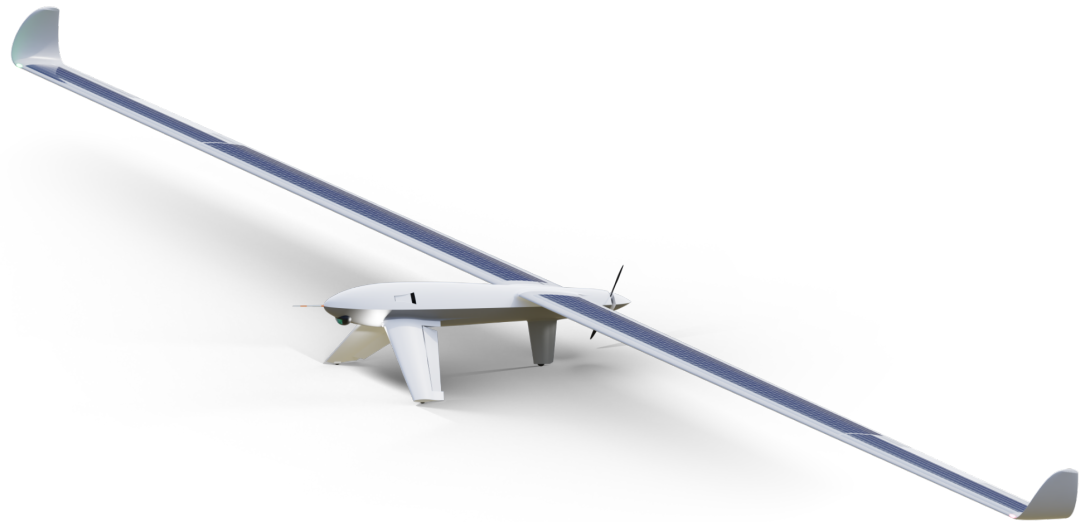


## **DLR Design Challenge 2023: Kommunikationswege in Krisenfällen sichern**



### ***HEIKE***

## **Hochfliegende, effiziente und intelligente Krisenkommunikations-Einheit**

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DLR Design Challenge 2023: The Team behind *HEIKE*

# Zusammenfassung

Der vorläufige Entwurf eines Flugzeugsystems zur Bereitstellung von Kommunikationsdiensten in Krisengebieten wird präsentiert. Missionsanforderungen und ein Entwurfsprozess werden entsprechend zweier Missionsszenarien definiert. Ein Konzept wird mithilfe einer Trade-Off-Studie ausgewählt. Die Systemarchitektur wird beschrieben und das TRL der involvierten Subsysteme diskutiert. Im ersten Schritt des detaillierten Entwurfs werden aerodynamische und antriebstechnische Parameter definiert. Beide Missionsszenarien werden vollständig analysiert. Die Dimensionierung der Strukturkomponenten folgt aus der Auswertung der aerodynamischen Parameter. Konzepte zum Betrieb und zur Infrastruktur des Flugsystems werden präsentiert. Das Flugsystem wird holistisch in Bezug auf Ausfallwahrscheinlichkeiten und Kosten bewertet. Den Abschluss bildet eine Diskussion über die Nachhaltigkeit des Konzepts, ein Thema welches in der Luftfahrt zunehmend an Bedeutung gewinnt.

*Schlagnorte: DLR Challenge, Hochfliegende Plattformen, Netzwerkwiederherstellung*

# Abstract

The preliminary design of an aircraft system for the provision of communication services to disaster-affected regions is presented. Based on two mission scenarios, mission requirements and a design process are defined. A concept is chosen through a trade-off study. The system architecture is outlined, and the TRL of the involved subsystems is discussed. For the detailed design, an initial sizing defines the aerodynamic and propulsive parameters of the aircraft system. Both mission scenarios are fully analyzed. Structural sizing follows after the evaluation of the aerodynamic parameters. Concepts for the operation of the aircraft system and its infrastructure are presented. The aircraft system is holistically evaluated, consisting of a failure probability analysis and a cost analysis. Lastly, the sustainability of the concept is discussed as an increasingly important aspect of aviation.

**Keywords:** *DLR Challenge, High-Altitude Platform, Network Deployment*

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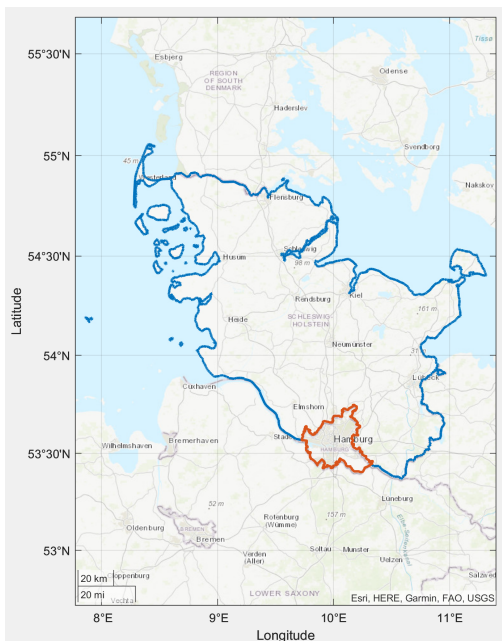
# List of Symbols

## *Abbreviations*

A/C	Aircraft
AoA	Angle of Attack
AV	Aerial Vehicle
AVL	Athena Vortex Lattice
CoG	Center of Gravity
DC	Direct Current
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DoF	Degrees of Freedom
EIS	Entry into Service
EU	European Union
FCS	Flight Control System
FL	Flight Level
HALE	High-Altitude Long-Endurance
HAP	High-Altitude Platform
HEIKE	Hochfliegende, effiziente und intelligente Krisenkommunikationseinheit
ILR	Institute of Aerospace Systems
INS	Inertial Navigation System
MSL	Mean Sea Level
MTOM	Maximum Take-Off Mass
NM	Nautical Miles
PMADC	Power Management and Distribution Control
SoC	State of Charge
TCAS	Traffic Alert and Collision Avoidance System
TCR	Technology Compliance Level
TLAR	Top Level Aircraft Requirements
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

# 1 Introduction and Scenario

Communication capabilities and access to the Internet are central elements of modern society in the 21st century. Networks of the globalized world determine trade routes, geopolitics, along with global connectivity. A critical infrastructure outage would have serious consequences and, in the event of a crisis or disaster, would pose challenges for which people need to be prepared. To effectively carry out aid and rescue missions, permanently functioning communication networks must be created. For the restoration of important communication networks and internet coverage, communication satellites in low orbits have been used so far. However, the deployment and operational duration of such systems are associated with extremely high costs and satellite overflight times. Since private companies, such as SpaceX are technologically advanced, they dominate the market, and the market for the so-called *NewSpace* has become a fiercely competitive arena in recent years. A possible alternative solution in this context involves an intelligent system of aerial vehicles [1–4]. This system should restore the communication capability, *i.e.*, access to the Internet, over a large area, as shown in Figure 1.1, for an extended period of time.



**Figure 1.1:** Areas to be covered affected by, *e.g.*, nature catastrophe and consequently communication loss [5]

time. Furthermore, the aircraft shall be able to perform additional situational awareness in a time-critical (local) disaster scenario. Overall, a system of aircraft shall be designed that most effectively fulfills the requirements of the following two operational scenarios:

In **Scenario 1**, each aircraft system shall be capable of performing a flight from an operational base outside the target area to the point of operation. For design purposes, a range of 100 NM is assumed. Upon reaching the target area and operational altitude, each individual system enters a loiter phase. The duration of this phase and the mission altitude shall be selected based on the concept of operations. The time to restore the internet shall be minimized. After successful completion of the mission, the aircraft systems shall return to base and land. The areas that shall be covered are reported in Table 1.1.

In addition, Earth observation of the affected area should be possible. The combination of efficiency in continuous operation, high electrical power supply for the mission equipment, rapid operational readiness, and optimal mission planning poses high demands on an overall design concept of the aircraft, which has to be robust against any take-off and landing conditions, day and night, in all weather conditions.

In this year’s DLR Challenge, we have taken up this challenge and developed a system of aircraft that meets these requirements. An overview of this system is presented in Chapter 2, followed by the detailed design in Chapter 3. Chapter 4 concludes by evaluating the concept with a holistic view in terms of costs, failure rate probability, and sustainability of the developed system. Chapter 5 concludes with a summary of the developed system and gives an outlook on future topics.

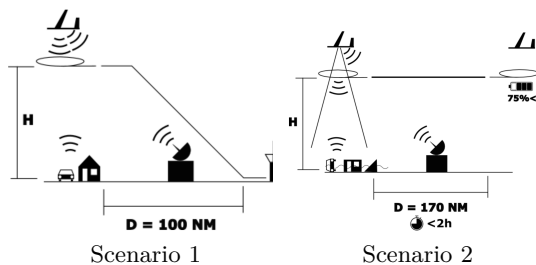
## 1.1 Design Mission Requirements

The goal is to develop an aircraft for Internet recovery and coverage of a large area in order to maintain communication channels over an extended period of

State	Area [km <sup>2</sup> ]	Population [-]	Population Density [residents/km <sup>2</sup> ]
Hamburg (HH)	755	1.854.000	2.453
Schleswig-Holstein (SH)	15.804	2.922.000	184

**Table 1.1:** State Area and Population for design mission

**Scenario 2** represents a local and time-critical disaster outside the target area of the first scenario. In addition to the restoration of the Internet supply, situation monitoring of the affected area is to be continuously feasible. The communication networks shall be restored within 2 hours, for an area of 700 km<sup>2</sup>. The distance to the target location of scenario 1 shall be equivalent to 170 NM. Deployment site and base are 100 NM apart. The aircraft shall already be in flight with 75% of the mission energy remaining. In summary, both mission scenarios are shown schematically in Figure 1.2.



**Figure 1.2:** Design Missions from DLR Challenge Task [6]

In addition to the scenario-related requirements, it shall be possible to always operate the entire system of aircraft systems regardless of the weather, time of day, and season. Likewise, operation up to the 55<sup>th</sup> degree of latitude shall be enabled. To provide communication, requirements are specified for the payload. A total of 13 kg of relays, antennas, and radar modules with a combined system power of 950 Watts shall be carried and supplied.

## 2 System Design Overview

The following chapter describes the design process. This is followed by a brief presentation of the key features of the developed aircraft system.

### 2.1 Design Process

In order to develop a suitable system of aerial vehicles, a design process is established, which is schematically shown in Figure 2.1. Initially, the task is studied and TLARs are identified. This is followed by a list and ranking of derived evaluation criteria. Five exemplary concepts were developed, which are defined by the solution space from the derived Zwicky Box in Figure 2.2. An attempt was made to obtain a wide range of solutions in order to identify tendencies and maintain flexibility in the design process. A subsequent pairwise comparison is used to select the best concept, which is initially laid out in the initial sizing process, and important parameters for the further design process are identified. A detailed design of the subsystems is then presented, which are subsequently tested in a mission simulation. Findings about the performance are directly fed back into the detailed design step and thus, a holistic evaluation of the flight performance with respect to the required mission is possible. Lastly, the costs for the developed aircraft systems are analyzed, a sustainability analysis is performed. Additionally, multi-use/multi-role capabilities are considered.

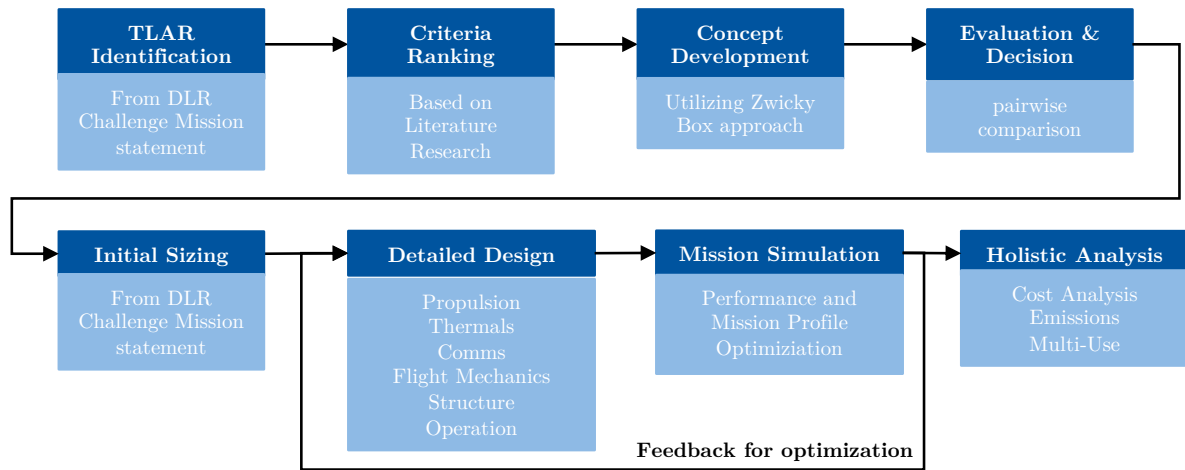


Figure 2.1: Design Process adapted from [7–9]

### 2.1.1 Design Criteria

The following criteria represent the key requirements for the final aircraft. **Fast deployment** and **operational readiness** are essential in the event of a disaster, and the time required to prepare the aircraft for take-off is essential. Likewise, **efficiency in continuous operation** must be ensured so that the duration of the mission can be maximized. Short-duration operations contrast sharply with long-duration emergency operations, where **full recovery of critical communications infrastructure** on the ground can take several months. Internet recovery is essential for the affected population and for the situational awareness of the emergency responders. Fail-safe systems with built-in redundancies and energy as well as power backups are of high importance. **Earth observation and sufficient coverage** are defined and must be met with the failure of some units. This requires wisely choosing flight performance parameters, such as service ceiling and cruise speed. Intelligent mission planning and optimized operational strategies for the use of available energy sources and regenerative systems must be used. Eventually, the developed system must be set up, maintained, and used by humans under difficult conditions, *e.g.*, at night or in time-critical emergency situations. This places demands on **easy handling** and requires that the **user experience** is kept in mind throughout the system conceptualization. Resulting design criteria and their respective weighting (applied during the concept evaluation in Section 2.1.2) are collected in Table 2.1.

