

# Methodology for Design and Evaluation of More Electric Aircraft Systems Architectures within the AVACON Project

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## Abstract

Within the research project AdVanced Aircraft CONfiguration (AVACON) a collaborative conceptual design of a mid-range aircraft with ultra high bypass ratio (UHBR) engines and an envisioned entry-into-service in the year 2028 is conducted. In this paper, the approach for overall architecting, sizing, and evaluation of aircraft on-board systems in AVACON is presented. To this end, important contributions to conceptual system design methods proposed in the literature are reviewed to identify directions for methodological improvements. The role allocation of contributing partners and their methodologies for system design activities is described. Having different contributors guarantees, that tasks from overall aircraft to detailed subsystem design with a successive increase in the fidelity of system models is covered. In addition, a state-of-the-art baseline architecture is defined, which will serve as a starting point to conduct trade-off studies for investigation of the potential of system architecture concepts and innovative technologies. Substantial system design requirements and novel boundary conditions, implied by the advanced aircraft configuration, are derived to give an outlook for planned technology studies.

## 1 INTRODUCTION

One of the major challenges during the complex task of aircraft design is to coordinate the data flow and harmonize calculation results obtained by the related design disciplines. This is especially true for distributed and collaborative design teams. Hence, it is necessary to further advance processes for digital aircraft development by synchronizing and improving methods and data interfaces among the involved discipline experts. Within the project AdVanced Aircraft CONfigurations (AVACON), a consortium of industry partners, research facilities, and academia improve their joint capabilities for the overall aircraft design (OAD) process during the conceptual phase. An optimized baseline concept of a more-electric mid-range transport aircraft with ultra high bypass ratio (UHBR) engines and an envisioned entry-into-service in the year 2028 is conducted collaboratively within the ongoing research project. The obtained virtual aircraft model lays the foundation for technology studies regarding concepts for aircraft intended to serve the new mid-range aircraft market.

The idea of improving the design process in order to decrease development costs and the risk of poor design decisions in the early design stage has already been subject to past and recent research [1–4]. In the course of the AGILE project, for instance, a collaborative multidisciplinary design optimization environment is developed and tested [4]. Hereby, the major emphasis is on developing and testing frameworks, which support coordination and management of a collaborative multidisciplinary design optimization process. This is achieved by means of consistent and harmonized tool interfaces and the usage of knowledge-based technologies. Although an improvement of cross-site communication of dedicated sizing and simulation tools is also regarded within the AVACON project, the main focus lies on improving a more expert-centric rather than a tool-centric design optimization process. This expert-centric process captures cross-disciplinary effects and considers an increasing level of detail throughout the project.

When studying the impact of innovative system architectures on vehicle-level metrics like fuel efficiency and

maintenance costs for a not yet investigated aircraft configuration, it is of considerable interest for the system design engineer to be supplied with sufficiently accurate boundary conditions specified by the individual design disciplines. For instance, a good estimate of the maximum hinge moment coefficient of the flap obtained by aerodynamic calculations is required for the design of the high-lift actuation system. In addition, the flap geometry and its position on the wing surface estimated by stability and control considerations is a determining factor. So is the available installation space for the actuation system in the wing dictated by structural wing design analyzes. Thus, novel system boundary conditions induced by the considered aircraft configuration and technologies have to be identified. A constellation of partners for system design activities is presented in this paper. Contributions of different partners guarantee to consider these new constraints and identify coupling effects between overall aircraft design and detailed subsystem design.

Based on an assessment of a suitable baseline systems architecture, more detailed technology studies can be conducted. Hereby, the baseline system is sized by means of available handbook methods adjusted with state-of-the-art technology factors. The trade-offs will be focused on more electric aircraft (MEA) systems architectures including concepts for power consumers and their supply systems. Assessment on subsystem-level and across system-system boundaries with varying level of fidelity will contribute to deriving holistically optimized MEA system architectures. System parameter sensitivities are then provided for overall aircraft design synthesis.

Since it is a major objective of the AVACON project to improve design methods and processes throughout the project, the paper begins with a review of already existing methods for the conceptual design of aircraft systems in Section 2. In this regard, potential research topics for methodological improvements are identified. In Section 3, the overall system design (OSD) methodology and the distribution of roles for partners contributing to system design activities is outlined. To this end, selected methods from these partners are outlined. The reader is provided with the description of considered technologies for system design trade-off studies and the definition of the baseline system architecture in Section 4. The paper concludes with an outlook for the upcoming system design activities within the scope of AVACON in Section 5.

## 2 REVIEW OF EXISTING APPROACHES TO CONCEPTUAL SYSTEM DESIGN

A primary objective of conceptual system design is to provide the overall aircraft design synthesis with suffi-

ciently good estimates of relevant system parameters and support early architectural decision-making on system-level. For aircraft systems, conceptual design activities may thereby be subdivided into sizing and simulation, architecting, and assessment.

### Sizing and simulation

In order to estimate the size of a system or its components in terms of mass, maximum design load, or required installation space, several methods with varying level of fidelity can be found in literature. For advanced sizing methods, their results yield parameters for system component models, with which the system behavior can then be simulated to analyze and assess system performance over a given flight mission profile.

In this paper, the reviewed approaches for sizing and simulation models are assigned a ranking order from 0 to 2 to indicate their level of detail as it is listed in Table 1. Level-0 methods provide empirical system mass and power consumption estimates. Level-1 methods relate to simple and advanced physics-based sizing models, which make use of regression-based component scaling laws like power-to-mass ratios. The system is commonly sized based on propagation of its design loads through the system's power path components in reverse to the actual power flow. Hereby, individual component efficiencies are considered. Thus, for the analysis of a predefined overall systems architecture, the components are sized starting from power consumers continuing to power distribution components and ending up with the sizing of power generation systems. The fidelity of Level-1 simulation approaches thereby ranges from simple power consumption estimates for mission segments like takeoff, climb, cruise, descent, and landing to mission-dynamic analyses of quasi-static system models.

Current sizing and simulation methods in literature combine Level-0 and Level-1 methods. They leverage knowledge-based model libraries in order to reuse and scale parametrized component models. Systems, which are not sensitive to overall aircraft parameters or which have nearly constant power requirements like the avionics system, are typically sized by means of Level-0 methods. Systems with a high impact on overall systems weight and a variable power consumption are modeled in more detail using Level-1 methods. However, if detailed conceptual system analyses are necessary during early design evaluations, Level-2 methods are used. They comprise detailed geometry-based system sizing optimization approaches to yield the physical dimensions of the components. Material properties like mass densities are then used to estimate the mass of components. Analysis tools like Finite Element Method (FEM) can thereby support the design

engineer to calculate component masses. For Level-2 system simulations, physical (acausal) modeling techniques are applied to solve ordinary differential equations (ODE) or differential-algebraic equations (DAE) which represents the transient component and system behavior. For physical component modeling and corresponding control design, extensive system knowledge is required. Although these methods are not necessary to perform conceptual architecture studies, they enable the consideration of dynamic system requirements early in the system design process. Doing so can lead to more accurate component sizing results [5].

