Conceptual Design of a High-altitude Solar-powered UAV

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Abstract. *This paper describes a multi-disciplinary design and optimization task undertaken for the conceptual design of a high-altitude solar-powered unmanned aerial vehicle (UAV). A study on existing configuration outselect the Zephyr developed by UK based QinetiQ as baseline configuration. The disciplines of aerodynamics, structures, stability, weight, and systems are considered and integrated in a workflow, capable of providing an initial simplified sizing, but highly realistic.*

Keywords*: aircraft design, solar enregy, multi-disciplinary design and optimization, unmanned air vehicle*

1. INTRODUCTION

The first flight of a solar-powered aircraft took place on November 4, 1974, when the remotely controlled Sunrise I, designed by Robert J. Boucher of AstroFlight, Inc., flew following a launch from a catapult.

Following this event, AeroVironment, Inc. (founded in 1971 by the ultra-light airplane innovator, Dr. Paul MacCready) took on a more ambitious project to design a human-piloted, solar-powered aircraft. The firm initially took the human-powered Gossamer Albatross II and scaled it down to three-quarters of its previous size for solar-powered flight with a human pilot controlling it. This was more easily done because in early 1980 the Gossamer Albatross had participated in a flight research program at NASA Dryden in a program conducted jointly by the Langley and Dryden research centers. Some of the flights were conducted using a small electric motor for power.

The scaled-down aircraft was designated the Gossamer Penguin. It had a 71-foot wingspan compared with the 96-foot span of the Gossamer Albatross. Weighing only 68 pounds without a pilot, it had a low power requirement and thus was an excellent test bed for solar power.

AstroFlight, Inc., of Venice, Calif., provided the power plant for the Gossamer Penguin, an Astro-40 electric motor. Robert Boucher, designer of the Sunrise II, served as a key consultant for both this aircraft and the Solar Challenger. The power source for the initial flights of the Gossamer Penguin consisted of 28 nickel-cadmium batteries, replaced for the solar-powered flights by a panel of 3,920 solar cells capable of producing 541 Watts of power.

The battery-powered flights took place at Shafter Airport near Bakersfield, Calif. Dr. Paul MacCready's son Marshall, who was 13 years old and weighed roughly 80 pounds, served as the initial pilot for these flights to determine the power required to fly the airplane, optimize the airframe/propulsion system, and train the pilot. He made the first flights on April 7, 1980, and made a brief solar-powered flight on May 18.

The official project pilot was Janice Brown, a Bakersfield school teacher who weighed in at slightly less than 45 kg and was a charter pilot with commercial, instrument, and glider ratings. She checked out in the plane at Shafter and made about 40 flights under battery and solar power there. Wind direction, turbulence, convection, temperature and radiation at Shafter in mid-summer proved to be less than ideal for Gossamer Penguin because takeoffs required no crosswind and increases in temperature reduced the power output from the solar cells.

Consequently, the project moved to Dryden in late July, although conditions there also were not ideal. Nevertheless, Janice finished the testing, and on August 7, 1980, she flew a public demonstration of the aircraft at Dryden in which it went roughly 3.14 km in 14 minutes and 21 seconds.

This was significant as the first sustained flight of an aircraft relying solely on direct solar power rather than batteries. It provided the designers with practical experience for developing a more advanced, solar-powered aircraft, since the Gossamer Penguin was fragile and had limited controllability. This necessitated its flying early in the day when there were minimal wind and turbulence levels, but the angle of the sun was also low, requiring a panel for the solar cells that could be tilted toward the sun.

Using the specific conclusions derived from their experience with Gossamer Penguin, the AeroVironment engineers designed Solar Challenger, a piloted, solar-powered aircraft strong enough to handle both long and high flights when encountering normal turbulence.

Figure 1 Manned solar-powered airplanes: at left, the first piloted solar plane, the Gossamer Penguin; at right, Solar Impulse flight on April 7th, 2010

The last big step in aircraft powered by solar energy is the first flight of Solar Impulse on December, 3rd 2009. Solar Impulse is a European long-range solar powered plane project currently being undertaken at the École Polytechnique Fédérale de Lausanne. The project is promoted by Bertrand Piccard, who piloted the first balloon to circle the world non-stop. This project hopes to repeat that feat using only solar power. The first aircraft, officially named HB-SIA, is a one-seater, capable of taking off under its own power, and intended to remain airborne up to 36 hours. Building on the experience of this prototype, a slightly larger follow-on design (HB-SIB) is planned to make circumnavigation of the globe in 20–25 days. On 7th April, 2010 the HB-SIA underwent an extended 87 min test flight (Figure 1). In contrast to earlier tests, the April flight reached an altitude of 1,200 m (3,937 ft). A night flight is planned for later in 2010.

In recent years, European countries are taking a more central role in the development of High Altitude/Long Endurance (HALE) solar-powered unmanned aerial vehicles (UAVs). Several projects are either ongoing or being planned for advanced solar powered vehicles. From 2000-2003 a team from the Politecnico de Torino in Italy together with a team from the University of York in the U.K developed a concept for the Heliplat - a Very-Long Endurance Solar Powered Autonomous Aircraft (VESPAA). Heliplat and other VESPAA UAVs could play the role of a "pseudo satellite", with the advantages of being closer to the ground, more flexible and at a cost much less than an actual satellite. Heliplat-like HALE flying above a major city will be able to cover an area 1000 km across, and process a predicted 425,000 cell phone conversations simultaneously. This means a user community of 8.5 million per unit (although this does not take into account data transmission).

