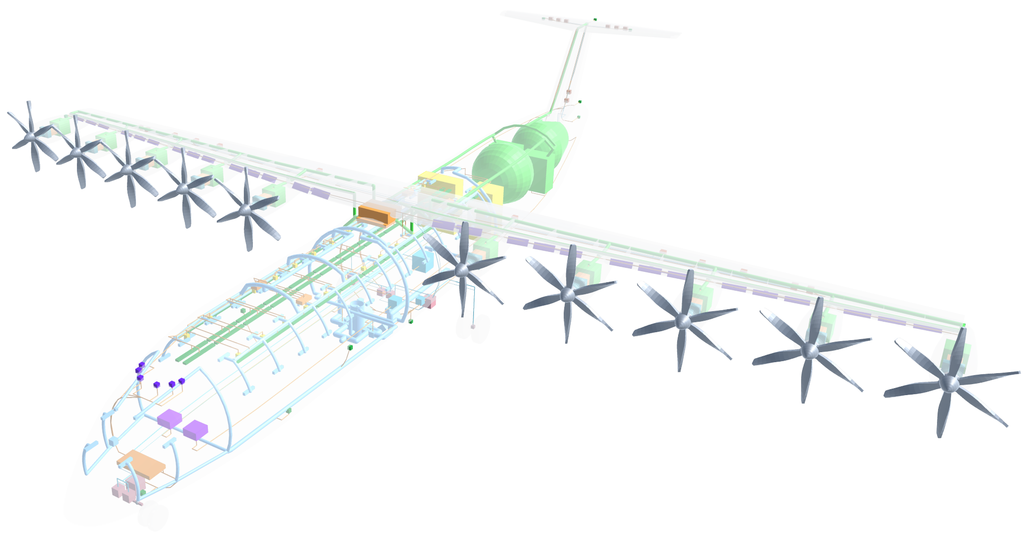


FIG 5. System topology of the *ESBEF-CP1*

cabin, cargo, and cockpit, as well as all relevant exterior lights (e.g., landing lights, navigation lights, and strobe lights).

- **Other Systems:** This category includes avionics, instruments, navigation, communication, oxygen, fire protection, and water & waste systems.

After designing the relevant consumer systems of the *ESBEF-CP1*, the supply systems are designed based on the requirements of those consumer systems, as described in the following.

- **Hydraulic Power:** A central, electrically powered hydraulic power package (HPP) is integrated in the aircraft. The HPP powers the landing gear actuators and some actuators of the FCS, as described above.
- **Electric Power:** Since the main power sources in the pods (fuel cells and batteries) generate electric power, the EPSS is the primary supply system on the aircraft. A $\pm 270\,\mathrm{VDC}$ bus network is used as the power specification, along with a $28\,\mathrm{VDC}$ bus, which is powered by the $\pm 270\,\mathrm{VDC}$ main bus. Alternating current (AC), such as that required by the pumps inside HPP, is generated locally by inverters [14]. The system architecture is based on a distributed architecture similar to that of a More Electric Aircraft (MEA) [5], featuring a primary power distribution for flight-critical systems and high-load systems, and a secondary power distribution for cabin and cargo loads, as well as non-flight critical systems. Compared to conventional aircraft, new consumer systems, such as the electric ECS, the hybrid wing IPS, and the hydrogen conditioning, are also supplied by the EPSS.
- **Hydrogen Storage and Supply:** It is assumed that hydrogen is transported in liquid form to the pods. For this, triple-walled pipes are used: the inner pipe for hydrogen flow, the second pipe for insulation, and the third pipe for leakage detection and venting, since the hydrogen is routed inside the pressurized area of the aircraft. Additionally, it is assumed that both tanks can supply all pods, ensuring redundancy (cf. fig. 6). Lastly, it is assumed that carbon fiber reinforced plastic (CFRP) is used as material for the tanks.

