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CONCEPTUAL OPERATION AND COST ANALYSIS OF A HIGH ALTITUDE, LONG ENDURANCE AIRBORNE SYSTEM TO PROVIDE INTERNET SERVICE TO DISASTER AREAS

Lukas Deuschle, Edgar Kirchner, Lara Obert, Erwin Aust, Luca Stoll, Niels Marr
Duale Hochschule Baden-Württemberg

Abstract

This paper describes the operational concept of a High Altitude Long Endurance (*HALE*) system used to reestablish internet connectivity under disaster conditions over a large area.
To identify the scope of the system, the causes for the internet outage are determined and researched. By identifying different natural disasters, high-level requirements for the operational system are derived in order to allow operations under the derived disaster conditions. Robustness is identified as the key property of the entire system and is to be achieved on every system level.
After establishing the requirements, the airborne as well as the ground segment is designed. This includes the determination of the operating altitude of the *HALE* with respect to various influences, such as area coverage, flight performance, the jet stream as well as air traffic.
The operational base is defined, including equipment and stock for operation under disaster conditions, such as a sufficient fuel supply and power generation capacity. A responsive operational procedure is proposed. The required number of personnel and qualifications as well as the time intervals for maintenance of the aircraft are determined. Based on these data, the response time of the system for continuous and time critical operation is determined.
Costs for personnel, fuel, production and fixed expenses are approximated, based on the design mission.
Within the scope of this paper, the performance of the system as well as the operational limits are analyzed and discussed. As a future outlook, applications aside from reestablishing internet connectivity are investigated.
This preliminary system design was conducted as part of the *2023 DLR Design Challenge*, a yearly competition among teams of students, organized by the *German Center for Aerospace Research*. The basis for this paper is the proposed *Sentinel*-system by the team of the *DHBW Ravensburg*. The operational aspects of the *Sentinel* system are the main focus of this paper and are further expanded upon.

Keywords
Conceptual Aircraft Design Securing Communication in Crises; DLR Design Challenge 2023

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1. MOTIVATION

The air transport sector is facing enormous economic and environmental challenges in the coming years, among other factors due to climate change.They require innovative and sustainable solutions and approaches in order to drive value for society.

2. TASK OVERVIEW

Communication via internet and mobile networks has become an inevitable part of modern life. Especially in times of crises and disasters, continuously functioning communication pathways are crucial, as they facilitate the execution of aid and rescue missions. However, ground-based internet infrastructure can be destroyed in the event of a disaster, rendering this communication method unavailable in a critical situation.
Two remarkable cases to emphasize the statement are presented:

The Ahrtal-flood

An example of the devastating impact of a natural disaster on communication infrastructure is the 2021 flooding of the Ahrtal in Germany. As a result of the flooding, many cell phone towers responsible for the affected communities have been destroyed or rendered inoperable. As a result, both internet connectivity as well as phone service was greatly hampered. Not only where emergency calls to rescue services very unreliable, but coordination of the relief effort was disorganized, as communication links into and out of the disaster area, relying on internet connectivity, were broken [1].

Power outage in Texas

Another proving example of the problem at hand is the blackout in Texas in 2021. Due to an unexpected cold snap in the state, a rolling power outage took almost 35% of the state's population off-grid during the worst period.
As a result of a large-scale power outage and internet connectivity over large areas can be lost. This poses major challenges for the daily life of the population, as applications like online-banking or remote-work are impossible [2].
The two case studies give an indication of the causes of internet outages as well as the extent of the impact.

For this reason, this year's Design Challenge states the task to design an aircraft system to restore internet connectivity over a large-scale area for an extended period of time. In addition to securing this communication pathway, the aircraft should also be able to rapidly enable a situational overview of a disaster-stricken area. The requirements for operational efficiency and quick readiness in times of disaster must be combined into one aircraft system. The exemplary emergency scenario that serves as the basis for the design can be divided into two phases. In the first phase, a widespread and long-term communication and internet outage affecting the states of Hamburg and Schleswig-Holstein has occured. The goal is to restore internet connectivity as fast as possible. In the second phase, there is an additional local and time-critical disaster scenario which requires reaching an area located $170NM$ away in less than two hours, along with internet restoration and situational monitoring.

3. PARTICIPANTS & RESULTS

The field of participants in this year's DLR Design Challenge consists of five different teams and a total of 25 students. The following universities are represented: RWTH Aachen, TU Dresden, DHBW Ravensburg, University of Stuttgart and Trier University of Applied Sciences. The submitted designs feature a wide variety of aerodynamic configurations and propulsion concepts. Further information on the designs can be found in the press release [3]. Concept *Sentinel* is presented in detail below.