The UAV platform of major interest of the present work is that capable to reach stratospheric altitudes and powered by solar energy (HALE concept). In this context, the Zephyr, developed by UK based QinetiQ is a configuration that is very close to that intended by the authors: small payload without need of sophisticated assisted takeoff systems or prepared airfields. The airplane is a lightweight airplane that uses a combination of a solar array and batteries to power its flights. The plane weights a relatively low 31 kg and has a wingspan of about 18 meters. In 2008, the airplane registered a recorded flight remaining airborne for a total of 82 hours and 37 minutes, which is a very impressive number for a solar powered vehicle. The Zephyr went for two straight nights without stopping or refueling relying on its solar powered batteries for flying. It made it all the way up to 18 km (58,000 ft). Applications for Zephyr include earth observation and communication relay. Some highlights of Zephyr configuration

- Zephyr's lightweight structure allows it to travel non-stop over long distances.
- The unique propeller design gives the aircraft a high power to weight ratio.
- The wing design maximizes on thermal air currents to lift the aircraft to high altitudes.
- The aircraft flies day and night powered by solar energy – recharging its batteries during the day.
- No complicated launching mechanisms - the aircraft is launched by hand.
- Zephyr is environmentally friendly.
- Flies silently – no noise pollution.

Figure 2 QinetiQ's Zephyr during an assisted takeoff (Photo: QinetiQ)

2. METHODOLOGY

2.1 Aircraft systems

Before designing a solar-powered unmanned aerial vehicle it is required the knowledge of how to convert the solar energy into propulsion and how to power for the airplane systems. Usually the wing is an appropriate place to be covered with solar cells, which collect solar radiation and transforms it into electrical energy. Batteries, propulsion and systems operate under different conditions and thus a converter package is necessary. An appliance called Maximum power point Tracking (MPPT) enable the extraction of maximum power of solar cells and supply the aircraft systems. During night, there is considerably less energy from solar cells and battery shall fulfill all power needs. Some modern solar cells are able to convert the infrared radiation into electric power, enabling that the batteries continue to be loaded during dark periods. That was not considered in the present work.

For a complete description of the system it is necessary model the solar radiation and of the systems responsible for his transformation into useful energy.

2.1.1 Solar irradiation model

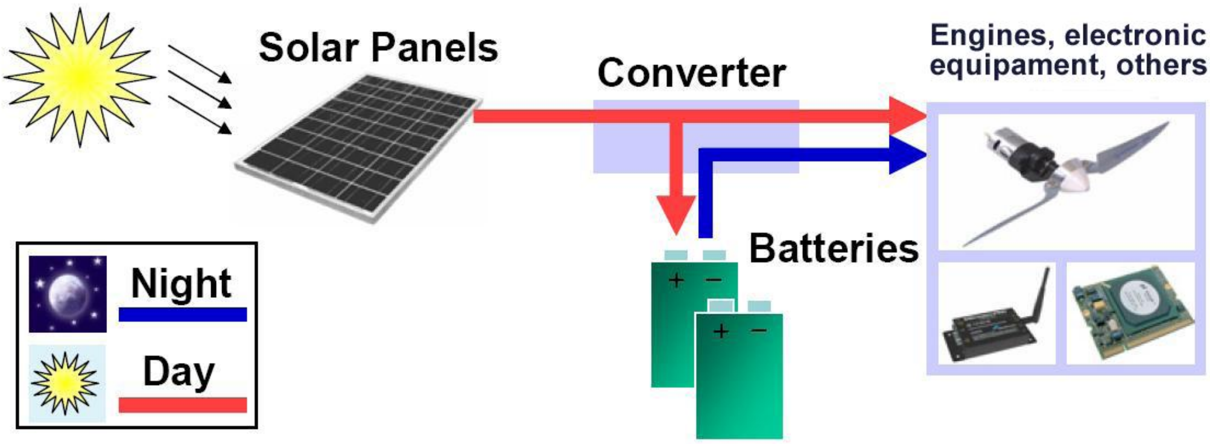

Figure 3 Solar energy conversion system to power engine and other aircraft systems

For the definition of the available radiation for the aircraft, in a determined position, day and hour, it is necessary to understand the relative movement of the Earth around the Sun and of our planet around its axis.

The earth has an elliptical orbit around the Sun, with an average distance of 150 million kilometers. Period of revolution is of 365 days and 4 hours. On January 1st it is registered the nearest distance between our planet and the sun; and on 1st July the remotest position, around 3.3 % longer than that in the closest position. Such points are important for the astronomy and are called a perihelion and aphelion, respectively. Considering that the incident radiation depends on the inverse of the square of the distance, the perihelion receives around 7 % more radiation than the Earth in the aphelion. Another four points also are very important in the astronomy: the autumn and spring equinoxes; and summer and winter solstices (Figure 4).

