33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

A CREDIBILITY-BASED CRITERION FOR THE ASSESSMENT OF FUTURISTIC AIRCRAFT CONCEPTS

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Abstract

Aircraft designs concerning (hybrid-)electric aircraft often have large discrepancies in the underlying assumptions regarding highly influential design parameters. These mostly concern assumptions regarding the predicted performance of the electric energy provider such as batteries and fuel cells, but also for electric motors and other novel airframe technologies. Having these variations makes it difficult to assess the viability of a proposed novel aircraft design. Furthermore, it makes a comparison between aircraft for comparable missions or performance difficult, as differences in the assumed performance of these subsystems can yield a large impact on the overall design feasibility and performance. The aim of this research is to investigate current trends in the market for a range of highly influential design parameter for futuristic (hybrid-)electric aircraft designs and create a forecast for the near future. This will then be used to create a credibility-distribution for performance assumptions that can be applied to a full aircraft design. Using this criterion, the credibility of the futuristic aircraft can be assessed. An exemplary application is shown in this paper on a newly developed hybrid-electric aircraft design.

Keywords: credibility, electric aircraft, aircraft design, hybrid-electric

1. Introduction

In an age where climate change poses a significant challenge for humanity, while at the same time having a constant increase in air travel [1], it is of paramount importance for aircraft to become more sustainable and reduce carbon emissions. With the European Union imposing more stringent regulations on air travel [2], novel technologies are necessary to stay competitive. In this aspect, (hybrid-) electric flight is a promising solution. Hence, the interest in such designs as well as the research effort has increased drastically in the last years.

Within the currently available research regarding (hybrid-)electric aircraft, most design studies are investigating the performance of aircraft using an expected technology level for the future [3, 4, 5, 6, 7]. Due to the nature of this factor, the performance of many highly influential design parameters is solely based on predictions of their achievable performance. Hence, these assumed values are depending on the data source or best judgment of the aircraft designer. Exemplary, one of the parameters with the highest influence on the feasibility of an electric aircraft is the batter energy density[6]. Within

current studies, this assumed value varies between $250-1000\frac{Wh}{kg}$ on pack-level [3, 6, 7]. The current state of the technology has energy densities around $200\frac{Wh}{kg}$ [8]. Some studies take the uncertainty within their estimations into account, by providing different designs with assumptions for short ($250\frac{Wh}{kg}$) and longer-term improvements ($500\frac{Wh}{kg}$) [6]. Other studies start with optimistic assumptions of the attainable energy density for mid- and longer-term, such as designs utilising $700\frac{Wh}{kg}$ [3] or even $650-1000\frac{Wh}{kg}$ [7]. In order to attain these energy densities, large improvements in the current state of the art are required. However, this limitation is rarely taken into account when designing and presenting a new (hybrid-) electric aircraft concept. As a result, the expected performance varies largely between different studies. This makes it difficult to assess the validity of these assumptions and in turn the credibility of the predictions regarding feasibility of the resulting designs in the near future.
The goal of this research is to attempt to quantify the uncertainty of six important design variables and to develop a measure for the credibility of a certain assumed performance level for these parameters. Future performance figures are estimated and fitted with statistical distributions. These formulations are then applied to (hybrid-) electric aircraft designs, developed using current extrapolations of achievable performance, to assess the effect of changes in credibility.
Section 2. introduces the definition of credibility used in this study as well as the chosen uncertain parameters. The creation of the credibility curves for each parameter is detailed in sec. 3. Lastly, an exemplary comparison between a low-credibility and high-credibility hybrid-electric aircraft is shown in sec. 4.

2. Methodology

2.1 Credibility

The first step in the creation of a credibility-based assessment criterion is the definition of credibility. Within this study, the expected performance level for a parameter will be given by a statistical distribution. The credibility is then defined as *The probability that the technology will have reached at least a certain performance level.* This is shown in Eq. 1. This equation also shows that the credibility is equal to the inverse of the cumulative density function (CDF) of the parameter. Thus, the current state of the art will result in a very high credibility, a large improvement over this value will result in a low credibility.

$$C = P(X > x) = 1 - P(x \leq X) = 1 - CDF \tag{1}$$

Figure 1 shows this relationship between probability density function and credibility function (CF) in a graphical format for a selection of three different common probability distributions, a uniform distribution, an exponential distribution and a normal distribution. Depending on the underlying distribution model for an uncertain parameter, different CF shapes are created. For the exemplary distributions, the expected value is equivalent to an improvement of 3.5% to the status quo.

2.2 Uncertain variables

The goal of the study is to assess concepts for future aircraft designs to their credibility. Thus, every individual required design input might be considered an uncertain variable and be used in conjunction with a credibility distribution for this investigation. In an initial step, a range of potential parameters from the fields of novel airframe/aerodynamic concepts, propulsion subsystems and energy storage and distribution systems were selected for further investigation to their suitability for this study. Following an assessment of a range of input variables for their impact on a viable aircraft design, and their projected performance uncertainty, six parameters were chosen for further investigation as uncertain variables for this study.

- Gravimetric battery energy density
- Gravimetric fuel cell system power density
- Gravimetric electric motor power density
- Volumetric electric motor power density

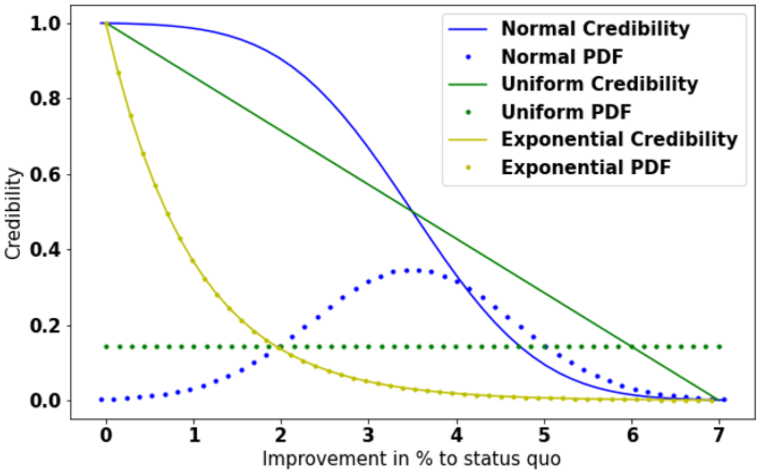

Figure 1 – Credibility functions for different kinds of probability density functions

- Percentage of laminar flow over the main wing
- Percentage of structural weight reduction due to novel materials and production techniques

All six parameters have a direct and significant impact on (hybrid-) electric aircraft designs. They are applicable to a wide range of possible architectures and for aircraft of all sizes. Furthermore, some parameters and their future performance is already well established in research, while others are still at a laboratory phase. Hence, the approaches of quantifying the credibility will have to be varied for each component, necessitating the establishing of different methods for literature studies and performance predictions. Thus, while the selection of only six parameters for a full aircraft design is low, the differences in nature of these parameters will require varied approaches that can easily be extended to further parameters in the future.