4. INTRODUCTION TO THE OPERATIONAL SYSTEM

Although the airborne segment and its payload are the end product and service provider of an *High-Altitude, Long Endurance* (HALE) system, the ground segment as well as the corresponding operational procedures are essential to enable smooth operation.
This applies to all kinds of subsystems as well as infrastructure and needs to be considered for the described *HALE* system, as the aircraft in itself is unable to achieve the goals given during the *2023 DLR Design Challenge*.
The following paper discusses the disasters which shape the design process as well as operational limits of the developed system including the maintenance requirements. A discussion of the system cost, the operational procedures as well as the ground segment are described.

5. DESIGN-CONSTRAINING DISASTER

As the disaster, which originally caused this internet outage in the first place might still be present, the *Sentinel* system needs to operate under a variety of unfavorable weather conditions to reestablish internet connectivity as quick as possible.
In order to define the worst-case weather conditions which may be encountered by the *Sentinel* system, multiple scenarios that lead to the widespread destruction of communication infrastructure are investigated:

- Flooding has damaged cellphone towers or has disabled the electrical grid, as happened in the Ahrtal
- Intense rain or snowfall has led to destruction of primary and secondary communication infrastructure, as was the case during the *2021 Texas Power* Outage
- A storm has disabled ground-based infrastructure
- A solar storm has disabled the space-segment of modern communication infrastructure

The following *General Design Principle* as well as a set of additional requirements is derived:

General Design Principle
Robustness is the top priority of the *Sentinel* system, being both relevant for the ground station as well as the aircraft itself. Performance sacrifices are acceptable if a great increase in system robustness can be achieved in return.
The ground station needs to be able to operate self-sufficiently for extended periods of time and needs to hold a large supply of fuel and spare parts in stock. The aircraft design process mainly needs to take the flight physics aspect due to high winds into account as well as ease of maintenance and operations.

a	**The *Sentinel* system needs to be able to operate:**
1	With an unstable or disabled electrical grid
2	During adverse weather conditions such as strong winds
3	Mostly independent from external infrastructure
4	When spare parts as well as certain exotic fuel types might be unavailable
5	Without satellite navigation, enabled by satellite networks such as GPS or Galileo. As a solar storm is identified as a potential threat to communication satellites, it has to be assumed that it poses the same threat to navigation satellites as well.
6	With a minimized personnel present at the operational base as to the increased risk for the employees

TAB 1. Sentinel system high level requirements

6. AIRBORNE SEGMENT

6.1. Payload definition

The following payload is to be carried on board of each *Sentinel* aircraft. The properties of the individual modules are defined by the *DLR*. However, the number and positioning of each component is part of the design space.

Component	Amount	Tot. mass	Tot. Power
Internet relais	7	$35kg$	$3500W$
Radar module	1	$5kg$	$450W$
Internet antenna	1	$1kg$	$0W$
Comm antenna	1	$2kg$	$0W$
Sum		**43kg**	**3950W**

TAB 2. Payload of the *Sentinel* aircraft

6.2. Fleet concept

As the entire area of Schleswig-Holstein and Hamburg is to be covered continuously, multiple aircraft need to be in operation simultaneously. The number of aircraft is mainly determined by the operational altitude as well as the *Field of View* (FoV) of the internet relais. Furthermore, a time of 48 hours is set for continuous operation, because of the long-lasting impact on victims of natural disasters according to chapter 1.

6.3. Operating altitude

For reconnecting the area of Schleswig-Holstein and Hamburg, an area of $16000km^2$ needs to be covered. Based on the antenna beam angle of $45°$, the operational altitude of the aircraft during the mission is thus decisive. For this reason, a decision on the aircraft's flight altitude must be made to be able to consider operational and economic factors in the concept of the Sentinel based on this decision. Therefore, table 3 presents a matrix designed to evaluate the concepts of different flight altitudes.

Criterion	5000m	10000m	18000m
Number of aircraft	- -	-	+
Jet Stream	-	-	+
Air traffic	- -	-	++
Cost	+	-	-
Robustness	++	0	-
Ease of maintenance	+	0	0

TAB 3. Decision matrix of operating altitude

6.4. The *Sentinel* aircraft

Design parameter	Value
Operational altitude	$18000m$
Time of flight	50 hours
Cruise velocity	$74\frac{m}{s} - 93\frac{m}{s}$
Mission design mass	$993kg$
Empty mass	$550kg$
Fuel mass	$400kg$
Mission payload mass	$43kg$
Wingspan	$17.32m$
Length	$7.382m$
Height	$2.531m$
Engine	*Rotax-914UL, tri-charged*
Fuel type	*SAF-AvGas*
Primary navigation	*Radar-guidance*
Backup navigation	*Inertial guidance*

TAB 4. *Sentinel* aircraft technical specifications [4]

As by chapter 6.2 and 6.3, the loitering time and altitude are selected as **18000m** and **48 hours**

6.5. Guidance & Navigation

As the disaster case of of a solar storm is considered as a potential hazard to space-based communication infrastructure, navigation satellite networks, such as *GPS* or *Galileo* cannot be relied upon to enable navigation by *Global Navigation System Satellites* (GNSS). Therefore, alternative navigation methods are required.