As a result of designing the on-board consumer and supply systems, the systems topology is visualized in fig. 5 and the masses of the designed systems are listed in table 3. It can be seen that the total system mass increases by $1095\,\mathrm{kg}$ compared to the *Systems* category in table 2.The significant

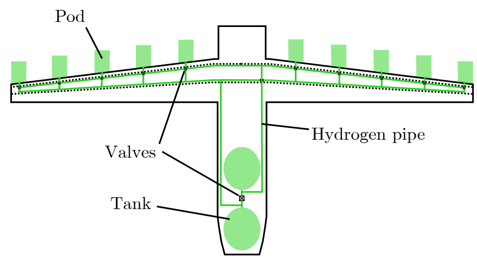
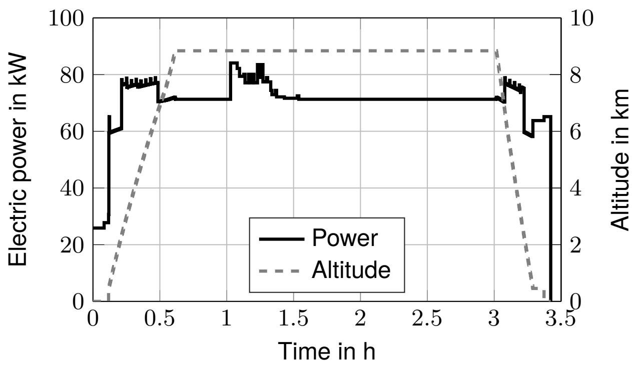


FIG 6. Architecture of the hydrogen supply system

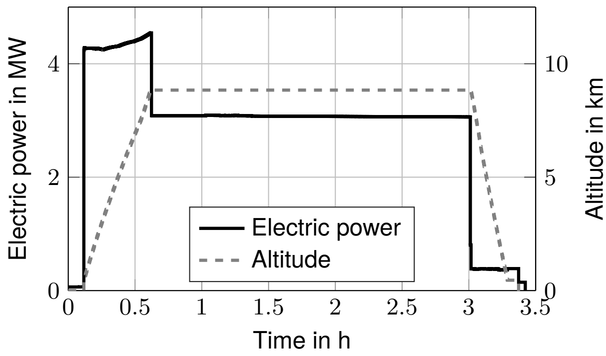
TAB 3. Estimation of the OBS masses of the *ESBEF-CP1*

System	Mass in kg
Environmental control	369
Electric power supply	561
Flight control	378
Hydrogen supply	1629
Hydraulic power supply	161
Ice protection	8
Landing gear (systems)	130
Lights	95
Other systems	398
Total system mass	**3729**

mass increase is primarily due to the hydrogen supply system, whose mass was initially estimated at $619\,\mathrm{kg}$ during OAD based on simplified assumptions during the preliminary phase of the *EXACT* project (cf. section 1). For the redesign of the aircraft, $67\,\mathrm{kg}$ of the EPSS mass in table 3 are assigned to the *Propulsion* category (cf. table 6) to account for the power management unit in each pod [3,5]. Lastly, the power requirements of the OBS are shown in fig. 7a as load profile over the design mission. The peaks at the beginning and end of the mission are caused by the FCS, as well as the retraction and extension of the landing gear. The peaks before $0.5\,\mathrm{hours}$ and after $3\,\mathrm{hours}$ of flight time are attributed to the IPS. The peak at $1\,\mathrm{hour}$ of flight time is due to galley operation, reaching the maximum value of the required electrical load of approximately $85\,\mathrm{kW}$. The increased base load during climb, cruise, and descent is a result of the electric ECS.



(a) Load profile of secondary electric power



(b) Load profile of primary and secondary electric power

FIG 7. Electrical load profiles of the *ESBEF-CP1*

The architecture of the propulsion systems within each pod consists of two fuel cells with a two-phase liquid cooling system, an air supply system, an electric power train including one electric motor, one motor controller, and a gearbox, as well as a capacitor and a battery for hybridization [3,5]. Relevant assumptions regarding these technologies for 2040 are listed in table 4.

TAB 4. Assumptions for technology predictions for the power sources

Component	Parameter	Source
Lithium-based battery	500 Wh/kg	[23]
Fuel cell stack	6 kW/kg	[23, 24]