Criteria	Rank [-]	Weighting [%]
Mass	17	2.16
Emissions	20	0.86
Scalability	18	1.73
Flight duration	4	6.48
Maintenance effort	15	3.45
Cost	22	0.65
System Responsiveness	6	6.26
Transportability	12	4.75
Total System failure rate	1	8.64
Resistance to environmental influences	3	8.20
User Handling	19	1.51
Range/Endurance	6	6.26
Required Infrastructure	14	4.10
Multiuse capability	16	2.59
TRL	20	0.86
Certification compliant	13	4.32
Safety	2	8.42
Launch Distance	10	5.40
Glide ratio	8	6.04
Climb rate	9	5.61
Altitude	5	6.30
Speed	10	5.40

Table 2.1: Criteria ranks and weighting

Function	Variant A	Variant B	Variant C	Variant D	Variant E	Variant F	Variant G	Variant H
Aerodynamic Configuration -Wings	Classic (Dragon)	Canard	Boxwing	Sweep Wings	Truss-Braced	Tandem Wing	Flying Wing	Blended Wing Body
Aerodynamic Configuration -Tail	T-Tail	H-Tail	V-Tail	X-Tail	Multiple Rudders	Y Tail		
Propulsion	Hybrid-Serial	Hybrid-Parallel	Mixed Serial-Parallel	Mono				
Power Delivery	Electro	Fuel Cell	Piston Engine	Rotary Engine	Turbine	Solar		
Structural Load	Carbon Fibre/Glass Fibre	Aluminium/Steel tube	Wood	3D Engine	Mixed (Wood+Carbon Fibre)			
Payload Integration	Wingpods	Fixed	Part of Structure					
Energy Storage	Battery	Unpressurised tank	Pressurised tank					
Transportable Configuration	Dismountable structure	Hinged structure	Rotatable structure	Very small AV				
Propeller Configuration	Pull	Push	Wingtip	Tailtip	Distributed Propulsion	Tilttable Rotors		
Takeoff and Landing capabilities	VT&VL Propeller	Catapult	Spinlaunch	Towed Flight	Conventional	Aerostatic	Tilting System	Mortar
Autonomy Level	Manned without support	Manned with support	Full authority of the autopilot Flight condition level	Full authority of the autopilot Flight path level	Full authority of the autopilot Flight management level			
Control System	Remote control	Hand force control	Fly by wire	Feedback Control				
Lift Generation	Aerostatics by hot air	Propeller	Aerostatics by light gases	Dynamic Lift via surfaces				
Control Variables	Rudder	Flaps	Direct Force Generation	Thrust vector control				
Shielding	Spatial separation	Cable Insulation	Placement					
Recovery System	Horizontal Landing	Vertical Landing	Hook + net system	Parachute	Parawing	Airbag	Single Use	
Storage	Hangar	Container	Case	Open Field				
Possible Shipping	By Ship	By Plane (civil)	By Plane (military)	By truck	By car			

Figure 2.2: Zwicky Box used in the concept design phase [8, 9]

## 2.1.2 Concept Analysis and Evaluation

A variety of concepts have been methodically developed using the Zwicky Box, covering the entire solution space to the greatest extent possible. In the selection process, attention was paid to combining various technologies in a meaningful way without limiting each other. The features are summarized in Table 2.2 and design sketches were drawn for visualization, as shown in Figure 2.3. A comprehensive analysis was carried out using the pairwise comparison. The following evaluation is only a compact part of the overall concept evaluation.

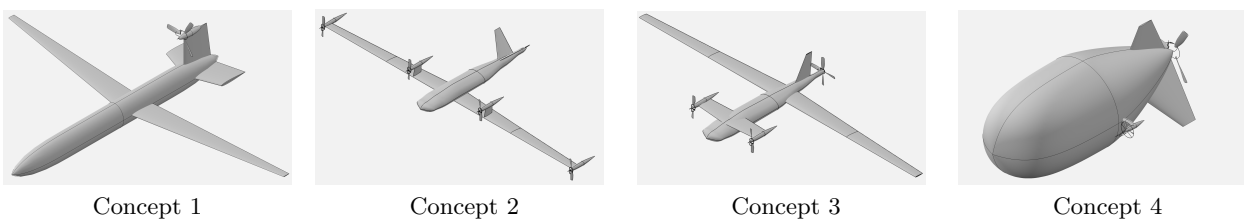


Figure 2.3: Proposed concepts, modeled with OpenVSP [10]

**Concept 1** is not considered due to the necessity of a pilot in the aircraft; in case of pilot incapacitation, total loss of control ensues. Furthermore, the reliance on mono-electric propulsion presents a lack of redundancy in the event of failure of the power supply. The hand-force control further diminishes the handling quality. **Concept 2** reduces the risk of loss of control by having the pilot steer the aircraft remotely. However, the hangar storage limits the flexibility of the concept. Service deployment is limited to regions in the vicinity of the hangar location. This problem is mitigated by opting for a container-storable, for instance, **Concept 3**. Additionally, this concept poses minimal requirements towards the take-off and landing site by incorporating tilttable propulsion elements. A drawback of the innovative *VTOL* (vertical take-off and landing) capability,

No.	Configuration	Average Score	TCR [%]
1	Manned motorized glider, mono-electric propulsion utilizing batteries and solar cells, pull prop, T-Tail, modular/dismountable structure, conventional TO&Landing, hand force control, hangar stored	1.88	37.6
2	Unmanned hybrid-serial propelled, electric motor paired with battery, rotary engine and AvGas, V-Tail, unpressurized fuel tank, pull and wingtip propellers, remote controlled, Fly-by-Wire, conventional TO&Landing, hangar stored	2.91	58.2
3	Unmanned canard/tandem type VTOL capable, mixed hybrid-serial propulsion, battery storage, unpressurized fuel tanks, tiltable rotors and elevator, fully autonomous operation, container stored	3.72	74.4
4	Unmanned Airship, inverted Y-Tail, mono-propulsion with fuel cells, H2 filled, deflatable, push prop (back) and pull prop (lateral fixed), aerostatic lift generation, fully autonomous operation, hangar stored	3.26	65.2
5	Unmanned fixed-wing, Canard/Tandem type, inverted V-Tail with integrated landing gear, STOL capable, hybrid-electric driven, utilizing fuel cells and batteries, solar cells on wing, pushprop with large diameter, fully autonomous operation	4.07	81.4

**Table 2.2:** Evaluation of developed concepts

however, is the increased risk of failure associated with the complexity of the additional subsystems (*e.g.*, propeller actuation). Also, the difference in hover and cruise power requirement does not represent a suitable solution. As a fundamentally different approach, an airship configuration was considered for **Concept 4**. This concept provides several benefits, such as flexibility regarding the launch location, a long airborne phase, and the potential for the spatial separation of components. However, considering that the deployment scenario requires a fast response time, the high cost of Helium, and airspeed make this concept inadequate [11]. Also station-keeping in the wind is not feasible [3]. The final **Concept 5** eliminates all of the above design and operational flaws:

- Autonomous vehicle removes human point of failure.
- Container transportation provides quick and spatially flexible emergency response.
- Hybrid energy source (solar cell and fuel cell) ensures operation independent of weather situation.
- High aspect ratio wings for improved gliding performance and thus long airborne phase.

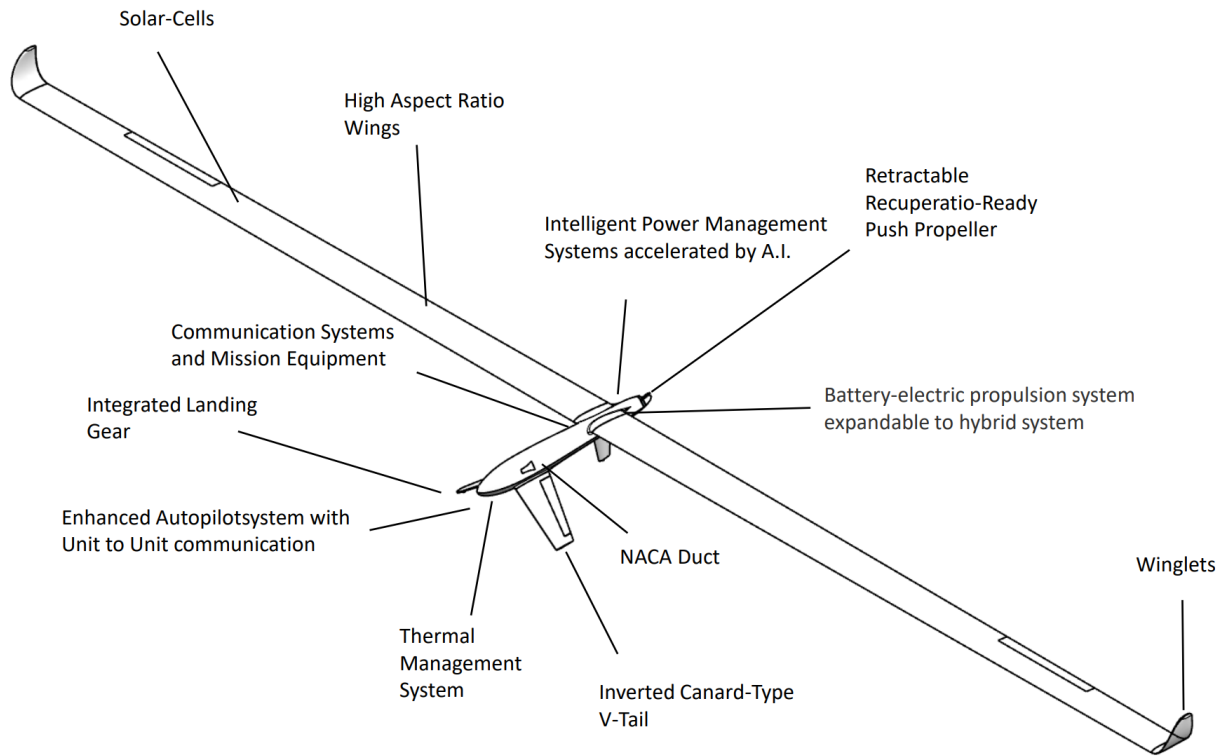
## 2.2 Concept 5: System Architecture *HEIKE*

In the course of the DLR Design Challenge, the system *HEIKE*, which is the German abbreviation for *Hochfliegende, effiziente und intelligente Krisenkommunikationseinheit* and elegantly pays homage to our institute's Professor by incorporating his first name, is shown below in Figure 2.4 was developed, which meets the mission goals, TLARs and performance specifications listed in Table 2.3 considering the used simulations.

The combination of a small payload in terms of mass but with a high power requirement over an extended period of time presents a design challenge for this aircraft system, which our developed solution meets through the use of advanced design methods and novel solution concepts as presented in Chapter 3. Ensuring a continuous operation, as well as rapidly deployable at the same time with high coverage, poses particular challenges to *HEIKE*. The targeted minimum duration of the design mission is 30 days in the most conservative case with the presented system as suggested by [12]. This entails:

- Launch in a winter month at the highest latitude (55°)
- Weather: closed cloud layer up to 12 km altitude
- Launch time of 10 a.m. so that a subsequent recharge phase using solar power cannot be relied on due to the early winter break of dusk

A manned system would significantly increase system mass due to required life support systems, *e.g.*, pressurized environment, as well as limit mission time due to human abilities and regulatory



**Figure 2.4:** Developed high-altitude aerial platform concept *HEIKE*

work schedules. Accordingly, an autonomous system was chosen because it offers the following advantages: Higher control speed, reproducibility, increased accuracy, lower risk of failure as human errors are reduced, and therefore, higher reliability [13]. In addition, acceleration limits, temperature and pressure limits for unmanned aircraft systems are higher than for manned platforms [14]. The mission posed special requirements to the thermals and power supply as there are different design points for maximum temperature in summer at high latitudes (long days) and simultaneously maximum solar power available which contradicts thermal cooling power and powertrain power supply. A careful consideration of these factors was made.

For optimal efficiency in operation, the thrust vector is placed along the x-axis of the body-fixed coordinate system so that no additional torque to be compensated is generated, especially in the loiter phase. Therefore, a push propeller is placed at the tail of the aircraft, which is equipped with a retraction mechanism to minimize drag during the thrustless trimmed night glide phase. Distributed Electric Propulsion is not considered because of undesired propwash effects on aerodynamic surfaces and their negative effect on handling, transportation, maintainability, mass, and cost.

In the coasting phase, the ability to recuperate is not envisioned until the EIS in 2040. There are several reasons for this: The propeller must operate as efficiently as possible at several aerodynamic operating points, for instance, at low altitudes with high air density, at high altitudes with low air density, and at different temperature levels over a longer period of time. Moreover, the propeller has to be designed to be foldable in order to be smoothly transported to the point of use. For reasons of system complexity, integration into the high-voltage electric powertrain would also add higher costs in terms of development and supply. After consideration the trade-off between recovered energy through recuperation and drag created

Top Level A/C Requirements	Value
MTOM	357.9 kg
Cruise Speed	50 m/s
Deployment Rate	<20 min
Number of required A/C	20
Continuous Operating Time	minimum 30 days
Max. Flight Level	820
Battery Size	56 kWh
Solar Cell Area	25.72 m <sup>2</sup>
Max. Climb Rate	4 m/s at MSL
Entry into Service	2040
Take-Off Field Length	<100 m
Glide Ratio	54

**Table 2.3:** Top Level Aircraft Requirements achieved by *HEIKE*

by windmilling, makes this option unfeasible for the performance analysis but will be integrated into the system once the technologies achieve a high enough TRL. *HEIKE*'s system architecture is schematically shown in Figure 2.5.