6.5.1. Navigation

Primary navigation is to be achieved by radar, positioned at the operational base or other locations in the disaster areas. The determined radar vector is send to the aircraft to update the state vector.
In case of a radar failure or a descent below the radar horizon, navigation is to be switched to inertial guidance to propagate the state vector [4].

6.5.2. Guidance

In order to determine orientation, both in relation to the air stream as well as to the local surface of the earth, the typical aerodynamic sensor package of angle-of attack sensors and pitot tubes is to be carried.
In order to determine spacial orientation, an attitude determination platform, utilizing the local magnetic field vector as well as the gravity vector is to be incorporated [4].

7. OPERATIONAL PROCEDURES

During the following chapters, procedures, plans and infrastructure are defined in order to fully utilize the potential of the *Sentinel* system.

7.1. Continuous operation

As explained in chapter 6.2, the *Sentinel* aircraft fleet has to cover the area of Schleswig-Holstein and Hamburg continuously. To enable smooth operation, a standardized pre-flight procedure as well as a maintenance concept for application during the ongoing mission is been outlined.

7.1.1. Preflight procedure

The basic pre-flight concept was developed within the scope of the *DLR Design Challenge 2023* [4].

This pre-flight procedure is essential to deploy all aircraft as quickly as possible during a crisis situation. For that reason, the following staff is required:

- Incoming order: Aerospace Engineer
- Clear out hangar: Logistician, Aircraft mechanics
- Refueling: Truck driver, Aircraft mechanics
- Assembling aircraft: Aerospace Engineer, Aircraft mechanics
- Visual inspection: Aerospace Engineer, Aircraft mechanics
- System take-over: System Engineers
- Rolling procedure: System Engineers
- Takeoff procedure: System Engineers

After the pre-flight procedure is completed the management of the ongoing flight mission starts. For that reason, it is important to clarify how long the aircraft must stay airborne to simulate the maintenance demand of all aircraft.

7.1.2. Design mission

The coverage of a large area like Schleswig-Holstein and Hamburg during continuous operation presents a great logistical challenge. The maintenance intervals of the *Rotax 914 UL* engine of the *Sentinel* aircraft are of particular influence. The manufacturer's exact maintenance specifications are shown schematically in the table below.

Control	25 h	100 h	200 h	300 h	2000 h
100 h	X	X	X	X	X
200 h			X		
600 h					

TAB 5. Excerpt from the maintenance instructions of the Rotax 914 UL [5]

It is specified that after a one-time inspection after the first 25 hours of operation, each engine must be routinely serviced every additional 100 hours of operation. This maintenance is subject to a deviation of $\pm 10\%$. As can be seen from the table, the manufacturer requires the motors to be subjected to more detailed checks every 200 and 600 hours. For this reason, these controls are not discussed in detail in the following remarks on maintenance during continuous flight operations, since maintenance times are difficult to estimate. In addition, it should be noted that, according to the manufacturer, the time between overhauls of *Rotax* engines is 2000 hours of use or 15 years, depending on which scenario occurs first [5].

With this information, the aircraft mechanics of *Sentinel* have a time slot of 20 hours from the 90th up to the 110th operating hour to complete the maintenance checklist of *Rotax* to provide a safe flight operation with the *Rotax* 914 UL piston engine.
Furthermore, to develop a structural maintenance system, it is assumed that one aircraft mechanic needs two hours to complete the check of one piston engine. Based on the operational area of Schlewsig-Holstein and Hamburg and the required number of aircraft, the maintenance procedure as depicted in figure 1 is defined.
The outlined maintenance procedure enables a continuous coverage of 96%, exceeding the minimum requirement of 80%.
Due to the fact that a total coverage of the area needs 25 aircraft present at the operational altitude of $18km$ above main sea level at the end of the maintenance interval at the 110th hour, there will be five aircraft grounded at the same time while four of the aircraft are used as spares. From an economic point of view, it should be noted that the hiring of additional aircraft mechanics is required to enable 100% coverage. However, 100% coverage of the operational area is desirable in order to