3. Parameter Estimation and Curve Fitting

Following the definition of the uncertain parameters, this section describes the literature study results and the parameter fitting process for each of the six parameters.

3.1 Energy provision and storage

Two of the identified and investigated uncertain variables regard the energy density of the energy provision and storage systems. For hybrid-electric aircraft, this concerns the performance of batteries and hydrogen fuel cells which provide electricity for the motors. For this investigation, the gravimetric energy density of battery cells, as well as the specific power of fuel cell stacks is analyzed. While the volumetric energy density is also a relevant factor, it is deemed less critical overall. A high gravimetric energy density is of utmost importance for a successful electric aircraft design due to its significant impact on the maximum takeoff mass and thus all other subsystems.

3.1.1 Battery

The model created aims to predict a battery systems weight for the future years up to 2035. However it is hardly possible to define a specific, not yet developed and tested, future battery cell in detail. Therefore, when designing the battery system, the number of cells connected in series and parallel cannot be evaluated. Due to this, a simplified approach is taken to determine future battery performance. Future systems will be based on the same configuration as for a currently available cell technology, while increasing the energy density at cell level. The effects of an increasing specific energy are shown in figure 2. Here the cell mass of a battery system with a usable energy of around 900 kWh, already considering a state of charge (SoC) from 85% to 15%, is plotted over different degrees of hybridization, as the quotient of energy provided by the battery and energy stored in the conventional form of kerosene, and over the upcoming years. The prediction of the decreasing mass

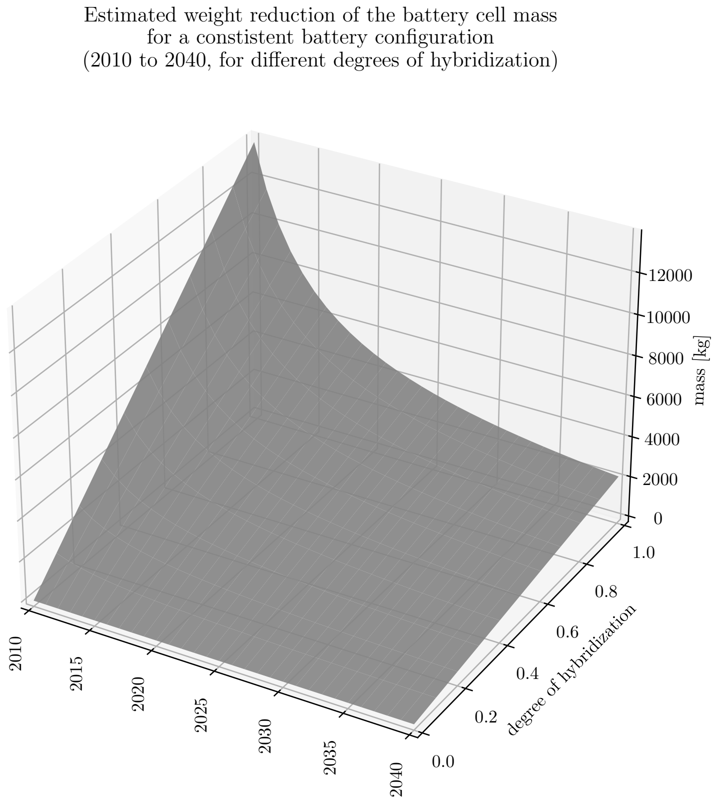

Figure 2 – Exemplary effects of the weight reduction of the battery cell mass

is based on the linear interpolation from [9], also shown in Figure 3. The conversion from battery cell mass to battery system mass is done using a scaling factor that can be extracted from either [10] or [11]. This factor is assumed to be $m_{bat,system} = 1.43 * m_{bat,cells}$.

In the case of the battery it is expected that technologies based on Lithium will remain predominant [12], however the chemistry, anode and cathode materials are expected to change paving the way to improved energy densities. An extract taken from [9] for the different technologies to be expected for the upcoming years is depicted in table 1.

Table 1 – "Roadmap" for Li-Ion battery technology, taken from [9]

Technology	Timeframe	Gravimetric energy density [Wh⁄kg]	Cathode material	Anode material
Current Li-T formulations	2014 – 2017	150 – 260	NCA	Graphite 95%, Silicone 5%
Next gen. Li-T formulations	2018 – 2020	180 – 280	NCM622-NCM811	Graphite 95%, Silicone 5%
Advanced Li-T formulations	2021 – 2024	250 – 300	Ni-rich (e.g. NCM910)	Graphite <90%, Silicone >10%
Li-Metal/solid state technology	2025 – 2030	400 – 450	Ni-rich (e.g. NCM811)	Li-Metal, Ceramic-based structure
Li/O2 (Li air) technology	2030 +	>500	Li/O2 (Li air) technology	

Repeatedly a gravimetric energy density of approx. 500 Wh/kg is named as a minimum goal for all-electrical propulsion to become competitive with today's conventional propulsion systems. Currently, the automotive industry is the main driver for the development of batteries with higher energy density. However, for the application in aircraft, further developments beyond this are necessary [9, 12]. The technological progress, which is enabling the energy densities of batteries to increase is reviewed in several publications. Based on the presented performances development and predictions made, estimations for the gravimetric battery energy density on cell level for the upcoming years are created. An advantage of this approach is the use of a wide range of predictions, which makes the results more robust. Linear regression is chosen, because typical technology prediction in literature often show linear forecasts for Li-Ion battery energy densities [11]. The set of resulting linear trajectories is shown in figure 3. The calculated slopes a and the y-intersects b are shown in table 2.

Table 2 – Details on interpolated energy densities

	Publication date	Resulting linear equation	Source
A	2017	a = 17.41; b = -34901	[9]
B	2018	a = 18.39; b = -36864	[12]
C	2019	a = 9.05; b = -17949	[13]
D	2020	a = 12.28; b = -24497	[14]
E	2020	a = 12.95; b = -25884	[11]

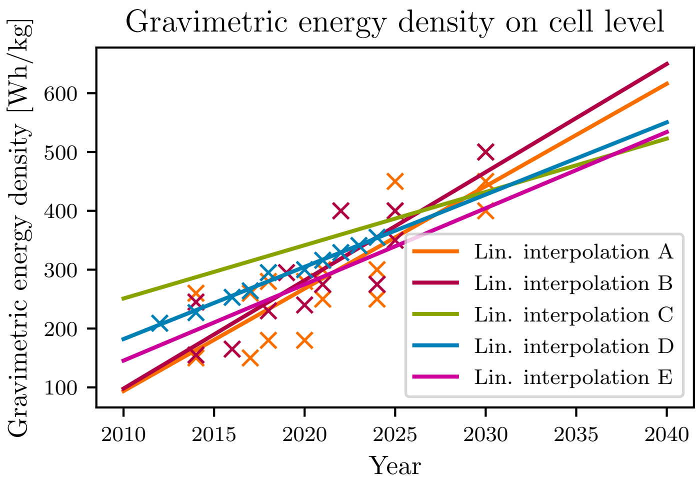

Figure 3 – Expected increase of the gravimetric energy density of lithium-based battery technologies

Based on the interpolations, it is possible to derive a set of energy density estimates for the desired year 2035. From these estimations, a mean and a standard deviation can be calculated, which can then be used to obtain a distribution function. A normal distribution for energy densities in 2035 is shown in Figure 4. It gives a sense of the uncertainty of the predictions for the given year.