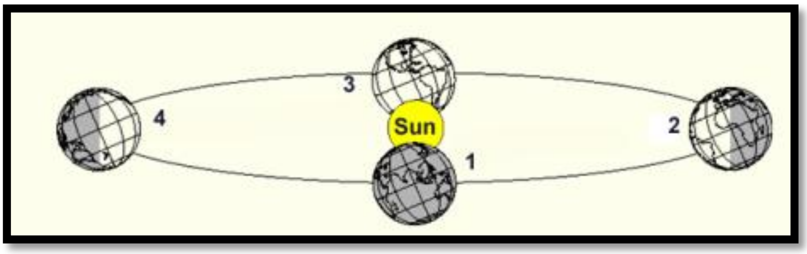

Figure 4 Earth special orbit positions: 1-vernal equinox, 2-summer solstice, 3-autumnal equinox, 4-winter solstice

It can be affirmed that the aphelion and the perihelion are the days of radiation more and less intense, respectively. The summer and winter solstices are the longer and shortest time exposed to solar radiation. Being conservative, it is considered that the aircraft should able to fly in any condition and so the point of project is the critical day of the year, in which it receives the least radiation along the day.

The solar irradiance models found in the literature are based on data collected in the northern hemisphere, mainly in the United States and Europe. For the present work the model R.SUN was employed. This sophisticated model was distributed by the Photovoltaic Geographical Information System (PVGIS) of the European Union. PGVIS provides online interactive maps of photovoltaic potentials in Europe and Africa. Figure 5 shows such a map considering the yearly sum of solar electricity generated by 1 kWp system with optimally-inclined modules. R.SUN was developed for the European and Africa environment and it is able to predict the direct and diffuse irradiation and that reflected by the Earth's surface. This last part of the solar irradiation is not taken into account in the present work since the solar panels are located on the wing upper side of our solar-powered UAV.

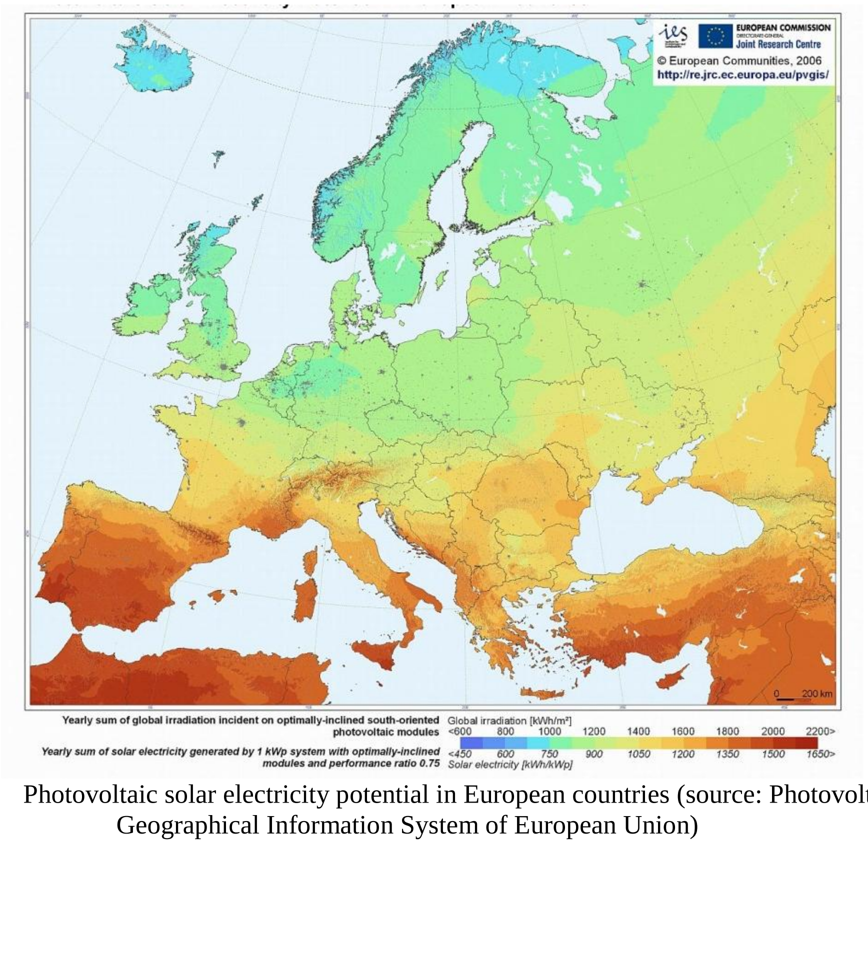

Figure 5 Photovoltaic solar electricity potential in European countries (source: Photovoltaic Geographical Information System of European Union)

R.SUN is able to estimate the solar irradiation according to latitude, altitude, date and time of the day. In this way, it can be computed the radiation accumulated during an unclouded day. From this estimation, the density of energy per area is shown in Figure 6.

Figure 6 Yearly variation of accumulated daily radiation

According to the R.SUN model, for an aircraft at latitude of 40º N and flying 16 km above sea level the critical day is December 21st. In this day, the distribution of radiation is given by the Figure 6. The choice of the latitude is due being the reference for the model of radiation and atmospherically, and what, when that the electric demand is provided there, in the intertropical region, where Brazil is located, was secured is also satisfied, since the radiation incident is bigger.

2.1.2 Electrical load

In the preceding paragraphs it was outlined the available power from solar irradiation. At this point, we are now concerned with the electrical power demand for the aircraft.

Power required for the payload package can vary. For this reason, it was considered an electrical demand of 100 and 200 W. Power required for the control systems actuators and is estimated to be 25.5 W. The engine power can be modeled in the following way

$$P = \frac{C_D}{C_L^{1,5}} \sqrt{\frac{(mg)^3}{S} \frac{2}{\rho}} \qquad (1)$$

QinetiQ's Zephyr presents an estimated electrical load of 174 W. This figure occurs close to the stall condition, being necessary to adopt a safety margin.

