DESIGN SPACE EXPLORATION FOR SMALL AIRCRAFT WITH HYBRID-ELECTRIC POWERTRAINS AND DISTRIBUTED ELECTRIC PROPULSION

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Abstract

Due to the ongoing technological progress in the field of electric components, such as motors, batteries and power electronics, the electrification of aircraft powertrains is becoming increasingly relevant. In these days, this is particularly true when it comes to general aviation class aircraft. The prospect of designing and building better aircraft in terms of efficiency and operating costs due to electric components in aircraft powertrains has resulted in a recent increase in development projects of “small” aircraft. While first companies have already demonstrated the flight capabilities of hybrid- and all-electric aircraft, several others are set to start developing and testing. Many of those new vehicles are designed for on-demand air mobility (ODAM) transportation options, which are envisioned to provide affordable air transportation on short- and regional-distance missions. While most vehicles for ODAM for intra-urban routes are designed with vertical takeoff and landing capability, it is expected that aircraft for regional-distance missions will still need to be designed as fixed-wing aircraft for conventional takeoff and landing procedures in the future. This is mainly due to efficiency reasons. One of the ideas to take advantage of the benefits of electric propulsion for small fixed-wing aircraft is sizing the wing for cruise flight conditions instead of high-lift conditions, resulting in a smaller wing due to higher airspeeds in this design point. The smaller wing is more efficient during cruise flight, which is usually the longest mission segment, while the necessary high-lift during takeoff and landing can be provided by an active high-lift system. This active high-lift system consists of several propellers attached to the wing’s leading edge. The most popular example for a configuration like this is NASA’s X-57 Maxwell aircraft.

In recent months, the Institute of Aerospace Systems’ (ILR) multidisciplinary integrated conceptual aircraft design and optimization environment MICADO has been extended to model small aircraft with conventional, hybrid- and all-electric powertrains. This also includes the capability of modeling active high-lift systems based on distributed electric propulsion (DEP) technology. The first part of this paper gives an overview of the process of modeling small aircraft with DEP technology within MICADO. A special focus is on electric components of the powertrain and the propeller-wing-interaction model. In the second part, the results of a multi-dimensional study on the design space for small aircraft with hybrid- and all-electric powertrains and DEP as active high-lift system are presented. Study parameters comprise the degree of hybridization, the number of high-lift propellers, design maximum high-lift coefficient, cruise speed, wing aspect ratio and the influence of battery energy density.

1. INTRODUCTION

Although the very first beginnings of electric flight go back several decades, significant progress in this field has not been made until recent years. In the last decade, however, technological progress in the field of electric components has significantly increased and has now reached a level that makes all-electric and hybrid-electric aircraft a feasible solution for certain applications in aviation. This has already driven many companies towards developing all-electric or hybrid-electric aircraft. Many projects are in the field of intra-urban mobility and rely on vertical takeoff and landing (VTOL) capability. Others aim at building new air vehicles for short routes and the so-called thin-haul market. Only a few projects so far intend to develop electric aircraft for the regional market segment. All of the projects, however, have to cope with the fact that storage solutions for electric energy available today are far from reaching the performance level of fossil fuel in terms of gravimetric and volumetric energy density. That is why aircraft designers need to know in detail what the impact of their design decisions is on the performance of their vehicle.

In general, the introduction of electric components to aircraft powertrains comes with several new configurational options for aircraft designers. On the top level, the distribution of mission energy on different storage options, such as fuel tanks, batteries or hydrogen tanks, can be chosen. Moreover, the rather free scalability of electric engines without efficiency losses offers new possibilities with respect to the number of engines installed. Distributed propulsion technology can be used for, e.g., allocating thrust generation to more than the usual one or two engines or to designing active high-lift

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systems. The latter is a rather new approach. It has come to public attention, in particular due to NASA's X-57 Maxwell aircraft [7]. The idea of designing general aviation class all-electric and hybrid-electric aircraft with distributed electric propulsion (DEP) as active high-lift system was taken up at the Institute of Aerospace Systems (ILR) and implemented in ILR's conceptual aircraft design environment MICADO.
Following a discussion of the current state of the art, a brief overview on ILR's design tool is given. After that, a study on the impact of design parameter variations for all- and hybrid-electric aircraft with distributed electric propulsion as active high-lift system is conducted. The study parameters comprise the degree of hybridization, the number of high-lift propellers, design maximum high-lift coefficient, design cruise speed and wing aspect ratio. Since battery energy density is a key aspect with regard to technical feasibility of electric aircraft, its impact is investigated.

2. STATE OF THE ART

As part of the Scalable Convergent Electric Propulsion Technology Operations Research (SCEPTOR) project [1], NASA has been investigating for several years how the efficiency of small aircraft can be increased through both the use of electric motors and the concept of distributed propulsion. In addition to the generally increased efficiency in electric powertrains compared to conventional powertrains, the use of DEP is intended to improve aerodynamic efficiency as well. The reason for this is that the wing of today's general aviation class aircraft must be relatively large in order to produce sufficient lift in low-speed flight conditions. In cruise flight, however, the large wing is rather inefficient. For demonstration purposes, a Tecnam P2006T, originally powered by two conventional piston engines, will be equipped with an all-electric powertrain. The idea of SCEPTOR is to distribute propellers at the leading edge of the wing, which in low-speed flight provide an additional flow to the wing and thus increased lift. This allows the wing area to be smaller overall. Consequently, the efficiency of the cruise flight efficiency, usually the longest mission phase, is improved. Prior to the technical conversion of the demonstrator aircraft, extensive studies at different levels of detail, e.g. in Borer et al. [1], and in Borer and Moore [8], were carried out to identify the best possible configuration. In conclusion, for an all-electric retrofit of the Tecnam P2006T an aspect ratio of $\Lambda = 15$ was identified as most efficient. This is almost double the original wing's aspect ratio ($\Lambda = 8.8$). Moreover, 12 high-lift propellers in total are distributed along the wing's leading edge, 6 on each side of the aircraft. Selected cruise conditions are a true airspeed of 150 kn (278 km/h) and 8,000 ft altitude.