3.1.2 Fuel Cell

The fuel cell model is based on a standard, state-of-the-art PEM (Polymer Electrolyte Membrane) fuel cell. A more detailed description of this technology can be found in [15]. The main objective is to obtain a sufficiently accurate analytical model that can predict both the weight of the fuel cell system and stack. Considering the fuel cells efficiency and the cumulative efficiency of the power train, the energy which needs to be stored in the form of hydrogen is determined. Using hydrogen's gravimetric, 33.3 kWh/kg = 120 MJ/kg, and volumetric energy density (in liquid state: 70.8 kg/m3) the approximate volume and mass of the hydrogen is predicted. Since the mass of the H2-tank is geometry dependent, a spherical tank, as the form with the smallest surface-to-volume ratio, is considered here. Using an area-specific mass for the walls of the tank, as presented in [15], the

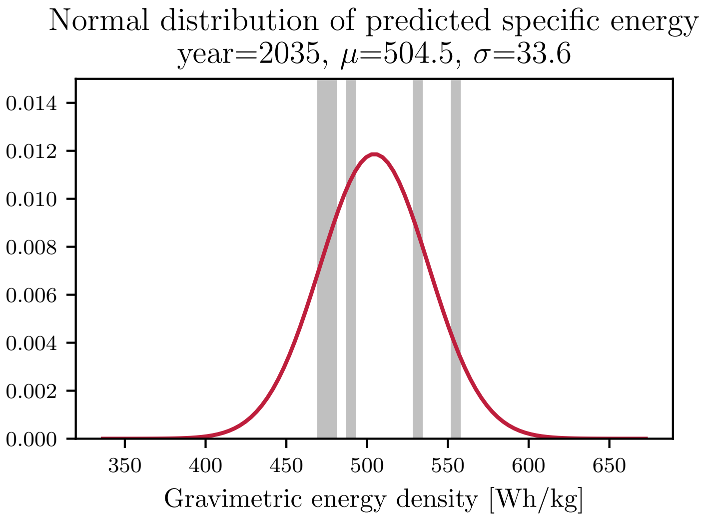

Figure 4 – Expected uncertainty of the battery gravimetric energy density prediction in the year 2035

mass of the tank can be calculated. Moreover, it is assumed, that the fuel cells system volume is largely determined by the H2-tanks and therefore the hydrogen's volume. Besides the tank and its contents mass, the fuel cell system itself needs to be considered. This is done through a specific power of the fuel cell stack and its periphery [15, 10]. To include peripherals in the weight estimations, a scaling factor is introduced to reduce the stack level specific power to the specific power at system level. This scaling factor is obtained from the given power densities in [15] and results from the power density of 2 kW/kg on stack- and 1.6 kW/kg on system-level for current state-of-the-art fuel cells.

While for the batteries it is the energy density that is expected to develop significantly in the future, the literature suggests that improvements in the specific power of the fuel cell will be the key factor in reducing the mass of the energy system [16]. The data available for predicting the power density of fuel cell stacks is much less distinctive than that for Li-ion batteries. However by analyzing past realized fuel cell systems and the predictions for the future development sparsely made, a rough trend for the development of the specific power can be derived. The starting point for this analysis is the Toyota Mirai fuel cell, unveiled in 2015, which represents one of the first large-scale series production applications of fuel cells in the transportation sector. Here, the gravimetric power density is given as 2.0 kW/kg [17], a value which by many is still assumed to represent the state of the art in 2017 [10, 15] and in 2020 [18]. Past power densities are estimated at 0.83kW/kg for advanced fuel cell systems in the year 2008 [17]. The German Aerospace Center assumes the FC stack specific weight to be 1 kW/kg in the year 2013 [19]. In an analysis of fuel cell systems for aviation from the TU Braunschweig and the LU Hannover from the year 2017, the currently prevalent power density is assumed to be 1.6 kW/kg and 2.0 kW/kg on system and stack level, respectively. A future specific power of the fuel cell plus periphery is put at 8 kW/kg, however no year for this estimation could be found [15]. The United States Department of Energy set its development target for fuel cell stacks at 2,7 kW/kg for the year 2025 [18]. An analysis by TU Braunschweig and LU Hannover assumes that the currently best-performing fuel cells on lab-scale might be available by 2035 for their prediction of future fuel cell systems. According to the authors, those fuel cells achieve approximately 4 kW/kg [10].

Analyzing the specific powers of state-of-the art fuel cells and predictions made on the development within the last decade, expected values for future gravimetric power density of fuel cells are derived. Similar to the battery energy density predictions, these value are obtained using linear regression. The resulting linear development is depicted in figure 5 and can be characterized by a slope of 0.118 and a y-intersect of -236.5.

The uncertainty prediction for the specific power of the fuel cell stack is based on the analysis of the accuracy of predictions made in the past. [20] evaluates the specific power of a fuel cell power system at 0.14 kW/lb or 0.31 kW/kg for the year 2004. The assumptions for advanced technology in 25 years from the publication date assume a doubling of the power-to-weight ratio for the fuel cell based

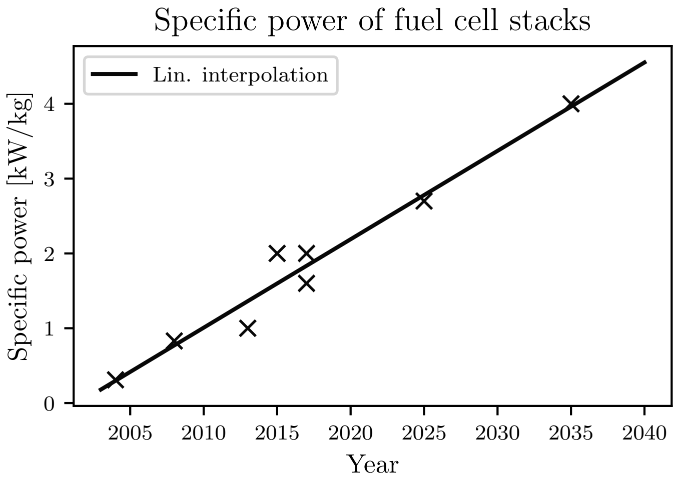

Figure 5 – Expected increase of the specific power of fuel cell stacks

propulsion system, resulting in a specific power of 0.31 kW/lb (0.68kW/kg). Since these values refer to the entire system (which also includes power electronics, fuel delivery, etc.). The values presented must be scaled down according to [20] in order to properly represent the fuel cell system only. This leads to power densities of 1.1 kW/kg and 1.75 kW/kg for 2004 and 2029 respectively. Assuming the previously introduced conversion factor, mediating from stack to system power densities of 1.25 [16, 15], the predicted power density at stack level increases to 2.2 kW/kg, falling short roughly 0.5 kW/kg compared to the prediction of 2.7 kW/kg made for the year 2025 in [18]. Assuming the herein made prediction for the year 2035 will incorporate a similar error in the prediction, the predicted power density will lie in an interval of $\pm$0.5 kW/kg around the value 3.96 kW/kg for the year 2035.