Level	Characterization
0	<ul style="list-style-type: none"> <li>- At system-level</li> <li>- Regression-based equations</li> <li>- No simulation of behavior</li> <li>- No volumetric sizing</li> </ul>
1	<ul style="list-style-type: none"> <li>- At system or component-level</li> <li>- Simple or advanced physics-based models</li> <li>- Static simulation models (quasi-stationary system behaviour)</li> <li>- Scaling-law-based component sizing (power densities and efficiencies)</li> </ul>
2	<ul style="list-style-type: none"> <li>- At component-level</li> <li>- Physical (acausal) modeling</li> <li>- Dynamic simulations (transient system behaviour)</li> <li>- Geometry-based component sizing (volumetric mass densities and efficiencies)</li> <li>- Optimization techniques for system sizing</li> </ul>

TABLE 1: Definition of system model fidelity levels

Level-0 system mass estimation methods for aircraft design are well known and published for example by Roskam [6], Torenbeek [7], Raymer [8], and *Luftfahrt-technisches Handbuch* [9]. These methods provide empirical equations for aircraft systems, which contribute a relevant amount to the aircraft's empty weight. These equations are of the form

$$(1) \quad m_{\text{sys}} = f(\underline{\theta}_{\text{AC}}, \underline{\theta}_{\text{sys}}) \quad .$$

That is, the system mass prediction  $m_{\text{sys}}$  is a function of aircraft-related parameters  $\underline{\theta}_{\text{AC}}$  (e. g. maximum takeoff weight, wing span, etc.) and system-related parameters  $\underline{\theta}_{\text{sys}}$  (e. g. flap chord length, landing gear strut length, etc.).

Koeppen [10] compares a collection of these methods and identifies the need for physics-based system modeling, if novel systems architecture concepts are assessed on aircraft level. As one of the first, he proposes a Level-1 approach for conceptual sizing and

simulation of the overall aircraft systems architecture in order to perform studies which capture coupling effects between system-system boundaries and their impact on overall aircraft design. In his approach, aircraft on-board systems are sized through an analytical bottom-up approach which avails knowledge-based scaling laws for component weight prediction. An assessment of the influence of system parameters on overall aircraft figures like takeoff weight is then conducted by coupling the systems design tool with the conceptual aircraft design environment *PrADO* [11]. Koeppen's focus, however, lies on analytical mass prediction methods rather than on simulating system's power consumption. Therefore, Liscouet-Hanke [12] further advances Koeppen's approach by introducing a model-based power-flow-oriented sizing and simulation method. The simulation results are aggregated on overall aircraft level to perform MEA systems architecture studies. Volumetric sizing and thermal aspects are also addressed in her dissertation. Budinger [13] proposes a scaling-law based approach for derivation of estimation models, which are used for model-based design. He considers parameters for installation space estimation, power sizing, and component dynamics. The approach is exemplified with sizing results of an electromechanical actuator. Lammering [14] describes a method to integrate suitable power flow oriented Level-0 and Level-1 system sizing and simulation methods into the multidisciplinary integrated conceptual aircraft design optimization (*MICADO*) environment. The integrated approach enables the assessment of system concepts on overall aircraft level considering aircraft resizing effects. Chakraborty [15] further advances these methods and complements them with heuristics for 3D power distribution network design. In addition, he investigates the use of probabilistic uncertainty quantification techniques for aircraft system design. Chiesa et al. [16] also propose an analytical sizing approach for generic sizing of several systems architecture variants. These Level-0 and Level-1 methods are implemented within the tool *ASTRID*. Prakash et al. [17, 18] and Fioriti et al. [19] apply this framework, specifically to identify coupling effects between system parameters and overall aircraft design parameters.

Using Level-2 methods during conceptual design, Bals et al. [20] present the concept of a *virtual iron bird* to model and simulate power demands of aircraft systems architectures by means of the modeling language Modelica and an associated model library. Thereby, inverse Level-2 models are employed, which solve the DAE for the inputs given the values for the outputs. Moreover, modeling and analysis of model uncertainty is considered in order to estimate simulation accuracy. At Linköping University, researchers have been focused on implementing Level-2 methods into the conceptual aircraft design process. Krus et al. [21] present

the application of the multi-domain simulation software *Hopsan NG*, which supports multi-core simulation. Due to this multi-core functionality it is suitable for a coupled dynamic simulation of aircraft systems, flight dynamics, and propulsion system during conceptual design. Likewise, parametric definition of aircraft systems like the aircraft fuel system (c. f. Lopez et al. [22]) is used to integrate conceptual system design into the knowledge-based aircraft geometry design tool *RAPID*. Within the *RAPID* framework, a joint CAD model of the aircraft and its systems is used for conceptual aircraft design and optimization [23]. In addition to the geometry model, a model generated with Modelica is updated by the geometry model and is executed to simulate the dynamics of the control surfaces [24]. The underlying parametric actuation system model sizing approach is presented by Munjulury et al. [25] and Munjulury and Puebla [26]. Safavi et al. [27] further advance this simulation-centric framework to a collaborative MDO environment for aircraft conceptual system design. An entire systems architecture sizing and simulation framework with Level-2 methods, though, has not been developed so far.

Most of the approaches stated before use simple Level-1 methods to conduct systems sizing. Yet, there is still a lack of an integrated process for advanced Level-1 and Level-2 methods during overall conceptual system design. Detailed system design methods for system-specific domains, for instance, proposed by Doberstein [28] (landing gear), Bauer [29] (primary flight control), Pfennig [30] and Benischke [31] (secondary flight control), Scholz [32] (flight control and hydraulics), Dunker [33] (hydraulics), Lüdders [34] (fuel cell), Annighöfer [35] (avionics), and Sielemann [36] (environmental control system) facilitate detailed system design and optimization within an individual system domain. Seizing their results on the overall systems and aircraft level as well as managing varying fidelity of analysis results has not been considered in the literature so far. However, van Driel et al. [37] present a framework to combine component simulations of different types of power flows to an overall aircraft power system optimization. He concludes that the implementation of a local-global optimization is necessary to combine system-specific optimization with the overall power systems architecture-level optimization as it is also described by de Tenorio et al. [38].

