MICADO: RECENT DEVELOPMENTS OF MODELS FOR DESIGN AND EVALUATION OF ELECTRIC AIRCRAFT PROPULSION SYSTEMS

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Abstract

This paper presents an overview on recent activities regarding development of models for electric propulsion systems within the Multidisciplinary Integrated Conceptual Aircraft Design and Optimization Environment (MICADO) developed at the Institute of Aerospace Systems (ILR) of RWTH Aachen University. While in early versions of MICADO only conventionally powered aircraft were considered, electric propulsion concepts have been addressed since 2016.

The development started with a PhD thesis with regard to on-demand air mobility, in which different propulsion system architectures were investigated, including electrically driven high-lift propellers. The models have later been refined and extended to gain flexibility and to increase the fidelity level of the calculations. For large commercial aircraft the development started considering a decoupled parallel hybrid propulsion system for a reference aircraft based on the Airbus A320.

In the scope of this paper, the different evolution steps of propulsion system definition, modeling, and utilization within MICADO are presented. While in the initial phase of the development the methods were rather tailored towards the specific system architectures at hand, the software was gradually generalized to gain flexibility. The traditional way of modeling the propulsion system as a single component, which is designed externally and only scaled within the aircraft design iteration, was abolished; the propulsion system was split into its individual components using component performance maps within the mission simulation. Finally, a new propulsion system library has been introduced, which is independent of the other software modules, and allows for arbitrary propulsion system architectures and flexible substitution of component models.

Keywords

Electric propulsion; Conceptual aircraft design; MICADO

1. INTRODUCTION

Conventional propulsion systems, such as turbo-fan, turbo-prop, and piston engines, have dominated in most areas of aviation mainly due to high gravimetric and volumetric energy density of aviation fuels and due to a lack of feasible alternatives for aircraft propulsion. However, the combustion of fossil fuels in aviation has a significant climate impact. In order to align the continuously increasing demand for air mobility with politically set climate goals, more than only incremental improvements in the efficiency of the current transportation system are necessary.

As a result of technological progress in components for electric powertrain systems, the relevance of electric propulsion concepts in aviation has grown in recent years. In addition to a significantly improved efficiency from tank – or rather battery – to propeller, the electrification of propulsion does not only increase the number of possibilities for designing the propulsion system itself, but also the possibilities for designing the overall aircraft configuration. Nevertheless, we have not yet seen the breakthrough of electric propulsion particularly due to constraints from electric energy storage side. As current battery technology offers only a fraction of energy density of aviation fuels, the range performance of electric propulsion is currently not competitive. There are, however, various new applications enabled by electrification of the propulsion system that have not been completely investigated.

The new aircraft design space, which results from an increased number of possible energy storage options as well as the possibility of designing distributed propulsion concepts, needs to be explored on a conceptual level to understand its potential, risks, and challenges. The aircraft design software environment MICADO developed at the Institute of Aerospace Systems (ILR) can be utilized to gain these insights. MICADO allows for fast and quantitative design, assessment, and optimization of different aircraft concepts. The software has been developed since 2008 and was first presented to the public in 2012 [1]. MICADO enables calculating consistent aircraft data sets based on minimum user input such as top-level aircraft requirements (TLARs) and design specifications. The functional structure of the MICADO design and sizing process is shown in Fig. 1. Each blue box in the figure represents one of the sizing and analysis modules. For clean-sheet aircraft designs, the design process starts with an initial sizing to determine thrust-to-weight (T/W) or power-to-weight ratio (P/W) and wing loading (W/S) based on TLARs and design specifications as well as a subsequent constraint analysis.

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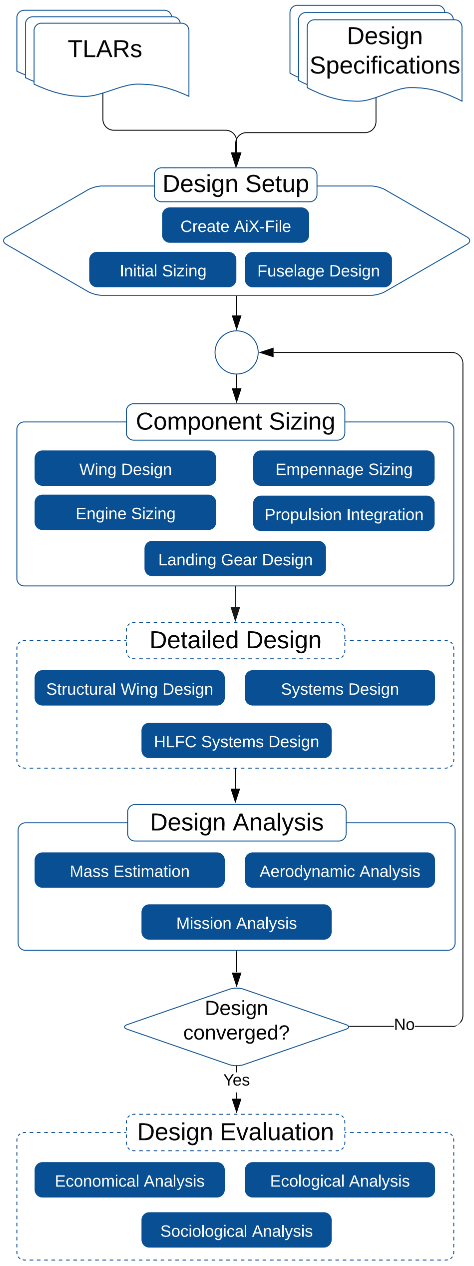