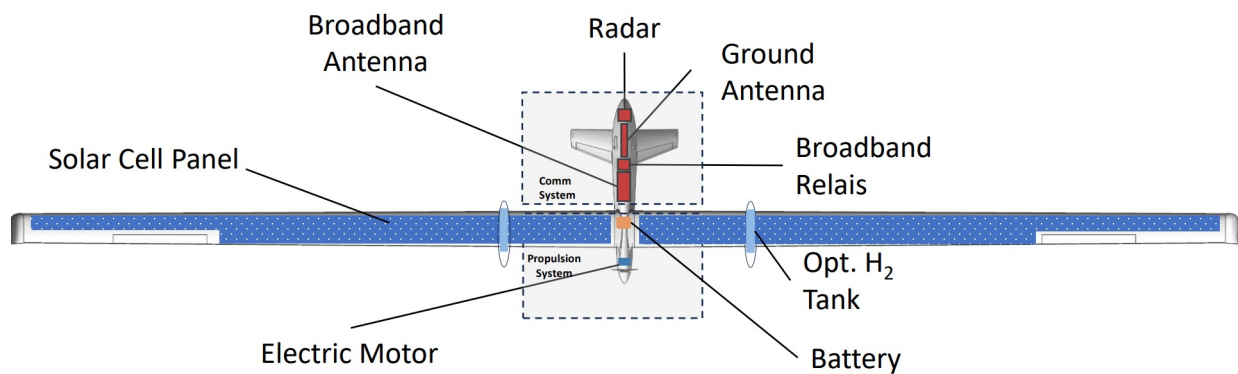


Figure 2.5: System architecture for proposed *HEIKE* design

Paramount is that continuous deployment of network capabilities and communication systems by *HEIKE* can only be achieved by the future integration of terrestrial, HAPs, and satellite networks in the long-term [2]. As an unmanned HAP, following the example of gliders, thermals play a central role. *HEIKE* exploits the available environment for heating and cooling and uses not only chemical, gravimetric but also meteorological available energy sources like gliders.

### 2.2.1 Coverage, Fleet Concept, Operational Readiness, and Multi-Role Design

With its modular design, *HEIKE* may be applicable in scenarios beyond the provision of communication services. Other potential customers for the communication services may include passenger airlines, railway operators, cruise ships, and alpine resorts. *HEIKE* may also be used for observational tasks both in the direction of Earth (*e.g.*, wildfire monitoring, agricultural monitoring, and large-scale effects of climate change) as well as at higher altitudes in the direction of the outer space (*e.g.*, research of the upper atmosphere and ozone layer, the possibility of improved conditions for astronomy). It will also demonstrate important technological advances for long-endurance unmanned aerial vehicles to support space exploration such as in the atmosphere of Mars. In general, the modular payload unit of *HEIKE* allows a wide variety of alternative payloads to be carried.

### 2.2.2 Safety Architecture and Certification Requirements

Mission Profile planning needs to be in compliance with air traffic controllers and regulations. EASA's regulation [15] for unmanned aircraft systems are applicable. Regarding autonomous flight operation, sensor fusion, and measurement consolidation ensure safe autonomous operation. High-performance signal processing is included. Emergency systems are integrated into the flight control software, providing various levels of safety. For example, if the pitch damper receives warnings of a failed sensor, the angle of attack is estimated by filtering, and limited authority is used. In case of a total failure of the system, a backup control law via remote control by trained personnel is integrated. This ensures guiding the unit safely to a nearby field for landing and retrieving the failed units, thus, it can be redeployed once the systems are running nominal again. In a gimbal system equipped with various optical measuring instruments, the system can navigate independently. In addition to shielded GPS/GALILEO receivers, Terrain Reference Navigation, and an Image Based Navigation are available.

### 2.2.3 Future technologies for EIS 2040 & TRL

The aim of *HEIKE*'s design is to utilize currently available technologies and to provide a solid foundation for its design. In this context, many of the selected components have achieved level 8 or 9 on the TRL scale by 2023 [16]. However, it has always been considered to ensure that *HEIKE* remains a state-of-the-art aircraft upon its introduction in 2040. For this reason, *HEIKE* is not heavily dependent on further development, but it can benefit from advancements such as higher-efficiency solar cells, robust flight control, or lighter structures.

The battery is the most reliant on further development, specifically in terms of energy density at pack level. Currently, energy densities of around 180 Wh/kg are used [17], whereas *HEIKE* requires at least 400 Wh/kg. Obtaining reliable data for future battery technologies is challenging due to the potential for significant breakthroughs like solid-state batteries. However, such advancements are not guaranteed, but a target of 400 Wh/kg is considered relatively pessimistic compared to other predictions [18]. If these advancements are indeed achieved, *HEIKE* will benefit from increased mass capacity, allowing for a larger battery or higher payload. Based on collected information, the Battery is estimated to have a current TRL of 3 to 4 [16].

According to the Unmanned Aircraft System Road map 2005–2030 published by the U.S. Department of Defense [19], the necessary autonomous capability level for *HEIKE*, ranks ninth on a 10-level scale, is expected to be widely achieved by 2030. In the future, the hybrid propulsion system, consisting of both a battery and a fuel cell, should be reevaluated [20, 21]. However, the use is dependent on significant weight reductions in the area of hydrogen storage. Regenerative fuel cells can also be integrated into the proposed system in the long term.

To improve flight performance *HEIKE* uses morphing wing flaps, thus, an optimal L/D can be achieved in different flight environments [22, 23]. Furthermore, it could be considered to equip *HEIKE* with Lufthansa Technik's *AeroSHARK* [24] to reduce drag. Also, a novel method is used to combine structural components with thermal conduction systems, which will be introduced in Section 3.3 and briefly discussed.

### 2.2.4 Technical Drawing of *HEIKE*

Figure 2.6, Figure 2.7 and Figure 2.8 show the Front, Top, and Side-View.

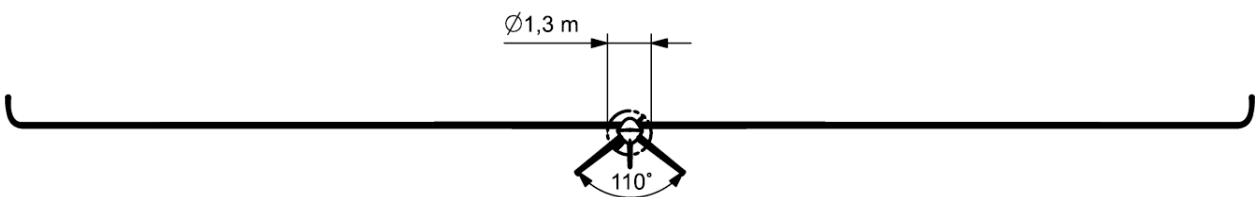


Figure 2.6: Front View

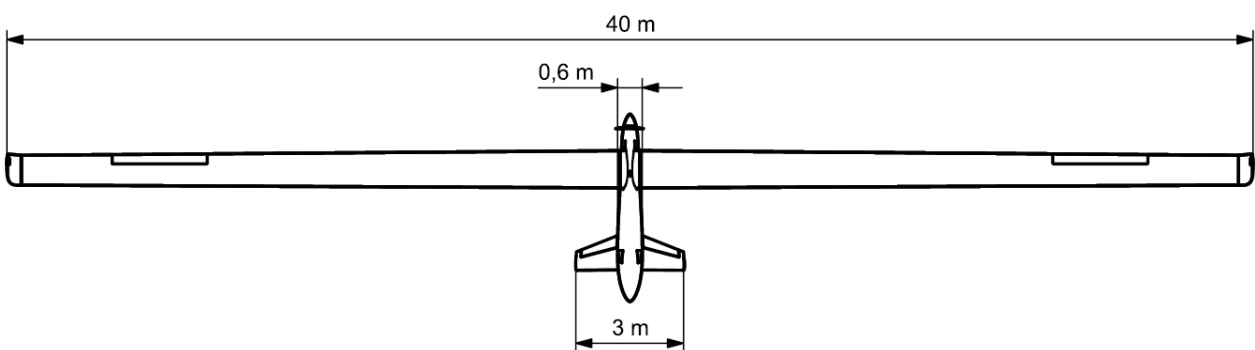


Figure 2.7: Top View

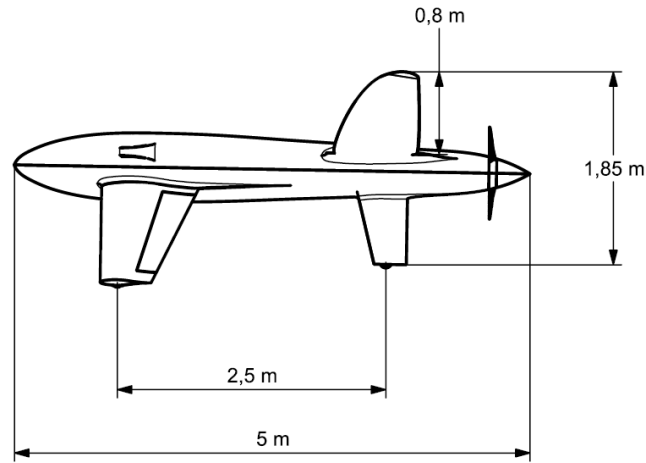


Figure 2.8: Side View

### 3 Detailed Design Analysis

In order to design a suitable aircraft system in detail, advanced design and analysis approaches have been used: *Evolutionary algorithms* similar to [25] accelerate the process of finding optimal aerodynamic configurations [26], which are simulated in a *rapid virtual prototyping* process. In this way, it was also possible to obtain a *digital twin* at medium system level [5]. Thus, the design process shown in Figure 3.1 was developed. This design process is supported by various built-in tools.

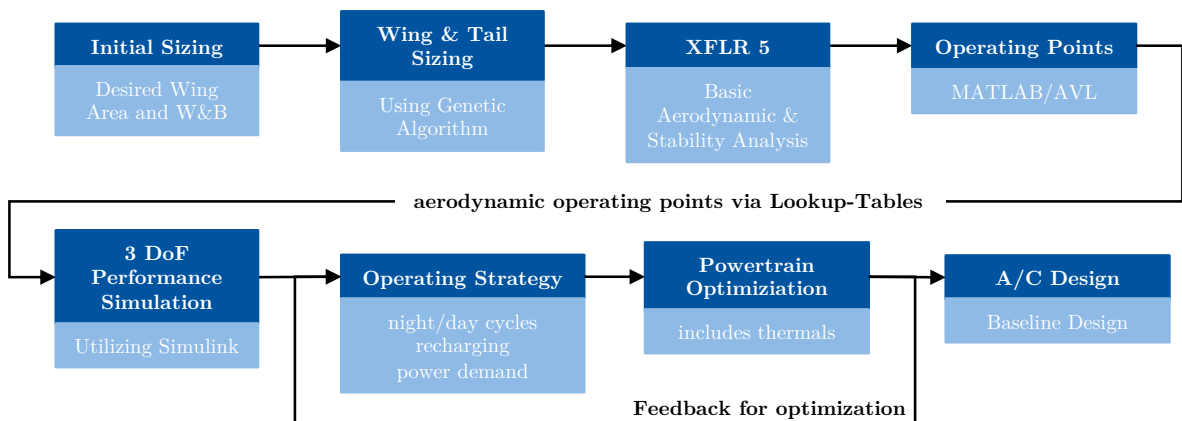
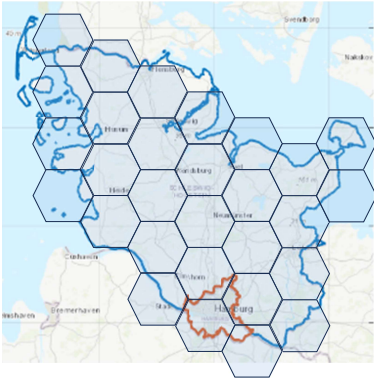


Figure 3.1: Detailed Design Process utilizing flight dynamics and performance simulation

#### 3.1 Initial Sizing

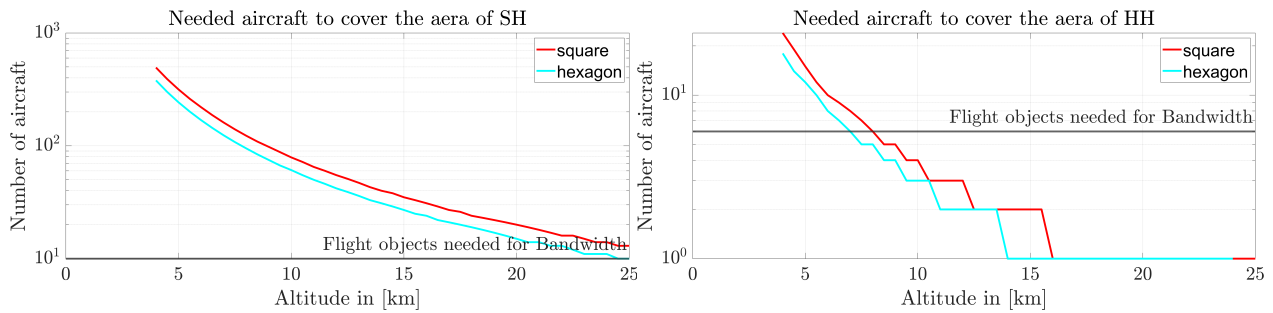
For the initial sizing, the flight performance requirements are derived from the mission details. Firstly, the requirements for scenario 1 were analyzed. The broadband antenna beam creates a cone, resulting in a round projected area on the ground. However, this poses a challenge because it is not feasible to arrange circles in a manner that covers every bit of land without overlapping. Therefore, the objective is to employ a shape that enables full coverage with minimal overlap. Hence, the hexagon shape was chosen (see Figure 3.2). In Figure 3.3, the number of aircraft required for area coverage is visualized for the largest possible hexagon and square shape that can fit within the cone.