Within the scope of a doctoral thesis by Kreimeier [6], various all-electric and hybrid-electric small aircraft designs for on-demand air mobility concepts were examined at ILR. In particular, configurations with distributed electric propulsion (DEP) for providing active high-lift were considered. Since the studies carried out in this paper are follow-up studies to the work of Kreimeier, a short but not exhaustive overview of Kreimeier's results [6] is given.
For analyses of general aviation class aircraft, the MICADO design environment, initially intended for the conceptual design and evaluation of airliners, was extended in advance to include functionalities for the preliminary design of small aircraft. As a starting point, Kreimeier used publicly available data to model two different design points of the Cirrus SR22T G5 in order to validate the extended design method for small aircraft and to calibrate the model itself. A comparison of the results from the modeling with the characteristics of the Cirrus SR22T G5 revealed that useful results can be generated with the selected calibration settings. Based on the calibration of the model on the Cirrus SR22T G5, Kreimeier examined the influence of design parameter changes on mainly maximum takeoff mass and operating costs for various small aircraft configurations. Aircraft designs with both all-electric and hybrid-electric powertrains were investigated. The configurations included a conventional version with a central propeller in the aircraft nose and a new version with two thrust generating propellers at the wing tips and high-lift propellers distributed over the wing leading edge. The latter variant is comparable to NASA's X-57 Maxwell configuration.
With regard to conventional aircraft configurations, Kreimeier investigated the influence of combinations of aspect ratio and cruise speed, design range and cruise speed, and battery specific energy and design range with respect to maximum takeoff mass and operating costs. The influence of the aspect ratio on the maximum take-off mass is rated as rather low. However, their influence increases with increasing design cruise speed. At high cruise speeds (400 km/h), the total mass of the aircraft increases sharply. While at moderate flight speeds (250-300 km/h) an increase of the aspect ratio has a positive effect on the total energy demand for the mission, at high design cruise speeds the energy demand increases with increasing aspect ratio. An increase in the design range is associated with an increasing maximum take-off mass. This is because more energy and thus more battery mass must be included for the longer transport distance. Since the energy density of batteries is considerably lower than that of fossil fuels, the additional demand for energy is all the more important. The increase in maximum takeoff mass in relation to the design range is overproportionately. This effect is amplified by both increasing design cruise speeds and decreasing battery energy density. With regard to increasing

battery energy density, it should be noted that the possibility of saving total takeoff mass through more efficient batteries is not linear but decreases as batteries become more efficient in terms of gravimetric energy density. This results from the obvious fact that the higher the battery energy density is, the lower the battery's weight gets. This in turn leads to a lower total weight, which results in a smaller energy demand for the mission and thus, enables a smaller and lighter battery.
Kreimeier concludes from the variation of aspect ratio in conventional layouts that the influence on the aircraft design is only moderate. Consequently, the influence of wing aspect ratio in aircraft with active high-lift by DEP was not investigated. For these aircraft, Kreimeier analyzed the influence of the number of high-lift propellers, the design high-lift coefficient to be achieved by using DEP and the influence of design cruise speed. The results show that the influence of the number of high-lift propellers on the aircraft mass is coupled with the magnitude of the design high-lift coefficient. While the number of high-lift propellers has almost no influence on the aircraft mass when the aircraft is designed for small high-lift coefficients, this changes with increasing design high-lift coefficient. A local minimum of aircraft mass can then be found around 10 high-lift propellers. If design cruise speed is included as a further parameter in the study, it can be seen that the use of active high-lift provided by DEP only pays off with increasing cruise speed. While the aircraft mass increases with increasing design high-lift coefficient when designed for low cruise speeds, this effect reverses as the design cruise speed increases. Although the aircraft will then become heavier overall, the use of DEP will contribute to a relative weight reduction. Based on data from Kreimeier [6], this relationship is shown in FIG. 1.

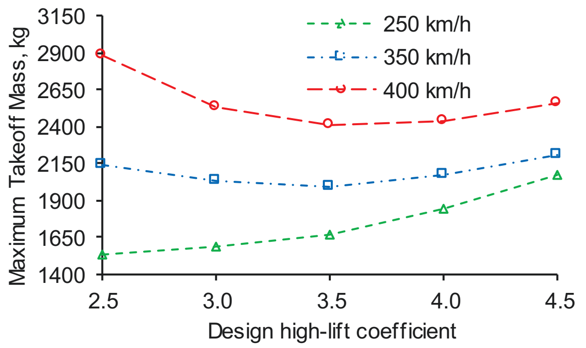

FIG. 1 Influence of design high-lift coefficient on maximum takeoff mass at different design cruise speeds based on [6]

3. AIRCRAFT CONCEPTUAL DESIGN WITH MICADO

The multidisciplinary integrated conceptual aircraft design and optimization environment (MICADO) has been developed to perform fast evaluations of different aircraft concepts in terms of technical, economic and environmental aspects. While previous versions of MICADO were limited to the design and evaluation of CS-25 class aircraft, a major extension has added capabilities to model small aircraft according to EASA's CS-23 standards [6]. In addition to conventional powertrain layouts with combustion engines, new design options include hybrid-electric and all-electric powertrains. In the following, a brief overview on the MICADO design loop in general, as well as the modeling of distributed electric propulsion and active high-lift systems in more detail is given.

3.1. General design and sizing loop

The program structure of MICADO follows the typical iterative process of preliminary aircraft design. A visualization of the modular program structure is given in FIG. 2.

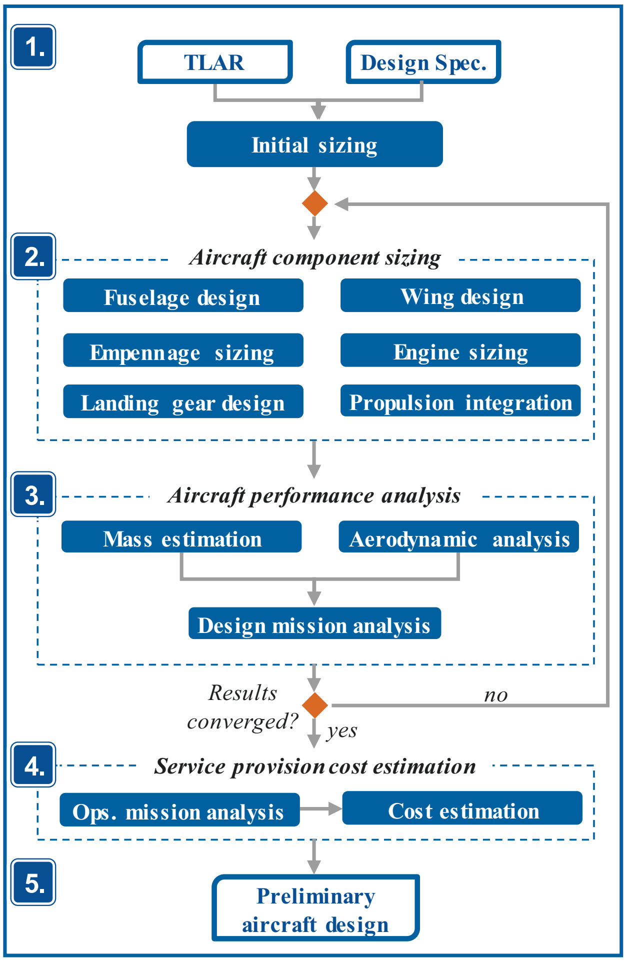

FIG. 2 Functional structure of the MICADO design loop

First, based on market studies and customer wishes, top level aircraft requirements (TLARs) as well as design specifications, such as number of engines and type of powertrain, can be chosen. Next, an initial sizing is carried out. Most important output of the initial sizing is the wing loading W/S and the power-to-weight ratio P/W. In addition, a first estimate of maximum takeoff mass is calculated. After that, the iterative part of the sizing loop follows. Based on

TLARs, design specifications and the output of the initial sizing, a detailed sizing of all aircraft components (step 2) is performed. This includes among others sizing and integration of the powertrain, which is described in more detail in section 3.2. In the subsequent performance analysis (step 3), a detailed estimation of aircraft component masses and aerodynamic performance is carried out. By means of simulating the design mission, the necessary amount of fuel and/or electric energy for the design mission can be estimated. Based on this outcome the corresponding fuel and/or battery mass is calculated. Steps 2 and 3 of the MICADO design loop are repeated until certain aircraft parameters, such as maximum takeoff mass and fuel/energy demand, meet preset convergence criteria. Post-processing steps may include the calculation of operating costs, environmental impact, and the rendering of a 3D model. An integrated parameter study manager and optimizer enables the user to carry out automated parameter studies and optimizations with regard to user-selected parameters. A more detailed description of MICADO can be found in Risse et al. [10].