FIG 1. Functional structure of the MICADO aircraft design process [2]

After that, detailed aircraft component sizing and performance analysis steps are repeated iteratively until all predefined convergence criteria, which include maximum takeoff mass, operating empty mass, block fuel and/or block energy consumption, and the center of gravity's position along the aircraft's longitudinal axis, are below a user-defined threshold for the percentage change of these parameters between two consecutive iterations. In addition to clean-sheet aircraft design, it is also possible to re-design existing aircraft with MICADO. To do so, geometry and engines can be specified beforehand; not required program modules can be deactivated if desired. An integrated parameter study manager allows to investigate the influence of changes to input values, such as design parameters and mission profile, on overall aircraft design, performance, economics, and ecological impact.

Data related to the investigated aircraft is stored in an an XML (Extended Markup Language) file. This so-called AiX-file is also used to exchange data between the individual program modules. It is characterized by a fixed structure with blocks for user input and tool outputs. User inputs are, among others, aircraft requirements and design specifications, as well as definitions for design and off-design missions. The output blocks feature sections dedicated to aircraft geometry, mass breakdown, propulsion, systems, aerodynamic characteristics, and performance.

Due to the modular based software architecture, individual modules can be easily extended or exchanged. More detailed information on the general development of MICADO, the software code structure, and its individual modules can be obtained from Schültke et al. [2].

When the first version of MICADO was put together in 2008, it supported only conventionally powered large airliners. All- and hybrid-electric propulsion concepts were first introduced to the software in 2016 when development on a major extension for evaluation of small, General Aviation-class aircraft was started. It soon became clear that some fundamental changes to the previous modeling were necessary. These changes include the introduction of new models for electric components and adapted simulation methodologies to cope with enhanced energy and power sources.

This paper is intended to give an overview about the developments in MICADO with respect to design and evaluation of electric propulsion. In Ch. 2, models and simulation methods for conventional propulsion systems of large transport aircraft are introduced. Afterward, modifications induced by electric propulsion concepts are described in Ch. 3. Chapter 4 gives an overview about the studies that have been carried out on electric aircraft design at ILR so far. The paper concludes with an outlook on future developments in Ch. 5.

2. CONVENTIONAL PROPULSION IN MICADO (STATUS 2016)

Before electric propulsion concepts were first introduced to MICADO, the software was tailored towards classical turboprop, turbojet, and turbofan systems. This section gives a brief overview on the status before the year 2016 in terms of how the propulsion system was defined, sized, and used within MICADO (as described by Risse et al. [1]) and points out the necessary adjustments for a transition to electric propulsion systems.

2.1. Engine definition

The basic principle behind the engine definition in the traditional versions of MICADO is the use of predefined engine models during the execution of the actual design process. These models are simply scaled to match the iteratively changing thrust requirements of the aircraft. An XML file is used to store basic engine information. The file also serves as an interface for engine map data stored in Comma Separated Value (CSV) tables, which contain detailed information about the engine's thermodynamic cycle for the entire range of operations. While being able to install multiple engines of the same type on an aircraft, it was not possible to use different types of engines simultaneously in MICADO versions prior to 2016.

2.2. Engine modeling

The engine models are created with the help of the software GasTurb, which allows for modeling of the thermodynamic cycle of air-breathing engines [3]. The GasTurb results for design and off-design conditions are exported into CSV files containing fundamental data, such as available thrust and required fuel flow, as well as detailed information (e.g., temperatures, pressures, Mach numbers) at all thermodynamic engine stations. The previously mentioned engine XML file provides an interface between the engine and the aircraft data in the AiX-file.

The sizing of the engines within the iterative process of MICADO is performed in a dedicated engine sizing module. In addition to selecting a desired engine manually, the module is able to automatically choose the best-fitting engine from a set of baseline engines of different thrust/power categories. Scaling of the selected engine is performed with a scaling factor (SF), which results from the ratio between the maximum available Sea Level Static Thrust (SLST) of the unscaled engine model and the required SLST calculated from the Maximum Takeoff Mass (MTOM) and the constant thrust-to-weight ratio (T/W).

$$SF = \frac{(T/W) \cdot MTOM}{SLST_{unscaled}}$$

The engine XML file also contains geometry information which is scaled based on the thrust scaling factor SF. As an output of the engine sizing module, performance properties of the scaled engine at characteristic operating conditions (takeoff, maximum continuous, maximum go-around) are written into the AiX-file. After the engine performance calculation the mass of the propulsion system is estimated using empirical mass information of existing engines based on data from the Aeronautical Engineering Handbook (LTH) [4]. Obviously, the LTH engine mass data only contains information on already existing engines and can therefore not be adopted for novel electric propulsion concepts.