**Figure 3.2:** Full coverage with hexagons

With regard to speed, two cases are relevant. Firstly, a slow cruise flight at a high altitude is preferred to minimize energy consumption and reduce the number of aircraft required for scenario 1. Using the diagrams shown in Figure 3.3 the cruise altitude was set to 20,000 m. Due to the fact that minimum thrust speed and stall speed are nearly identical for our configuration, a cruise speed of 125 % of the stall speed is selected. Secondly, scenario 2 necessitates a minimum ground speed of 45 m/s at an altitude of 15,000 m.

As shown in Figure 3.3, a high service ceiling is necessary to limit the number of aircraft. Furthermore, a service ceiling higher than the set altitude cruise altitude allows *HEIKE* to store energy in the form of gravimetric energy. Therefore, a service ceiling of 25,000 m is selected. To quickly cross general aviation airspace, two rates of climbs are determined to 4 m/s at sea level and 2 m/s at cruise altitude. For these requirements, a constrained analysis is carried out with additional functions for the take-off distance and a level turn.



**Figure 3.3:** Number of aircraft needed for area coverage: A comparison between square and hexagon

Subsequently, a maximum airspeed-stall speed carpet plot is created for an estimated mass and the power requirements from the constrained analyses. In addition to the speeds for a range of wing surfaces based on the results of the constrained analyses, also the propeller efficiency is calculated based on a blade efficiency of 85 % [7]. This process runs iteratively where the propeller efficiency is used to recalculate the power requirements from the constrained analysis. All calculations shown in Figure 3.4 and Figure 3.5 are based on Chapter 3 "Initial Sizing" of the General Aviation Aircraft Design [7]. In the early stages of the design process, empirical mass estimations for *HEIKE*'s fuselage and tail [27]. The wing mass, however, was estimated directly through an idealized structure model featuring a single-cell torsion box [7]. As the design process progressed, these methods were eventually replaced by the structure calculation described in Section 3.4.

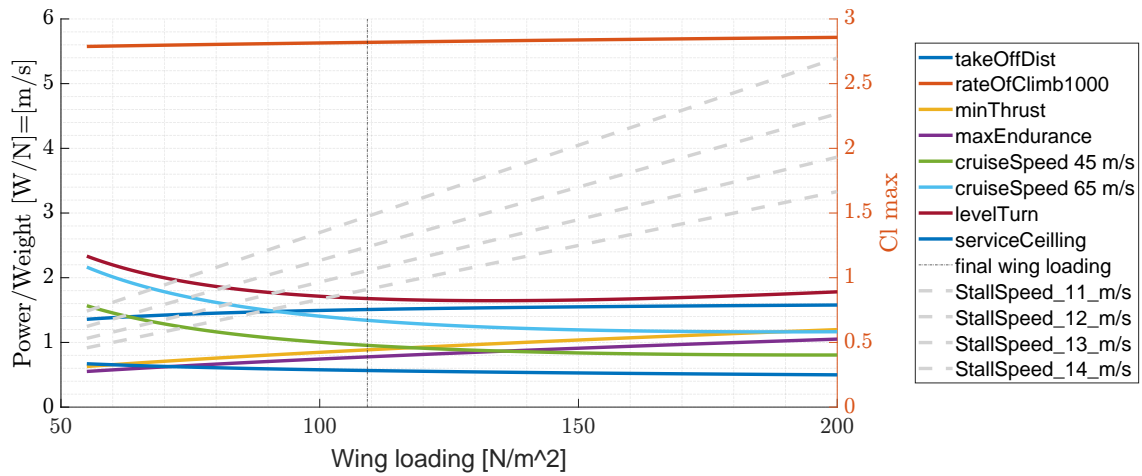


Figure 3.4: Constrained Analysis

For further calculations, a wing loading of approximately  $110 \text{ N/m}^2$  has been chosen. This selection is based on the results in Figure 3.4 and represents a trade-off between power consumption at lower speeds and wing mass. Furthermore, the stall speed at cruise altitude remains manageable, as shown in Figure 3.5, and the power consumption curve at high speeds shows a clear flattening. Additionally, the required maximum coefficient of lift ( $C_{L,max}$ ) for takeoff is realistically low. Considering these factors, a wing loading of around  $110 \text{ N/m}^2$  provides a suitable balance between power consumption, wing mass, stall speed, and takeoff requirements.

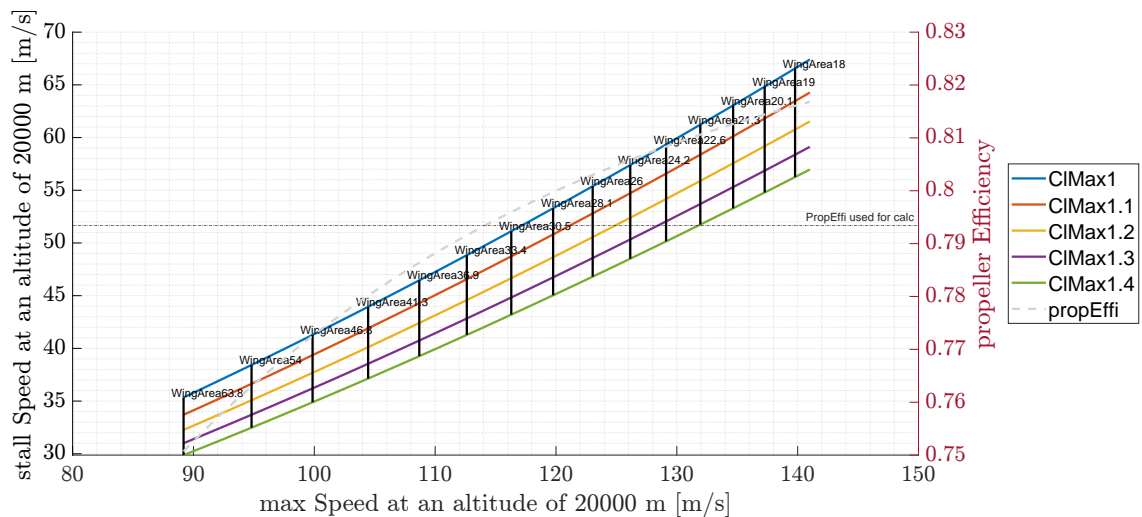


Figure 3.5: Stall Speed - Cruise Speed Plot

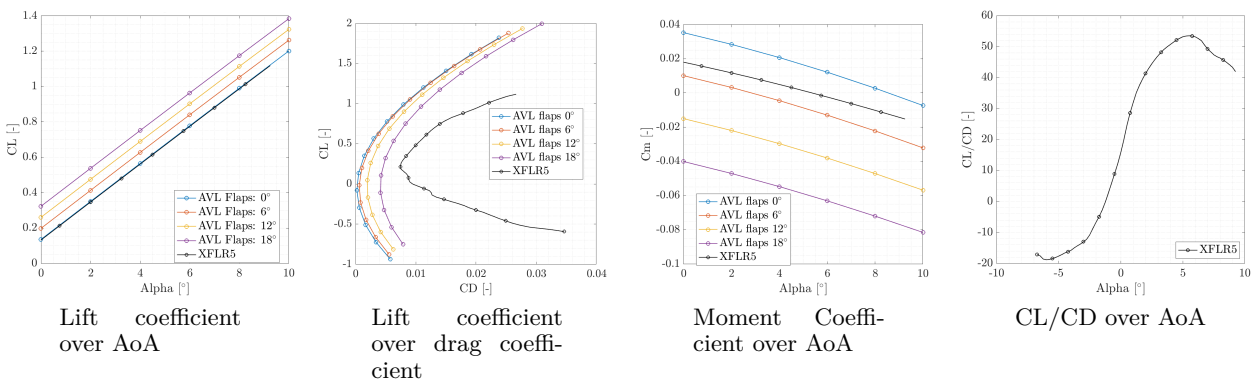
The initial sizing process generates a loop with the flight mechanical design and the powertrain sizing to continuously improve the estimation of aerodynamic coefficients and total mass.

## 3.2 Aerodynamics, Flight Mechanics, Operating Strategy and Autonomous Systems

In order to be able to make a holistic evaluation of the proposed concept, the self-developed software modules of an aerodynamic analysis by means of utilizing a vortex lattice method *Athena Vortex Lattice* (AVL) [28, 29] as well as XFOIL [30] and a built-in 3DoF simulation environment were combined to investigate the concept in detail. *HEIKE* has control of the longitudinal flight conditions by means of classical PID control [31–34]. Dynamics of the rudder and actuator system as well

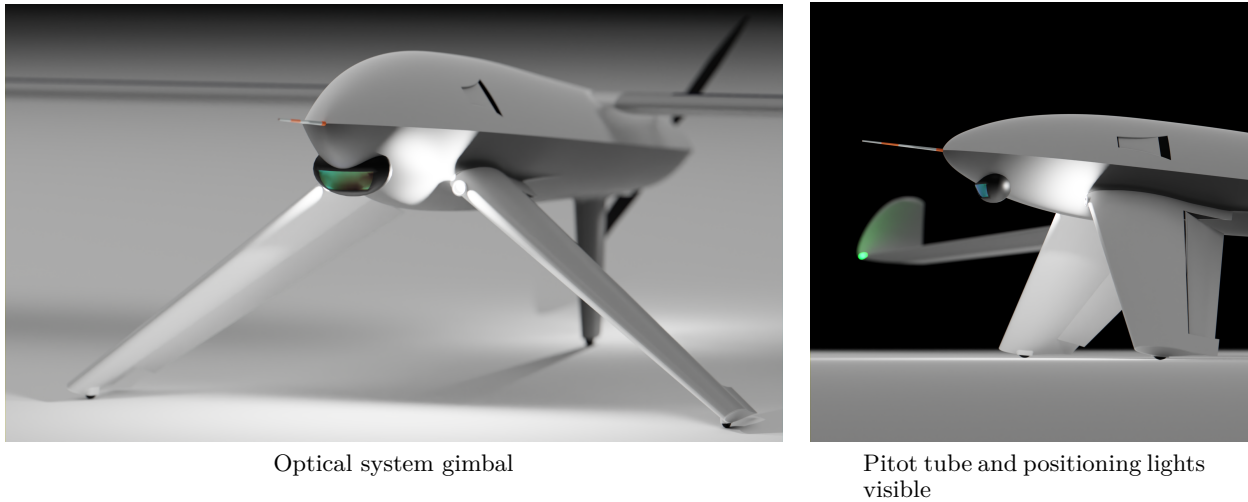
as thrust actuators were considered. The outer control loop, which includes the mission sequence control, was modeled with finite-state machines. This is done to allow flexible modeling and, in turn, to include optimal operation strategies proposed in [35–37]. Thus, a preliminary Level-D Simulator was achieved according to [38]. Basic aerodynamic performance and stability analysis were first carried out in XFLR 5 [39]. The chosen aerodynamic design ensures that no wings or payload modules reduce solar radiation in level flight. In turned maneuvers, the inverted V-tail maximizes the possible irradiated solar cell area if solar cells would be applied there in future configurations of *HEIKE*.

In addition, the shoulder deck configuration was also selected to avoid shadows on the solar cells during roll maneuvers. Polyvinyl chloride film coatings for improving the aerodynamic performance of solar cell integrated within the upper wing surface and a protection layer against weather conditions or chemicals extends lifetime but decreases the efficiency of the solar cells [40] are being used. In fact, a large camber reduces the possibility of mounting solar cells over a large area without severe bending. For these reasons, the airfoils are of a relatively low camber. The dominant criteria for the selection of the airfoil profiles were indeed the highest possible L/D with a simultaneous minimum moment coefficient, both of which are optimally combined in the corresponding Reynolds number range. With all this considered in combination with the canard configuration [41], the appropriate wing and tail airfoil are as follows: for the wing, a slightly changed *FX63-137* airfoil (maximal relative thickness 12.36% at 34.53% chord, maximal relative curvature 4.87% at 47% chord) was chosen and for the tail, a symmetric *FX71-L-150/30 Wortmann* airfoil is used, both are optimized for the flow regimes of *HEIKE* [42–44]. The aerodynamic geometry is twisted accordingly for flight characteristics while ensuring spacial distribution for the sensitive payload and high-voltage powertrain components. The aerodynamic performance is shown in Figure 3.6. *HEIKE* uses a teardrop shape for the fuselage for higher aerodynamic efficiency but also a semi-monocoque approach to make it fairly easy for manufacturing, Maintenance, Repair, and Overhaul (MRO) and cost-effective.



**Figure 3.6:** Aerodynamic performance parameters using [28][39]

*HEIKE*'s autonomous navigation systems consist of an Inertial Navigation System (INS), which includes three accelerometers, three gyroscopes, a barometric altimeter, and a receiver to the Galileo and GPS network, which is used for support, stability, and drift compensation of measurement data. Other elements include Pitch rate gyro and pitch attitude gyro [13, 45]. Roll rate gyros, yaw rate gyros, and roll attitude gyros are also included. Below the cloud layer, *HEIKE* has a radar altimeter, which is incorporated into the control system through low-pass filters. Additional weather radar in the nose of the aircraft system estimates the weather as well as occurring wind gusts, which operate with combined laser and infrared measurement. In this way, the control system of *HEIKE* can react dynamically to wind speed loads and significantly reduce structural loads through gust load alleviation. Maximum winds occurring at the respective altitudes have been added to the system simulation as a disturbance, and a sufficient stable system response has been found. To mitigate dynamic eigenmodes such as phugoid and short period, *elerudder* (combination of elevator and rudder) deflection controlled by FCS is successfully utilized. The gimbaled system as well as the pitot tube can be seen in Figure 3.7.