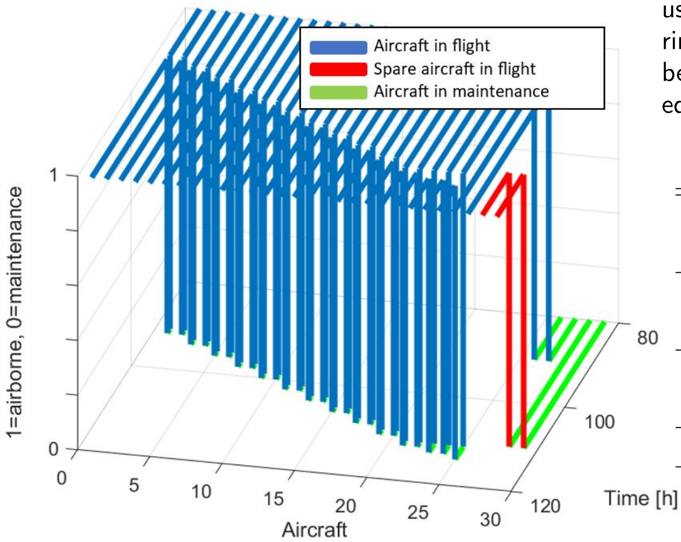

FIGURE 1. Flight mission procedure

provide disaster relief, which is why the design mission strikes a balance between economic and humanitarian interests.

7.2. Time critical operation

In addition to permanently restoring internet connectivity over a large area, a second, smaller scenario needs to be reached within two hours [6].
Internet communications must be restored within two hours during this mission. It will be shown in chapter 7.3 that one *Sentinel* aircraft is needed.
The time to remove the aircraft from the hangar is reduced to approximately 10 minutes. Similarly, the time required for refueling and visual inspection is expected to be 15 minutes. As only one aircraft is required, the assembly of additional aircraft is not necessary. Furthermore, the aircraft's takeoff time after the taxi phase is estimated to be one to two minutes. Therefore, it can be stated that under the same conditions as in continuous operation. In summary during a time-critical flight operation, a Sentinel aircraft is ready for deployment in less than an hour and the coverage of a smaller area such as Hamburg can be realized on a permanent basis.

7.3. Area coverage

At the loitering altitude of $18km$, the FoV of the internet antenna allows to cover an area of $1017km^2$. Aside from Hamburg, one relais module provides sufficient bandwidth to deal with the population density of the respective area. To cover Hamburg, seven relais modules are required [4].
An Internet relay on the Sentinel aircraft has a bandwidth of 30 Gbps, while for the mission it is assumed that the average person needs 0.1 Mbps to communicate on the Internet [6]. Thus, using all Internet relays simultaneously and providing $1017\ km^2$ of coverage per aircraft, a population density of 2360 people per km^2 can be provided with Internet.
By covering such a population density, it is possible to use only one aircraft at a time for Internet recovery during time-critical operations above large cities. The table below lists the Internet coverage characteristics of a fully equipped *Sentinel* aircraft.

Criterion	Characteristics
Bandwidth of one Internet relay module	$30\ Gbps$
Average Internet consumption of one person	$0.1\ Mbps$
Area coverage of one *Sentinel* aircraft	$1017\ km^2$
Maximum population density	$2360\ people/km^2$

TAB 6. Characteristics of Internet coverage

7.4. Modular structure

It is paramount to guarantee full system capability over extended periods of operation. For that reason, in similar fashion to many gliders, *Sentinel* is designed as a modular system with regards to the fuselage and the wings. Advantages to this construction are the easy maintenance, transport and the quick replacement of damaged parts. The disadvantages to this construction method are the difficult construction and the complex wing attachment structure which requires pre-flight inspection.

8. OPERATIONAL CONDITIONS

In order to delve further into the concept for the base and aircraft, it is imperative to scrutinize the conditions during the aircraft's deployment, drawing insights from the design-constraining disasters and the operational procedures. These conditions manifest differently depending on the various considered catastrophes.

8.1. Takeoff distance & wind considerations

First, the runway of the aircraft needs to be considered. The optimal runway was calculated using the formula 1. The rolling resistance of the aircraft is not accounted for during the optimal case.

$$\ddot{x} = \frac{F_{prop} - \dot{x}^2 \cdot S \cdot C_W \cdot \rho \cdot 0.5}{m} \quad (1)$$

It is determined which length of runway would be required if take-off is to take place on a grass runway under various weather conditions. The used factors are retrieved from source [7] to calculate the results in table 7.
These values do not take wind during take-off into account. Assuming there is a head wind, the runway will shorten and *Sentinel* can take off even quicker. However, the aircraft is not always hit head-on, which means that a sine and cosine component of the wind must be considered. The cross-wind component is counteracted by a regulator to guarantee yaw and roll stability.