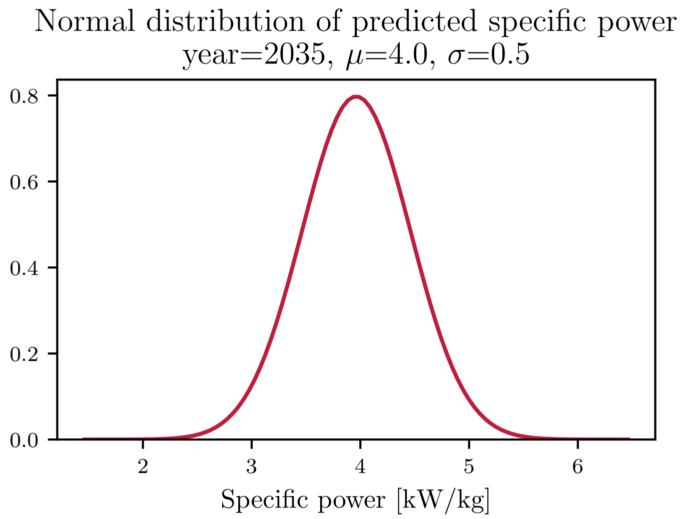

Figure 6 – Expected uncertainty of the fuel cell stack specific power prediction in the year 2035

3.2 Electric machine

Depending on the application, different powers are required for the electrification of aviation. The total power required depends on the size of the aircraft. In [21], different power ranges are classified according to the number of seats. Figure 7 shows these power ranges. A current development in hybrid-electric aircraft is the E-FAN X project, in which one propulsion unit is driven with a power of 2 MW. In the future, projects such as the NASA N3-X may require a total electrical power of about 25-30 MW for an aircraft with 300 seats [22].

The key parameter for electric machines in aviation is therefore the gravimetric power density. This

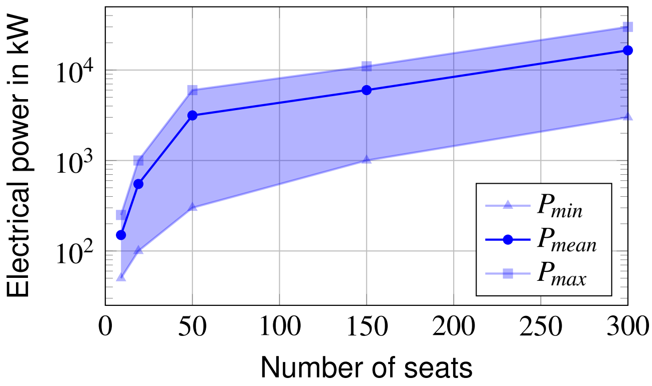

Figure 7 – Required electrical power for the number of seats

parameter is also assumed to be uncertain. In a recent study, the continuous power density of current electric machines is investigated [23]. The study includes 25 machines from various manufacturers with an average power density of 4.072 kW/kg. The machine with the highest power density has 8.3 kW/kg. It was investigated whether the research on current gravimetric power densities of electrical machines satisfies a certain distribution function. Figure 8 shows the statistical distributions of these machines. In addition to the distribution functions, the scale λ and shape k parameters are given, or in the case of normal distribution, the mean μ and standard deviation σ, which describe the distribution functions.

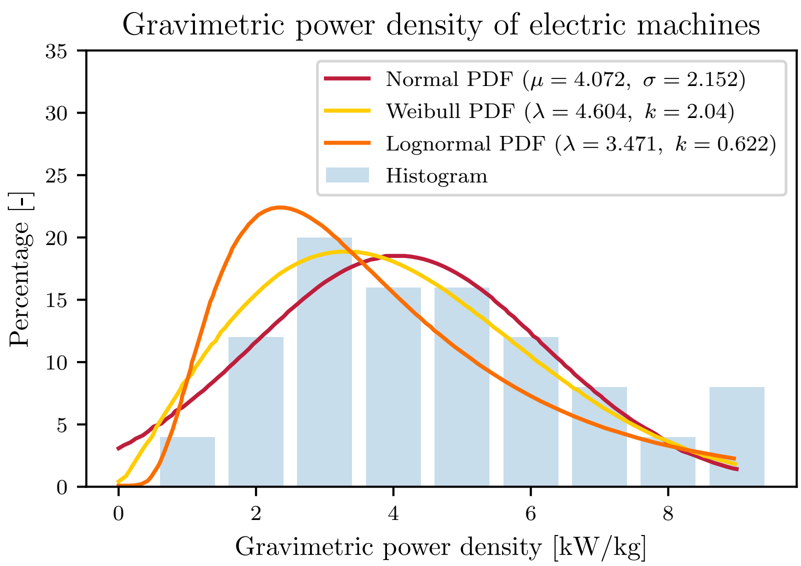

Figure 8 – Distributions of gravimetric power density of current electrical machines

In order to select a suitable distribution function for the uncertain parameter, a statistical analysis using the Chi-Squared test was performed. This statistical test examines whether there is a statistically significant relationship between two variables. Since here the empirical data are compared with those of the distributions, the chi-squared test is an instrument to measure the goodness of fit of the distribution. The goodness is measured by two factors. The Chi-Square value measures the deviation between the empirical bin counts and the bins that would be projected by the respective fitted distribution function. The smaller the deviation, the lower the Chi-Square value and the better the goodness of fit. The best fit was achieved with the Weibull distribution, which was chosen as the final distribution for this parameter.

The second uncertain parameter characterizing the electric machine is the volumetric power density. The methodological procedure for the volumetric power density is identical to the gravimetric power density. To establish a uniform basis, the same machines as in Figure 8 from Bird's study were investigated [23]. Figure 9 shows the distribution functions for volumetric power density. Compared with Figure 8, it is noticeable that there are outliers in the volumetric power density which have a significantly higher performance than average electrical machines. The reason for this is that these are high-speed machines operating above 20,000 rpm. These machines have high gravimetric and volumetric power densities and also max out at over 8kW/kg for gravimetric power density. This effect is even more pronounced for the volumetric power density. Compared with other machines, however, it should be noted that the speed is also physically limited and therefore the total power is rather low. Nevertheless, high-speed machines are also constantly being developed and should be taken into account. Again, the Weibull distribution shows the best fit.