## Architecting

In principal, aircraft systems architecting is concerned with the efficient selection of an aircraft systems architecture configuration from a large space of component alternatives, that fulfill the required system functions in an optimal manner. Model-based systems engineering techniques have been introduced in conceptual systems design, e. g., by Mohr [39]. Since their introduc-

tion, the idea of automatically generating alternatives of systems architecture configurations from a design space of available system technologies is subject to recent literature. Armstrong [40] presents a method for automated generation of systems architecture alternatives from a functional viewpoint. His approach starts with the definition of top-level functions, which are then mapped to several combinations of physical components capable of fulfilling these functions. The selected components themselves require, for instance, power supply. Thus, they induce new functions to be fulfilled. This approach is called *functional induction approach*. An algorithm thereby performs a full enumeration of all component combinations that may fulfill the required product functions and considers predefined constraints that exclude specific component combinations. In his dissertation, de Tenorio [1] uses the same idea and examines the additional use of the modeling language SysML for architecture meta-modeling. Likewise, Jackson [41] adapts Armstrong's approach to develop a method for robust conceptual architecting studies under parameter uncertainty. Chakraborty and Mavris [42] integrate these design space exploration capabilities into an architecting algorithm, which automatically connects architecture components based on identified heuristics that consider redundancy requirements. Fioriti et al. [43] use the design inputs stated by Chakraborty to perform a full enumeration of possible systems architecture configurations. However, he discards infeasible solutions manually in order to size and assess all feasible architecture alternatives. An approach for architecting fault-tolerant systems, which considers redundancy aspects by means of reliability block diagrams (RBD) is proposed by Raksch [44]. Based on this work, Bornholdt et al. [45] present the *GeneSys* methodology for function-driven design of fault-tolerant aircraft systems architectures, which is outlined in Section 3.3. As part of the methodology, the design space of possible architecture variants is generated and then down-sized by a rapid preliminary system safety assessment (PSSA) using RBDs. The remaining feasible architectures, which comply with predefined safety requirements, are then sized and evaluated to identify the dominant architecture concept. Similar algorithms for architecture design space explorations for aircraft system modeling frameworks are presented by Garriga et al. [46] and Judt et al. [47–49]. A generic algorithm to optimize the architecture of cyber-physical systems (Level-2 models) is proposed by Finn et al. [50]. They demonstrate their approach with a candidate search of an optimal aircraft environmental control system configuration.

The algorithms reviewed so far explore the design space by generating possible architecture variants and downsizing the design space by means of evaluating constraints (e.g. safety or redundancy requirements), using heuristics or relying on expert judgment. Auto-



mated design space explorations can be supportive for system-specific trade-offs as can be seen from studies by Bornholdt et al. [45]. A full enumeration of the entire aircraft systems architecture design space, however, implies an enormous effort in setting up the problem. In addition, automated design space explorations on OSD-level seem to over-examine the architecture definition problem. They often yield dominant architecture configurations, that have already been envisioned by system designers. Hence, it is concluded that automated design space explorations can be helpful. Yet, a manual design space definition by the tacit knowledge of an experienced engineer may lead to the same conclusions more efficiently. As a result, the already proposed methods are regarded as sufficient for future architecture design studies.

## Assessment

Available alternatives for architectures can be evaluated using either system-level or aircraft-level metrics. System-level metrics like the cumulative system mass of the architecture, power consumption, and system acquisition costs are typically used for comparison of competing system concepts. In addition, Bornholdt et al. [45] use the technical dispatch reliability (TDR) as an operational assessment criterion. Hereby, RBDs are employed to calculate the probability of the system being able to comply with the master minimum equipment list (MMEL). As the MMEL is typically not available during the early design phase of novel aircraft concepts, this criterion is only meaningful for retrofit studies.

The system-metrics mentioned before are typically opposing. Hence, the system designer has to select the best alternative based on the generated Pareto-front of non-dominated alternatives. However, the system-metrics can also be combined to a single aircraft-level metric. For this purpose, the impact of mass and power consumption on fuel efficiency can be evaluated by coupling static system simulation models with detailed 2D-mission simulation codes [12, 14, 15, 17, 51]. For example, Dollmayer [51] presents the mission simulation tool *SysFuel*, that interacts with the gas turbine simulation program *GasTurb*. This interaction enables the estimation of the impact of systems on the actual engine thermodynamic state for each mission point during the flight simulation. Lüdders [34] advances this approach by implementing simple functions to predict aircraft resizing effects of system mass changes on structural elements like wing, empennage or landing gear. Chakraborty [15] describes a similar procedure for early assessment of aircraft systems by means of a mission performance analysis and aircraft resizing rules. Lammering [14] proposes an integrated approach for assessment of system's impact on aircraft resizing effects. To this end, a systems design tool is integrated

into *MICADO*. A detailed mission simulation is performed taking into account average power consumption estimates for every mission segment. In addition, the detailed aircraft cost model proposed by Lammering et al. [52] is able to combine system acquisition costs, fuel efficiency, and maintenance aspects into a single economic metric, namely direct operating costs. Bineid [53] proposes a top-down method for conceptual aircraft system design considering reliability and maintainability as contradicting aspects. Hereby, RBDs are utilized to predict aircraft dispatch reliability, allocate failure rates and component dispatch reliability from system to component level, and comparing actual to allocated component dispatch reliability in order to identify the dominant architecture with respect to availability (reliability and maintainability).

Despite the abundance of methods for system assessment on overall aircraft level, a technique to consider assembly costs as a target metric hasn't been proposed in literature.

## Future research directions

Conceptual systems design has advanced considerable in recent years. The approaches implement model-based systems engineering techniques and models with increasing fidelity level. However, a full OSD framework with methods ranging from Level-0 to advanced Level-1 or Level-2 methods is still not available. In this context, knowledge-based engineering (KBE) techniques become even more meaningful to ensure the reusability of component models, design pattern and 3D-models. Moreover, dynamic system requirements on system components should be studied in more detail during conceptual design, since their consideration contribute to more accurate predictions.

Thermal models have already been addressed in the literature. The ongoing electrification of aircraft systems, however, requires that heat rejection from aircraft components is modeled in more detail in order to study heat management strategies.

The concept of propagating data from bottom-up sizing (detailed system design) to top-level assessment (overall aircraft design) raises the question of how to manage the data flow and the interpretation of aggregated results on the OAD level. For instance, this is the case, if the majority of the aircraft systems are modeled with simple Level-1 methods, whereas a specific system under investigation is modeled with detailed Level-1 or Level-2 methods. The overall systems design evaluations then require to collate analysis data with varying level of detail. In literature, however, means to estimate the accuracy of an aggregated overall assessment result has not been scrutinized. The employment of uncertainty management and analysis techniques with consideration of parameter and model uncertainty can support the evaluation of study result accuracy within

multi-fidelity design environments.

Although system design tools have already been tested in collaborative and distributed MDO frameworks, an integrated system and engine sizing procedure has not been proposed. Especially in the context of UHBR engines, an integrated design of aircraft systems and power plant is required to study the sizing effects of conventional and all-electric power extraction from the engine as it is discussed in Section 4.