Runway condition	Length
Optimal	$260m$
Firm, level grass track with short vegetation	$312m$
Wet grass, softened ground, damaged turf, high grass cover (max. 8 cm), standing water, large puddles, slush	$744m$
Wet grass soil, softened subsoil, damaged turf, high grass cover (max. 8 cm), wet snow	$858m$

TAB 7. Takeoff run under various vegetation conditions

When considering the wind, gust loads must also be considered. Gust loads are caused by turbulence in the atmosphere. In this, discrete gusts can occur. This is a sharp increase in velocity limited by a specific space. As a result, the inflow is significantly changing, which leads to a rise and fall of the influencing air forces. Therefore, the effects of gust loads, when reaching the operating height, on the *Sentinel*-aircraft are analyzed below. For horizontal and vertical gusts, the following assumptions must be made:

- a horizontal or vertical gust field with constant velocity
- a gust speed against the direction of flight

The following values were used for the calculation according to [8]:

Design parameter	Value
Mass	$970kg$
Maximum cruising velocity	$93\frac{m}{s}$
Lift coefficient for maximum cruising velocity	1.3946
Design wing area	$20m^2$
Mean chord	$1.154m$
Slope of C_A per degree	$6.8\frac{1}{rad}$
Limit load factor	2
Ultimate load factor	3
Acceleration of gravity	$9.81\frac{m}{s^2}$
Air density	$0.12\frac{Kg}{m^3}$

TAB 8. Design parameters for gust loads

This results in the following gust loads:

Load factor	Horizontal gust
Limit load factor $2g$	$\approx 30\frac{m}{s}$
Ultimate load factor $3g$	$\approx 61\frac{m}{s}$

TAB 9. Gust loads for *Sentinel*

These values are higher than the required gust envelope in the CS-23 [9]. This means that, unlike an aircraft of a similar design, *Sentinel* can withstand stronger gusts. This qualifies the system to operate in strong head-winds, giving the system an edge on the market.

8.2. Temperature and deicing

Another important environmental variable for the *Sentinel*-aircraft is to be able to fly in all temperatures. Due to the high operational altitude, the temperature drops as low as $216.5K$. When breaking down the operating temperatures for critical components, it is determined that additional heat must be provided to certain parts.
Ice formation has to be avoided due to the following reasons [8]:

- Changes in the shape of airfoil and airflow
- Increasing weight
- Maneuverability due to blocking of the control and trim surfaces
- Reduced propeller efficiency due to out-of-round propeller
- Detached ice from the propeller destroying other components

For these reasons, the *Sentinel*-System uses a pneumatic boot deicing system. This involves mechanically inflating and deflating rubber mats at a certain interval. This causes the ice to lose its adhesion to the surface and is transported by the airflow. The advantages of this system are that it requires little energy, is lightweight and cost-effective. However, it must be noted that although a vacuum source is used, the air resistance is slightly increased. The pneumatic boot deicing system is to be monitored by electronic detection, where a probe in the free air stream measures frequency changes due to icing. Other systems, such as hot air systems or fluid ice protection systems, are disqualified for the *Sentinel*-system due to high energy consumption or weight.

9. OPERATIONAL BASE

For all these diverse utilization scenarios, but particularly for providing internet connectivity in the event of a catastrophic failure, the establishment of an operational base is essential. From this base, the deployment and monitoring of the aircraft can be organized. Additionally, the base provides space for storage and maintenance facilities.

9.1. Facilities at the operational base

The operational base is to be located at the airfield Rendsburg-Schachtholm. This location is ideal for the missions because it is close to larger cities like Kiel, ensuring a reliable fuel and parts supply. Furthermore, the airfield has the necessary infrastructure of fuel depots and hangars. Additionally, the airfield features a 960-meter asphalt and a 600-meter grass runway with nearly a north-south and east-west direction [10]. Because of this, the aircraft can take off and land against the wind nearly at any time. These runways can reduce the required landing and takeoff distance as well as the crosswind components to which the aircraft is exposed. Thus, the safety during take-off and landing of the *Sentinel* system can be increased. More detailed information on the deployment limits especially during

the start-up phase is described in chapter 8.
In addition, Rendsburg-Schachtholm has many hangars that could be used for *Sentinel* aircraft [10]. For aircraft maintenance during sustained flight operations, it is envisioned that the *Rotax* engine maintenance will be performed on an operational basis to provide time-efficient aircraft maintenance. For light maintenance work due to the mentioned circumstance, a hangar is converted into a workshop for simple maintenance work. Therefore, the facility is able to perform all checks within the base and only in case of serious accidents send the aircraft to the manufacturer.