3.2. Modeling of distributed electric propulsion and active high-lift systems

One of the essential innovations in the functional scope of MICADO is the possibility to model small aircraft with hybrid-electric and all-electric powertrains as well as distributed electric propulsion technology being employed as active high-lift system. While the first part of this section gives a brief overview on the method for modeling all-electric and hybrid-electric powertrains, the second part goes into more detail on the method for modeling distributed electric propulsion technology for generation of high-lift in low-speed flight conditions. A more detailed description can be found in Kreimeier [6].

The model for all-electric powertrains includes electric motors, converters, power controllers, batteries and cables connecting the individual components. For each component, the respective mass and efficiency are estimated and taken into account. The current version of MICADO is capable of modeling serial-hybrid powertrain architectures. In more detail, this means that electric power is provided by both batteries and an electric generator driven by a combustion engine. The combination of an electric generator and a combustion engine is called a range-extender. A hybridization degree ϕ is specified for the design of the range extender. This parameter defines the proportion of the power P_{bat} at the input side of the electric motors, which is contributed by the batteries. Accordingly, $(1-\phi)$ is the share of electric power that needs to be provided by the range extender.

The aircraft design under investigation employs propellers for provision of thrust and active high-lift. The propellers are directly attached to electric motors distributed along the wing's leading edge. Depending on the type of powertrain, the power provision to the electric motors differs. With all-electric powertrains, the electric motors are solely connected to batteries. In contrast, electric motors within hybrid-electric powertrains are provided with electric power by both a range extender unit and batteries. The range extender unit consists of a piston engine whose shaft is linked to an electric generator producing alternating current (AC). For both powertrains, the model includes power controllers, converters and cables.

In the *Engine sizing* module, two different types of propulsion units, consisting of a combination of propeller and electric motor, are designed. While the first type is meant for producing thrust during cruise flight conditions, the second type is primarily designed for generating high-lift in low-speed flight conditions. In the course of this paper, these two types are referred to as *cruise propellers* and *high-lift propellers*, respectively.

Regarding the cruise propellers, the interaction of propeller wake and wing aerodynamics is neglected. For this reason, a rather simple approach is used to size the cruise propellers and described in the following. Required shaft power for each cruise propeller is determined according to the initial sizing's thrust-to-weight ratio and the current maximum takeoff mass (MTOM). The diameter of cruise propellers is sized as large as possible. However, a diameter limitation of $d_{max} = 1.5\ m$ is applied to allow high-lift propellers to cover as much of the wingspan as possible. Next, a generic propeller map from Gudmundsson [4] is combined with the efficiency map of an electric motor scaled to the required shaft power. Lift and induced drag of the clean wing configuration are calculated using DLR's LiftingLine [5] software. The induced drag is supplemented by form and friction drag based on semi-empirical formulas within the aerodynamics module of MICADO. By using a further set of semi-empirical formulas, the influence of flap deflections on lift and drag polars is considered. Finally, lift and drag polars for the occurring flight conditions are calculated.

Since for the second propulsion type high-lift propellers are used for slipstream-induced lift augmentation, it is imperative to take into account the interaction of propeller wake and wing aerodynamics. For this reason, a more complex design procedure is necessary for the sizing of high-lift propellers. By means of an iterative coupling of blade element theory and impulse theory (BEMT), the induced speed in the propeller wake is determined as a function of cruise speed, aircraft angle of attack, propeller speed and input power on the propeller shaft. Required inputs for the BEMT are propeller geometry and blade airfoil data, both taken from Patterson et al. [9] as suggested for the SCEPTOR project. The presence of the wing behind the propellers is neglected when BEMT is executed. Up to a diameter of 0.8 m high-lift propellers are sized as large as possible. The upper threshold is applied to avoid undesired thrust production. The implementation of an iterative loop ensures that the engine power of the electric motors is sufficient to meet the design maximum high-lift coefficient requirement. Dynamic pressure multipliers that indicate the factor by which the dynamic pressure at the wing increases during operation of the high-lift propellers are calculated. The calculations consider the installation position of the high-lift propellers relative to the wing as well as the contraction of the propeller wake dependent on installation position and operating condition. A look-up table for the dynamic pressure multipliers, called prop-wing-interaction-map, is created for a predefined set of flight and high-lift propeller operating conditions. Within the mission analysis tool, the prop-wing-interaction-map is used to determine lift and drag of the aircraft during high-lift propeller operation. Again, clean wing aerodynamics are provided by calculations from LiftingLine [5].

4. DESIGN SPACE EXPLORATION

Aircraft can be evaluated and optimized according to many different evaluation criteria. The most frequently used criteria are fuel and electrical energy demands as well as operating costs. Other criteria may include aircraft mass, cruise speed or emissions. In contrast to previous analyses at ILR [6], the focus of this work is not economic viability but energy consumption of aircraft with all-electric and hybrid-electric powertrain architectures. Instead of comparing aircraft designs with respect to maximum takeoff mass, the block energy demand on the design mission is evaluated. Similar to the analyses of Kreimeier [6], the influence of the three design parameters number of high-lift propellers, design high-lift coefficient and design cruise speed on block energy consumption is examined. In addition, the influence of wing aspect ratio is considered.
To allow for easy comparison with all-electric aircraft, for hybrid-electric aircraft the total block energy demand $\mathrm{E_{total}}$, resulting from the sum of the required electrical energy $\mathrm{E_{el}}$ and the energy $\mathrm{E_{fuel}}$ from the fuel, is determined. Therefore, the mass $\mathrm{m_{fuel}}$ of the burned fuel is multiplied by the energy density of aviation gasoline [2]:

(1) $$E_{total} = E_{el} + E_{fuel} = E_{el} + m_{fuel} \cdot 12.083\ kWh/kg$$

4.1. Description of aircraft baseline configuration

The aircraft in this analysis is designed to carry up to four passengers including a pilot. In more detail, the design payload is chosen to be 306.8 kg, which corresponds to the full fuel payload of the Cirrus SR-22. This amount of payload is assumed sufficient for three people aboard including light baggage. Regarding configurational aspects, the baseline aircraft is designed as follows: the design of the fuselage follows the tadpole style. The high wing with an aspect ratio of $\Lambda = 15$ is accompanied by a conventional tail. Similar to NASA's X-57 Maxwell, one cruise propeller is attached to each wing tip. Furthermore, the baseline aircraft is equipped with 12 high-lift propellers which are equally distributed along the wing's leading edge. The arrangement of the high-lift propellers is done in a way, which allows folding away the high-lift propellers during cruise conditions in order to reduce aerodynamic drag. The design maximum high-lift coefficient is $c_{L,max}^{DEP} = 3.0$. It is assumed that this value can only be achieved when high-lift propellers are activated. Furthermore, the baseline aircraft is designed for a stall speed of $v_{stall} = 58\ kn$.
With regard to current state of the art battery technology, battery weight is probably the most restrictive factor for designing all-electric powered aircraft. Design ranges that can be easily achieved by using fossil fuels as an energy source are not possible when batteries alone are used as energy storage devices. Moreover, with regard to a whole flight mission, not only energy for the actual flight between origin and destination, but reserves for alternate routes or holding must be carried with. In order to obtain aircraft designs with maximum takeoff masses that correspond approximately to those of comparable, conventionally powered aircraft, the all-electric aircraft in this analysis are designed for a range of only 300 km. Furthermore, reserves for additional 45 minutes of flight at a power setting of 55% are taken into account. Design cruise speed is chosen to be 300 km/h at a cruise altitude of 12,000 ft. The baseline configuration is shown in FIG. 3.

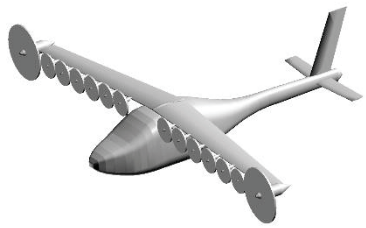

FIG. 3 Aircraft in baseline configuration

4.2. Analysis for all-electric aircraft configurations

To illustrate the influence of battery energy density on aircraft design, a study on this parameter is performed. While a battery energy density of 250 Wh/kg roughly corresponds to the current state of the art, a battery energy density of around 400 Wh/kg could be possible in 2030 according to the Fraunhofer Institute for Systems and Innovation Research ISI [3]. Aircraft designs with battery energy densities between 250 Wh/kg and 400 Wh/kg at pack level are calculated with a step size of 25 Wh/kg.

Results of the study in the form of block energy demand and maximum takeoff mass are shown in FIG. 4.

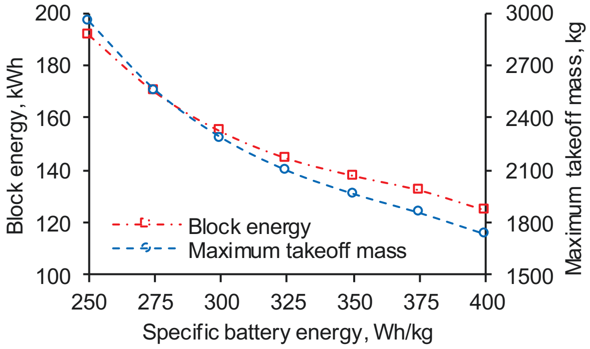

FIG. 4 Influence of specific battery energy on maximum takeoff mass and block energy

FIG. 4 clearly shows that the battery energy density has a strong influence on both energy demand and maximum takeoff mass. Both parameters decrease for increasing battery energy density. While the energy demand drops from about 190 kWh at 250 Wh/kg to around 125 kWh at 400 Wh/kg, the maximum take-off weight is reduced from about 2950 kg to 1730 kg. Overall, however, it also turns out that the positive effect of saving mass and energy by increasing the battery energy density is not linear, but declines towards higher battery energy densities. This is due to the already mentioned effect that higher battery energy densities lead to lighter batteries and thus to lower takeoff mass. The lower takeoff mass, in turn, results in lower energy demands for the mission and thus also in lighter batteries.

4.2.1. One-dimensional analysis of design parameters for all-electric aircraft

In a next step, the influence of variation of a single design parameter on the block energy demand during the design mission is investigated. The results are determined for specific battery energy densities of 250 Wh/kg and 400 Wh/kg at pack level, respectively. By considering these two specific energy densities, the progress expected over the next years in the field of battery technology is to be reflected.

Results of an investigation on the influence of different numbers of high-lift propellers are shown in FIG. 5. The number of high-lift propellers is varied from 8 to 16 in steps of 2. In each case, high-lift propellers are equally distributed to both wings.

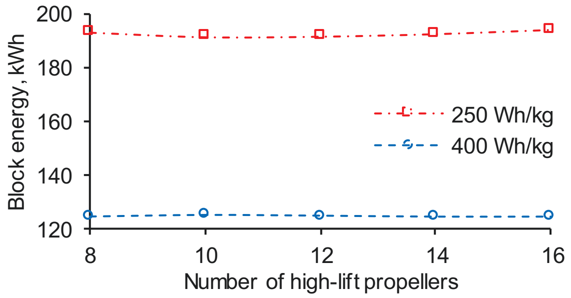

FIG. 5 Influence of the number of high-lift propellers on block energy demand

The diagram reveals that, in relation to the baseline configuration, there is almost no influence of the number of high-lift propellers on the block energy demand for the design emission. This applies to both the lower and the higher battery energy density. The results shown in FIG. 5 are in good agreement with the previously discussed findings regarding the change of takeoff mass with variation of the number of high-lift propellers by Kreimeier [6] for comparable aircraft configurations. The influence of the number of high-lift propellers on aircraft performance at deviating design cruise speeds and design high-lift coefficients as described by Kreimeier [6] will be discussed in the further course of this paper.

Starting with the baseline aircraft's aspect ratio of $\Lambda = 15$, this parameter is varied from 12 to 18 with a step size of $\Delta_\Lambda = 1.5$. Results for the two selected battery energy densities are shown in FIG. 6.

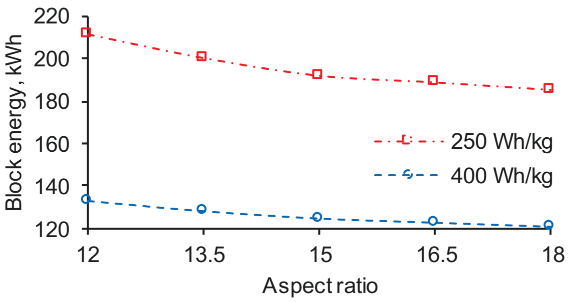

FIG. 6 Influence of aspect ratio on block energy demand

Overall, it becomes clear that an increase in aspect ratio has a positive effect on energy demand for the design mission. This is expressed by a monotonously falling curve for the block energy demand. This generally applies to both battery energy densities examined. However, it is noticeable that the effect of saving energy is greater for lower battery energy densities. As for a battery energy density of 400 Wh/kg it is observed that the influence of the aspect ratio, as assumed by Kreimeier [6], is rather small.