In addition, there is still a lack of a standardized data exchange format for the definition and characterization of systems architectures comparable to the Common Parametric Aircraft Configuration Schema (CPACS) [54].

An approach to conceptual design of aircraft systems with a special focus on design for optimal assembly costs is missing. A consistent methodology considering and trading opposing assessment criteria for fuel efficiency, assembly, and availability should be developed.

In summary, following directions can be identified from literature for improvement of conceptual system design methods in future research:

- Develop an overarching multi-fidelity methodology for conceptual system design, which uses methods from Level-0 to Level-2
- Consider effects of dynamic system requirements on component sizing
- Advance thermal models applied during conceptual system design
- Establish an uncertainty quantification and management strategy for multi-fidelity aircraft system design
- Investigate an integrated system and engine sizing procedure on the overall aircraft level
- Define a standardized data exchange format for substantial systems architecture information
- Examine advanced assessment criteria for more integrated architecture studies considering the effects of fuel efficiency, assembly, and maintenance

### 3 OVERALL SYSTEMS DESIGN METHODOLOGY WITHIN THE AVACON PROJECT

A holistic approach to conceptual system design covers tasks ranging from overall aircraft to detailed subsystem level. For this purpose, different methods from contributing partners are combined for the systems design activities within the AVACON project. The related allocation of responsibilities for this constellation is depicted in Section 3.1. Methods for all-electric Level-0 system sizing, overall systems architecting, sizing and assessment, and integrated system design of a

hybrid laminar flow control system are outlined in Sections 3.2, 3.3, and 3.4, respectively.

#### 3.1 Constellation of system design partners

System design tasks are subdivided into overall aircraft design (OAD), overall systems design (OSD), and detailed subsystem design (DSD). As depicted in Figure 1, Bauhaus Luftfahrt e.V. (BHL) is mainly concerned with design activities on OAD and OSD level. This includes, for instance, technology assessments on OAD level and systems design with Level-0/1 methods. The main focus of the Institute of Aircraft Systems Engineering (FST) at Hamburg University of Technology (TUHH) is to govern the physics-based sizing, simulation and assessment approach on the OSD- and DSD-level. Moreover, FST conducts detailed design studies (Level-2) for selected system domains, which are discussed in Section 4.

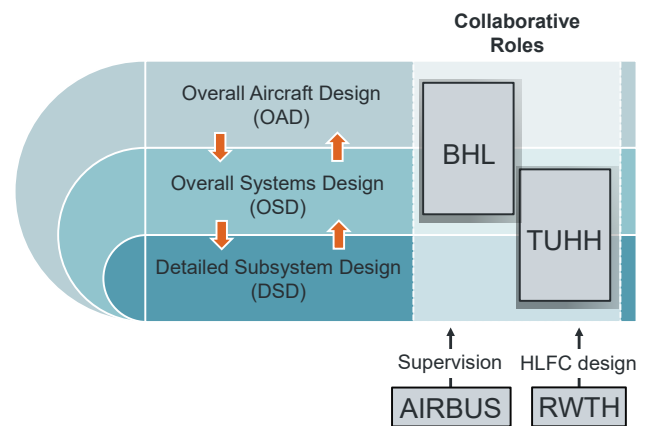


FIGURE 1: Collaborative roles within AVACON system design workpackage

Both partners thereby contribute towards application and improvement of sizing and simulation methods. BHL uses a dedicated Level-0/1 sizing method for all-electric systems architectures, which is outlined in Section 3.2. Instead, FST improves Level-1 sizing methods and successively integrates Level-2 sizing methods into the overall systems design and assessment methodology *GeneSys* presented in Section 3.3. This partnership constellation enables a design procedure that starts with top-down analyses serving as a starting point for detailed bottom-up system design activities. The results from detailed studies are then fed back to OAD synthesis by means of system parameter sensitivities. With the sensitivities, a holistically optimized systems architecture for the target aircraft can be derived.

For the sizing of the hybrid laminar flow control (HLFC) system, an integrated approach is necessary. The system laminarizes the flow by means of boundary layer suction and thereby improves aerodynamic performan-

ce. However, the suction distribution and the amount of suction flow determines the size of the system components like the air compressors. Thus, a sizing and assessment on overall aircraft level has to be conducted to find the optimal system size. To this end, a dedicated method developed by the Institute of Aerospace Systems (ILR) at RWTH Aachen is applied. It is described in Section 3.4.

The industry partner AIRBUS revises the definition of requirements and assumptions for state-of-the-art component properties to assure the quality of results.

For exchange of systems architecture information and quantitative data of requirements, an interface between involved system design partners is needed. It is therefore an objective to contribute to a standardized data exchange format suitable for future implementation in the CPACS standard, that holds substantial information about systems architecture properties.

### 3.2 Methodology for Level-0 sizing of all-electric aircraft systems architectures (eFlow)

The performance assessment of aircraft concepts with an envisioned entry-into-service date for 20 to 50 years in the future is a frequent task at Bauhaus Luftfahrt e.V. (BHL). Hereby, the incorporation of a realistic systems architecture and the assessment of its performance is a vital component of a sound overall aircraft evaluation. For the investigation of future system architecture concepts, alternative energy sources (e.g. fuel cells) as well as major changes in the consumers (e.g. hybrid and all-electric propulsion architectures) have to be considered. Often there are not many details available for the concepts in this early design stage. This makes it necessary to provide a methodology for sizing and assessment with a minimum amount of input data. For this reason, the *Energy Flow Analysis (eFlow)* methodology has been developed at BHL. The *eFlow* methodology is a set of methods to estimate weight and power consumption for all electric systems architectures including advanced components. These methods are mainly based on Level-0 methods. Level-1 methods are applied for components that are of major importance for new architectures as, for instance, circuit breakers, converters, and cables. The methods are implemented in MATLAB. They enable the calculation of power loads for a mission comprised of the segments taxiing, takeoff, climb, cruise, descent, diversion, and landing. Furthermore, the consumers are grouped into non-essential, essential, and vital loads in order to size the architecture according to critical failure cases. An interface for an automated import of data from the preliminary aircraft design platform *APD Pacelab* is available. As mentioned, the ability to execute a preliminary estimation of loads and masses of the systems architecture with minimum input data is important in order to consider its impact in early conceptual design

stages. Therefore, all implemented methods can be executed using data from reference cases, which are scaled by a few aircraft characteristics of the concept under consideration (e.g. maximum take-off weight, wing and empennage area, passenger number, design range, and mission segment duration). Electrical consumers of conventional systems architectures like avionics and instrumentation are modeled with methods taken from the literature [55]. For substantial electrical consumers of a MEA systems architecture, methods from literature have been gathered to estimate their power demand and mass. For example, the flight control actuators are considered as electro-mechanical actuators [56] within eFlow. The landing gear is modeled assuming a local hydraulic system for each gear [57] and the wing de-icing system is implemented as an electro-thermal de-icing system [58].