9.2. Equipment

To ensure safe flight and rapid operational capability of the Sentinel system, the right equipment is required at the operational base. The technical equipment includes:
- Forklift
- Trollies
- Trucks
- Fuel bunker
- Emergency generator

The equipment performs several functions on an operational basis. The forklift and trollies are necessary for taxiing aircraft in and out of the base hangar. Furthermore, this concept operates space-saving, because all aircraft stand sideways in the hangar. A suitable trolley is shown in figure 2. The trucks and fuel bunker are used to supply fuel to the base in crisis situations before and during flight operations and to transport aircraft. According to chapter 7.1 and 10.3 for a two-day flight operation above Schleswig-Holstein and Hamburg, it is necessary to provide 11800 liters of AvGas.

FIGURE 2. Trolley [11]

In order to have such a quantity of fuel permanently on hand the operational base contains a tanker truck that can procure the required fuel in the vicinity of the crisis area by the truck driver before and during the missions. The fuel bunker is dimensioned in such a way that a flight mission is always possible with a reserve of 1000 liters for other uses. Similarly, the truck driver is responsible for delivering and removing aircraft that cannot be serviced on-site at the shop for light maintenance. In addition, a truck for transporting aircraft can ensure that additional aircraft can be brought to the operational base in the event of a potential expansion of the operational area.
Furthermore, the emergency generators of the operational base should be noted, due to the aim of the *Sentinel* system to operate self-sufficiently on the base. To ensure an electricity supply on a permanent basis even in crisis situations and to operate in an equally environmentally friendly manner, solar and wind-powered generators are preferably used. Only if the operation of these is denied due to local weather conditions, a diesel generator is used. In this case, as described above 1000 liters of AvGas are reserved in the fuel tank.
To summarize, the equipment guarantees smooth flight operations within crisis areas. Particular attention is paid to ensuring that the equipment is as simple and intuitive to use as possible so that especially during time-critical operations every employee can physically help to ensure that the Sentinel aircraft are quickly ready for operation.

10. ESTIMATION OF COSTS

Based on the requirements for the aircraft and the operational base, a preliminary cost analysis is conducted. The cost to provide safe operations of the *Sentinel* system is divided up into the following sectors:

- Annual salary of the employees
- Fixed costs to provide the function of the ground segment
- Fuel costs
- Costs of manufacturing the aircraft and acquiring spare parts

10.1. Annual salary expenses

As a point of orientation a 40-hour working week according to the IG-Metall collective wage agreement is assumed for calculation purposes. [12] These salary structures are an estimate of the variable hourly rates that an employer pays for an employee. Furthermore, in the following calculations, a rise in the salary of the employees is not considered. For the year 2023, following annual salaries are determined:

Responsible	Hourly wage €/h	Staff size
Aircraft mechanic	70	2
Logistician	70	1
Systems engineer	120	5
Aerospace Engineer	120	1
Truck driver	50	1
Annual salary	2038400 €/y	10

TAB 10. Anual salary of employees

It is considered that for the commissioning of the *Sentinel* system in 2040, the salaries of all employees have increased based on inflation. For that reason, the median of the inflation in Germany by year 1992 to 2023 is determined. With that information, the growth rate of the annual salary of all employees is modeled. By assuming an inflation of nearly 2% per year as a growth factor, annual salary expenses are expected to be 2865367€ per year.