2.3. Engine utilization

The last aspect worth mentioning with respect to engine models in former versions of MICADO is their utilization within the mission analysis module as displayed in Fig. 2.

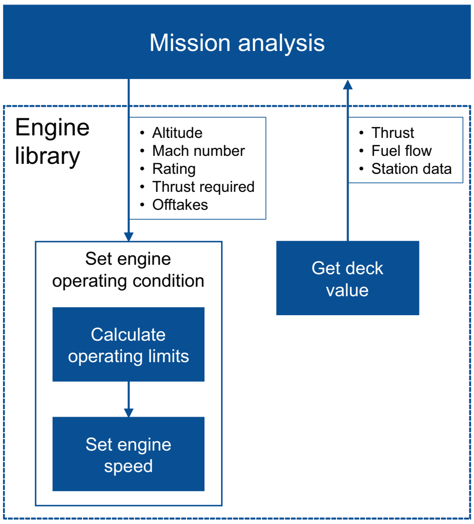

FIG 2. Integration of the engine model in the mission simulation

The scaled engine performance deck is used to calculate available thrust and required fuel flow at each incremental step of the mission flight profile. For this purpose, MICADO utilizes a dedicated C++ engine deck library. The three main parameters defining the operating condition of the engine are flight altitude, Mach number, and relative low-pressure spool speed. In any point of the mission flight segment, the current flight Mach number and altitude are usually known, whereas the engine speed needs to be calculated for the given condition. Besides altitude and Mach number, calculating the relative engine speed depends on a number of input parameters from the current operating condition, namely engine rating (e.g., takeoff, maximum continuous, cruise), required thrust (if not specified, the maximum available thrust is assumed), as well as shaft power and bleed air offtakes (as external loads from the on-board systems). Within the calculation of the operating condition, the engine deck library considers all possible limitations due to temperature limits or surge margins using the underlying thermodynamic station data. Considering a different propulsion system type (e.g., electric propulsion), this method cannot be adopted. With respect to on-board systems, in old MICADO versions only shaft power and bleed air offtakes were considered. This is because in a conventional fuel-powered aircraft, electric power is provided by a generator connected to the engine shaft; bleed air is directly extracted from the compressor. Therefore, direct supply of electric power – as it would, for instance, occur with electric consumers connected to a battery – could not be accounted for.

2.4. Summary

As presented in this chapter, prior to 2016, MICADO was only suitable for conventional engines in many regards. Chapter 3 will give an overview on the introduced changes resulting from the transition from conventional to electric propulsion systems.

3. ELECTRIC PROPULSION IN MICADO (SINCE 2016)

One of the principles when designing the code structure of MICADO is to keep the entire software framework as general as possible in order to allow for easy connection of new design and evaluation methods as well as integration of new aircraft technologies. With the introduction of electric propulsion in the software, it became clear that a number of fundamental changes, especially in propulsion modeling, were needed to capture the new design flexibility. While on aircraft conceptual design level, a conventional turbofan engine can be easily modeled as a single component independent of its energy supply (i.e. fuel supply), this is no longer true for all- and hybrid-electric architectures, which are characterized by a strong interdependence of the individual components from tank or battery to propeller. Therefore, the entire MICADO engine sizing module was re-designed to allow for detailed sizing of the individual powertrain components. Moreover, the flight control logic within the mission performance analysis module required a major update to cope with more than one type of propulsor.

Besides changes to modeling and simulation of the propulsion system itself, which are described in the following subsections, it turned out to be necessary to adjust the module for initial aircraft sizing. The new methodology allows for an initial estimation of aircraft empty and maximum takeoff mass as well as fuel mass and battery mass depending on hybridization degree and battery specific energy.

3.1. Powertrain definition

As mentioned in Sec. 2.1, information on aircraft propulsion is used in both the input and output blocks of the AiX-File. With regard to conventionally powered aircraft it is sufficient to specify the propulsion system as turbofan or turboprop and decide on the proper engine selection mode. When it comes to electric propulsion, however, more information needs to be provided to specify the aircraft and powertrain design properly. First, the general architecture (e.g., serial hybrid, parallel-hybrid, or all-electric) must be specified. Second, the user needs to decide on the degree of power hybridization or energy hybridization, where applicable. Third, if different types of engines are used, their location and relative size, need to be defined. Similar to fuel tanks, the location of batteries needs to be specified. Additionally, MICADO allows the user to choose between a battery sizing on pack level by specifying gravimetric and volumetric energy density, and a battery sizing on cell level. The latter process is described in the next section in more detail.

One of the most significant data given in the AiX-file is the mass breakdown of the aircraft. The introduction of novel propulsion systems also called for a more generic definition of the propulsion system mass breakdown, where specific sub-components of turbofan and turboprop engines where present before. Therefore, a generic mass component block has been introduced to enable dynamic extension of the mass breakdown based on the propulsion system architecture at hand.