Next, the influence of the design high-lift coefficient $C_{L,max}^{DEP}$ is investigated and results are presented in FIG. 7.

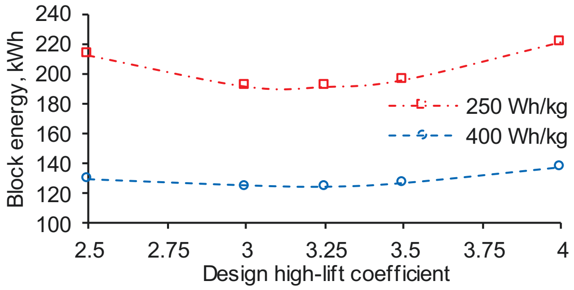

FIG. 7 Influence of design high-lift coefficient on block energy demand

In contrast to the aspect ratio, the results of the investigation on the influence of the design high-lift coefficient $C_{L,max}^{DEP}$ do not show a monotonous course in the range under consideration, but a course with a local minimum. As can be seen in FIG. 7, this minimum is approximately between $3.0 \leq C_{L,max}^{DEP} \leq 3.5$ regardless of the energy density. Nonetheless, results indicate again that the effect is much more pronounced at lower battery energy densities.

The last parameter to be investigated is design cruise speed. To do this, design cruise speed is varied between 200 km/h and 400 km/h with a step size of 50 km/h. The resulting block energy demand for aircraft designs with battery energy densities of 250 Wh/kg and 400 Wh/kg is presented in FIG. 8.

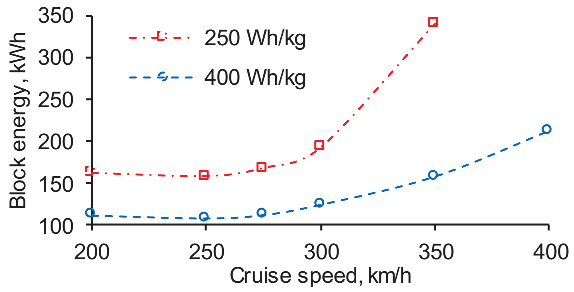

FIG. 8 Influence of design cruise speed on block energy demand

As can be seen from FIG. 8, the choice of cruise speed has a considerable influence on block energy demand. This applies to both considered battery energy densities. However, the effect is lower for the higher battery energy density. Starting at the lowest design cruise speed investigated of 200 km/h, block energy demand remains rather stable up to a design cruise speed of 300 km/h of the baseline configuration. A further increase in design cruise speed results in a sharp increase in energy consumption. It is noted that for aircraft configurations with a specific battery energy density of 250 Wh/kg and design cruise speed above 350 km/h, the weight of the battery becomes so heavy that the design loop no longer converges.

4.2.2. Multi-dimensional analysis of design parameters for all-electric aircraft

Following the investigation of the influences by changing only one variable, the effects by varying several variables simultaneously are analyzed below. The study parameters include aspect ratio, number of high-lift propellers, design cruise speed and design high-lift coefficient. Since results so far have revealed that low battery energy densities lead to inefficient and heavy aircraft designs, only a – yet to develop - battery energy density of 400 Wh/kg is considered for the following investigations.
The study of the variation of the design cruise speed has shown that it has a great influence on the energy demand for the overall mission (see FIG. 8). With increasing design cruise speed, the energy demand also increases. The same picture can be seen in the multi-dimensional analysis of design parameters, as shown in FIG. 9. The diagrams show the block energy demand for different aircraft designs. Each diagram includes 60 designs according to their design high-lift coefficient.

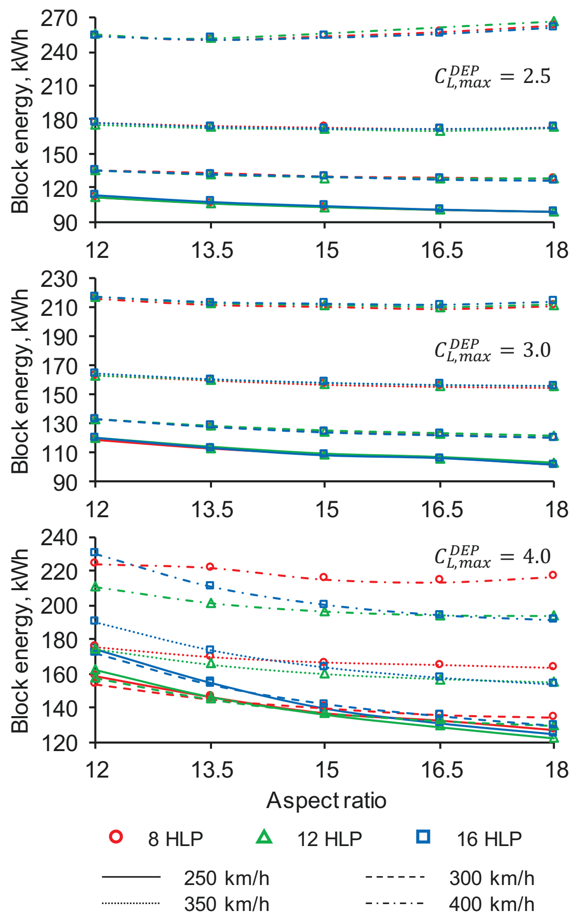

FIG. 9 Results of multi-dimensional analysis grouped by design maximum high-lift coefficient

The upper diagram shows the resulting block energy demand for aircraft designs with a design high-lift coefficient of $C_{L,max}^{DEP} = 2.5$. It can be seen that the number of high-lift propellers has almost no influence

on the block energy demand. In contrast, an increase in design cruise speed is a strong driver for block energy demand. At $v_{cr} = 400\ km/h$ the required energy is about twice as large as at $v_{cr} = 250\ km/h$. In general, the influence of the wing's aspect ratio is rather small. Except for designs with $v_{cr} = 400\ km/h$ an increase in aspect ratio results in smaller block energy demand. In contrast, there is a slight trend towards increased block energy demand with increased aspect ratios for aircraft designs with $v_{cr} = 400\ km/h$.
Results for aircraft designs with a design high-lift coefficient of $C_{L,max}^{DEP} = 3.0$ are presented in the middle diagram of FIG. 9. Qualitative conclusions to be drawn from this diagram are very similar to the diagram described before. An exception regards the results for aircraft designs for $v_{cr} = 400\ km/h$ with regard to the influence of aspect ratio. In contrast to the findings associated with the lower design high-lift coefficient, an increase in aspect ratio results in decreasing block energy demand. This is expressed by monotonously falling curves.
A less distinct picture is drawn by the output of a study on aircraft with a design high-lift coefficient of $C_{L,max}^{DEP} = 4.0$. Regarding design cruise speed, results for block energy demand for aircraft designs with $v_{cr} = 250\ km/h$ and $v_{cr} = 300\ km/h$ are relatively close together. Regarding higher design cruise speeds, energy demand increases proportionately to speed, similar to the findings in the diagrams analyzed before. In contrast to aircraft with design high-lift coefficients of $C_{L,max}^{DEP} = 2.5$ and $C_{L,max}^{DEP} = 3.0$, the number of high-lift propellers has an influence on block energy demand for aircraft with a design high-lift coefficient of $C_{L,max}^{DEP} = 4.0$. It can be seen that a large number of high-lift propellers is efficient for high design cruise speeds while a small number of high-lift propellers is more efficient for small design cruise speeds. In addition, it turns out the number of high-lift propellers has an influence on the influence of the aspect ratio. While the influence of aspect ratio on block energy demand is small for 8 high-lift propellers, the influence of aspect ratio increases with increasing number of high-lift propellers.