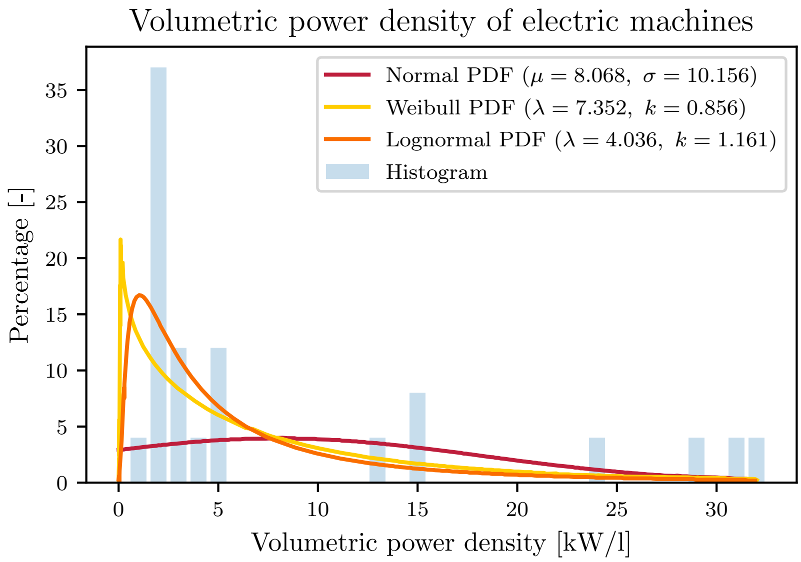

Figure 9 – Distributions of volumetric power density of current electrical machines

Based on today's average gravimetric power density of about 4 kW/kg and volumetric power density of about 8 kW/l, future projects will require power densities almost 3 to 4 times higher. In [24] the required current and future power density of electrical machines in aviation is discussed. A technology that could enable power densities of 15 kW/kg and more are superconducting machines, which are currently the focus of electrical machine research. Based on the current distribution functions, the future development of the gravimetric and volumetric power densities are estimated. Gravimetric power density increases are assumed and given in Table 3 for the years 2025 and 2035. Table 4 additionally shows the values for volumetric power density. The uncertainty of the parameters is indicated by the quantiles.

Table 3 – Data on the grav. power density of electrical machines today and in the future.

Year	Mean [kW/kg]	5%-quantile [kW/kg]	50%-quantile [kW/kg]	80%-quantile [kW/kg]
2022	4.079	1.074	3.847	5.814
2025	8	4.245	8.055	9.91
2035	10	6.017	10.104	11.95

Table 4 – Data on the vol. power density of electrical machines today and in the future.

Year	Mean [kW/l]	5%-quantile [kW/l]	50%-quantile [kW/l]	80%-quantile [kW/l]
2022	7.965	0.229	4.791	12.821
2025	25	9.098	24.534	33.818
2035	30	12.766	29.77	39.152

Since the predictions in the literature sometimes differ considerably, the presented methodology can be extended by another future uncertainty. In [25], different superconducting machines are analyzed and their low technology readiness levels (TRL) is given. Regarding aviation, two machines are presented that have a TRL of 3 (characteristic proof of concept) and are expected to achieve gravimetric power densities of 15 kW/kg and even 25 kW/kg, respectively. Starting from a TRL of 3, the development to a TRL of 9 (proven technology) and thus the availability of the propulsion systems for aviation may take between 12 and 20 years. For the assumed distribution functions predicted into the future, a distinction can be made between a best case and a worst case. Figure 10 shows this approach.

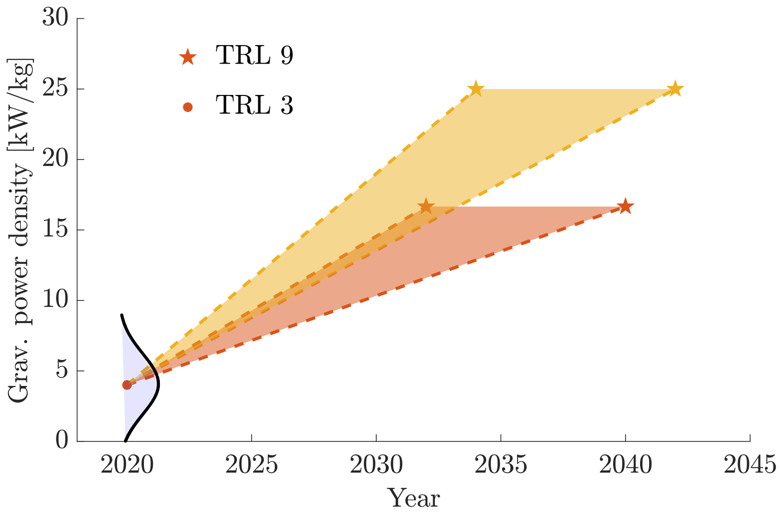

Figure 10 – Future uncertainty due to the specification of the current TRL using the example of gravimetric power density

3.3 Airframe technologies

The third major part of the credibility distributions considered in this study concern aircraft technologies. Due the current TRL of both technologies, and hence a lack of reliable forecast data for an entry-to-service date, a different approach needs to be taken. For both parameters, an extensive literature study is performed with the aim to find datapoints of achieved performance in a laboratory setting, either through flight test, wind tunnel testing, or high-fidelity numerical simulations. This is done with the underlying assumption, that once these technologies have matured enough to be used on new aircraft designs, the achievable range in performance gain will be distributed similar to current studies on the topic. As such these distributions are not directly related to a specific forecast year, but to a forecasted expected performance of the technology. To find a distribution that will best fit the data, SciPy is used. SciPy has more than 90 continuous distributions that are fitted over the data. Using the Kolmogorov-Smirnov-test (KS-test), the probability distributions with the best overall fit are identified. Due to the scarcity of the data, in this case the KS-test is preferred over the Chi-Square-test used to estimate the fit for the electric motor parameters as it can be used with sample sizes as small as one per section of the histogram [26]. The Chi-Square-test requires at least 5 points per histogram bar, which would severely distort the shape of the samples. Scipy allows fitting of data over non-normalised datasets. For a shift in location and scale, the 'loc' and 'scl' parameters are used and shown in the relevant figures in addition to the fitting parameters required by the probability distributions.