3.2. Powertrain modeling

Compared to conventional propulsion systems, electric propulsion necessitates models for many more component types. In order to avoid an over-simplification of the powertrain model, an electric propulsion system can no longer be modeled as a single component as it is done with conventional propulsion systems. In fact, the individual components of the electric powertrain need to be separated and modeled individually before integrating them on the upper system level.

Generating thrust in an electric aircraft is directly related to propulsors (propellers/fans) driven by electric motors. To model the performance of these components, efficiency maps are used in MICADO. Propeller efficiency, for instance, can be processed from maps featuring advance ratio and power coefficient values. Corresponding propeller mass is estimated based on handbook methods. The user can decide on whether they want to design with constant propeller diameter or adjust the propeller diameter to engine design power based on a regression formula.

The so-called rubber engine-concept mentioned in Ch. 2 is used for electric propulsion concepts as well. This means models of existing or generic components are scaled to fit the required performance by scaling the performance maps to align the design point of the respective model with the required design point from the sizing process.

Electric motor mass is calculated depending on aircraft size. For large commercial airliners, motors utilizing high temperature superconducting (HTS) technology are considered using a method adopted from Stückl as described by Aigner et al. [5]. For aircraft with lower power requirements, electric motor mass was initially calculated with design power and a user-defined power-to-weight ratio. As mass of this type of component rather scales with torque than power, the mass estimation methodology has been adjusted accordingly and is now based on regressions taken from contemporary electric motors [6]. A similar evolution has been made with respect to calculation of geometric volume. While motor dimensions were initially estimated based on design power and a respective scaling of the dimensions of the Siemens SP260D motor, a refined methodology now considers both design power and torque.

Performance maps of piston engines for hybrid-electric powertrains are scaled accordingly to electric motors. Piston engine dimensions are estimated based on regressions from contemporary aviation piston engines and piston engine mass is estimated based on a user-defined specific power constant and installed engine power.

In addition to components directly associated with thrust generation, such as propellers and engines, the following powertrain components are taken into account: cables, power electronics, such as converters and controllers, batteries and internal combustion engines (for serial hybrid configurations).

Wiring is considered with a constant efficiency, which is conservatively determined with the maximum occurring current. Required cable length for connection of two components is determined by connecting the reference points of the particular components. While cable volume is currently neglected, cable mass is estimated based on the density of the cable material, i.e. aluminum, copper, or HTS and its length and cross section, the latter of which is related to the maximum occurring current.

The efficiency of power electronics such as inverters, controllers, and rectifiers is assumed to be constant and independent of external factors. For inverters, not a particular geometric volume is calculated, but nacelles of electric motors are generally oversized to account for inverters being placed close to the motors. The geometric volume of controllers and rectifiers is currently neglected. The mass of each type of power electronics is estimated with a constant power-to-weight ratio and the respective power the component is sized for.

Battery mass and volume can be modeled either on pack or cell level. If modeling on pack level is chosen, required battery capacity is calculated first. This calculation considers both energy and discharge power requirements. Furthermore, battery capacity degradation due to cyclical and calendrical aging is taken into account. This ensures that the design mission can still be operated at the battery's end of life. Finally, battery mass and volume are determined based on design capacity, as well as user-specified gravimetric and volumetric energy density constant. If, on the other hand, battery modeling on cell level is chosen, a sizing algorithm automatically selects the most suitable cell type from a list of cells to minimize either battery mass or volume. In both cases a dynamic model for battery discharge efficiency is used. This model considers dynamic open-circuit cell voltage depending on current state of cell charge.

For serial hybrid architectures an internal combustion engine as well as a generator need to be modeled. The combination of combustion engine and generator is called range extender unit. While the combustion engine part is modeled similarly to thrust generating combustion engines, the generator model is based on the models for electric motors. If small aircraft are designed, the user can choose between placing the range extender unit in the aircraft nose or tail, depending on available space.

3.3. Integration of powertrain model in simulation

The integration of the electrical powertrain models has evolved from the way conventional engine models such as turbofans and turboprops are integrated into the mission simulation. This evolution has happened in three major steps which are described in the following paragraphs.

Due to computational efficiency of the approach for conventional engines and the possibility to maintain the proven structural concept of the old models, initially the same way of integration was chosen for electric motors. In case of ducted fans powered by electric motors, the bypass of a traditional turbofan engine from the GasTurb software was extracted as a first guess for ducted fan performance and integrated in the same way as described in Sec. 2.3 [5]. As there was no software available which allows for generation of reduced engine decks for combinations of propellers and piston engines or electric motors, the original module for engine sizing was supplemented with a methodology to calculate these reduced decks. This methodology searches for the most efficient combination of propeller and motor setting for each flight condition within a given range of altitudes, flight speeds, and power settings. As a result, basic performance data and engine conditions, such as values for thrust, power, and speed, are summarized in look-up tables as described in Sec. 2.2. This approach allows to dynamically determine the condition of the propeller-motor-combination for each step of the mission simulation. With regard to electric powertrains, losses caused by components between battery and motor, such as cables and converters, are statically, but conservatively estimated based on the worst case scenario. Battery discharge efficiency is dynamically simulated based on discharge current. This powertrain simulation approach is computationally very efficient; however, it does not allow to find overall optimized settings for all powertrain components in each simulation step as the interdependence between the efficiencies of individual components (except for propeller and motor) is not accounted for. At the same time, this approach is not feasible for simulation of parallel hybrid architectures with a non-constant power split between electric motor and combustion engine because an additional dimension in the look-up tables would be required.