Within the scope of AVACON, the existing set of methods will be further improved and extended. Methods for the non-electrical components and for conventional system elements will be implemented (e.g. environmental control, flight controls and de-icing) in order to enable a sound analysis of a baseline systems architecture. One of the major objectives of AVACON is to improve the exchange and cooperation of aviation research entities in Germany. For this reason an interface with CPACS has been implemented to reduce effort and necessary time to analyze the design iterations of the aircraft concepts in AVACON. In order to exploit all information included in the AVACON aircraft concepts, an extended mode for the methods will be regarded, which enables the incorporation of all available aircraft data (e.g. specific flight control surface geometries). Furthermore, a transfer of tool implementation to *Python* will be considered. This could enable the incorporation of CPACS support functions used by the aircraft conceptual design framework *VAMPzero* developed by the German Aerospace Center (DLR) as well as increased flexibility by enhanced object-oriented data structure.

### 3.3 Methodology for overall systems design and assessment (GeneSys)

The modular methodology toolbox for overall aircraft systems design and assessment *GeneSys* is proposed by Bornholdt et al. [45]. Main steps of the *GeneSys* procedure are illustrated in Figure 2. The first two steps are concerned with exploring the possible design space. Based on a top-down functional breakdown starting from top-level aircraft requirements, the combinatorial design space of architecture variants from a set of physical components, that may fulfill the required system functions, are identified (Step 1). A rapid PSSA by means of aircraft system RBDs is then performed to withdraw architecture variants, that do not comply with predefined system safety require-

ments (Step 2). The remaining systems architectures are then sized using either Level-0/1 sizing methods or surrogate models of system-specific Level-2 sizing tools (Step 3). An assessment of feasible architectures with respect to mission performance and predicted aircraft resizing effects (Step 4) can be performed using the dedicated mission simulation tool *SysFuel+*. If a master minimum equipment list is available, an operational assessment based on the technical dispatch interruption rate (TDIR) can be conducted (Step 5).

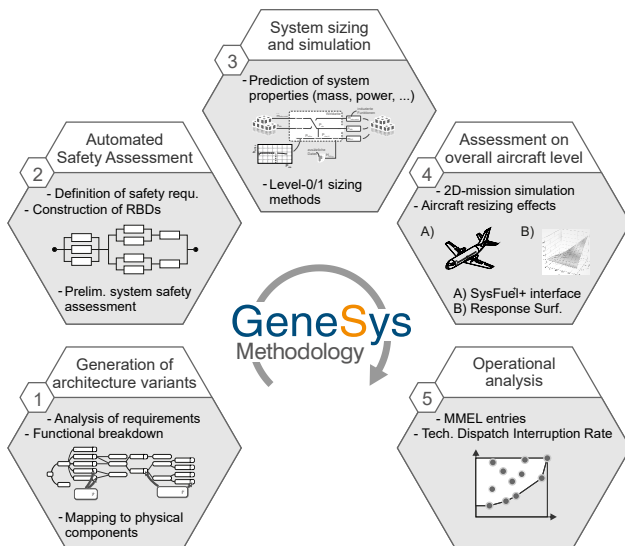


FIGURE 2: Aircraft system design and assessment procedure of the *GeneSys* methodology

*GeneSys* has already been applied, inter alia, to optimize electro-hydraulic power distribution systems [59], for conceptual design of an all-electric actuated flight control system and its corresponding electrical power distribution system [45], and for a power allocation optimization of a Sakurai flight control system concept [60].

### Systematic improvements for *GeneSys*

In the course of AVACON, the *GeneSys* methodology will be advanced to a framework with following additional capabilities:

- Overall systems architecting and system sizing with improved methods using models ranging from low to high fidelity
- Management of multi-fidelity analyses considering parameter and model uncertainty
- Advanced interfaces for integration in an overarching collaborative and distributed aircraft design environment
- Assessment based on refined operational criteria

- Visualization of architectures based on a standardized systems architecture data exchange format

A major objective of AVACON is to increase the integration of aircraft design disciplines. To this end, the *GeneSys* methodology will be improved for applications within collaborative and distributed aircraft design setups by means of dedicated interfaces, for instance, to *CPACS* as depicted in Figure 3. Integrated studies can then be conducted in order to identify coupling effects between systems and overall aircraft design. Hereby, an integrated systems and engine sizing approach will be investigated with respect to conventional and all-electric engine secondary power extraction, as it is discussed in Section 4.

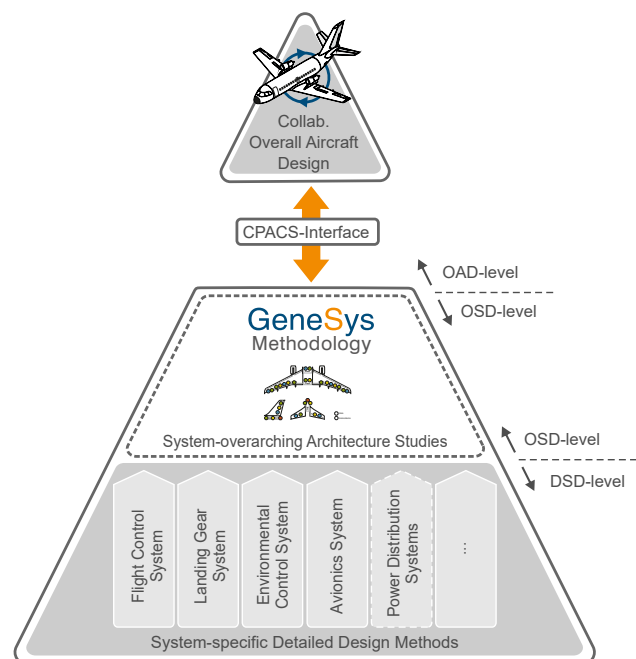


FIGURE 3: Planned interface of *GeneSys* for integrated assessment on overall aircraft level

*GeneSys* is fed with information from a collection of sizing methods with a large variety of fidelity. A first estimate for overall systems architecture mass and power consumption can be obtained by means of Level-0 sizing methods based on empirical relations. For rapid physics-based architecture studies, an analytical Level-1 method proposed by Koeppen [10] is available. The underlying concepts will be improved and updated in the course of the project. The foundation of *GeneSys*, however, is its accessibility to Level-2 design tools for system-specific domains, which have been developed at FST. Although Level-2 design tools have already been integrated in *GeneSys* by means of simple surrogate models during prior studies, a strategy to manage results with varying level of detail from several system analyses has not been developed. Thus, it is pursued



within the course of AVACON. In addition, the impact of uncertainty on the interpretation of study results will be quantified by means of uncertainty analysis and management capabilities. To this end, more advanced surrogate modeling techniques, suitable for propagating uncertainties from subsystem to overall aircraft level, can be applied.