There are some power losses in the powerplant system that makes the required power to increase. Such losses are caused by the propeller, control box, and gearbox, which present efficiencies of 87, 95, and 95%, respectively. Even considering these losses, the required weight-to-power ratio tops 100 kg/hp. Not only should the stabilized aircraft be considered when estimating the power requirements. There are some critical maneuvers that must be taken into account to define the required power. The aircraft must be able to handle gusts and other related severe conditions. However, in the present work, the approach that was used was based on similar weight-to-power ratios at cruise of some solar-powered planes (Table I). The adopted figure was slightly over that one for Zephyr, of 25 kg/hp.

Table I: Weight to nominal power ratio for some solar powered airplanes.

Airplane	Weight-to-power ratio (kg/hp)
Solar Challenger	60.98
Pathfinder	29.53
Pathfinder plus	23.77
Centurion	27.46
Zephyr (Estimated)	22.37

The average cruise power for electrical driven airplanes lies around 56% of the engine nominal power. Thus, for the Zephyr airplane this represents an increase of 140% and the adopted figure in the present work was of 17.9 kg/hp.

2.1.3 Actuators

German company Volz is the supplier for Zephyr actuators. However, its portfolio is oriented for environment in the -30º to 70º C range but the temperature faced in the tropopause is of -56.5º C. For this reason, it was necessary to develop an experimental and special actuator able to withstand temperatures below -70º C (DA 13-05-EXP 11859).

Figure 7 Selected actuator for the solar-powered UAV under study

Actuators are employed in control surfaces like ailerons, rudder, and elevators. In the airplane under development is configured with no high-lift devices and present no landing gear.

All actuators of the DA-13-05 Volz family have the same size (37,4mm x 34,9mm x 13,3mm), operating voltage (4.8 to 5V), angle (130°), and mass (19 g) but differentiate by available torque, device rotating speed and electrical current (power). Zephyr's actuator is the most advanced and but there is not public data available and therefore we adopted the specification of the do DA 13-05-60 device.

2.1.4 Solar panels

The solar panels are extremely important components, since they are the unique source of energy, except the charged batteries in the first day of operation. The impact of solar panels on the project is unquestionable. Their development was recorded to be slow and always has been a critical bottleneck for this kind of airplane. For example, Pathfinder and Pathfinder Plus were developed with the same characteristics, at the same time and technology, and by the same team, but the difference in service ceiling is about 30,000 ft, thanks to increased efficiency of solar panels.

Several next-generation panels were selected and compared, considering efficiency and weight per area, restricting the analysis to flexible panels. It appears that the weight is not an important variable, because almost all of them are very light, so the efficiency is the factor that will be taken into account. In a conservative way, this study we consider ISA+15 atmosphere conditions, as the efficiency increases with decreasing temperature. As result, the panel with CIGS technology produced by Swiss company Flisom(http://www.flisom.ch) was selected, providing maximum efficiency of 18.8%.

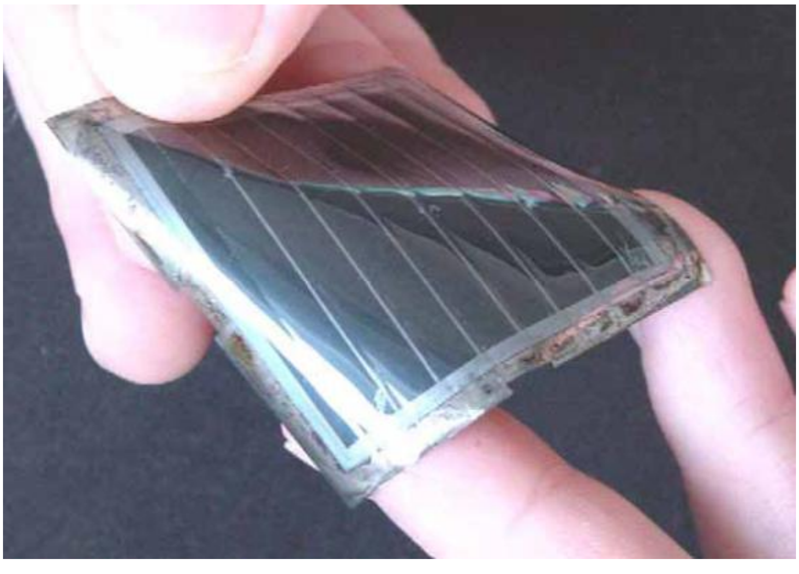

Figure 8 Demonstration of flexibility of a typical next-generation solar panel

2.1.5 Batteries

The most used batteries for portable equipments have lithium in their composition. However, a new generation of batteries based on chemical reaction between lithium and sulfur is available, but technology is not so mature. The advantages are weight and volume reduction for the same charge capacity. Lithium-sulfur batteries made by Sion Power (http://www.sionpower.com/) are very advanced and some versions have specific energy above 265Wh/kg, value adopted in this present study.

2.2 Optimization framework

The optimization task employed the commercial software package modeFrontier 4.0 that is developed by Esteco. Figure 9 displays the workflow created to carry out the optimization studies. MATLAB® was used to perform some sub-tasks like the aerodynamic coefficient calculation and evaluation of stability and control characteristics. The initial population was determined with quasirandom algorithm SOBOL that is ideal for use with the multi-objective genetic algorithm employed in all optimization tasks that were carried out.