**Figure 3.7:** Autonomous Systems of *HEIKE*

Aerodynamic modeling, environmental conditions as well as solar energy models are included in the simulations using modeling techniques from [46, 47]. In the design of control surfaces and control signals within the mission simulation, a limited actuation speed and a load-dependent bandwidth were also taken into account. The rudder hinge does not exceed the critical structural loads according to our results. *FLARM* and TCAS system as well as strobe and position lights to operate in the different airspaces according to the legal regulations are installed in the system. In designing the controller, an elastic structure model is used, which enables the dampening of the structural vibration with the help of notch filters. An automatic controller also enables the generation of set trajectories, calculation of set values such as throttle level, and *elerudder* deflection for the control. A higher level control optimizes the mission strategy in coordination with other *HEIKE* units as well as ground personnel and authorities.

We have chosen a flight mechanically rather unstable design that favors the choice of smaller control surfaces, and lighter structures, as loads are automatically controlled away with powerful control systems [13, 14, 45]. An unstable design provides a range of solutions to the *HEIKE* system: Lift requires a trim tab deflection that results in a lift gain and a simultaneous drag reduction. Maneuvering by changing the lift coefficient results in a supporting moment, thus promoting the maneuver. Gust load alleviation leads to a reduction of structural loads and reduction of maneuver loads for influencing the lift distribution and thereby increasing the structure's lifespan and saving structural weight [13].

The sufficient positioning of the payload antennas during the change of inclination is being compensated with the use of a gimbal system in the internal structure [48]. *HEIKE* is utilizing an intelligent Power Management and Distribution Control System (PMADC) which enables the system to make use of the different energy sources available in an optimal way. Incorporating weather forecast data, wind gusts, and internal power states it will decide on its own when to use which energy source best. If solar power is available to *HEIKE* during the day, the intelligent PMADC uses this power source to operate the payload and power adjusted according to the current demand to fly the desired trajectory. The excess energy is stored in the battery systems. In this process, the excess energy is also used in such a way that *HEIKE* reaches its service ceiling and thus stores gravimetric energy, which is later converted into kinetic energy during a night phase to save any energy [49]. *HEIKE* also uses thermal circumstances such as winds to exploit additional existing sustainable energy sources. At night, the payload is always provided with the necessary power so that mission success is not affected by external circumstances [12, 40]. A maximum power point tracking device ensures optimal operation of the solar cells.

### 3.3 Energy System and Thermal Management

For the design of the powertrain, the battery must be able to handle several load cases: The launch phase and the first long climb phase to get to mission altitude, then the sustained provision of payload power, the storage of energy for the supply of propulsion power and payload power at night, and the charging capability by external as well as optional internal energy sources. The interplay between dimensioning the propulsion system and the mission profile results in an optimization problem. A trade-off was made as there are different design points for maximum temperature in summer at high latitudes (long days) and maximum available solar energy, although the temperature of the system must be kept at an acceptable level.

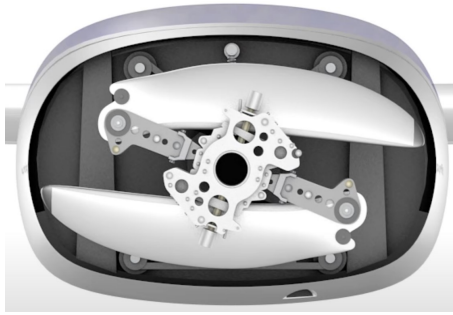
Significant considerations must be made regarding a thermal system, as these represent one of the greatest challenges in the realization of high altitude platforms such as *HEIKE* that are continuously operated [50]. Thermal Management imposes therefore a high risk for failure of the whole HALE system and thus must be addressed. Since at high altitudes heat transfer is no longer primarily dominated by natural or forced convection but by radiation, this must be taken into account in the design of *HEIKE*. The remaining convection must be supported by largely turbulent flow for better-forced convection performance on the suction side and laminar flow on the pressurized side. Phase change materials such as paraffin are a potential solution for the cooling of battery systems, which has already been extensively simulated and tested in the FVA 30 project [51]. Two NACA ducts at the front of *HEIKE* ensure sufficient airflow for the thermal systems and potential turbo-charging capabilities for hydrogen-based fuel cell systems. Also *HEIKE* will be equipped with 3D-printed lattice structures to incorporate new advances in the combined structural and thermal design. It will make use of phase change-material and structural elements shown in Figure 3.8b.

As a result of our design method, a battery electric powertrain, which can convert solar energy into electricity through photovoltaic modules, was chosen due to the high efficiency and the required energy demand for our mission. The advantages of a hydrogen-powered drive system outweigh the disadvantages due to the lower system weight and less complexity. Due to the entry into service in 2040, it can be assumed that the fuel cell technology will be more mature, and thus a hybrid concept solution could be possible due to better specific performance data combining another energy source with careful integration into PMADC.

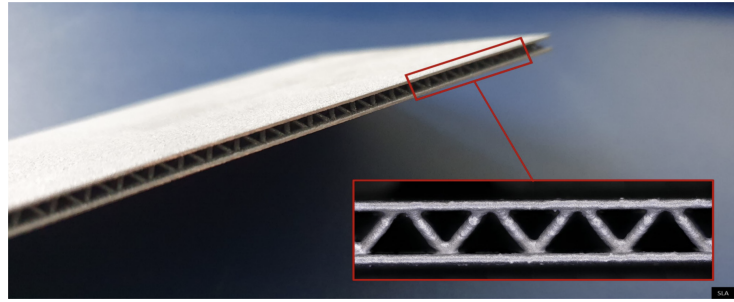
*HEIKE* is driven by an Axial flux e-motor. The energy source is a 56 kWh lithium-ion battery, which can provide specific energy of 400 Wh/kg through cell-to-pack technology. To charge this battery during flight, 80 % of the wing is covered by mono-crystalline solar cells. For Entry into Service in 2040, the efficiency of photovoltaic modules is expected to improve, which will further reduce the system weight of the powertrain. Efficiency for the solar cells of 14 % is being used inside the performance simulation which gives a good estimate regarding installation losses and pack-level efficiency as well as the temperature sensitivity of the cells. It is important to mention that the scaling of solar modules will also further reduce the purchase price, so it is assumed that the efficiency will increase at the same price.

To minimize drag during the glide phase, the propeller is equipped with a retraction mechanism that makes use of centripetal force. This system is inspired by the aircraft manufacturer Stemme [52], which already uses this retraction mechanism in the S10. Figure 3.8a shows the design of the system

Detailed results of *HEIKE*'s performance simulation in both scenarios is shown in Figure 3.9 and Figure 3.10 using a sophisticated flight performance analysis tool developed by the team incorporating modeling techniques and methods from [14, 55–63] using SIMULINK [5]. Within 164 minutes after launch the target area is reached at 100NM distance from the launch site. Within 4 hours after launch *HEIKE* reaches its service ceiling of 20km and thus the mission of network deployment can be initialized. During the whole mission, the state of charge will never drop below the safety margin of 10 % according to our simulated results. Due to the system design and the choice of cruise speed over ground, *HEIKE* reaches the target area after about 105 minutes in scenario 2. This is a trade-off between the aerodynamic design, the resulting load factors and, accordingly, the structure and propulsion power. Starting with only 75% energy reserve the system exploits the environment thus energy can be recovered, which the operational strategy takes into account.



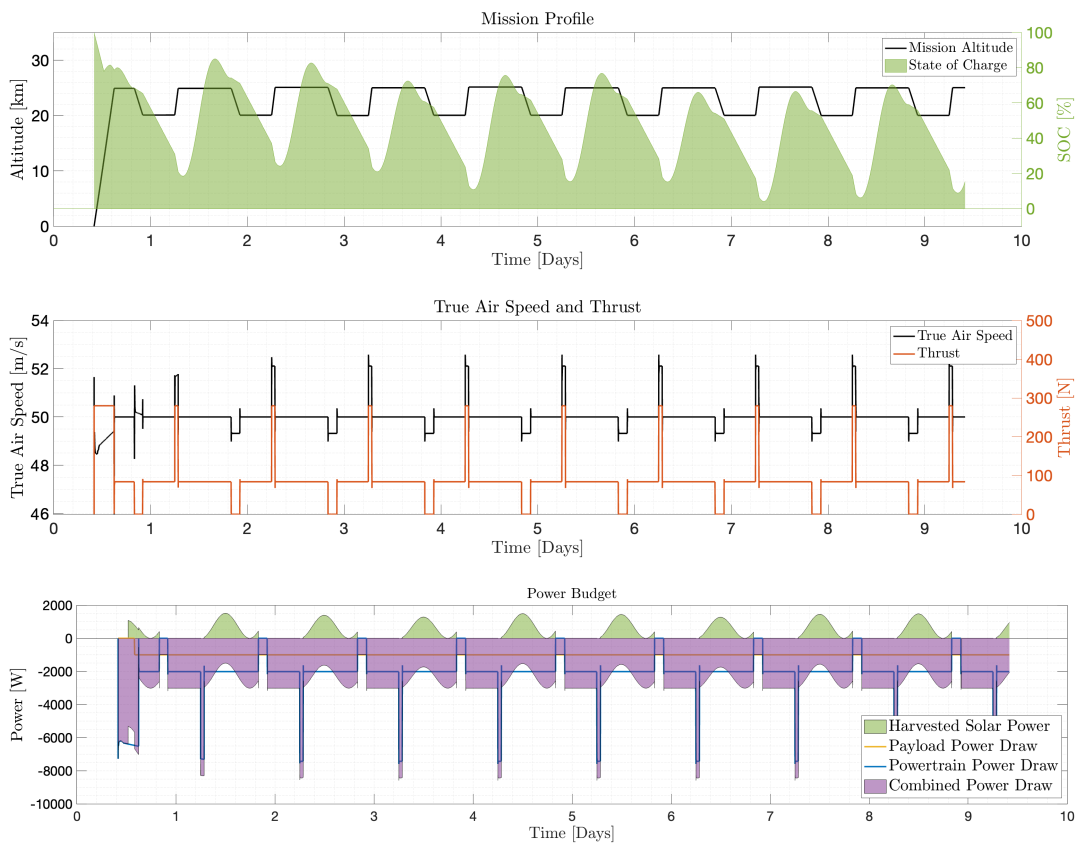
(a) Propeller System of the Stemme S10 [52]



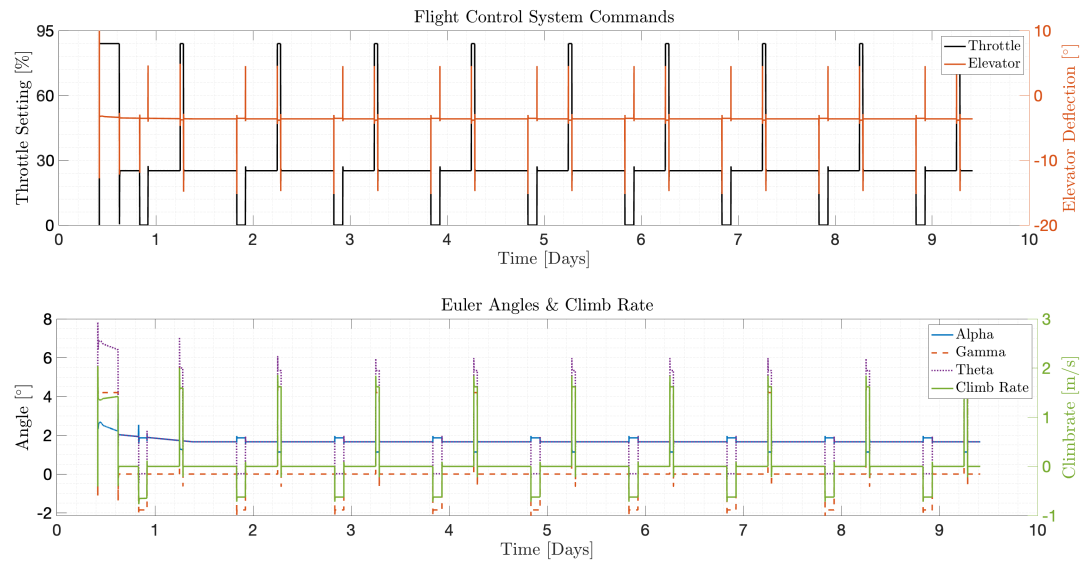
(b) Thermal management structure [53, 54]

**Figure 3.8:** Innovative systems in *HEIKE*

Optional expansion of a hybrid-electric powertrain by adding a regenerative fuel cell can further improve performance.



**Figure 3.9:** Flight Performance of *HEIKE* for the first 10 days out of a minimum of 30 days of the mission using a 3 DoF- Simulation Framework with integrated aerodynamic operating points



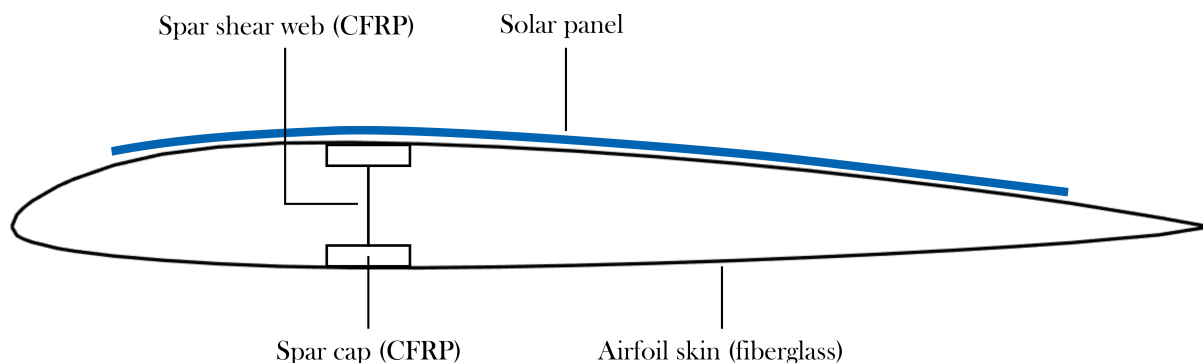
**Figure 3.10:** Flight Control System and respective attitudes (Euler Angles) of *HEIKE* for the first 10 days out of a minimum of 30 days of the mission using a 3 DoF- Simulation Framework with integrated aerodynamic operating points

### 3.4 Structural Design

The structural design here includes the dimensioning of the components of each set of wings (main and V-tail) as well as the fuselage. The design methodology is adapted from Reimerdes [64]. The selected materials were carbon fiber-reinforced polymer for the spars and fiberglass for the wing and fuselage skin. Figure 3.11 shows a sectional view with all principal structural components of the wing.