The second step of the evolution addresses the incompatibility of the aforementioned modeling and simulation approach with parallel hybrid powertrains. The innovation in this step is to completely abandon engine decks. Instead, component maps of motors and propellers are only scaled to fit the required performance. The actual setting of each component is calculated "live" during the simulation with regard to the particular flight condition. While this pays off in terms of flexibility, it comes at the cost of increased computation time.

The previously described evolution steps facilitated the utilization of increasingly complex powertrains within the MICADO framework. However, each of the advancements was mainly focused on the specific system architecture at hand. When arbitrary powertrain architectures with variable degrees of hybridization and flexible substitution of components are desired, an even broader generalization of the propulsion system modeling is necessary. This is addressed in a third evolution step, which is, due to its significance, presented in a dedicated subsection.

3.4. Changes for generalization of the propulsion system

A number of substantial modifications to the definition of the propulsion system in MICADO were conducted to obtain the desired generalization and flexibility. A generic propulsion system definition accompanied by a dedicated C++ library has been introduced for this matter [7]. Its main features will be briefly described in this section.

Propulsion system definition: To introduce the new propulsion system library, as a first step, the most relevant definitions will be explained. Within the library, the propulsion system consists of generic elements connected to each other via so-called nodes. An element is any type of component within the propulsion system and can contain multiple input and output nodes. Each node is assigned to a specific physical quantity to ensure a consistent connection among the components. On overall propulsion system level, the structure of the system composition is truly generic. While the type of the components (motor, generator, propeller, etc.) is insignificant on the upper system level, individual component properties come into play on component level. This generic way of describing the propulsion system allows for almost arbitrary system architectures. To give an example, Fig. 3 shows a parallel hybrid electric propulsion system with additional high-lift propellers, which are used to increase lift during low-speed phases of the flight mission (e.g., during takeoff and landing). While the thrust is primarily provided by dedicated propulsors, the high-lift propellers cause a cross-coupling between aerodynamics (accelerated flow over the wing) and propulsion (additional thrust). [7]

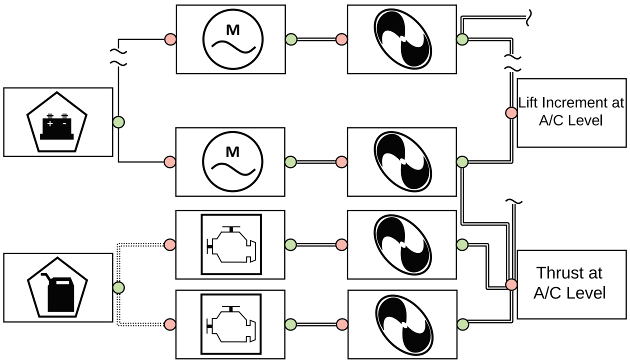

FIG 3. Hybrid electric propulsion system with high-lift propellers [7]

Propulsion system modeling: Each of the previously described generic propulsion system elements is assigned to a unique component with specific properties, for instance an electric motor with a specific power density, off-design performance, maximum rotational speed, and maximum output torque. The calculation of state variables across a component (and thereby through the propulsion system) is based on the calculation rules implemented within each of the component-specific C++ classes. These calculation rules can be empirical relations, sophisticated physical analyses, or external simulation procedures. This also allows for an easy exchange of component models based on the desired level of detail, because the upper system level remains unchanged. [7]

Propulsion system utilization in MICADO: The main idea of using the new propulsion system library within MICADO is that it is completely decoupled from the rest of the analysis. The MICADO program modules should not be affected by every single change in the propulsion system, when for example a new component is introduced, or the system architecture changes from a parallel hybrid to a fully electric system. Rather, all of the calculations related to the propulsion system are implemented in the library. Therefore, sizing, mass estimation, and calculation of operating points have been outsourced completely from the MICADO program modules, which solely call the respective functions in the library, without having information about the underlying systems architecture. Figure 4 displays the integration of the propulsion system library in MICADO.