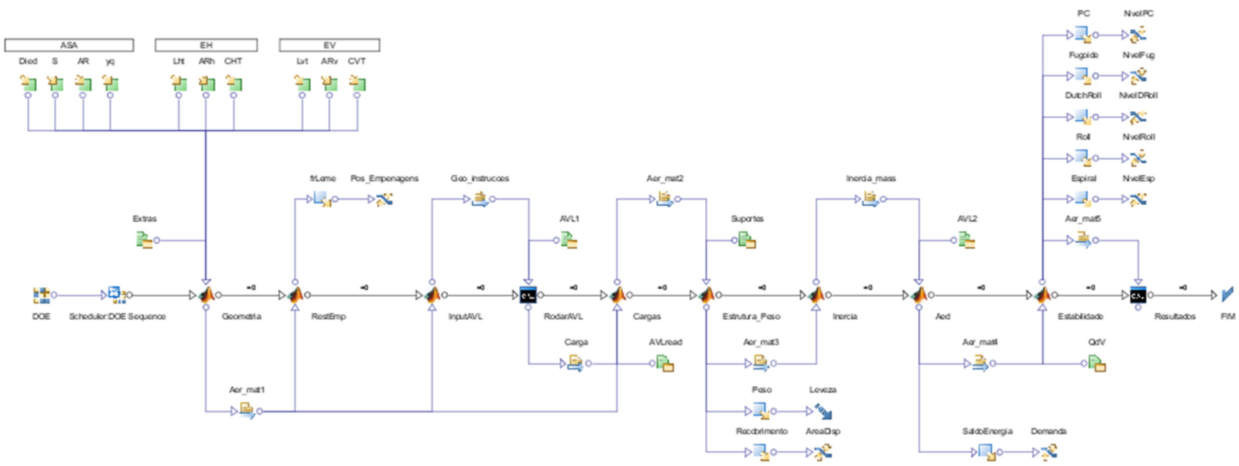

Figure 9 Overview of the modeFrontier workflow for the UAV optimization task

In this study, the configuration chosen was similar to Qinetiq Zephyr, i.e. one rectangular wing with conventional tail interconnected by a boom, and fuselage and engines mounted in the wing. The considered variables were area, aspect ratio, break position and dihedral after break (wing definition) and aspect ratio, volume coefficient and relative positions to wing (tails definition). It was assumed no aerodynamic and no geometric torsion. One extra variable was considered, but fixed for each optimization: payload electrical demand, which assumes values of 100W or 200W.

As the amount of material used is proportional to weight, it is reasonable to accept that light airplane will be cheaper. Still, size is proportional to its weight, and if there are two airplanes, one small and one large, with the same payload, the smaller is more efficient since it requires less structure to perform the same function. Thus, we have that weight is an excellent efficiency indicator of the airplane and thus it is the objective to be minimized. The restrictions considered are handling qualities, rudder shadowing at stall condition of the horizontal tail and required area of solar panels lower than available area on the wing.

2.2.1 Aerodynamics

The aircraft under study shall operate at high altitudes and low speeds, which implies low Reynolds number, in the 150,000-200,000 range, and high values of C_L. Due to the critical energy supply, a low drag configuration is also necessary. Considering similar aircraft Zephyr, the required C_L is about 0.83 at 17 km of altitude, since typical values of speed was about 60 km/h. In this condition, almost 80% of span operates at $C_L > 0.8$, as shown in Figure 10. Thus, the challenge was to find out a low-drag airfoil for high C_L conditions. Due to low Reynolds number, a laminar airfoil was considered, with "drag bucket" covering the needed C_L range. NACA 6-digit airfoil family have a great number of laminar airfoils, being selected NACA 63412, which combines all the desired characteristics, good C_{Lmax}, C_M not so negative and high thickness-to-chord ratio. All the aerodynamic curves were computed with XFOIL and adjusted from experimental results from Abbott (1959).

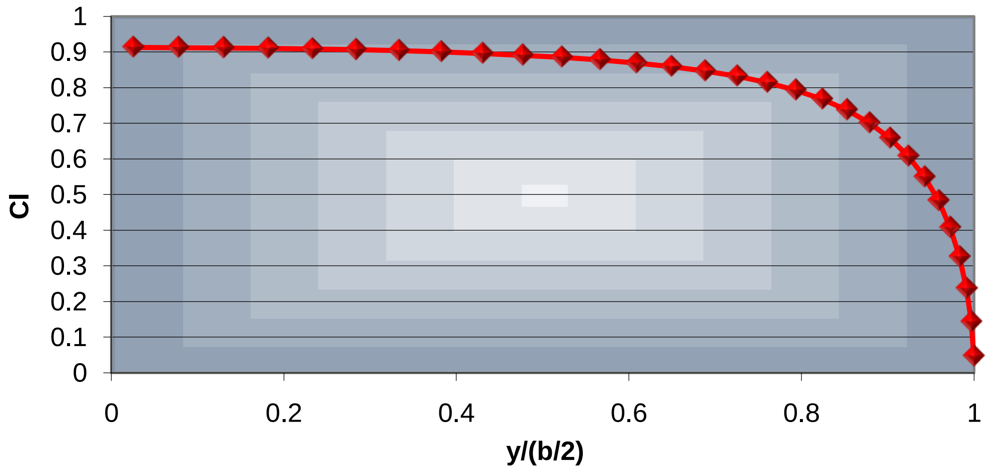

Figure 10 C_l along semi-span computed with AVL vortex-lattice code

The airfoil definitions were the same for tail surfaces, being selected NACA 63010 for the horizontal and vertical tails.