The load cases are calculated from aerodynamic data generated by *Athena Vortex Lattice* [28]. A Matlab function to convert the AVL data to usable load cases was developed. Concerning the wing structural analysis, the load cases are defined by a shear force, a bending moment about the vehicle  $x$ -axis, and a torsional moment about the vehicle  $y$ -axis. It is assumed that

- the spar caps bear the bending moment.
- the spar sheet bears the transverse (lifting) force and the torsional moment.
- the airfoil bears the torsional moment.



**Figure 3.11:** Sectional view of the wing structure

The spar caps are subject to the bending stress

$$\sigma_b = \frac{M(y) \frac{H}{2}}{I_{sparcap}} \quad (3.1)$$

with the area moment of inertia of the spar caps

$$I_{sparcap} = \frac{b}{12} (H^3 - h^3). \quad (3.2)$$

The dimension to be sized is the spar cap width  $b$ . The spars are placed within the airfoil skin so that the airfoil is divided into two cells of equal cross-sectional area. The shear flow in the airfoil skin can then be calculated with Bredt's formula:

$$\tau = \frac{T(y)}{2 A_{cross-section} t_{skin}} \quad (3.3)$$

The spar sheet (located between the two spar caps) is subsequently dimensioned to limit the shear stress from both the torsional moment and the transverse force below the maximum shear stress of CFRP. Each component is dimensioned accordingly at discrete spanwise locations. With this methodology, a locally optimized geometry is achieved. Using a gust load factor of 2.5 and a safety factor of 1.75, a lightweight wing design with a total mass of 136 kg is achieved.

The fuselage wall thickness is dimensioned to prevent shell buckling. As a conservative estimate, a simple cylindrical shell without stiffeners is assumed. The principal load acting on the fuselage is the combined bending moment resulting from the aerodynamics at the main and tail wing. First, the bending stress is calculated in analogy with Equation (3.2). Then, the fuselage wall strength is sized to satisfy

$$\sigma_{cr} = 3.92 E_{fiberglass} \left( \frac{t_{fuselage}}{R} \right)^{1.54}. \quad (3.4)$$

For the given loads, a fuselage wall thickness of 2.2 mm is sufficient, resulting in a fuselage shell mass of 40.8 kg. It is to be expected that significant mass savings can be achieved with a stiffened shell design.

### 3.5 Communication and Connectivity, Data Management and Environmental Protection

The communication subsystem is a crucial aspect of *HEIKE*, as it is required to fulfill two roles: The provision of communication services to the affected area, and the data exchange with the ground infrastructure.

A critical design constraint for the communication system is posed by the close proximity to high-voltage components of the energy supply subsystem. These high-voltage components (*e.g.*, inverter, and DC-DC converter) are a source of Electromagnetic Interference (EMI). EMI is an umbrella term for the adverse effects caused by the electromagnetic waves radiated from the high-voltage components, such as induced electric currents, which in turn produce noise in the raw data. Two design options are feasible to reduce the intensity of the EMI at critical components:

- Spatial separation of high-voltage components from communication & data components.
- Enclosure of EMI sources in a Faraday cage.

As spatial separation is limited to the length of the fuselage, the Faraday cage is the appropriate option for this scenario. Nonetheless, it is proposed to additionally maximize the spatial separation by placing all high-voltage components towards the rear of the aircraft (near the electric motor and the power-generating solar) and the communication components towards the front. Concerning the Faraday cages, which are to enclose the inverter and the DC-DC converter, copper mesh is a highly effective EMI shielding material, which allows for a lightweight and failure-proof shielding concept.

The constant provision of communication services is a key requirement. Flight maneuvers may sporadically interrupt the connection. To mitigate this issue, all relays and antennas are flexibly mounted on gimbal joints. The actuation is provided in two rotation axes (about the  $x$ - and  $y$ -axes of the body-fixed reference system) using two linear electric servo motors per gimbal. A constant pointing of the antenna beam is enabled by feeding data from the autonomous flight computer to the gimbal actuation. Any yaw, pitch, or roll maneuvers are relayed to the gimbal control so that the rotation is instantly compensated.

Aside from rotational maneuvers, the antenna pointing also needs to compensate for the translational motion of the aircraft. The input data for this gimbal motion is extracted from the relative position, altitude, and heading relative to the targeted area. The position can in any case be provided by a navigation satellite system, such as GPS or GALILEO; if multiple ground stations are in service, additional telemetry data may be triangulated from the transmission distance to two or more ground stations. Heading is provided by a compass. Altitude may be provided by a barometric altimeter, with added triangulated data if possible.

### 3.6 Weight and Balance

An accurate understanding of Weight and Balance, as shown in Table 3.1, is crucial for the entire design process as it influences the flight mechanics, flight performance, and structural sizing of the aircraft. The masses of the structural components are calculated as described in Section 3.4, but their weights are heavily dependent on the masses located in the fuselage. The propulsion system, specifically the battery which weighs 140 kg, constitutes the largest portion of the non-structural masses.

Component	Mass [kg]	CoG x [m]
Payload	13.0	1.0
Propulsion System	157.0	3.5
Autopilot /Flight Systems	2.6	2.5
Landing Gear	0.7	1.8
Fuselage	40.8	2.5
Wing	136.0	3.4
V-Tail	5.8	1.2
Vertical stabilizer	2.0	3.5
EW	344.9	3.3
MZFM/MTOM	357.9	3.2

**Table 3.1:** Weight and Balance of *HEIKE*

to the maximum takeoff mass (MTOM). This is because *HEIKE*'s only energy storage comes from the battery, and the mass change of the battery between full and empty is considered negligible. The Weight & Balance of *HEIKE* is visualized in Figure 3.12.

Notably, the weight of the battery is dependent on further development, unlike the other components of the flight control and propulsion system, where the masses are based on currently available options. This approach is adopted because it was challenging to obtain reliable estimates for the masses of these components in the future. Furthermore, compared to the battery, the other masses are relatively light, implying that further developments resulting in lighter options would have minimal impact on the overall system.

In the case of *HEIKE*, the maximum zero fuel mass (MZFM) is equivalent



Figure 3.12: Weight and Balance visualization

### 3.7 Reliability, Maintainability, Supportability, and Transportability

As an emergency response aircraft system, fast and easy use is vital for an effective operation. The key for our strategy is *HEIKE*'s specially designed storage unit that is identical in its dimensions and pickup points to a 40-foot shipping container. Thus, every vehicle that is capable of transporting containers can carry *HEIKE*. This is a significant advantage since the logistics network for containers already exists. Therefore, worldwide transport is cheap and without any special permits possible. Additionally, it does not need to rely on one single transport infrastructure during a crisis [65].

The storage units are mainly located at a logistics hub with good access to rail, ship, and motorway. In addition, individual *HEIKE*-Systems are located at airfields throughout Germany, creating a network similar to the rescue helicopter network in Germany [66]. Thus, *HEIKE* can be involved in small operations without any major logistical effort, or the local system can already be deployed while the main fleet is still in transit for larger operations.

To ensure a quick response time, the container is equipped with solar panels on its top. This way, *HEIKE*'s batteries are always charged. When the units are stacked, connecting cables are used to provide power to the lower units as well. Alternatively, other power supplies can be connected as needed.

When the container arrives at the mission airfield, *HEIKE* needs to be rigged, similar to a glider. Due to the large span width, the wings are stored in shorter sections, which fit into the container. Each wing is split at the halfway mark. To facilitate quick (dis-)assembly, the selected design at this interface is realized by a bolt spring mechanism. The operating principle to create a safe connection point between the fuselage and the wing is inspired by concepts used by established glider manufacturers who have been implementing this system for a long time. In order to increase work safety and minimize possible errors, rigging aids are used. Redundant sensors are installed at all separation points enabling, together with the autonomous flight system, a comprehensive automatic function check. This, coupled with the rigging aids, facilitates the swift rigging of *HEIKE* even by personnel with limited training.

The number of moving parts is minimized to ensure low maintenance requirements. To achieve this, the servos for the rudders are directly mounted onto the rudders and can be easily accessed through maintenance hatches. Additionally, the payload and propulsion system can be separately replaced as complete packages. This design facilitates ease of work on the systems, reduces the likelihood of errors related to plugs, and enables faster maintenance by swiftly swapping to refurbished systems. Moreover, the storage unit is equipped with a built-in lifting table to assist in moving heavy components, such as batteries.

### 3.8 Infrastructure, Launch, Recovery Elements, and Ground Elements

The *HEIKE* system depends only on a very small infrastructure. This ensures rapid and uncomplicated operational readiness. Although an airfield would be desirable as a base of operations, *HEIKE* can operate as long as a sufficiently large, paved area is available. This is aided by *HEIKE*'s short take-off and landing capabilities (STOL) [67].

The concept for the ground station involves a main control unit that utilizes a standard 20-foot shipping container as its base. During normal operation, the mission is monitored in the main control unit, which provides the interface for mission adjustments. In the event of an autopilot failure, the main control unit provides three remote controls to take over command of *HEIKE*. Additional modules, such as crew quarters or an energy generator, can be added to the main control unit depending on the infrastructure available at the ground base. These additional modules are also container-based. However, it is worth noting that the ground station can also be powered by the grid or the solar panels on *HEIKE*'s transport units. This provides flexibility in terms of power sources for the ground station operation, especially during crises. A conceptual visualization of the described systems is shown in Figure 3.13. For further flexibility of the ground operation, the battery can be charged when it is integrated into the aircraft and when it is removed. This enables an optimal charging experience depending on the chosen option.



**Figure 3.13:** Conceptual visualization of *HEIKE*'s airfield-based charging equipment and transportation container

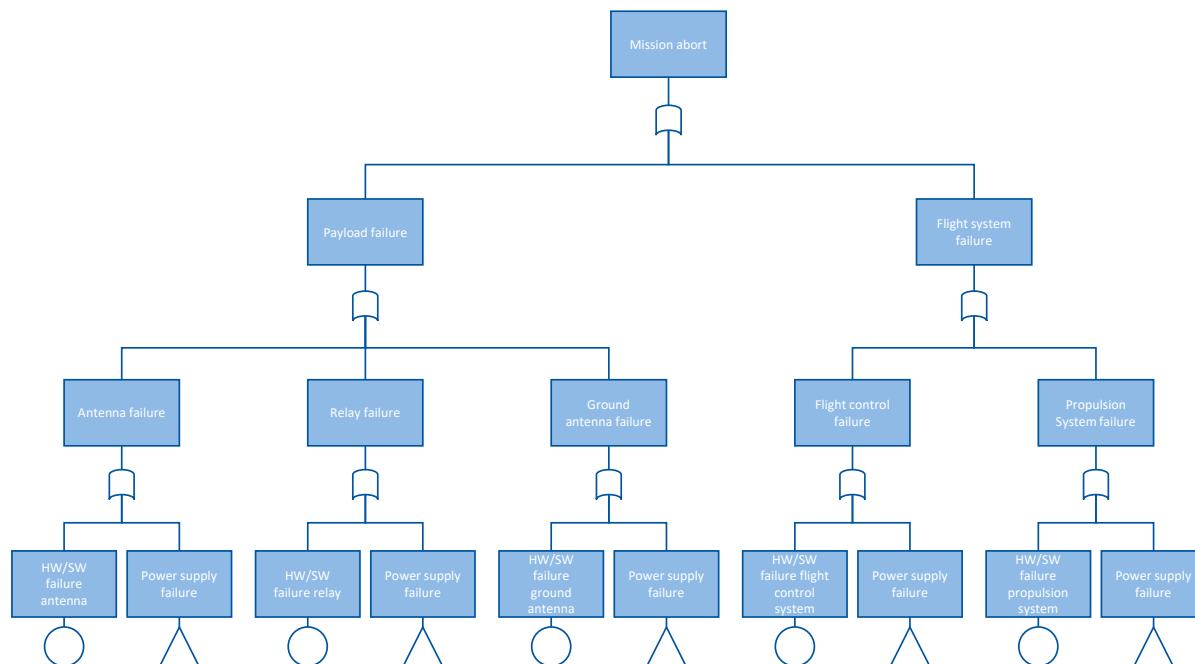
## 4 Holistic Evaluation

For a successful concept, other aspects must be taken into consideration, including economic and ecological factors. In the case of emergency response vehicles, cost plays a significant role, as high reliability often comes with high expenses. This is problematic because emergency vehicles are typically utilized at a relatively low rate, as they are primarily reserved for emergency situations. As described in Section 2.2.1, *HEIKE* has numerous potential applications during non-emergency use. Nevertheless, a carefully made cost and failure analysis is still necessary for long-term planning.

Moreover, ecological influences should also be considered, taking into account the environmental impact of *HEIKE*'s operation, energy sources, and overall sustainability.