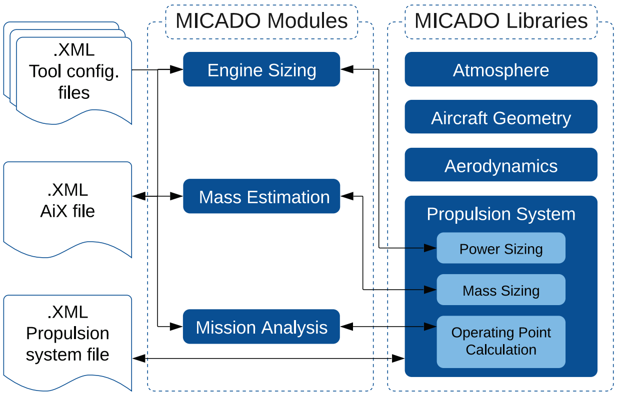

FIG 4. Integration of the propulsion system library within MICADO, adjusted from [7]

As shown in the figure, the MICADO modules mainly involved with the propulsion system are the Engine Sizing module, the Mass Estimation module, and the Mission Analysis module. A dedicated XML file contains the definition of the propulsion system including all components and their interaction. In this context, the propulsion system file defines how the components are connected to each other and how the power is distributed among the different components within the different mission phases. The propulsion system XML file serves as an interface for the library similar to the AiX-file for the MICADO program modules. The library updates the information on component properties within the XML file continuously throughout the analysis.

3.5. Changes on process level

Besides the previously described adjustments with respect to definition, sizing, and utilization of the propulsion system within the respective MICADO program modules, another issue arising when introducing electric propulsion is related to the upper process level, i.e. the convergence loop iteration. The main challenges and resulting necessary measures to cope with these challenges are described in this section.

Aero-propulsive coupling: In traditional aircraft design, the propulsion system unit is considered almost completely independent from the rest of the aircraft. With electric propulsion, however, new opportunities arise for integrating the propulsors into the aircraft. Utilizing a coupling between the aerodynamics and the propulsion system (aero-propulsive coupling) can raise synergies that are not easily realizable in conventional designs. One example is the so-called propulsive fuselage, which incorporates a propulsor at the rear of the fuselage ingesting turbulent boundary flow. This results in a higher propulsive efficiency due to the smaller incoming flow velocity compared to free-stream conditions. Furthermore, accelerating the flow aft of the fuselage fills in the fuselage wake and thereby reduces aerodynamic drag. In the course of investigations on electric propulsion, this concept has re-entered the focus of research activities [8].

Another example for aero-propulsive coupling is the utilization of propellers as an active high-lift system. This strategy is mainly considered for General Aviation, as aircraft of this class have poor aerodynamic cruise efficiency due to low wing loading which is necessary to meet low-speed requirements. Since scaling down combustion engines to the required size for high-lift propellers is not meaningful in terms of efficiency, if technically feasible at all, small high-lift propellers distributed along the main wing's leading edge are one of the innovations that come with electric propulsion. High-lift propellers serve the same purpose as traditional high-lift devices such as flaps and slats. However, achievable high-lift coefficients are considerably larger with active lift augmentation.

When it comes to high-lift propellers, proper consideration of aero-propulsive coupling is of utmost importance. Within modeling and simulation in MICADO it stretches across the modules for engine sizing, aerodynamic analysis and mission simulation. In the engine sizing module, high-lift propellers and their motors are sized towards the maximum power requirement determined during mission simulation. The impact of high-lift propellers on aircraft aerodynamics is reduced to dynamic pressure multipliers for a range of operating conditions in the aerodynamic analysis module. These values are stored in so-called prop-wing-interaction maps. During mission simulation, the dynamic pressure multipliers are used to adjust lift and drag coefficients of the free-stream polars to the flight and high-lift propeller operating condition. After each of these iterations, required high-lift propeller power is evaluated and adjusted at the beginning of the next iteration loop.

Battery sizing: A second issue for the overall process level arises due to the way battery sizing is currently implemented within MICADO. When using fuel as a primray source of energy, the required fuel for a flight mission is estimated (based on fuel planning regulations) immediately before the mission is simulated in the mission analysis module. Batteries, however, are designed in each iteration step of the convergence loop within the engine sizing module based on the required total mission energy resulting from the mission simulation of the previous iteration step. The battery mass is subsequently determined in the mass estimation module. This creates a new feedback coupling in the iteration process which needs to be accounted as an additional convergence criterion.

Interdependence of propulsion system sizing and mass estimation: The final example regarding the overall MICADO process is an issue, which occurred in a hybrid electric design study for large commercial airliners [5]. As already described, in each iteration step, the engine sizing module designs the propulsion system with respect to the estimated aircraft mass from the previous iteration. Because of the additional feedback in the iteration and the large mass fraction of the propulsion system, the aircraft design did not converge in some cases. To address this problem, an internal convergence loop between the engine sizing and the mass estimation module was introduced. MICADO allows for these kind of adjustments due to its modular program structure.

3.6. Summary

The developments described in this chapter enable design and evaluation of electric propulsion systems within MICADO. The main advancements are the newly implemented models to account for electric components, as well as a generic propulsion system definition which enables higher flexibility for defining even complex electric propulsion system architectures. Additionally, the overall convergence process level has been addressed to account for interactions between individual program modules resulting from, e.g., aero-propulsive coupling.