Aerodynamic calculations for the entire configuration was performed with the AVL code [Drela, 2010]. AVL employs the vortex lattice formulation for lifting surfaces and slender-body model for fuselage and boom. With this code and after some modifications, all aerodynamic and stability coefficients and derivatives could easily be provided.

2.2.2 Loads, structures and weights

There was no appropriated regulation for this kind of aircraft. So, some estimations of V-n diagram were made for Zephyr, testing FAR-23 from FAA and JAR-VLA from EASA, resulting in unreliable diagrams. Thus, this study considers maximum load factor as 3.8, cruise speed defined by minimum required engine power for leveled and straight flight and dive speed 25% superior to cruise speed.

The maximum load factor 3.8 was applied for wing sizing; tails were sized based on cruise condition at C_{Lmax} with control surface deflection set to 15º; and boom was sized considering simultaneous tails forces. Fuselage and engines were not calculated.

The employed methods of analysis were very simple, as described at Megson's book [6]. The bending moment is supported only by stringers and torsion by stringers and skin. The adopted topology is shown in Figure 11, extending from leading edge to 25% of chord, where aerodynamic center is localized. The skin thickness is the same along span, but stringers may vary for each station. Ribs were not computed but it was assumed 3 of them per meter, with constant thickness.

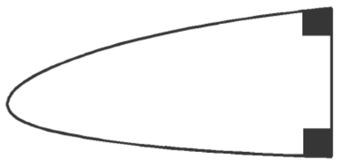

Figure 11 Topological model of wing section considered for structures

The boom is a cylindrical component with constant radius and thickness, approximated by thin-walled tube. It can easily withstand to loads. Thus, its deflection was a constraint and adopted as sizing criteria.

Carbon fiber was the standard material for solar airplanes, except skin that was made of Mylar. Densities of these selected materials are known and some estimative to consider other used materials are done, allowing calculation of distributed mass. Fuselage and payload had fixed weight; batteries' weight depends on needed charge to supply all systems during night; and engine weight was estimated based on methodology described in [1]. Thus, the weight and moment of inertia of each component can be estimated.

These calculations are iterative processes until convergence is reached. Electrical demand depends on drag, that depends on needed lift determined by weight that affects wing loading.

2.2.3 Stability

Stability is an important restriction particularly in autonomous airplanes. Eventual situations can occur and there is no pilot to control the airplane. Although an internal computer can control an unstable airplane, it is too risky, so flying qualities levels 1 or 2 were imposed, according to MIL-F8785C ([4]) with adaptation for UAVs ([7]). Longitudinal and lateral-directional analyses were done, assessing short-period, phugoid, roll, spiral and dutch-roll behaviors.

3. Analysis of Results

This optimization ran on an Intel Core2Quad Q6600 2.40GHz PC with 2.0GB RAM. Although memory had been limited, tests proved that it was satisfactory and processing was the limiting for this study.

At the same time, 4 individuals could be run simultaneously, but it was not possible to analyze one single individual in one quarter of time because algorithm did not support parallel processing. Furthermore, repeated individuals were not analyzed again.

In this study, standard payload electrical demand is set to 100W. Other optimization was done for assessing its influence, so it was increased to 200W.

3.1 Standard payload electrical demand

In this task, 20 generations provided satisfactory convergence.

Table II: Optimization general data for the optimization task considering standard electrical requirements.

Variable	Value
Generations	20
Number of individuals	400
Repeated individuals	41
Total processing time	7h 51m 25s
Average processing time for one individual	1m 19s
Average processing time for 4 individuals	5m 15s

The first run demonstrated a large number of individuals that violate restrictions. It is easy to understand, because in first generations genetic algorithm searches in all considered domain and more advanced generations are next to optimum. So, algorithm naturally reduced the domain to small range that offers good individuals, except mutations.

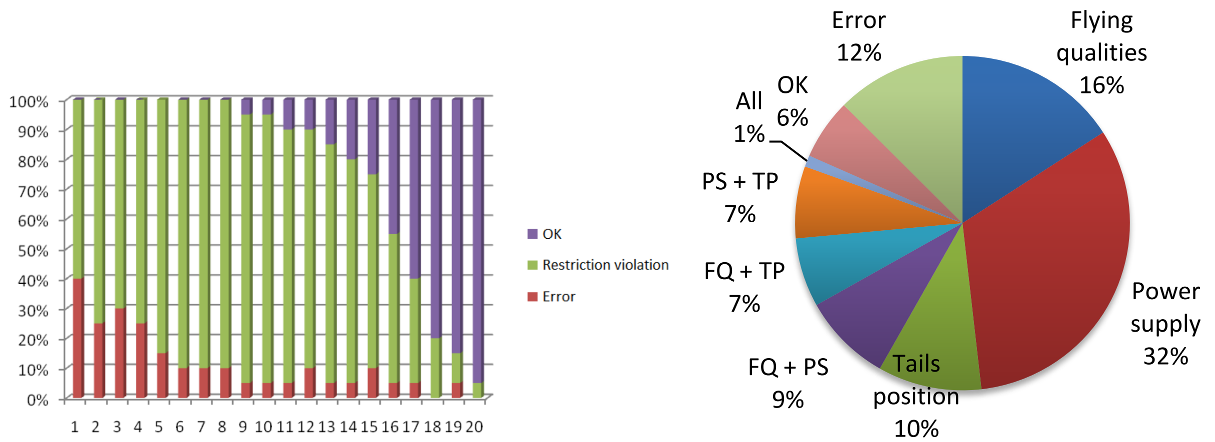

Figure 12 At left, evolution of individuals, and at right, individuals violation classification

The violation of power supply restriction is strongly associated with small wing area, while other constraints are more related to various tails parameters. Considering individuals that did not violate restrictions or only violate tails position, it was possible to obtain typical values of airplane data, as show in Figure 13.