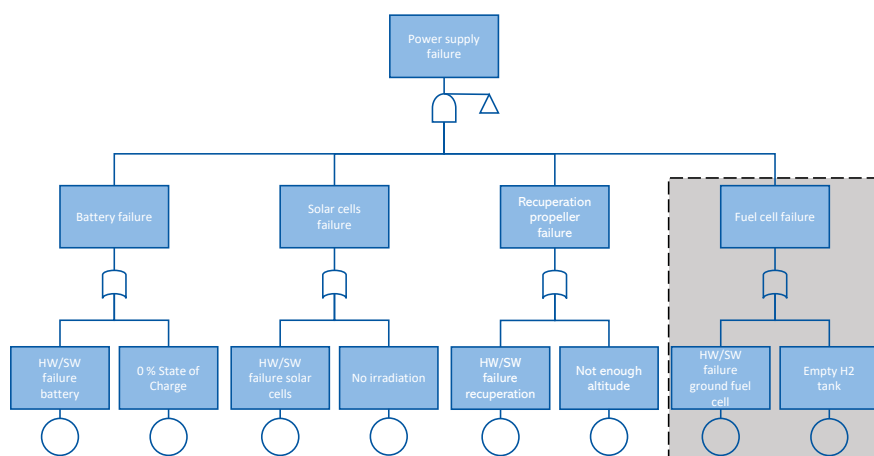
## 4.1 Failure Probability Analysis

A fault tree analysis [68] has been conducted to identify high-risk failure sources specifically for mission abort scenarios, shown in Figure 4.1.



**Figure 4.1:** Fault tree analysis: Mission abort

It is important to underline that this type of analysis differs significantly from an analysis conducted for a total loss of *HEIKE*. For example, a hardware failure in the relay is unlikely to result in a crash but would inevitably lead to a mission abort. Although there is no data at the moment to actually calculate the probability of mission abort, the analysis gives a good overview of critical components and systems.



**Figure 4.2:** Fault tree analysis: Power supply

One of the most critical systems is the power supply, shown in Figure 4.1. This system is critical not only because all other systems depend on it, but also because of the lack of redundancy during the ascent phase. To overcome this problem, the proposed hydrogen system could be advantageous. One possibility is to integrate the entire hydrogen system into a wingpod. This approach has the advantage of requiring only data and high voltage cables in the wings, which adds little to the complexity of the rigging compared to hydrogen lines. In addition, the wingpod could be equipped with a parachute,

allowing the hydrogen system to be jettisoned if the fuel cell becomes ineffective due to thin air or an empty hydrogen tank. If properly sized, *HEIKE* could reach altitudes above cloud level before the wingpod is jettisoned, allowing the solar cells to continue to provide power.

## 4.2 Cost Analysis

For the cost analysis, the Eastlake Business model was chosen, which can be found in Gudmundsson [7]. Various assumptions and corrections are made in order to be able to present an actual result. These include, for example, a price level correction through a CPI (Cost Price Index) adjustment, the so-called Cost Escalation Factor (CEF), which is calculated as shown below:

$$CEF = \frac{CPI(\text{now})}{CPI(2012)} \quad (4.1)$$

In Gudmundsson [7], reference is made to the year 2012, when the CPI of Germany was 91.7 according to statistica [69]. The CPI in 2022 was 110.2, resulting in a CEF of 1.202.

In order to obtain a tailored result, the following properties were selected:

- The number of aircraft to be produced within 5 years was set to 200. It should be noted that an increase in the number of aircraft produced has a positive impact on the cost structure due to economies of scale.
- The aircraft does not have a complex flap system.
- The aircraft structure is made of carbon fibre.
- The aircraft does not have a pressurized cabin.
- For the powertrain model, the model has to be adjusted to include an electric powertrain.

Concerning the cost model of the powertrain, a specific cost factor of 200 €/kWh was assumed, which results in a cost of 11.200€ for the selected battery (56kWh). The electric motor is estimated at a cost of 2,000 €. Mono-crystalline solar cells were selected, which have a specific cost factor of approximately 10,000 €/m<sup>2</sup>. This cost analysis takes into account that 80 percent of the wing area (32.15 m<sup>2</sup>) is covered by cells, the cost equals 257,200 €. Summing up the different cost points, an amount of 270,400 € is obtained.

The currency was changed to Euro and the experience effectiveness was set to 95 percent which resulted in a Quantity Discount Factor  $QDF$  of 0.6757 as calculated by

$$QDF = F_{\text{exp}}^{1,4427 \cdot \ln(N)} \quad (4.2)$$

with  $F_{\text{exp}}$  the experience effectiveness and  $N$  the number of units produced.

The detailed cost analysis is shown in Table 4.1.

Table 4.1: Cost Analysis

	Work-hours	Rate. €/hr	Total Cost	Cost per Unit
Engineering	11.621,83	100,00	2.928.630,85 €	14.643,15 €
Development Support			82.111,36 €	410,56 €
Flight test operations			293.946,56 €	1.469,73 €
Tooling	21208,84002	61	1.554.744,43 €	7.773,72 €
Certification Cost			4.859.433,20 €	
Manufacturing labor	141061,0293	53	18.839.652,88 €	94.198,26 €
Quality control			1.836.866,16 €	9.184,33 €
Materials/equipment			1.718.429,47 €	8.592,15 €
Units produces in 5 years				200
Quantity Discount Factor				0,6757
			Without QDF	With QDF
Fixed landing gear discount			- 7.500,00 €	- 5.067,75 €
Engine			270.400,00 €	182.709,28 €
Propeller			3.779,49 €	2.553,80 €
Avionics			15.000,00 €	10.135,50 €
<b>TOTAL COST TO PRODUCE</b>			<b>417.951,40 €</b>	<b>326.602,74 €</b>
Manufacturer`s liability insurance				50.000,00 €
<b>MINIMUM SELLING PRICE</b>				<b>376.602,74 €</b>

The cost analysis shows that the minimum selling price for a design of 200 aircraft is 376,602.74€.

### 4.2.1 Break Even Analysis

The break-even analysis is used to calculate how many units must be produced before revenues cover costs. With Equation (4.3), one is able to calculate the number of units to break even.

$$CEF = \frac{\text{total fixed cost}}{\text{unit sales price} - \text{unit variable cost}} \quad (4.3)$$

Figure 4.3 shows the break-even point plotted as a function of units. The cost analysis was designed for 200 aircraft being produced in 5 years. If the price of the aircraft is increased, the number of aircraft needed to reach the break-even point is reduced.

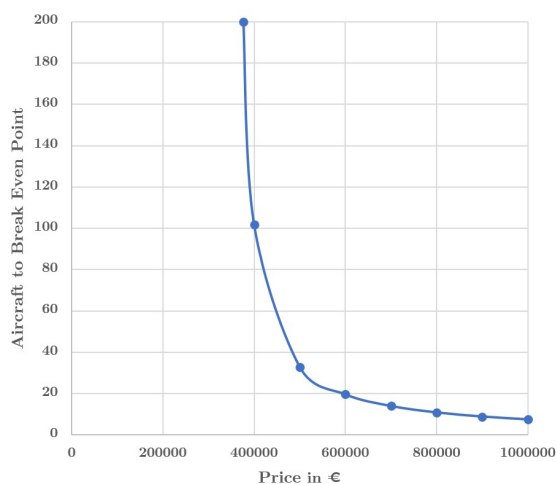


Figure 4.3: Break-Even Point Analysis

Figure 4.4 shows the break-even analysis graphically for 3 different prices. The grey curve represents the minimum selling price. The dark blue curve includes a margin of 5 percent, and the light blue curve has a margin of 15 percent. Furthermore, one can extract, for example, the *Net Present Value* (NPV) at a price of 395.432.88€.

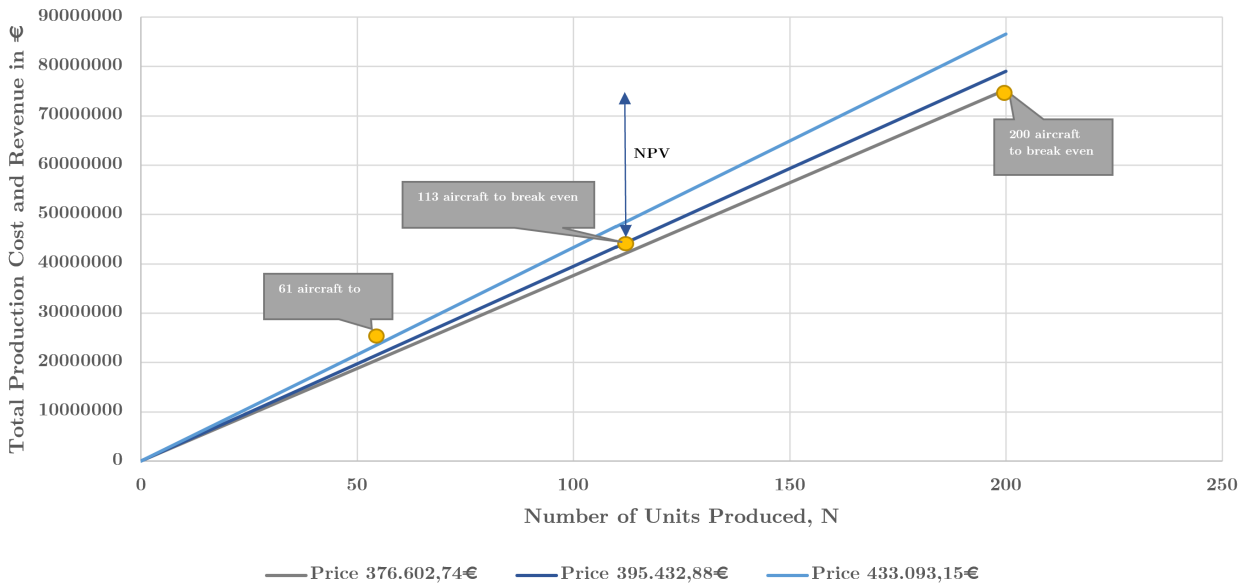


Figure 4.4: Break-even analysis assuming three different prices

### 4.3 Environmental sustainability

Sustainability is an important aspect and has been considered throughout the design process. The overall impact is analyzed in the three life stages of production, operation, and end of service.

For the structural components, the main emissions during production are from the autoclave, which is needed to give the CFRP its strength. However, systems are being developed to replace conventional heating elements with microwaves, which should lead to a significant reduction in energy consumption [70]. Similarly, the production of silicon for solar panels requires a lot of energy. The battery, with its high demand for Rare Earth Elements (REE) and energy, currently has the greatest environmental impact. The amount of research into more sustainable solutions is enormous, hence the potential of a more environmentally friendly production process is high. Overall, the industry is expected to have a lower carbon footprint in the future as a result of high investments in renewable energy and thus an increasing amount of green energy in the power grid.

Carbon-neutral operation is possible due to the container design of the storage unit and the electric propulsion system. Rail transport already uses carbon-neutral energy [71], and other forms of transport, such as ships and trucks, are expected to have green options by 2040. The solar cells on the container can charge *HEIKE*'s battery for deployment and then power the ground station. During flight, the high aerodynamic efficiency combined with the electric propulsion system minimizes noise pollution.

At present, there are only limited possibilities for recycling an electric aircraft in composite construction. However, with more and more mass-produced products being built in a similar way, e.g., electric cars, the need for a recycling solution for these components is likely to arise sooner than the first *HEIKE* systems are phased out. To support this argument, the EU is already discussing new recycling regulations with the aim of recycling 90 % of batteries by 2030 [72]. Therefore, there should be recycling options for the battery by 2040. CFRP is also difficult to recycle, but the hull is expected to have a long life due to its aerodynamic efficiency (Section 3.2 & Section 3.4) and the ability to replace technical components with newer equivalents [73–75].

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## 5 Conclusion and Outlook

Essential aspects of the mission scenarios were laid out and a design process for *HEIKE* was devised accordingly. An unmanned canard configuration with a pushprop with power supplied by a battery system, later expandable to a hybrid-electric system, was selected for further development. The concept was evaluated regarding the future development of the required technologies, highlighting the energy density of the battery as a crucial parameter. To begin the detailed design, an initial sizing with the power consumption and flight dynamic behavior as trade-off parameters was performed. An unstable configuration was favored over a stable one to reduce the control surface area. The resulting aerodynamic model was used for a full-mission analysis of two emergency scenarios, which demonstrated that *HEIKE* is capable of multi-day missions without the need for landing. For the thermal protection of the battery, the use of phase-change materials as well as 3D-metal-printed lattice structures was proposed. Structural elements were dimensioned with loads obtained from the flight dynamic calculations. The integration of the communication equipment was described, with the final design containing Faraday cages around EMI sources. The detailed design was finalized with concepts for the infrastructure and operation. Operational flexibility was enhanced by making the aircraft system transportable by container. The design was then evaluated for failure probabilities and financial viability. It was shown that the price-per-unit is affordable for a fleet size of 200. The result is a preliminary design for an aircraft system that is able to provide communication services to disaster-affected regions. Two major challenges are identified for the further roadmap of *HEIKE*: The lightweight design of the power supply, and the coordination of multiple aircraft in autonomous flight. At the time of writing, the available battery technology results in a high battery mass to meet the power demands of the aircraft system. With the global shift from fossil fuels to renewable energies across all industries, research interest in the area will remain high. As for autonomous coordination, research interest is similarly high in comparable areas of application, such as autonomous driving. This ongoing development, coupled with the rapidly growing field of artificial intelligence, will favorably impact the development of *HEIKE*'s autonomous flight system. The design is innovative insofar as it is a novel approach to the mission scenario, which to date has mostly been attempted via satellite networks (*e.g.*, *Starlink* by *SpaceX*). However, taking into account the targeted entry-into-service, it is anticipated that all required technologies will be at a serviceable level of readiness by 2040.