### 3.4 Method for integrated assessment of HLFC system architectures on OAD level

The main functionality of a hybrid laminar flow control (HLFC) system is the reduction of viscous aerodynamic drag. This is achieved by a laminarization of the flow along the aircraft surfaces using optimized aerodynamic surface shapes and applying active flow suction on the surface skin. The aerodynamic benefit, however, comes with an increase in mass and power consumption of the suction system. Compressors, pipes and wiring are required to provide a suction mass flow that energizes the transient area of the boundary layer. Hence, it is necessary to perform an integrated sizing and assessment of the HLFC system to consider cross-disciplinary coupling effects between aerodynamics and system design on OAD level.

Such an integrated HLFC design method has been developed by the Institute of Aerospace Systems (ILR) at RWTH Aachen University. It is used within the AVACON project. The method follows a sectional approach (quasi 3D approach) which divides the 3D object of the wing into several 2D sections. The geometric properties of each section is used to calculate the related flow characteristics. This yields the pressure distribution as well as lift and drag coefficients for each section along the wing span. The method supports calculations considering fully turbulent flow as well as partly laminar flow. A detailed description of the HLFC design process is given by Risse [61].

In order to set a specified suction distribution along the chord of a wing section, the wing has to be perforated and compressors have to generate a certain suction-pressure. These compressors require electrical power provided by the electric generators of the aircraft. The suction flow is thereby led through pipes to the outflow valve at the wing-fuselage intersection. The sizing of these components is based on the simplified suction concept developed during the ALTTA project [62, 63]. For this concept, Pe and Thielecke [64] propose methods and equations for the HLFC system components. They are implemented in the HLFC system method of ILR. The input design variables of the HLFC system design module are the pressure and suction distribution for the design Mach number and design altitude of the HLFC system. The most important outputs of the HLFC system sizing are the total HLFC system mass  $m_{HLFC,tot}$  and the total electrical power required to drive the suction system  $P_{HLFC,tot}$ . The total system

mass is composed of the mass of the compressors, motors, variable frequency drives, the pipes of the ducting system, and the electric wiring. The required system power depends only on the required power of the compressor and the efficiency of the motor and variable frequency drive.

In the following, the influence of the mass flow on both the aerodynamic performance and on HLFC system mass and power consumption is discussed. To this end, a preliminary sizing study of a wing-installed HLFC system for the AVACON research baseline is presented.

### Discussion of preliminary system sizing results

For the AVACON baseline aircraft, the HLFC system can be installed in different ways. Either a central architecture with a single large compressor or a decentralized architecture with several smaller compressors can be used. If a decentralized architecture is chosen, the number of compressors can be adapted. Further, it can be selected if the compressors are either connected to a separate or a collective duct. For the AVACON research baseline, a decentralized architecture with three compressors and a collective ducting system is chosen. Based on this reference configuration, several studies were carried out to test the influence of the suction system on the aerodynamic performance (measured in relative change of lift-to-drag ratio  $L/D$ ), the system mass  $m_{HLFC,tot}$ , and the system power consumption  $P_{HLFC,tot}$ . In this study, the cruise Mach number of  $Ma = 0.83$  and the initial cruise altitude  $ICA = 35\,000$  ft of the AVACON research baseline are taken as mission design point for the HLFC system. Thereby, the system is sized for different distributions of the suction velocity along the chord of the wing section.

The results are presented in Figure 4, Figure 5, and Figure 6. First, the interrelationship between a possible aerodynamic performance increase and the required mass flow obtained by an aerodynamic analysis is shown in Figure 4. It can be observed that different suction distributions can result in the same aerodynamic improvement. Thus, an optimization of the suction along the wing chord is necessary. The pareto-optimal points of optimal suction-distributions is highlighted with a solid line. Based on this pareto-front, it can be observed that an increase in the suction mass flow improves the aerodynamic performance.

In Figure 5 and Figure 6, the influence of the suction mass flow on the HLFC design in terms of system mass and power demand is shown. As already seen in Figure 4 for the relative  $L/D$  change, not every input value (mass flow) of the system sizing results in a discrete output value (system mass). This means that the system parameters mass and power consumption depend on the mass flow on the one hand, but also on

the suction distribution itself and the pressure distribution (i.e. lift coefficient) on the other hand. However, an increase in suction mass flow yields higher values for system mass and power consumption, since a more powerful suction system requires, for instance, more powerful compressors.

As can be seen from the study results, the HLFC system design objectives, i.e. high aerodynamic system performance and low system mass and power consumption, are contradictory. Thus, only an integrated assessment of these aerodynamic and system design sensitivities on OAD level can lead to a sound HLFC system design optimization.

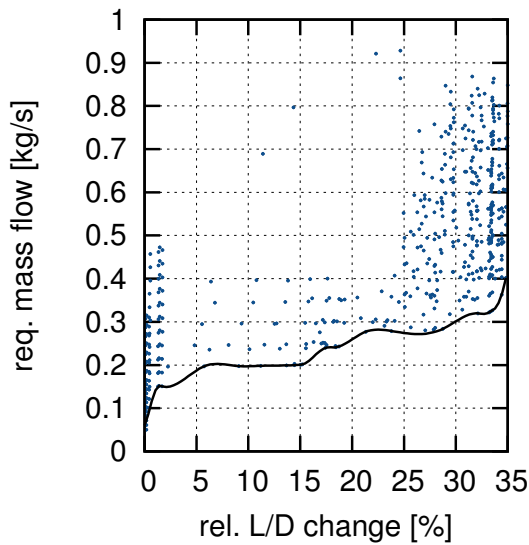


FIGURE 4: Required mass flow for aerodynamic performance improvement

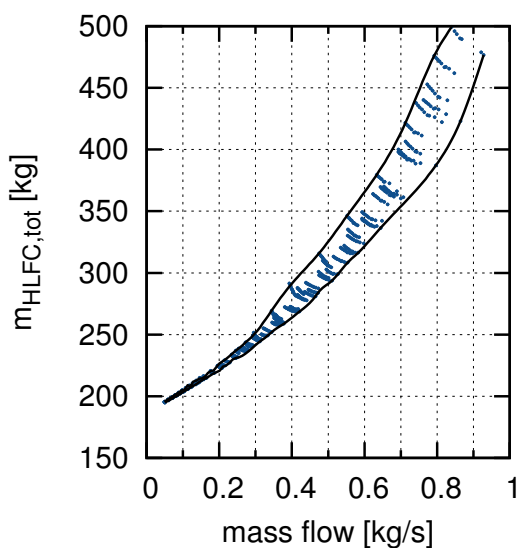


FIGURE 5: Boundaries of total HLFC system mass as a function of required mass flow