In FIG. 10, the same data is shown as in FIG. 9. However, the grouping is changed. While in FIG. 9 the data is grouped according to the design high-lift coefficient, in FIG. 10 the data is grouped according to the design cruise speed. This form of representation clearly shows how the change in the design high-lift coefficient affects the block energy demand for different design cruise speeds. At the smallest design cruise speed investigated (250 km/h), the block energy demand increases with increasing design high-lift coefficient. If design cruise speed is raised, it can be seen that an increase in the design high-lift coefficient can contribute to more energy-efficient aircraft configurations. Already at a design cruise speed of $v_{cr} = 300\ km/h$ the aircraft configurations with a design high-lift coefficient of $C_{L,max}^{DEP} = 3.0$ are more efficient than the aircraft configurations with a design high-lift coefficient of $C_{L,max}^{DEP} = 2.5$. At a design cruise speed of $v_{cr} = 400\ km/h$, the most efficient aircraft configurations can be designed by using wings with medium to high aspect ratio, 12-16 high-lift propellers and a design high-lift coefficient $C_{L,max}^{DEP} = 4.0$.

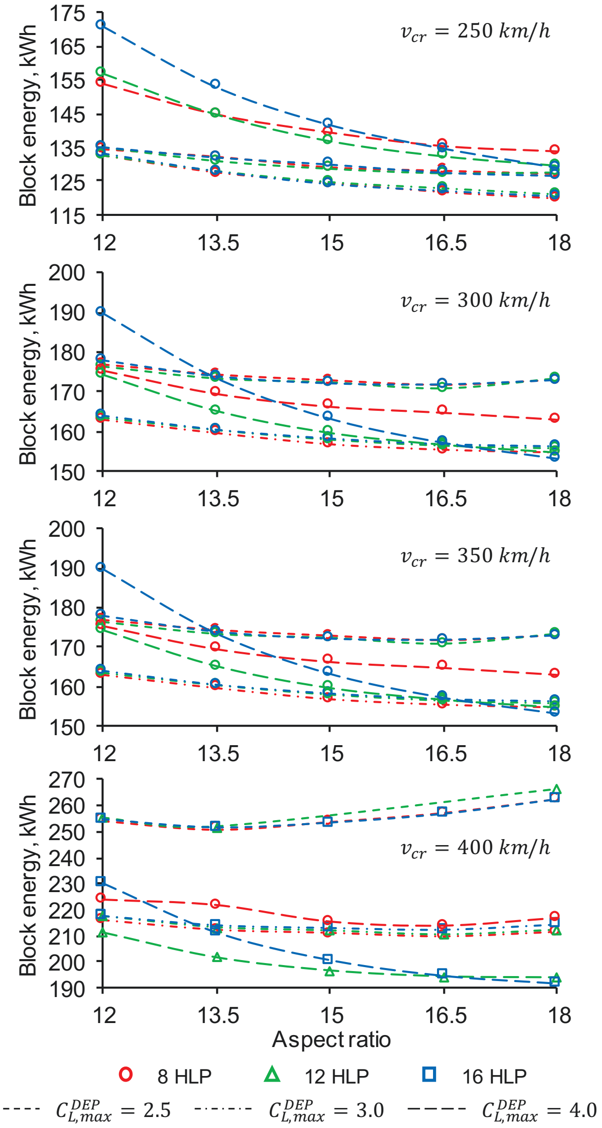

FIG. 10 Results of multi-dimensional analysis grouped by design cruise speed

Summarizing this subsection it is concluded that cruise speed is the main driver for block energy demand. The influence of the number of high-lift propellers needs to be taken into account for aircraft designs with large design high-lift coefficients and high design cruise speeds. In addition to the results of Kreimeier [6], it should be noted that the influence of aspect ratio should not be neglected.

4.3. Analysis for hybrid-electric aircraft

For aircraft with a hybrid-electric powertrain

architecture, the same study is carried out. In order to enable a direct comparison with the results for all-electric aircraft, the hybrid-electric aircraft are designed towards the same set of TLARs within the scope of this analysis. Two degrees of hybridization $\phi_1 = 33\%$ and $\phi_2 = 66\%$ are considered. Following the procedure of the analyses of the all-electric aircraft configurations, the influence of the same design parameters are investigated. In a first step, the influence of changing only one design parameter from the baseline configuration is considered.
Results of a study on the influence of the number of high-lift propellers on block energy and maximum takeoff mass are shown in FIG. 11. The number of high-lift propellers was varied between 8, 12 and 16.

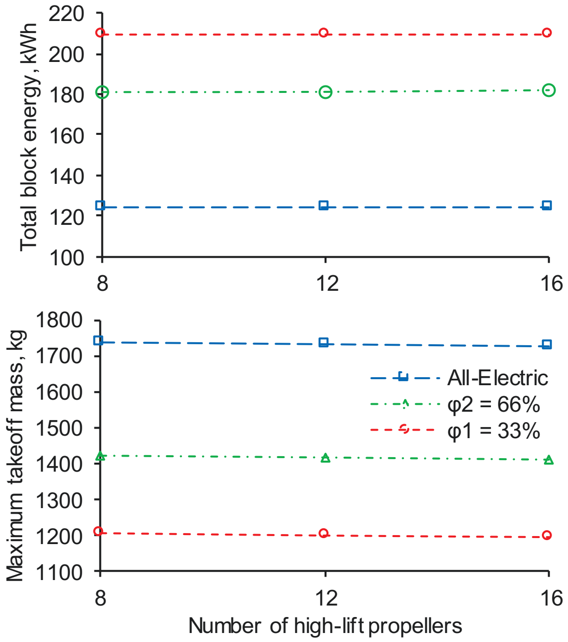

FIG. 11 Influence of the number of high-lift propellers on total block energy demand and maximum takeoff mass