3.3.1 Laminar flow control

For a sustainable aircraft, a further means to improve efficiency is by reduction of aircraft drag. For a large subsonic aircraft, skin-friction drag can amount of up to 50% of the total drag. For a laminar flow, skin friction can be up to 90% less than in case of turbulent flow [27]. Keeping a laminar flow over the

wing can yield significant reductions in overall drag. This concept is well applied to low-speed gliders for many years. However, transonic transport aircraft operate at much higher speeds and Reynolds-numbers [28]. Hence, keeping the flow laminar is more difficult to attain. For this, different methods can be employed [29, 28]. The two main research areas are natural laminar flow airfoils (NLF) and laminar flow control (LFC). For transport aircraft, LFC is more attainable, as it does not require the airfoil alone to provide extended areas of laminar flow, but utilise e.g. boundary layer suction systems to prevent boundary layer growth and thus a transition to turbulent flow. The technology has already provided promising results, albeit mostly in a laboratory environment. Using LFC over 15-20% of the wing chord for an A340 type aircraft could yield cruise drag reductions of 14% [27]. The LFC is mostly useful in cruise, hence the benefits are larger for long-range aircraft. Different LFC architectures have been developed and been tested in wind tunnels. Some were also applied to components in flight test aircraft. Flight tests of NLF airfoils have shown laminar flow over 20-45% of the chord [30, 31, 32, 33]. Numerical simulations predict higher achievable ranges up to 60% [34, 35, 3]. For LFC, flight tests have shown ranges of 12-65% of the wing chord [36, 37, 38, 32, 39], with simulations as high as 85% chord [40, 41, 42, 43, 44, 45].
Due to a scarcity of literature datapoints for the different technologies, the different technologies are considered together for the credibility estimations. A histogram showing the distribution and type of the datapoints is shown in Fig. 11.

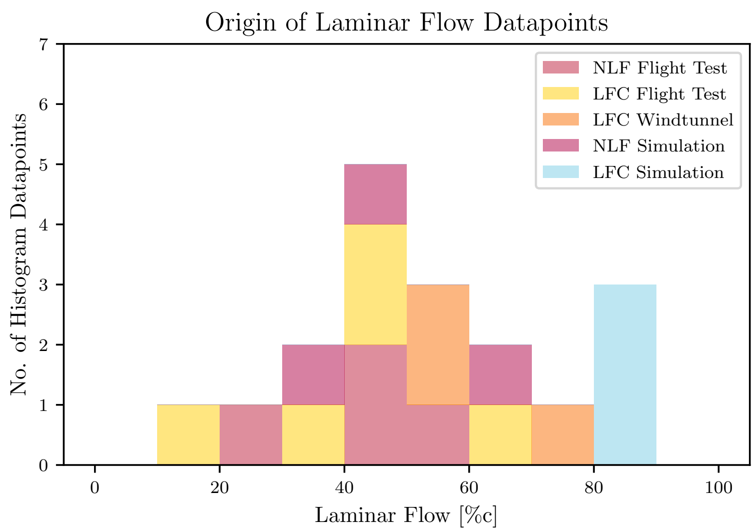

Figure 11 – Histogram and data type for laminar flow control datapoints

The results of the fitting process are shown in Fig. 12. The best fit is achieved with an inverse gamma distribution, a type of scaled inverse chi-squared distribution. Near identical results are obtained using an inverse gaussian distribution. Due to the similarities with a normal distribution, a fitted version is shown for reference as well. Following the data samples, it is expected to achieve around 50% laminar flow. While the lower valued datapoints come mostly from NLF test, it is expected that early LFC systems will also be limited in power, due to mass and energy requirements, as well as potential in-flight contamination. Hence, this is deemed a realistic fit. For laminarity below 20% the credibility as shown in Fig. 13 is very high, as such values can already be obtained with current transport aircraft wing designs. Maintaining laminarity beyond 80% chord is not significant. At those locations, movables such as ailerons or flaps are commonly mounted, and thus laminar flow is difficult to maintain [29].

3.3.2 Structural weight reduction

Current composite technology has revolutionised aircraft structural design. Modern aircraft such as the Boeing 787 or the Airbus 350 already demonstrated the benefits of largely composite structures on aircraft design and structural mass. Aircraft structures are currently built using a tape lay-up process.

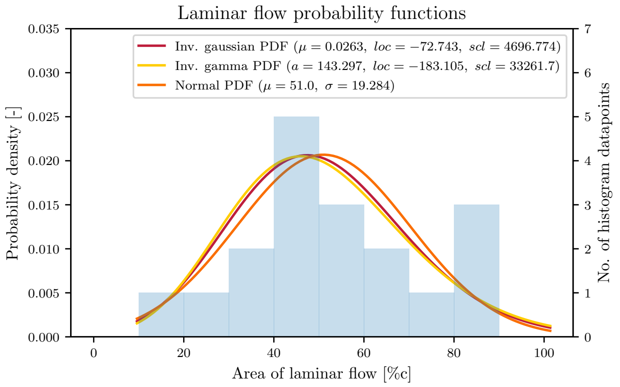

Figure 12 – Probability density functions for laminar flow control datapoints

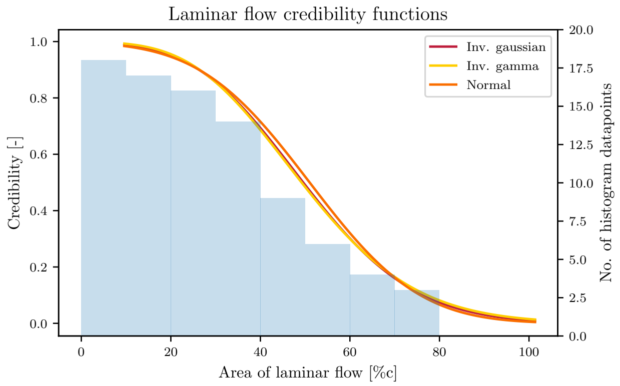

Figure 13 – Credibility distributions for laminar flow control datapoints

Advanced structure technologies have the potential to reduce wing weight by significant numbers. Thin plies could be used in Composite Fibre Reinforced Polymers (CFRP) structures to reduce interlaminate stresses due to finite ply thickness, resulting in the potential of wing weight reductions of about 10%. However, this would be at the expense of moderate increases of manufacturing costs. Variable angle tow steering (VAT) is a novel means in composite manufacturing to fully exploit the ability of the CFRP structure to comply with stresses that vary with the span, which can result in 15% reduction in structural weight compared to conventional composite structure design [46].

Current studies for advanced composite lay-up techniques investigate the effects of different levels of freedom regarding the lay-up. A simple method allows the individual plies to be rotated during the layup, allowing a better tailoring than the classical 0/45/90 orientations currently in use. Further advances in manufacturing techniques could allow full tow steering. Here, the fibre orientation is constantly varied along the component, either in one or two dimensions [47]. These novel manufacturing techniques have been proven in a laboratory setting, with tow steered coupons achieving significant benefits in strength compared to conventional composite panels [48, 49].

All current studies investigating the effects on wing mass are using high-fidelity simulation and optimisation techniques to compare mass savings over an optimised wing using conventional layup. Most studies are performed using the NASA Common Research Model (CRM) aircraft model with aspect ratios of 9 (CRM-9) or 13.5 (CRM-13.5) [47]. Using this aircraft, mass savings between 5-6% are found [50, 47, 51] for ply rotations. Using VAT, the mass improvements rise to 6-14% [50, 47, 51, 52, 53]. One paper even finds improvements of 15.7% for ply rotation and 24% for VAT [46]. In the paper, these high savings are attributed to additional savings due to also including the center wingbox in the optimisations. Other investigations using a mid-range aircraft wing or NLF forward-swept wings have found mass savings of 7-8% for ply rotation[54, 55].