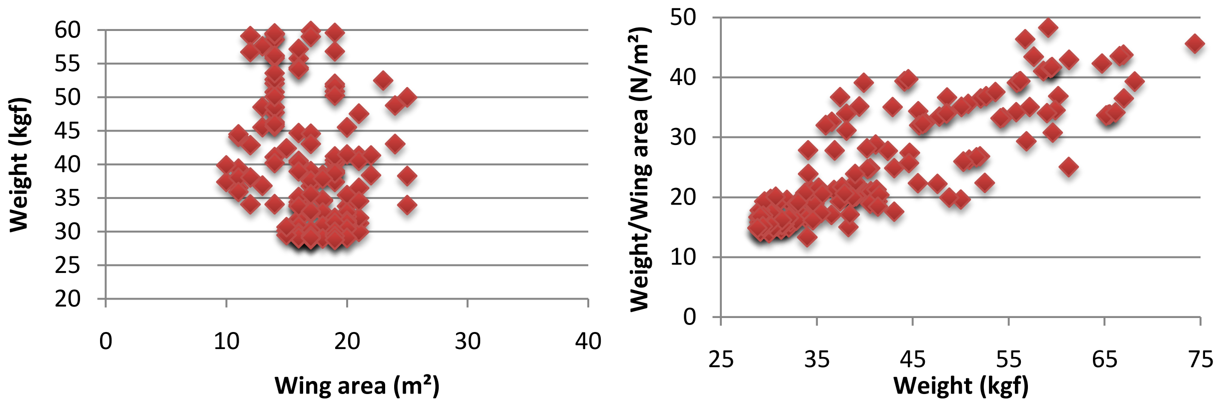

Figure 13 Optimization demonstrated that best solutions weight about 28 kg, resulting in wing loading about 16 N/m^2.

The area and weight are consistent with data from Zephyr, but its needed power supply is unknown and thus it does not validate the code. However, the wing loading of the best individuals is very close.

Considering only the best individuals that did not violate restrictions, it is possible to assert that minimum area of 16m^2 is required. Larger areas can feed systems with greater capacity during the day and must be turned off at night because the battery does not have sufficient capacity, as shown in Figure 14.

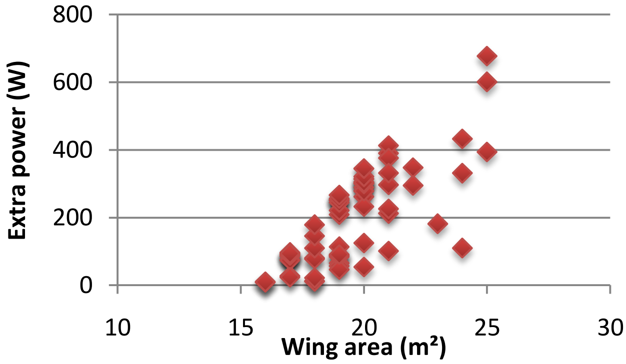

Figure 14 Available extra power for use in systems during the day.

For example, a system that needs 350W can work under daylight conditions and must be turned off at night for airplanes with wing area set to 20 m^2. The day chosen as the project point is very restrictive. If the same airplane flew in the summer, an 1800W system could be turned on during the day.

The final result of this optimization is given by a family of possibilities formed by the boundaries of graphics. Thus, a region of interest is well defined, corresponding to a subset of the initial domain. A person with knowledge and critical analysis will define the airplane(s) that will be the basis for refined calculus (Figure 15). The best aircraft of each stage will be probably different, but hold great similarity between them. Thus, the preliminary design avoids unnecessary work and reduces design time.

One of the best individuals was selected to assess its weight distribution (Figure 16). The chosen airplane had wing area set to 20 m^2 and aspect ratio 25, all handling qualities were level 1 in cruise condition and availability for extra system during the day.