The system masses for one pod are listed in table 5. Furthermore, the total load profile representing the power that needs to be supplied by the fuel cells and batteries is displayed in fig. 7b. In contrast to fig. 2, the efficiencies of the motor, motor controller, voltage transformers, and the OBS power requirements are taken into account in fig. 7b. The system mass of one pod is $89\,\mathrm{kg}$ higher than the mass calculated during the initial OAD (cf. table 6). This increase is attributed to different assumptions made during the system design. For instance, during the initial OAD, only a fuel cell system is assumed to be integrated in the pod as power source. However, life cycle analyses during OSD have shown that batteries and capacitors are required to extend the lifespan of the fuel cell systems [25]. To this end, it is assumed that the fuel cell operates at three power levels according to the required power during the design mission: approximately $360\,\mathrm{kW}$ during take-off and climb, about $310\,\mathrm{kW}$ during cruise, and around $40\,\mathrm{kW}$ during descent and landing (cf. fig. 7b). Further scenarios, such as recharging the battery during cruise or descent, are not considered within the scope of this paper. Additionally, the batteries are operated within a state of charge range of $10\,\%$ to $90\,\%$ to facilitate fast recharging on ground and to reduce cyclic capacity loss [26].

TAB 5. Estimation of the systems masses of a *ESBEF-CP1* propulsion unit

System	Mass in kg
Power train	70
Fuel cell stacks	67
Air supply	25
Cooling system	105
Batteries	67
System mass of one pod	**334**

In total, the mass of the OBS and propulsion systems is calculated to be $7069\,\mathrm{kg}$, exceeding the mass estimated during the initial OAD by $1980\,\mathrm{kg}$ (cf. table 6).

5. REDESIGN OF THE HYDROGEN-POWERED CONCEPT AIRCRAFT

The resizing process in the OAD workflow is initiated by including the results generated by OSD. These results provide detailed mass estimates for the liquid hydrogen (LH2) storage and distribution system, the electric propulsion components, and the OBS. The integration of these results into the OAD process (cf. section 2.1) follows this procedure:

- **System and LH2 Distribution Masses**: The masses for the OBS and LH2 distribution are set as constant values in the input to *openAD*, ensuring they remained fixed during subsequent design iterations.
- **Electric Propulsion Components**: The electric propulsion components are included with a fixed specific power in the *openAD* input. This means that as the aircraft's power requirements increase, the mass of these components scales proportionally, allowing for realistic adjustments in the sizing process.
- **LH2 Storage Mass**: The LH2 storage mass is assumed to be proportional to the fuel mass. In each convergence loop of the OAD workflow, the *AMC* calculates the fuel mass required for the design mission. Based on this value, the LH2 storage mass is determined and then fixed as an input in *openAD* for subsequent iterations.

By integrating the OSD results in this manner, the workflow accounts for the effects of aircraft resizing on the propulsion system and energy storage masses. This iterative feedback process enables the resized aircraft model to be further refined, accelerating the convergence between the OAD workflow and OSD calculations in subsequent iterations.
The impact of this resizing process on the aircraft masses is summarized in table 6, while the changes to relevant aircraft geometry parameters are presented in table 7. As shown in table 6 and table 7, the geometry parameters of the aircraft increase. The maximum take-off mass of the redesigned aircraft increases by $3034\,\mathrm{kg}$ compared to the initial design. Consequently, the total power requirements also increase, as illustrated in fig. 8.
As mentioned above, the resizing process presented here represents only the first iteration loop. Although full conver-

TAB 6. Mass breakdown of the redesigned aircraft

Component Breakdown	Mass in kg	Dev. in kg
Wing	2366	+ 253
Fuselage structure	4035	+ 85
Horizontal tail plane	207	+ 21
Vertical tail plane	205	+ 21
Landing gear	791	+ 93
Propulsion	**4585**	**+ 1341**
Propeller	*280*	*+ 25*
Nacelles & structure	*587*	*+ 53*
Elec. comp. & systems	*3718*	*+ 1263*
Systems	**3797**	**+ 1163**
On-board systems	*2033*	*+ 18*
LH2 storage	*918*	*+ 399*
LH2 supply	*846*	*+ 746*
Furnishings	1400	+ 0
Manuf. empty mass	**17387**	**+ 2978**
Operating items	1400	+ 0
Operating empty mass	**18787**	**+ 2978**
Max. payload	7500	+ 0
Max. fuel	751	+ 56
Max. zero-fuel mass	**26287**	**+ 2978**
Max. landing mass	**26512**	**+ 2994**
Max. take-off mass	**27038**	**+ 3034**