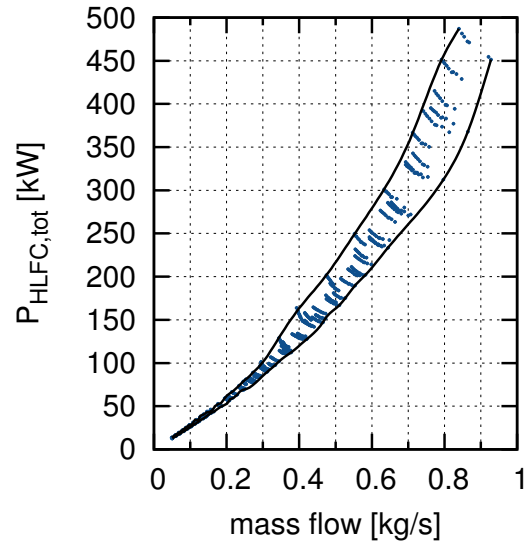


FIGURE 6: Boundaries of total HLFC system power as a function of required mass flow

#### 4 CONSIDERED SYSTEM TECHNOLOGIES FOR ARCHITECTURE TRADE STUDIES AND BASE-LINE SYSTEMS ARCHITECTURE

Employing over-wing UHBR engines in conjunction with a hybrid laminar flow control (HLFC) system for the main wing implies novel requirements for system design. In the following, concepts for relevant system domains are described, that satisfy these requirements. In addition, system technologies for the AVACON baseline systems architecture are selected with respect to a close resemblance to the A350 aircraft systems architecture.

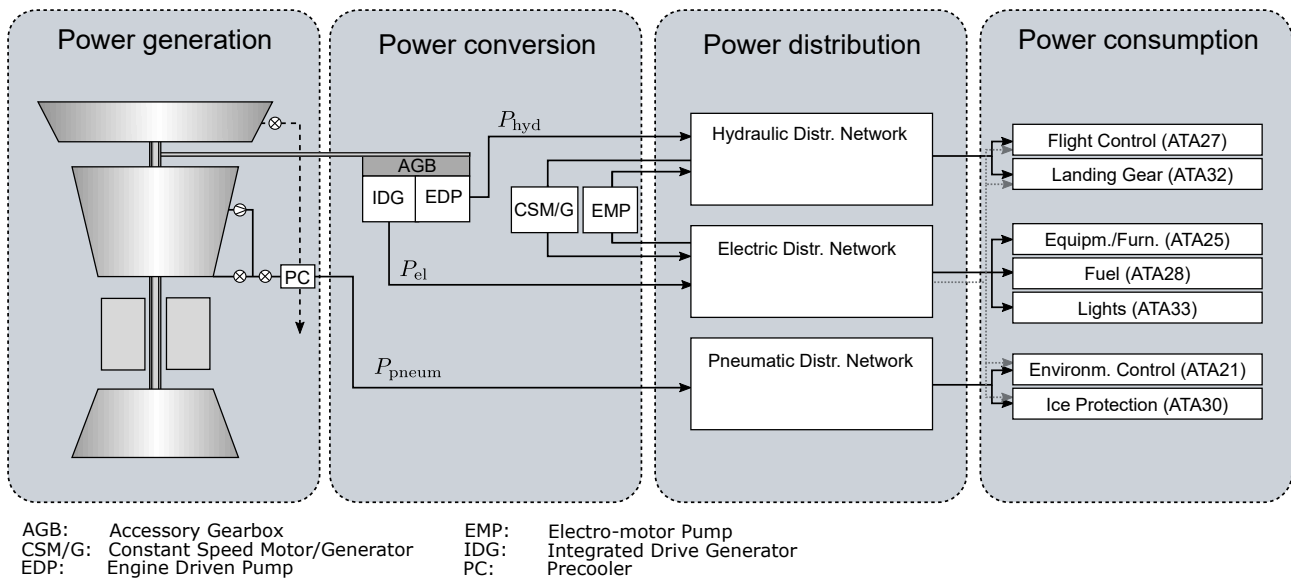
##### 4.1 Power supply systems

Aircraft systems require to be supplied with either mechanical, hydraulic, electrical or pneumatic power. A common source is the aircraft engine. It provides secondary power for the aircraft systems beside the primary propulsive power. The engine is regarded as the main source for secondary power within the scope of AVACON as well. The concept of a MEA systems architecture is thereby considered as the target configuration for all architecture trade-off studies. In this context, the two extremes of engine secondary power extraction architectures – i.e. a conventional and an all-electric concept – are described in the following. They serve as starting points for more detailed power supply architecture studies.

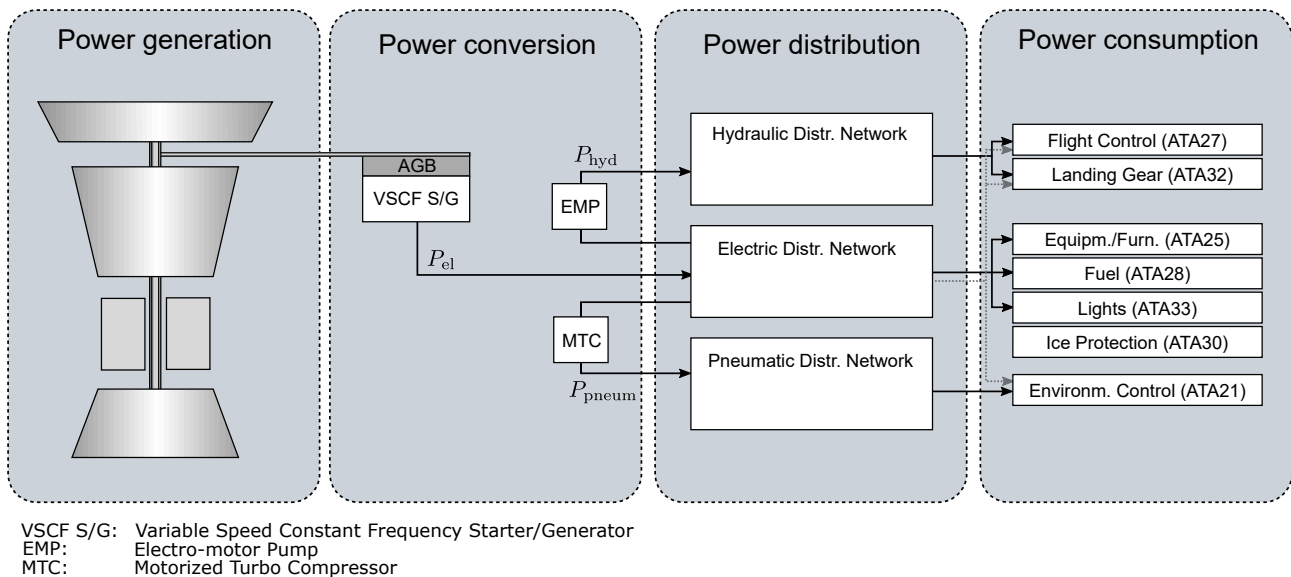
### Conventional engine secondary power extraction