Comparable to the findings from the investigations of all-electric aircraft, a variation of the number of high-lift propellers has only a small influence on total block energy demand and maximum takeoff mass of hybrid-electric aircraft. A comparison between aircraft with different degrees of hybridization reveals that, due to the high weight of batteries, the all-electric configurations are by far the heaviest. As can be seen in FIG. 11, in contrast to just over 1700 kg for the all-electric configurations, maximum takeoff mass of about 1200 kg is calculated for the configurations hybridized to 33%. A hybridization degree of $\phi_2 = 66\%$ results in maximum takeoff mass of around 1400 kg, which is between the other two groups. From the available data, it is concluded that an increasing degree of hybridization further increases the mass growth.
Surprisingly, as can be seen in FIG. 11, the block energy demand can be reduced by an increasing degree of hybridization despite increasing maximum takeoff mass. While all-electric aircraft configurations require approximately 120 kWh total block energy to perform the design mission, regardless of the number of high-lift propellers, a total energy demand of approximately 210 kWh is necessary for the configurations hybridized to 33%. The high overall energy demand for hybrid-electric configurations is in particular due to the low efficiency in the conventional part of the powertrain. While the efficiency in the electrical part of the powertrain between battery and propeller shaft is around 90%, the efficiency in the hybrid part of the powertrain from fuel tank to propeller shaft is around 30%.
It can be seen that the need for block energy for the design mission decreases significantly more for a transition from an aircraft hybridized to 66% to an all-electric aircraft than when the degree of hybridization increases from 33% to 66%. The conclusion is drawn that the reduction in total energy consumption increases disproportionately to the degree of hybridization.

Next, the influence of aspect ratio on block energy demand and maximum takeoff mass is investigated. To do this, is aspect ratio varied between $\Lambda = 12$ and $\Lambda = 18$ with a step size of $\Delta_\Lambda = 1.5$. The outcome of this study is presented in FIG. 12.

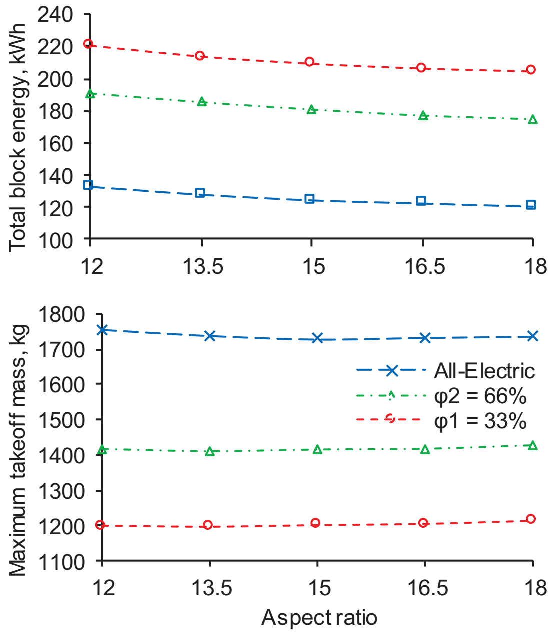

FIG. 12 Influence of the aspect ratio on total block energy demand and maximum takeoff mass

With regard to the influence of the aspect ratio on the total energy demand, the hybrid-electric configurations behave qualitatively the same as the all-electric configurations. This means that the total energy demand for the design mission can be reduced by increasing the aspect ratio. While an increase of the aspect ratio from 12 to 18 leads to a reduction of the energy demand by about 8-10%, the maximum takeoff mass at the examined points varies by only about 1.5%.

An analysis of the variation of design cruise speed and design high-lift coefficient also provides the same qualitative results for the hybrid-electric configurations as for the all-electric configurations. This applies to both the total block energy demand and the maximum takeoff mass. For increasing design cruise speed starting at 250 km/h, both block energy demands and take-off mass increase sharply. With respect to the design high-lift coefficient, a local minimum for block energy and maximum takeoff mass is available between $3.0 \leq C_{L,max,DEP} \leq 3.5$ for both all-electric and hybrid-electric configurations. Again, the all-electric configurations are the most efficient whereas the least hybridized configurations are the least efficient. The maximum takeoff mass increases if the degree of hybridization is increased.

A multi-dimensional analysis of the influence of aspect ratio, number of high-lift propellers, design cruise speed and design high-lift coefficient reveals that hybrid-electric aircraft configurations, independent of the hybridization degree, behave qualitatively similar to all-electric aircraft configurations in terms of block energy demand. For this reason, a detailed analysis is dispensed with, the corresponding diagrams can be found in the appendix of this paper.

5. CONCLUSION AND OUTLOOK

The outcome of the presented analyses clearly underlines that further progress in battery technology is imperative to make electric flight feasible. Even when future specific battery energy of 400 Wh/kg is assumed and design range is reduced to 300 km, which is around one fifth to one quarter of the usual design range of conventionally powered small aircraft, MTOM of all-electric aircraft is at most as low as in conventionally powered aircraft designed to similar TLARs.

In order to use DEP as efficiently as possible, the design high-lift coefficient $C_{L,max}^{DEP}$ should increase with increasing design cruise speed. The influence of the number of high-lift propellers becomes more relevant with increasing design high-lift coefficients. For low design cruise speeds, in particular, the use of DEP does not seem promising.

Furthermore, it turns out that hybridization is a reasonable intermediate step towards all-electric aircraft. Due to the high efficiency of electric components, the overall energy demand can be reduced by using serial hybrid powertrains. In addition, aircraft configurations with hybrid-electric powertrains are not as heavy as all-electric aircraft.

The current version of MICADO provides a solid basis for the design and evaluation of general aviation class aircraft with conventional and new powertrain architectures. However, a continuous improvement is in progress. Current activities include the implementation of parallel-hybrid powertrain architectures, consideration of the influence of propeller slipstream on induced drag, an extension of engine and propeller databases, enhanced mass estimation methods for aircraft designs with DEP and the implementation of unconventional aircraft design options.