gence has not yet been achieved, the deviations in subsequent loops are expected to be significantly smaller, as the propulsion and energy storage masses have already been adjusted to meet the new power and energy requirements, albeit only proportionally. Future iterations will primarily refine these results to capture non-linear scaling effects.
Nevertheless, the redesigned aircraft is deemed feasible. However, altering the assumptions within OSD may lead to different results. For example, assuming aluminum instead of CFRP as the material for the hydrogen tanks increases the OBS mass by approximately $640\,\mathrm{kg}$ and significantly shift the center-of-gravity toward the rear. Additionally, if the assumptions regarding the technology factors in 2040 are more conservative, such as selecting an energy density of $300\,\mathrm{Wh/kg}$ for the batteries, the propulsion system mass increases by around $500\,\mathrm{kg}$. In this scenario, the influence of OSD on the redesigned aircraft could be significantly

TAB 7. Geometry parameters of the redesigned aircraft.

Parameter	Unit	Value	Dev.
Wing. ref. area	m^2	67.90	+ 7.30
Wing span	m	30.80	+ 1.70
Wing aspect ratio	–	14.00	const.
HTP ref. area	m^2	12.00	+ 1.40
VTP ref. area	m^2	11.20	+ 1.36
Nacelle max. diameter	m	0.93	+ 0.03
Nacelle length	m	2.38	+ 0.08
Propeller diameter	m	2.43	+ 0.13
Total LH2 tank vol.	m^3	10.60	+ 0.80

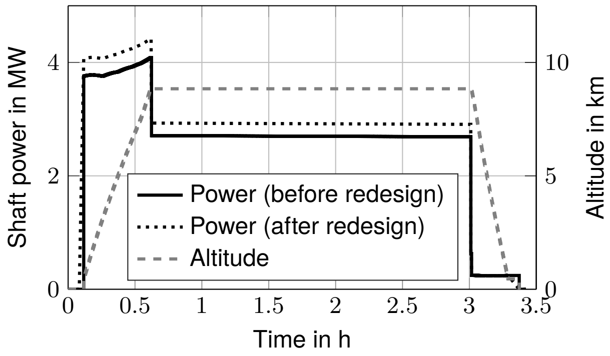


FIG 8. Total shaft power of all pods

higher, potentially leading to changes in the propulsion system.
However, the interface between the OAD and OSD tools has now been established, allowing for a fully integrated workflow in future collaborative studies. Such an integrated workflow will enable the collaborative evaluation of the aircraft at both the aircraft and system levels.

6. CONCLUSION

The collaborative approach for overall aircraft and overall systems design on the example of a hydrogen-powered regional concept aircraft using the CPACS v3.5 as interface file has been presented in this paper. Based on an initial aircraft design of the hydrogen-powered concept aircraft conducted by the DLR, a CPACS file is created that includes relevant parameters such as aircraft geometry, relevant design masses, and a design mission trajectory. Masses for on-board systems are initially estimated using regression functions and other statistical methods. Subsequently, a physics-based design of the on-board systems is performed by the TUHH using their *SArA* and *GeneSys* methodologies. The CPACS file is then updated with the resulting system parameters, including the number and position of components, the type and routing of connections, masses, and relevant load cases. These updated parameters are used in the redesign of the aircraft. In the example presented in this paper, the mass of the on-board systems increases by $2426\,\mathrm{kg}$ (including scaling effects during the redesign), resulting in an overall maximum take-off mass increase of $3034\,\mathrm{kg}$ after redesign. Additionally, the geometry parameters of the aircraft also increase, along with a corresponding increase in the required energy for the design mission by approximately $8\,\%$.
This paper presents the first iteration loop between overall aircraft and systems design. Although more iteration loops are necessary to achieve a converged aircraft design, the changes in subsequent iteration loops are expected to be significantly smaller than those in the first loop. In summary, three key insights have been demonstrated:

- An interface for collaborative aircraft and on-board systems design has been established using the CPACS v3.5 as interface.
- On-board systems, as well as propulsion systems, have been designed for the hydrogen-powered regional concept aircraft with ten propulsion units.
- A redesign of the aircraft incorporating the updated designs of the on-board and propulsion systems, including the affected geometry parameters and masses, has been presented.

The established interface serves as a foundation for future collaborative work, enabling the assessment of disruptive technologies and concepts at both the system and aircraft levels. As a next step, various hydrogen-powered concept aircraft, for example with 4 pods, will be used for collaborative design and evaluation.

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