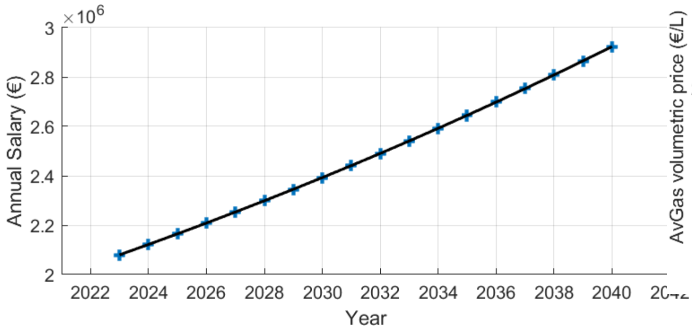

FIGURE 3. Growth function of annual salary

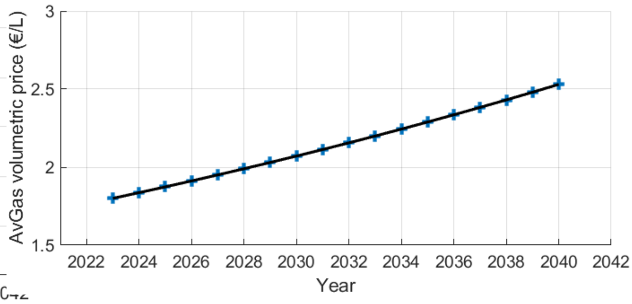

FIGURE 4. Growth function AvGas price per liter

10.2. Fixed costs

To provide an adequate ground segment, major expenses are expected for the operational base. Besides all the fixed costs listed below it is assumed that the rent of the operational base is €5000 per month. Table 11 represents all fixed costs for equipment and aircraft manufacturing required for the *Sentinel* system to cover the area of Schleswig-Holstein and Hamburg at the same time.

Equipment	Unit price [€]	Amount
Forklift	100000	1
Truck	150000	2
Sentinel aircraft, at a production run of 29 units	3300000	29

TAB 11. Unit price

As described, *Sentinel* systems need a forklift for the transport of the aircraft while being on the trolley for putting in or out of the hangar. Furthermore, there is a need for two trucks to provide fuel and heavy maintenance transportation.

10.3. Fuel expenses

With the concept of using the piston engine *Rotax 914 UL*, *Sentinel* has the advantage of being operable on a variety of different fuel types. As a primary propellant, a supply of a *Sustainable Aviation Fuel* alternative of *AvGas* is to be held in stock. However, should the supply run out during disaster conditions, conventional AvGas or even high-octane gasoline may be substituted.
From an economic perspective, it is important to consider the growth of the fuel price. Therefore, table 4 presents the fuel price for the year 2040 by using the median of the inflation of nearly two percent in the Federal Republic of Germany between 1992 and 2023 as a growth factor [13]. As is evident, the fuel price is expected to reach €2,5 per liter by 2040. The cost of a two-day mission with 27 aircraft accounting for the AvGas prices of 2023 and 2040 is shown in table 12.

Parameter	Value
Cost per liter (2023)	$1,8$ €/L
Fuel quantity per mission	11800 L
Mission fuel cost (2023)	21240 €
Mission fuel cost (2040)	29857 €

TAB 12. Fuel price in a two-days-mission

10.4. Manufacturing costs

The manufacturing costs, including *engineering, tooling, quality control, material*, and *engine costs* account for a significant part of the fixed costs of the *Sentinel* System. For that reason, a cost estimation algorithm, the *Eastlake* model is utilized for calculating unit prices, using basic aerodynamic data. Due to the early stage of development of the *Sentinel* system, the cost estimate of aircraft manufacturing is based on a variant presented by *Eastlake*. This method, based on the technical data of other aircraft in military use, allows to place the cost of *Sentinel* in relation to other airborne systems.
The *Eastlake* model with the following assumptions is applied to obtain a unit cost estimate. The obtained amount already includes a profit margin of 10% and insurance costs of 15%. Assuming an IG-Metall salary and a manufacturing rate of one aircraft per month, the data depicted in figure 5 is obtained showing the unit cost as a function of the total production run [14], [15]:

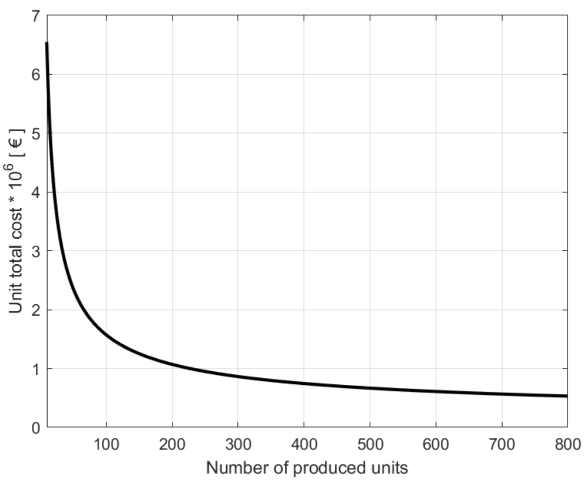

FIGURE 5. Unit price per aircraft

As at least 29 aircraft are required to enable full operation of the *Sentinel* system above Schleswig-Holstein and

Hamburg as described in chapter 7.1, the maximum unit price is 3.3 Million €, as by figure 5. If additional aircraft are produced, for exampled for other operational areas or alternative applications, the unit price may be reduced further.
For that reason, with rising units the manufacturing of the *Sentinel* System becomes more and more economically profitable. Including the alternative applications in chapter 11, it can be assumed that there will be more than 29 aircraft produced.