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6. APPENDIX

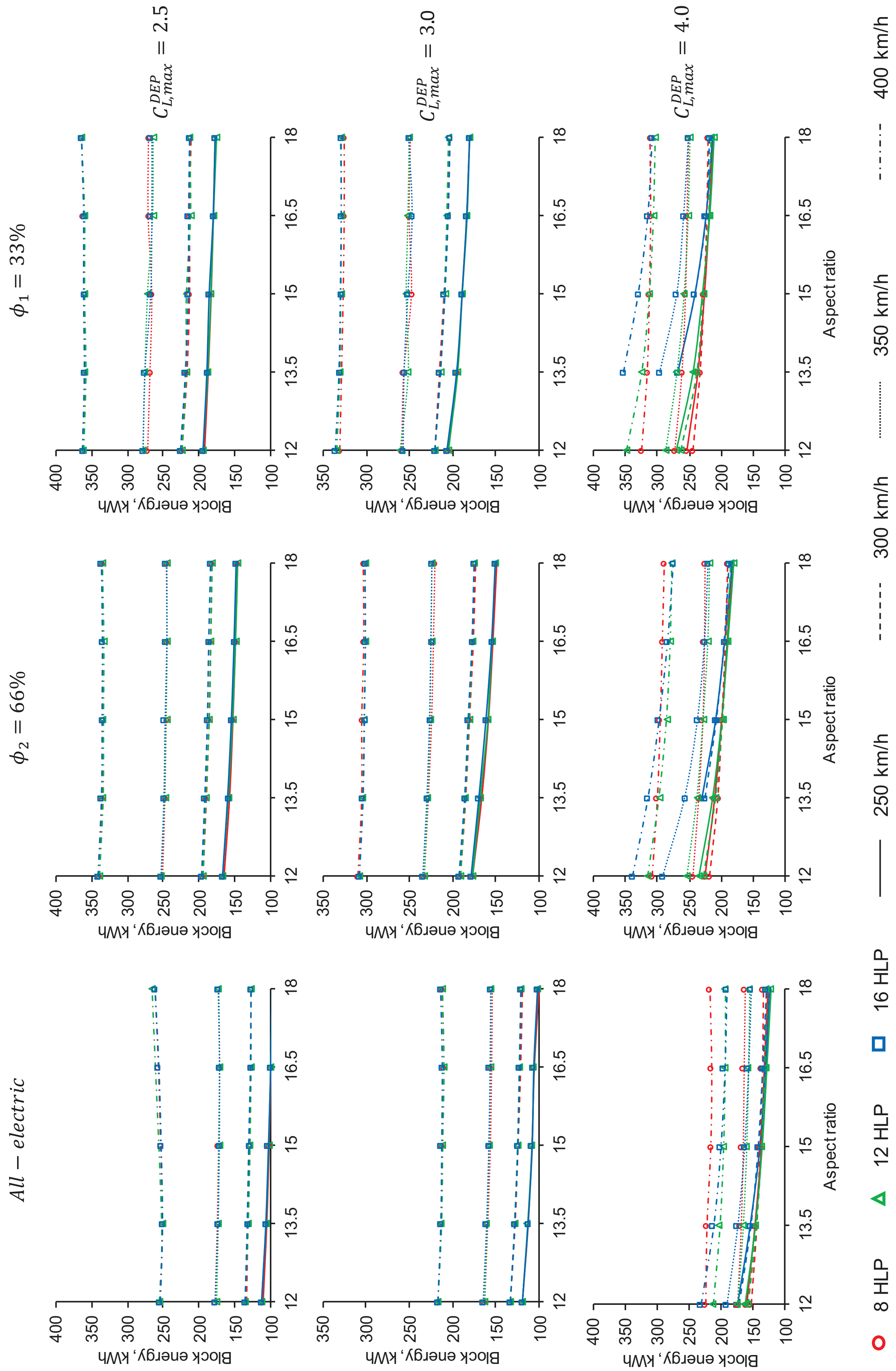

FIG. 13 Results of multi-dimensional analysis of hybrid-electric aircraft grouped by design high-lift coefficient

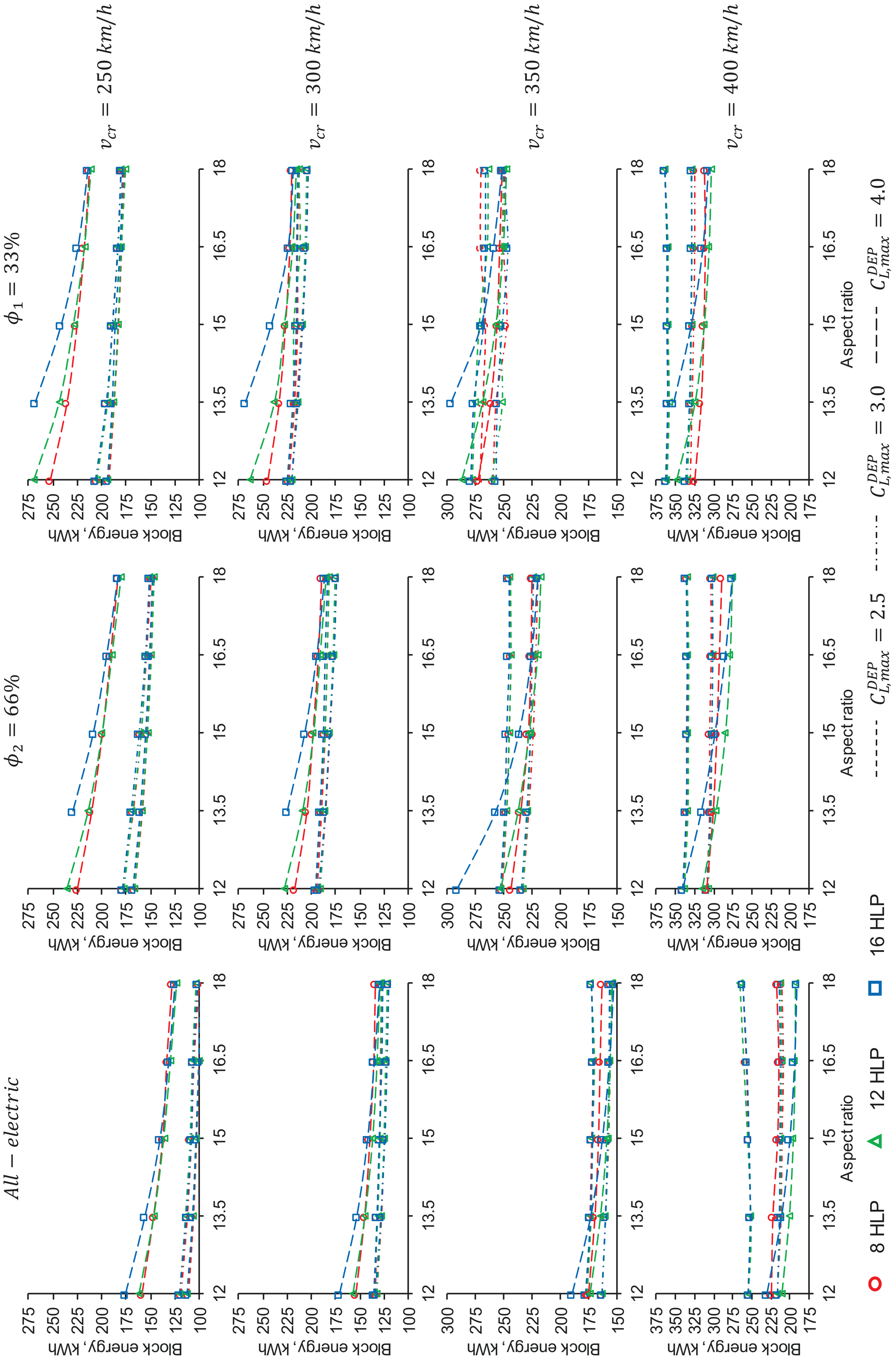

FIG. 14 Results of multi-dimensional analysis of hybrid-electric aircraft grouped by design cruise speed