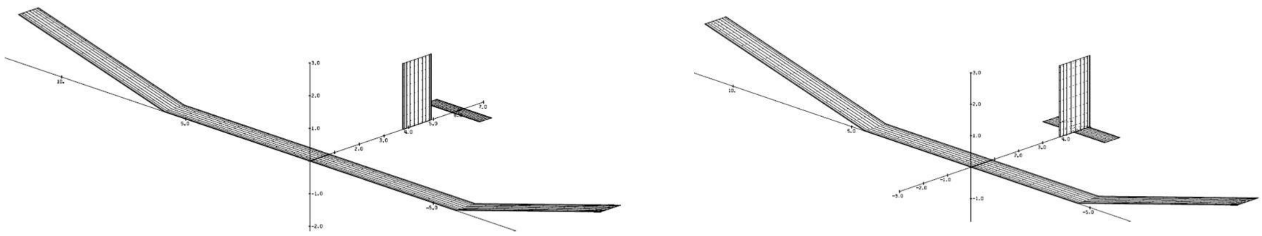

Figure 15 Selected configurations

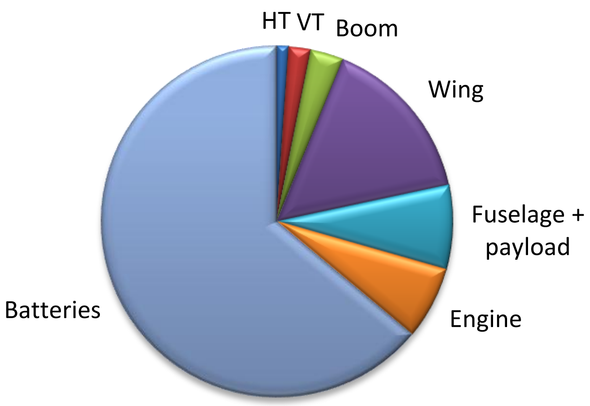

Figure 16 Weight distribution in airplanes with standard electrical demand

The components weights are consistent and the fraction of the batteries is huge, showing the importance for a solar aircraft. The chemical reaction used in the battery generates 350Wh/kg (265Wh/kg considering the wrapper), but development can increase this value until 600 Wh/kg, which would have great impact on solar aircraft.

3.2 Payload electrical demand Increased

As demonstrated in previous section, batteries are critical for design of solar powered airplanes. Thus electrical requirements is changed to 200W, affecting needed batteries charge capacity. Only analyzes that demonstrate demand influence are showed.

Table III: Optimization general data for the optimization task considering extra electrical requirements.

Variable	Value
Generations	50
Number of individuals	1000
Repeated individuals	192
Total processing time	18h 20m 54s
Average processing time for one individual	1m 22s
Average processing time for 4 individuals	5m 27s

All components of airplane must be resized with new value of parameter. The impact is impressive, needing wing area increased by 40% and weight increased by more than two thirds of original value. However, the wing loading has values close to those found previously; indicating that this variable is representative of similar aircraft.

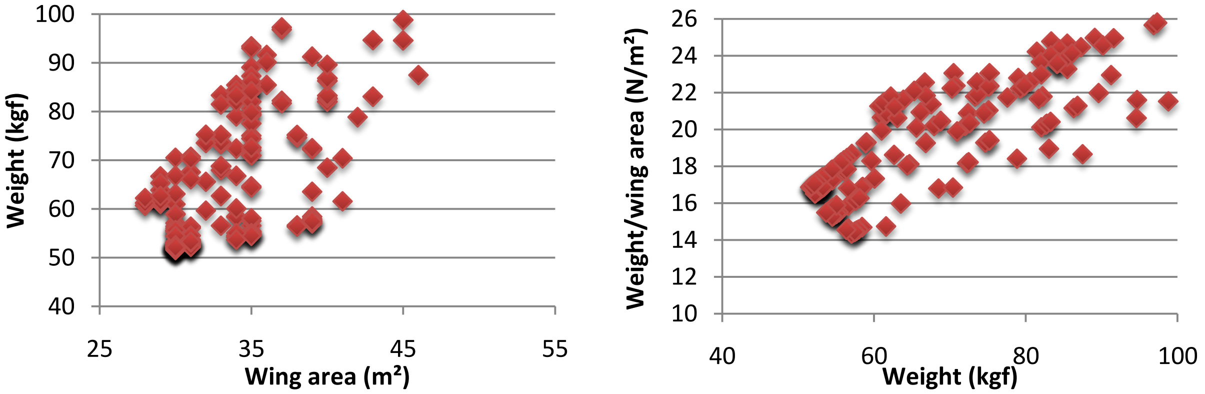

Figure 17 Optimization demonstrated that best solutions weight about 50 kg, resulting in wing loading about 17N/m^2

Moreover, the proportion by weight of the batteries is greatly increased, as revealed by Figure 18.

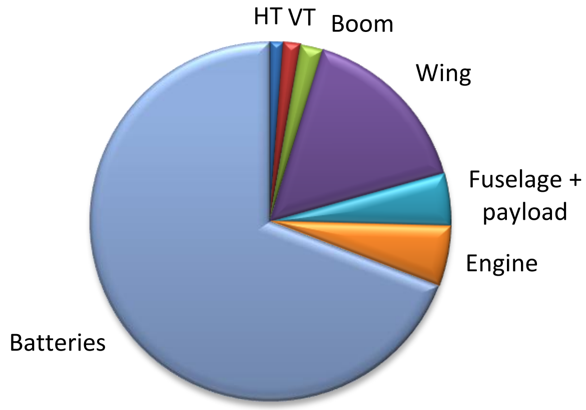

Figure 18 Weight distribution in airplanes with extra electrical demand

3.3 Concluding Remarks

The development of this type of aircraft in the past was directly affected by the technology of solar panels. Nowadays, the major concern with the project is the energy storage. Moreover, there are few systems for sale that are able to work under severe environmental conditions such as found in the tropopause.

The application of optimization tools proved to be quite appropriate, as provided in less than one day running a very large variety of aircraft, which can be identified strengths, weaknesses, and typical values of the variables for a good design.

The case study proposed is an excellent example of this, because there are few semi-empirical mathematical models and built aircraft data, and even then with the application of simple theories seen during the undergraduate course, it was possible to design and verify the consistency with the few existing models.

Because of this, the multidisciplinary optimization has been extensively developed in the aeronautical sector, providing more accurate results and faster.

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