4. APPLICATIONS

Since the first introduction of electric propulsion to MICADO, various studies on this topic have been carried out and published. In this context, key research questions have been technical feasibility, energy efficiency and economic viability. Investigated aircraft classes range from small General Aviation aircraft up to large transport aircraft. The following paragraphs give an overview about the studies and their key findings.

The most extensive study on the evaluation of electric propulsion concepts with MICADO to date has been carried out by Kreimeier as part of his dissertation [9].

The evaluation of on-demand air mobility (ODAM) concepts with utilization of electric powered small aircraft was conducted with a focus on feasibility of these concepts for the German market. A market analysis identified the following key aircraft characteristics: 400 km range would cover 85% of estimated demand while 500 km range would cover 96% of this demand. Cruise speeds between 300-400 km/h are recommended and a capacity of 2-4 seats seems most reasonable. According to Kreimeier, service provision costs should be "less than 0.2 €/km (better 0.15 €/km) more expensive than (perceived) car costs". If a runway performance of 800 m was realized, 157 airfields could be used in Germany.

Based on these requirements aircraft with four passenger seats and all-electric and serial hybrid propulsion systems are designed and evaluated. In addition to classic single-engine configurations, aircraft configurations with high-lift propellers are investigated. This form of active lift enhancement is expected to increase aerodynamic cruise efficiency of small aircraft by enabling higher wing-loading through smaller wing area while maintaining low stall speeds. It turns out that serial hybrid propulsion yields lower service provision costs than all-electric propulsion because battery mass drives overall aircraft mass and, thus, decreases aircraft efficiency. Even assuming specific battery energy of 400 Wh/kg at pack level, lowest operating costs can be achieved by reducing the share of electric energy in total mission energy to the technically feasible minimum, as seen in Fig. 5.

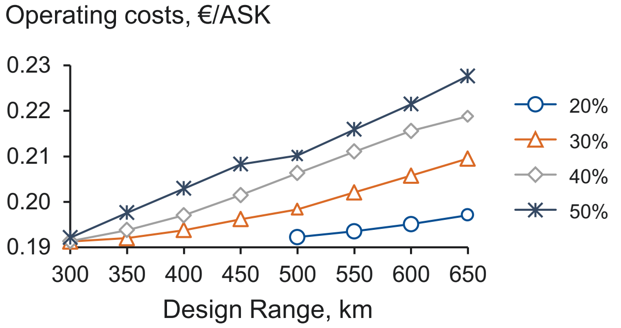

FIG 5. Operating costs per ASK for serial hybrid configurations with different hybridization degrees, adjusted from [9]

Analyses with respect to the application of high-lift propellers reveal that operating cost benefits increase with design cruise speed. If compared to aircraft with conventional high-lift systems, designs with high-lift propellers yield up to 10% operating cost benefit for cruise speeds around 300 km/h and more than 25% at speeds around 400 km/h. Based on the assumptions made, Kreimeier's study concludes that there is an overall positive business case for ODAM in Germany.

Since Kreimeier put the focus on operating costs, a follow-on study took a closer look on energy efficiency of aircraft configurations with high-lift propellers [10]. For both all-electric and serial hybrid powertrains, cruise speed was identified as the main driver for block energy demand in terms of electric energy and energy stored in aviation fuel. The impact of the number of high-lift propellers on efficiency turned out to be of particular relevance for aircraft with large design high-lift coefficients and high cruise speeds. Furthermore, the impact of aspect ratio on efficiency, a relationship neglected by Kreimeier, was highlighted and a notable sensitivity particularly for aircraft designs with high maximum design high-lift coefficients has been observed (see Fig. 6).

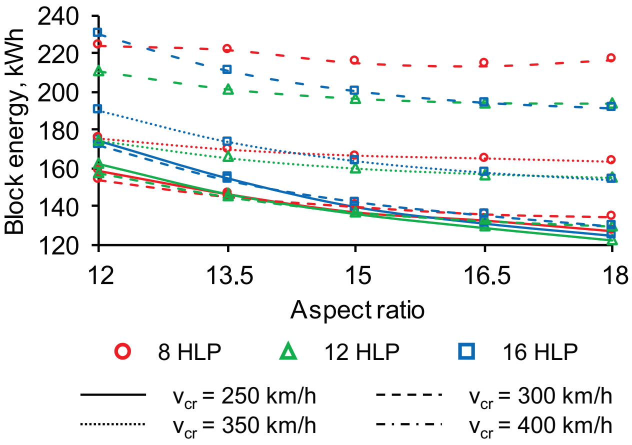

FIG 6. Block energy demand for configurations with high-lift propellers and a design high-lift coefficient of $C_{L,max,DEP} = 4.0$, adjusted from [10]

Due to the low specific energy of batteries and the resulting poor range performance, small aircraft configurations with a single conventional engine for cruise propulsion and electric high-lift propellers were investigated in a further study [11]. The propulsion architecture is depicted in Fig. 7.