11. ALTERNATIVE APPLICATIONS

Although disaster relief is an essential service to the population, disaster cases on the scale as described above are rare. Therefore, it should be avoided that the aircraft of the *Sentinel*-system remain on the ground without one of the mentioned disaster scenarios. Therefore, various use cases are considered and their compatibility with *Sentinel* analyzed. An advantage is the possible modular exchange of the payload of the main mission [7]. Conceivable alternative use cases would be:

11.1. Wildfire detection

By using an infrared heat sensor that can measure the earth's temperature, a warning system can be established for wildfires. By utilizing communication hardware on board the aircraft, affected people can be contacted by push-up messages on their mobile device. As an advantage of the *Sentinel* system, it should be added that the relatively low operational costs and the ability to fly in adverse weather conditions make it possible to operate continuously over areas at risk for wildfires worldwide.

11.2. Reconnaissance

By incorporating high-resolution cameras and thermal imaging systems, *Sentinel* can gather visual and thermal information from the air. This enables the drone to be utilized as a reconnaissance drone for both commercial and military purposes. It holds significance for scenarios such as disaster relief, search and rescue operations, as well as military applications like reconnaissance, target tracking, and activity monitoring. Through communication systems, the collected data can be immediately transmitted to the operational base and analyzed. This empowers response teams to swiftly receive information and act promptly as needed.

11.3. Weather Observation

By utilizing sensor systems for weather observation, *Sentinel* may be used to gather data about various weather conditions. During hazardous weather situations like severe storms, hurricanes or tornadoes, the use of a drone for data collection would eliminate the risk to human life. Moreover, the Sentinel system is designed to withstand harsh weather conditions without sustaining damage. Therefore, *Sentinel* is exceptionally well-suited for this task [16].

11.4. Agriculture and Forestry

A further potential application area would be agriculture and forestry. Through camera and GPS systems, location data can be collected for use in agriculture. This includes identifying issues such as pest infestations, diseases, or nutrient deficiencies. Thus, precise data about the condition of agricultural areas can be used to implement specific measures for the preservation and enhancement of these lands. This enables resource savings. Additionally, *Sentinel* can be utilized for accurate mapping and recording of large areas without the need to send humans into these regions [17].

11.5. Construction sector

The use of *Sentinel* in the construction industry allows for precise surveying and reconnaissance of construction sites through mapping devices. Additionally, 3D modeling of an area would be achievable. This offers the added benefit of inspecting infrastructure damages or damages to buildings, especially tall structures like towers, skyscrapers, or wind turbines [18].

There are still many other possibilities for the application of *Sentinel*. With advanced technology, additional use cases for drones, and consequently for *Sentinel* as well, continue to emerge.

12. CONCLUSION

After the operational procedures, the operational base as well as a preliminary cost analysis has been conducted, the fulfillment of the high-level requirements is to be examined.

1) As described in chapter 9.2, the fuel bunker with AvGas and the tanker truck allow to operate the *Sentinel*-system for extended periods of time.
   To provide power to the operational base in case of an electric grid failure, a solar and wind powered emergency generator is used. These two aspects make it possible to operate *Sentinel* with an unstable or disabled electrical grid.
2) Chapter 8 shows that *Sentinel* can operate in strong head-winds with respect to comparable aircraft. Deicing strategies are presented.
3) In the hangar, light maintenance work can be conducted, to enable quick repairs. Furthermore, if no runway is available, it is possible to take off on a grass runway.
4) With the option to use multiple fuel types for the engine, fuel availability is guaranteed everywhere. The modular structure, which is described in chapter 7.4 supports easy maintenance, simplified transportation and quick replacement of spare parts. A supply of spare parts is to be held at the operational base [4].
5) Building upon the navigation description provided in Chapter 6.5, it is feasible to navigate without relying on GNSS systems. An INS system allows for the execution of a safe emergency landing even in the event of a loss of communication between the base and the aircraft.

6) To ensure that as few people as possible have to work in the crisis area, the number of employees is kept low at 10, including aircraft mechanics, logisticians, system and aerospace engineers, as well as truck drivers.

In summary, the overall Sentinel system meets the requirements of the scenarios according to the design-constraining disasters. *Sentinel* is capable of providing internet connectivity to the population during disasters like the Ahrtal flooding or the Texas Blackout. This can alleviate the impact on affected individuals while also enabling secure communication channels for emergency responders. While *Sentinel* cannot prevent disasters, it can simplify their management and response. It should not be forgotten that the system can be used in many other applications under none-disaster conditions. On top of that, the minimized manufacturing costs make the *Sentinel* system competitive on the market. The interaction between a reliable and efficient ground segment and a robust aircraft guarantees assistance in any situation.

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