# Bibliography

- [1] ZINDEL, H.: Schwebende Infrastrukturen, 2020.
- [2] MOHAMMED, A.; MEHMOOD, A.; PAVLIDOU, F. N.; MOHORCIC, M.: The role of high-altitude platforms (HAPs) in the global wireless connectivity. Proceedings of the IEEE, Vol. 99, pp. 1939–1953, 2011.
- [3] TOZER, T. C.; GRACE, D.: High-altitude platforms for wireless communications. Electronics and Communication Engineering Journal, Vol. 13, pp. 127–137, 2001.
- [4] GRACE, D.; OODO, M.; CAPSTICK, M.; ZURICH, E.; GRACE, D.; MOHORCIC, M.; OODO, M.; CAPSTICK, M. H.; PALLAVICINI, M. B.; LALOVIC, M.: CAPANINA-Communications from Aerial Platform Networks Delivering Broadband Information for All, 2005.
- [5] MATHWORKS: MATLAB/Simulink 2023a, 2023.
- [6] DLR Design Challenge 2023, Deutsches Zentrum für Luft- und Raumfahrt, 2023.
- [7] GUDMUNDSSON, S.: General Aviation Aircraft Design, Elsevier, 2014.
- [8] FLEISCHER, B.; THEUMERT, H.: Roloff/Matek: Entwickeln Konstruieren Berechnen, Springer, 2018.
- [9] VDI 2221 - Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte, Verein Deutscher Ingenieure, 1993.
- [10] NASA: OpenVSP, 2023.
- [11] JAMISON, L.; SOMMER, G. S.; III, I. R. P.: High-Altitude Airships for the Future Force Army, 2005.
- [12] HASAN, Y. J.; ROESER, M. S.; HEPPELLE, M.; NIEMANN, S.; VOSS, A.; HANDOJO, V.; WEISER, C.: Flight mechanical analysis of a solar-powered high-altitude platform. CEAS Aeronautical Journal, Vol. 14, pp. 201–223, 2023.
- [13] MOORMANN, U.-P. D.-I. D.: Flugregelung Vorlesungsskript, Institut für Flugsystemdynamik, 2022.
- [14] AUSTIN, R.: Unmanned Aircraft Systems, Wiley, 2010.
- [15] EASA: Easy Access Rules for Unmanned Aircraft Systems — Revision from September 2022, 2022.
- [16] U.S. GOVERNMENT ACCOUNTABILITY OFFICE: Technology Readiness Assessment Guide. GAO Best Practices, 2020.
- [17] LÖBBERDING, H.; WESSEL, S.; OFFERMANN, C.; KEHRER, M.; ROTHER, J.; HEIMES, H.; KAMPKER, A.: From cell to battery system in BEVs: Analysis of system packing efficiency and cell types. World Electric Vehicle Journal, Vol. 11, pp. 1–15, 2020.
- [18] SURYATNA, A.; RAYA, I.; THANGAVELU, L.; ALHACHAMI, F. R.; KADHIM, M. M.; ALTIMARI, U. S.; MAHMOUD, Z. H.; MUSTAFA, Y. F.; KIANFAR, E.: A Review of High-Energy Density Lithium-Air Battery Technology: Investigating the Effect of Oxides and Nanocatalysts. Journal of Chemistry, Vol. 2022, 2022.
- [19] OFFICE OF THE SECRETARY OF DEFENSE: Unmanned Aircraft Systems Roadmap 2005-2030, 2005.
- [20] SUN, K.; ZHU, M.; WANG, L.; LIU, H.: Analysis of the Hybrid Power System for High-Altitude Unmanned Aircraft. Advances in Materials Science and Engineering, Vol. 2015, 2015.
- [21] PETERS, R.: Brennstoffzellensysteme in der Luftfahrt, Springer-Verlag Berlin-Heidelberg, ISBN 9783662467978, 2015.

- [22] PRISACARIU, V.; BOSCOIANU, M.; CÎRCIU, I.: Morphing wing concept for small UAV. *Applied Mechanics and Materials*, Vol. 332, pp. 44–49, 2013.
- [23] PECORA, R.: Morphing wing flaps for large civil aircraft: Evolution of a smart technology across the Clean Sky program. *Chinese Journal of Aeronautics*, Vol. 34, pp. 13–28, 2021.
- [24] LUFTHANSA TECHNIK AG: *Lufthansa Technik Aeroshark*, 2023.
- [25] BAKAR, A.; KE, L.; LIU, H.; XU, Z.; WEN, D.: Design of low altitude long endurance solar-powered UAV using genetic algorithm. *Aerospace*, Vol. 8, 2021.
- [26] MORRISEY, B.; MCDONALD, R.: Multidisciplinary design optimization of an extreme aspect ratio HALE UAV. In: 2009.
- [27] YI, Z.; HEPING, W.: A STUDY OF STRUCTURE WEIGHT ESTIMATING FOR HIGH ALTITUDE LONG ENDURENCE (HALE) UNMANNED AERIAL VEHICLE (UAV).
- [28] DRELA, M.: *Athena Vortex Lattice*, 2023.
- [29] CIPOLLA, V.; DINE, A.; VITI, A.; BINANTE, V.: MDAO and Aeroelastic Analyses of Small Solar-Powered UAVs with Box-Wing and Tandem-Wing Architectures. *Aerospace*, Vol. 10, 2023.
- [30] DRELA, M.: *XFOIL*, 2023.
- [31] NELSON, R. C.: *Flight Stability and Automatic Control*, WCB/McGraw Hill, ISBN 0070462739, 1998.
- [32] SCI-026, T. G.: *Flight Control Design-Best Practices*, 2000.
- [33] KÄMPF, P.: *Handbuchmethoden zur Leistungsabschätzung*, 2022.
- [34] MOORMANN, U.-P. D.-I. D.: *Flugdynamik Vorlesungsskript*, Institut für Flugsystemdynamik, 2020.
- [35] SUN, M.; SHAN, C.; SUN, K. W.; JIA, Y. H.: Energy Management Strategy for High-Altitude Solar Aircraft Based on Multiple Flight Phases. *Mathematical Problems in Engineering*, Vol. 2020, 2020.
- [36] GAO, X. Z.; HOU, Z. X.; GUO, Z.; CHEN, X. Q.; CHEN, X. Q.: Joint optimization of battery mass and flight trajectory for high-altitude solar-powered aircraft. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 228, pp. 2439–2451, 2014.
- [37] ARUM, S. C.; GRACE, D.; MITCHELL, P. D.; ZAKARIA, M. D.; MOROZS, N.: Energy management of solar-powered aircraft-based high altitude platform for wireless communications. *Electronics (Switzerland)*, Vol. 9, 2020.
- [38] ADMINISTRATION, F. A.: *AC 120-40B - Airplane Simulator Qualification*, 1991.
- [39] XFLR 5, GNU General Public License, 2023.
- [40] PE CIAK, M.; SKARKA, W.; MATEJA, K.; GUDE, M.: Impact Analysis of Solar Cells on Vertical Take-Off and Landing (VTOL) Fixed-Wing UAV. *Aerospace*, Vol. 10, p. 247, 2023.
- [41] CAI, Y.; XIE, J.; HARRISON, E. D.; MAVRIS, D. N.: Assessment of Longitudinal Stability-and-Control Characteristics of Hybrid Wing Body Aircraft in Conceptual Design. In: 2021.
- [42] DANJUMA, S. B.: Aerodynamic Design Consideration for Stability of a Lightweight Solar-Powered Aircraft CONSIDERATIONS OF DIFFERENT TYPES OF SOLAR POWER AIRPLANE DESIGNS, PROSPECTS TO AVIATION INDUSTRY View project Bashir Danjuma Safyanu Abubakar Tatari Ali Polytechnic Aerodynamic Design Consideration for Stability of a Lightweight Solar-Powered Aircraft. *Traektoriã Nauki = Path of Science*. 2022, Vol. 8, 2022.
- [43] HASAN, M. S.; SVORCAN, J. M.; SIMONOVIĆ, A. M.; MIRKOV, N. S.; KOSTIĆ, O. P.: OPTIMAL AIRFOIL DESIGN AND WING ANALYSIS FOR SOLAR-POWERED HIGH-ALTITUDE PLATFORM STATION, 2021.

- [44] HASAN, M. S.; SVORCAN, J.; TANOVIC, D.; BAŞ, G.; DURAKBASA, N. M.: Conceptual Design and Fluid Structure Interaction Analysis of a Solar Powered High-Altitude Pseudo-Satellite (HAPS) UAV Wing Model. In: 2021.
- [45] BROCKHAUS, R.; ALLES, W.; LUCKNER, R.: Flugregelung, Springer Berlin Heidelberg, 2011.
- [46] WU, M.; SHI, Z.; XIAO, T.; CHEN, Z. L.; ANG, H.: Effect of solar cell efficiency and flight condition on optimal flight control and energy performance for Z-shaped wing stratospheric solar aircraft. *Acta Astronautica*, Vol. 164, pp. 366–375, 2019.
- [47] BRIZON, M.: Solar Energy Generation Model for High Altitude Long Endurance Platforms, 2015.
- [48] MOIR, I. (; SEABRIDGE, A. G. ( G.: Aircraft systems: mechanical, electrical, and avionics subsystems integration, Wiley, ISBN 9780470059968, 2008.
- [49] LEICHTWERK AG: High Altitude Platform Stations (HAPS)-A Future Key Element of Broad-band Infrastructure, 2023.
- [50] ORTEGA, C. B.; ZIMMER, D.; WEBER, P.: Thermal analysis of a high-altitude solar platform. *CEAS Aeronautical Journal*, Vol. 14, pp. 243–254, 2023.
- [51] FVA: Batteriekühlung: PCM-Simulation, 2020.
- [52] Stemme S10 Retractable variable pitch propeller, <https://www.youtube.com/watch?v=pJqJiGkUpvA>.
- [53] Experimental analysis of the thermal energy storage potential of a phase change material embedded in additively manufactured lattice structures. *Applied Thermal Engineering*, Vol. 216, p. 119091, 2022.
- [54] BÜHRING, J.; NUÑO, M.; SCHRÖDER, K. U.: Additive manufactured sandwich structures: Mechanical characterization and usage potential in small aircraft. *Aerospace Science and Technology*, Vol. 111, p. 106548, 2021.
- [55] SCHEIDERER, J.: Angewandte Flugleistung, Springer Berlin Heidelberg, 2008.
- [56] FATHI, K. M.; MALAEK, P. S. M. B.: Wide Area Areal Protective Inspector, 2019.
- [57] ANDERSON, J. D.: Aircraft performance and design, WCB/McGraw-Hill, ISBN 0070019711, 1999.
- [58] KEANE, A. J.; SOBESTER, A.; SCANLAN, J. P.: Small Unmanned Fixed-wing Aircraft Design, Wiley, 2017.
- [59] GIRLEVICIUS, L.: Evaluation of solar powered systems in small scale UAV designs, 2022.
- [60] KÖHLER, J. A.: Entwurfsmethode für elektrische und hybride Kleinflugzeugantriebe, 2022.
- [61] GONZALEZ, J. E. G.: Assessment of High Altitude and Long Endurance Platforms for Operations in a Commercial Environment, 2016.
- [62] NOTH, A.: Design of Solar Powered Airplanes for Continuous Flight (PhD Thesis - Noth 2008), 1980.
- [63] KEIDEL, B.: Auslegung und Simulation von hochfliegenden, dauerhaft stationierbaren Sollarodrohen, 2000.
- [64] REIMERDES, H.-G.: Auslegung und Struktur von Leichtflugzeugen, Institut für Strukturmechanik und Leichtbau (RWTH Aachen), 2013.
- [65] ERTEM, M. A.; AKDOGAN, M. A.; KAHYA, M.: Intermodal transportation in humanitarian logistics with an application to a Turkish network using retrospective analysis. *International Journal of Disaster Risk Reduction*, Vol. 72, 2022.
- [66] ADAC LUFTRETTUNG GMBH: ADAC Luftrettung Standorte, 2023.
- [67] JOINT CHIEFS OF STAFF: Joint Shipboard Helicopter and Tiltrotor Aircraft Operations (JP 3-04), 2012.

- [68] HANKAMMER, F. E. M. S. R.: Fehlerbaumanalyse in Theorie und Praxis Grundlagen und Anwendung der Methode, ISBN 978-3-662-48165-3, 2015.
- [69] STATISTICA: CPI Index, <https://de.statista.com/statistik/daten/studie/2550/umfrage/entwicklung-des-verbraucherpreisindex/>.
- [70] ACHTERNBOSCH, M.; BRÄUTIGAM, K.-R.; KUPSCH, C.; RESSLER, B.; SARDEMANN, G.: Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft Analyse der Umweltauswirkungen bei der Herstellung, dem Einsatz und der Entsorgung von CFK-bzw. Aluminiumrumpfkompontenten, 2003.
- [71] DEUTSCHE BAHN: DB Strom, 2023.
- [72] EUROPÄISCHE KOMMISSION: VERORDNUNG DES EUROPÄISCHEN PARLAMENTS UND DES RATES über Batterien und Altbatterien, zur Aufhebung der Richtlinie 2006/66/EG und zur Änderung der Verordnung (EU) 2019/1020, 2020.
- [73] DAS, M.; CHACKO, R.; VARUGHESE, S.: An Efficient Method of Recycling of CFRP Waste Using Peracetic Acid. ACS Sustainable Chemistry and Engineering, Vol. 6, pp. 1564–1571, 2018.
- [74] BUTENEGRO, J. A.; BAHRAMI, M.; ABENOJAR, J.; MARTÍNEZ, M. Á.: Recent progress in carbon fiber reinforced polymers recycling: A review of recycling methods and reuse of carbon fibers. Materials, Vol. 14, 2021.
- [75] SHIBATA, K.; NAKAGAWA, M.: CFRP Recycling Technology Using Depolymerization under Ordinary Pressure. Hitachi Chemical Technical Report, 2014.