The datapoints and their origins are shown in the histogram in Fig. 14.

The fitting results of the PDFs are shown in Fig. 15. The data is best represented by functions of the exponential distribution family. The best representation is found using a Nakagami distribution, a form of generalised chi-distribution. Low weight reductions below 5% may also be achievable with improvements in the current set-up and some optimisation of current aeroelastic tailoring methods. Hence, the credibility in Fig. 16 is high and constant below this value. Due to the sample points, a rapid reduction in credibility follows with very unlikely values beyond 20% reduction. The baseline for these weight reductions is an optimised wing using conventional composite lay-up techniques. In order to apply the weight savings to a metal wing as reference, an additional factor of 20% should be applied [56]. For highly aeroelastically tailored composite structures, savings as much as 40% could be achieved [51, 57].

4. Aircraft Application

To illustrate the impact of the credibility functions on an aircraft level design, two aircraft with the same top-level aircraft requirements (TLARs) are presented. These aircraft concepts are provided by

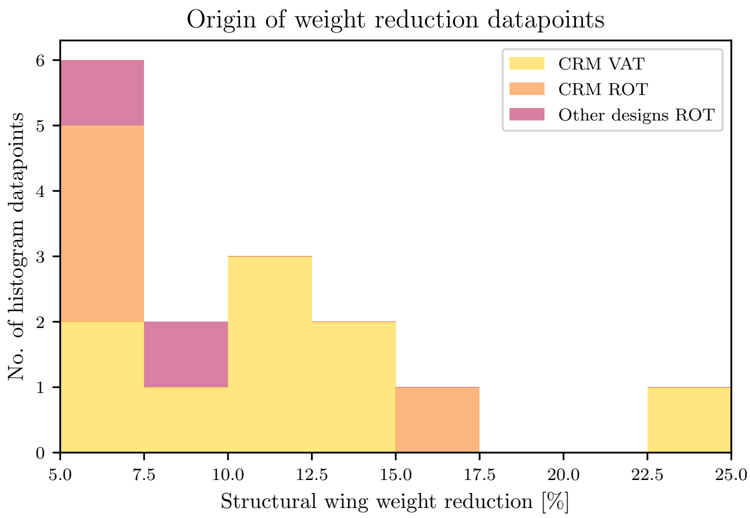

Figure 14 – Histogram and data type for structural weight reduction datapoints

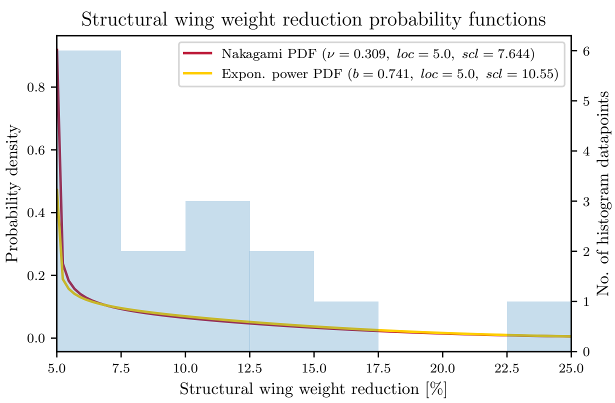

Figure 15 – Probability density function for structural weight reduction datapoints

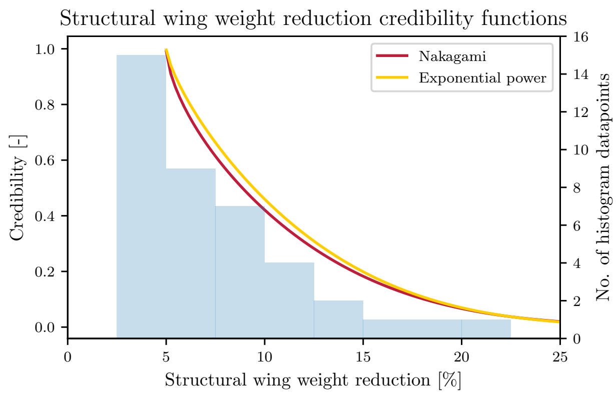

Figure 16 – Credibility distribution for structural weight reduction datapoints

TU Delft using their in-house tool Initiator [58]. The Initiator designs and sizes a clean sheet aircraft design based on a number of TLARs and a chosen design point. The performance along a specified nominal mission including climb, cruise, descent and diversion segments is evaluated and the aircraft component masses as well as performance data are determined. The aircraft design is then iterated automatically until a converged design is found that is able to perform the desired mission and has a consistent maximum takeoff mass.

The provided aircraft are regional hybrid-electric aircraft with a serial/parallel partial hybrid propulsion architecture [59]. This architecture consists of two powertrains. The primary powertrain consists of a gas turbine driven main propellers with additional electrical generators mechanically linked to the gas turbine shaft via a gearbox. The secondary powertrain consists of electric motors driving wing-tip mounted propellers, powered by batteries and an eventual electrical power off-take at the primary powertrain's gearbox. During the most energy intensive climb, the battery is assumed to provide between 1-5% of the total power, linearly increasing from sea-level to cruise altitude. The main propellers provide most of the propulsive power, with the shaft power provided to secondary propellers amounting to 7-5% of the total propeller shaft power during the climb and 5% during cruise. In cruise, the battery provides 10% of the required electrical power, the remaining energy is provided by the gas turbine driven generators using conventional Jet-A fuel. These electrification in this sample case is chosen to be low, to assess the impact of the uncertain parameters on a baseline design that is considered feasible by 2035, with very conservative estimations of a future degree of hybridization [60].

The relevant TLARs as well as the assumed values for the subset of uncertain parameters used for this design are shown in Tab. 5. The High Credibility (HC) variant is designed based on 95% credible values for the relevant uncertain parameters, the Low Credibility (LC) variant is based on 50% credible values according to the previously described distribution curves. With the assumption that all uncertain parameters are independent, the composite total credibility of the HC variant is 78% and 13% for the LC variant.

Table 5 – Inputs for Low-Credibility Design (50% component credibility) and High-Credibility Design (95% component credibility)

TLAR	LC	HC
Passengers	70	70
Cruise Speed	M 0.4	M 0.4
Cruise Altitude	23 000 ft	23 000 ft
Range	500 NM	500 NM
Gravimetric Battery Energy Density (Cell-level)	505.4 $\frac{kg}{Wh}$	448.7 $\frac{kg}{Wh}$
Gravimetric Power Density Motor	10.1 $\frac{kW}{kg}$	6.02 $\frac{kW}{kg}$
Structural Wing Weight Reductions	8.9 %	5.1 %