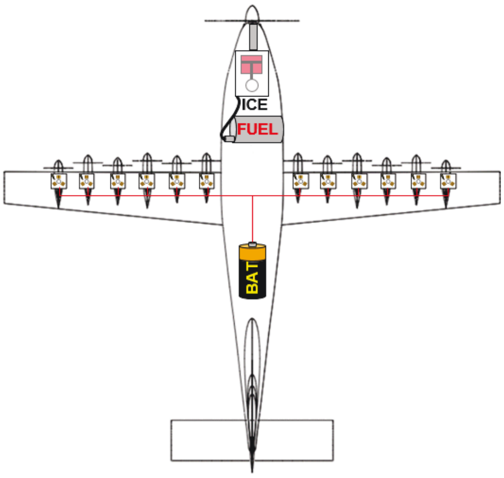

FIG 7. Concept for an aircraft configuration with combustion engine for cruise propulsion and electric high-lift propellers, adjusted from [11]

This configuration was chosen in order to take advantage from the high specific energy of aviation fuel as major energy source for cruise propulsion while increasing aerodynamic efficiency by using electric high-lift propellers, which can not be build with combustion engines due to disadvantageous down-sizing qualities. Results of this study indicate a potential to save up to 7% primary energy consumption, i.e. aviation fuel and electric energy in total, for a four-seat aircraft on a 650 NM mission and battery technology available to date. However, aspects of economic viability, which might not be given because of increased system complexity and related costs, has not been evaluated so far.

Even though electric propulsion is often said to require a new aircraft design thinking, there is a large share of research and development projects working on drop-in replacements of conventional powertrains. Therefore, a comparison of block energy consumption, i.e. aviation fuel and electric energy, for generic aircraft designed towards the top-level aircraft requirements of a Cessna 182 and conventional, serial hybrid, parallel hybrid, and all-electric powertrains was carried out [6]. The corresponding parameter studies on the degree of hybridization, which were conducted based on assumptions of technology levels available in the near-term future, reveal increased fuel consumption on the design mission for serial hybrid propulsion concepts. Only on very short off-design missions, a fuel saving potential was identified for this propulsion architecture. Parallel hybrid powertrain layouts turn out to be beneficial even for technology levels available to date if the degree of power hybridization, i.e. the distribution of design power between electric motor and combustion engine, is carefully chosen. However, potential savings of block fuel are in the range of single digit per cent. Mission ranges of all-electric aircraft designs are not even in the vicinity of those of conventional aircraft.

With respect to large commercial airliners (category CS/FAR 25), in an initial study an Airbus A320 reference aircraft was equipped with a decoupled parallel hybrid propulsion system consisting of two conventional turbofans and two ducted fans driven by battery-powered HTS electric motors [5]. While the study did not show any benefits on mission level compared to the reference aircraft due to the large mass of the electric components, it revealed some significant insights with respect to systems integration (see Fig. 8).

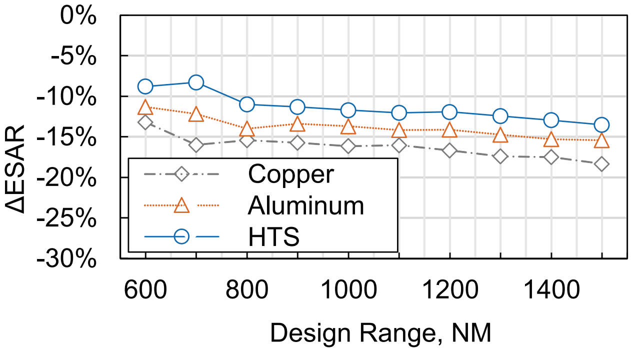

FIG 8. Impact of conductor materials on energy specific air range, adjusted from [5]

Comparing the three different cable materials aluminum, copper, and HTS, the most favourable combination of cable mass and efficiency can be obtained with superconducting cables resulting in the highest Energy Specific Air Range (ESAR). However, the difference compared to conventional materials is not sufficient to justify the additional system complexity resulting from HTS cables. Note that the values for ΔESAR in Fig. 8 refer to the reference configuration with conventional turbofans.

5. CONCLUSION AND OUTLOOK

The MICADO software framework developed at ILR is specialized on technology integration and evaluation for aircraft ranging from General Aviation to large commercial airliners. In recent years, electric propulsion has gained increasing interest for stakeholders within the aviation sector. Therefore, MICADO's functionalities have been extended to enable investigation of various types of propulsion systems for different classes of aircraft within three evolution steps. While numerous application studies have already been conducted, proving suitability of the implemented methods, there is still room for further improving the software. Except for the high-lift propeller use-case, at the moment, the applications are mainly focused on so-called drop-in replacement systems, where the combustion engine is directly replaced by an electric powertrain. A future goal is to investigate more advanced systems raising synergy effects on overall aircraft level, as for instance the propulsive fuselage. Another potential development is an optimization algorithm focused on overall mission consumption rather than on choosing the degree of hybridization based on the powertrain efficiency in each mission step.

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