The results of the aircraft sizing process are shown graphically in Fig. 17, with numerical results shown in Tab. 6. The results show that for the provided designs, the differences in the resulting aircraft are small. Both cases show a nearly identical wing geometry with a 3% difference in total wing area. Overall, the HC aircraft is approximately 3% larger than the LC variant, as can be seen in the differences in maximum takeoff weight and the power requirements. More significant changes can be seen in the parameters that relate to the uncertain parameters. The electric machine masses (motors and generators) show a 73% change and thus a significant impact of the credibility assumptions. This is partially due to the 40.3% reduction in specific power due to the credibility changes, but also a result of higher power needs. A similar exponential impact can be seen with the resulting battery mass. A decrease of 11.2% in the assumed energy density results in a 15.6% increase in battery mass.
The wing structural weight reductions due to advanced composite manufacturing techniques have a difference of 3.6% between the LC and the HC version, resulting in a overall increase in wing mass of 10.6%. Thus, for all three uncertain parameters, it can be shown clearly that they have a significant effect on the resulting aircraft's total mass and mass distribution. The exponential growth due to the snowball-effect and interactions between the parameters shows the relevance of credible assumptions in the aircraft design process. For these hybrid-electric aircraft, only a fraction ($\leq$ 7%) of the total propeller shaft power is provided by the secondary powertrain, and a maximum of 10% of the energy use in cruise comes from batteries. Thus, although the impact on the individual component masses are large, the overall increase in maximum takeoff mass is only 3.5%. As the necessity to reduce airframe mass is especially high for electric aircraft, these results show the relevance of assessing input parameters for their credibility for the given timeframe of any (hybrid-) electric aircraft design. For more electrified designs, the increases in mass and power will be even larger due to the exponential nature and may impact the credibility of such designs for the near future.

5. Conclusions

The paper presents a novel approach to quantify assumed technological advances for futuristic aircraft concepts. The proposed credibility criterion assesses the probability that at a specified time a certain technology will have reached at least a certain performance level. Six parameters were chosen as uncertain and of high impact on futuristic (hybrid-) electric aircraft designs. These parameters cover battery and fuel cell systems, electric motor performance as well as novel airframe technologies. For each parameter, a thorough literature study regarding the current state-of-the-art and expected improvements in the future was performed. Probability distributions were fitted to represent the probability of performance levels for 2035, from which the resulting credibility distributions can be directly extracted. For the battery energy density and possible performance improvements,

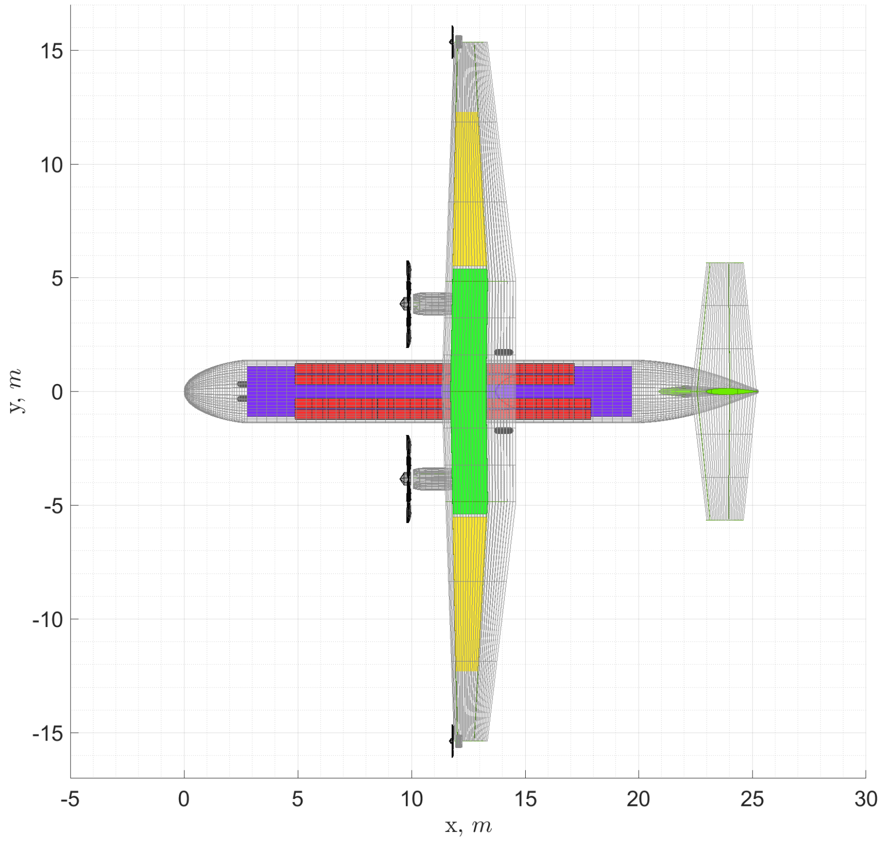

Figure 17 – Analysed Hybrid-electric Regional Aircraft (shown is the LC version)

probability distributions can be fitted well due to sufficient pre-existing data in literature. For electric motor power densities, the field shows clear trends, yet some novel technologies are emerging that could lead to larger than expected improvements in the mid-future. Regarding the investigated airframe technologies of laminar flow control and advanced composite manufacturing techniques, the low current TRLs and resulting scarce performance data make reliable estimations for a specific timeframe difficult. For such technologies, a distribution over the generally expected performance improvements independent on a specific date is a suitable approach.

The application of the presented credibility criterion to the provided serial/parallel partial hybrid regional aircraft has shown that even for aircraft designs that only use electric power for a small fraction of the total required propulsive power in flight, uncertainties regarding future performance of energy network components can have a significant impact on the aircraft design and performance. The influence of small changes in the component gravimetric density for this small energy network already showed a 3.5% increase in the maximum takeoff weight of the aircraft. Hence, it can be expected that for (hybrid-) electric aircraft that utilise the electric network for a significant part of the total propulsive power, these influences will be significantly higher and will have a direct impact on the feasibility of electric architectures for different aircraft classes and the credibility of the respective aircraft design.

In future research, the created credibility curves will be applied to a wider range of (hybrid-) electric aircraft with significant levels of electrification, and to optimise ambitious design concepts under credibility constraints.

Table 6 – Comparison of Key Parameters for the Resulting LC and HC Designs

Parameter	LC	HC	Difference [%]
Wing Area $[m^2]$	78.69	81.39	3.43
Wing Span $[m]$	30.73	31.25	2.57
Motor Mass $[kg]$	55.00	95.59	73.8
Generator Mass $[kg]$	72.19	124.9	73.0
Wing Mass $[kg]$	5759	6367	10.56
Battery Mass $[kg]$	2852	3296	15.6
Maximum Takeoff Mass $[kg]$	27189	28131	3.46
Total Generator Power $[MW]$	1.022	1.050	2.73
Total Motor Power $[kW]$	778.4	803.6	3.24
Total Thrust $[kN]$	48.9	50.7	3.50

6. Acknowledgment

Research presented in this publication was performed under the CHYLA project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101007715.

The authors wish to thank Vincent Bonnin and Maurice Hoogreef from the Department of Aerodynamics, Wind Energy, Flight Performance and Propulsion of the Aerospace Engineering Faculty of Delft University of Technology for the provided aircraft designs and performance figures used in this publication.

7. Copyright Statement

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