A conventional concept to extract secondary power from the engine is shown in **Figure 7a**. Hereby, engine shaft power is converted to electrical and hydraulic power by an integrated drive generator (IDG) and an engine driven pump (EDP), respectively. These power conversion components are mounted on an accessory gearbox (AGB) driven by the engine shaft. For conventional electrical power supply of large transport aircraft, the combination of a 115/200V AC system with either a nominal 400Hz constant frequency or a variable frequency (VF) ranging from 360 to 800Hz, and a 28V DC

power supply is still an industry standard for existing aircraft. However, concepts for high voltage alternate current (HVAC) at 230V AC and high voltage direct current (HVDC) at +/- 270V DC are considered to enable lighter and more efficient power distribution and management systems [65]. The EDP generates hydraulic power from mechanical shaft power at a constant nominal pressure level, which is defined as 3000 psi and 5000 psi for traditional and modern large transport aircraft, respectively. Electrical and hydraulic power supply systems are designed with redundant supply circuits to comply with safety requirements for fault-critical system functions like flight control actuation.



(a) Conventional power path architecture



(b) More electric power path architecture with all electric secondary power extraction from the engine

FIGURE 7: Examples of power path architectures from power generation to power consumption

Therefore, an optimal architecture of the electrical and hydraulic system is tightly coupled with the architecture of the primary and secondary flight control actuation system and has to be determined with dedicated architecture trade studies.

Moreover, bleed-air is extracted from the intermediate and high pressure compressor of the engine in order to provide pneumatic power to systems like the environmental control system (ECS) or the ice protection system (IPS). The air extracted from the two compressor stages is mixed and regulated to required temperature and pressure levels.

Additional energy conversion components ensure safe operation in case of failure of a single circuit or during ground operation. For the hydraulic system, for instance, an electric motor pump (EMP) converts electrical to hydraulic power, whereas a constant speed motor/generator (CSM/G) converts hydraulic to electrical power. An air driven pump (ADP) can be employed to transform pneumatic to hydraulic power. An auxiliary power unit (APU) provides additional bleed air for ground supply, engine start capability, and pneumatic power supply redundancy. The corresponding APU starter/generator supplies electric power during ground and abnormal operations.

### All-electric engine secondary power extraction

Although the described conventional engine secondary power extraction principle has been the dominant concept for large transport aircraft, there are at least two drivers in the light of the AVACON target configuration for a more electric engine power extraction concept:

1. Further electrification of aircraft systems due to benefits originating from power management strategies, advanced maintenance and monitoring capabilities, and improved system reliability
2. Reduced pneumatic power extraction efficiency due to unfavorable bleed-air conditions when extracted from an advanced UHBR geared turbofan engine

The all-electric engine power extraction concept depicted in **Figure 7b** overcomes these shortcomings. The extraction of compressed bleed air from the engine is thereby replaced by a motorized turbo-compressor (MTC) supplied by the EPS. In this example, electrical power is provided by a variable speed constant frequency starter/generator (VSCF S/G), which makes use of dedicated power electronics for transformation from variable to constant frequency. It also ensures engine start functionality. More advanced concepts consider an engine-mounted starter/generator to eliminate the AGB and thereby provide even higher efficiency and reliability. However, this advanced all electric engine (AEE) concept is not considered within the scope

of AVACON. Between the two extremes, more electric engine (MEE) concepts are subject to recent research. They consider to partly replace the mechanically-driven hydraulic and pneumatic power generation with electrical machines. Since this replacement reduces complexity of the power extraction concept, it improves dispatch reliability and maintainability [66]. Hence, the MEE is a potential candidate for systems architecture studies in AVACON.

### Electro-hydraulic power system architecture

With regard to more electric engine power extraction, the hydraulic system can be considered as an electric consumer. Instead of EDPs, the electro-hydraulic system power is then supplied by compact hydraulic power packages (HPP) which integrate an EMP with essential components of conventional hydraulic systems in a single module. While Trochermann et al. [5] conduct a trade-off with respect to central and distributed electro-hydraulic power generation systems with zonal HPPs for a short-range aircraft at a nominal pressure level of 3000 psi, a related study has not been performed for a mid-range aircraft. Hence, these concepts will be subject of AVACON trade-off studies.

Indeed, a conventional engine power extraction concept and a power supply architecture designed to obtain *Extended Twin Operations* (ETOPS) type approval is selected for the AVACON baseline systems architecture. It is characterized by following technologies:

- 2 hydraulic circuits with 5000 psi constant pressure control supplied by 1 EDP per engine
- 3 electrical distribution networks
  - 230V AC VF supplied by 2 engine generators per engine
  - 115V AC converted from 230V AC VF by auto transformer units (ATU)
  - 28V DC network supplied by the 230V AC network with transformer rectifier units (TRU)
- A 2H/2E power distribution architecture for the 230V AC electrical circuit and 5000 psi hydraulic circuit satisfies the safety requirements for flight control and landing gear functions.
- Bleed air extraction from intermediate and high pressure compressor stage and pre-conditioning via a precooler and dedicated valves
- 1 APU with a starter/generator 230V AC at 400Hz constant frequency for electrical backup
- 2 EMPs for ground power supply and electro-hydraulic backup



## 4.2 Environmental control system and ice protection system

For large aircraft, the selection of technology concepts for ECS and IPS depends on the underlying power supply system architecture. The primary functionality of the ECS is to supply fresh air for on-board occupants as well as to provide pressurization, temperature control, and ventilation for selected compartments. To satisfy these requirements, conventional ECS are supplied with bleed air, which is conditioned by bootstrap air cycle machines. Via a mixing unit and a ducting network with integrated recirculation and ventilation fans, the conditioned air is distributed to the corresponding compartments and regulated according to required conditions. However, if bleed air is eliminated due to a MEE power extraction concept, the air cycle machine has to be provided with compressed outside air delivered by a dedicated ram air inlet. To this end, an MTC can be utilized, which is powered by the electrical system. For this concept, an additional use of vapor cycle systems have to be considered in order to guarantee conditioning during ground operations.

The main function of the IPS is to enable safe operations in icing conditions by protecting, inter alia, wing leading edge and cockpit windshields. For conventional systems architectures of large transport aircraft, the wing ice protection system (WIPS) uses hot bleed-air from the engines to heat part of the leading edge area. Impinging supercooled water droplets are eva-

porated. In addition, electrical heater wires embedded into the windshields heat the cockpit windows. In the absence of bleed-air extraction, the functions of the WIPS can be adopted by electro-thermal solutions. Electrical heater mats, which are electrical resistors connected to the high voltage electrical circuits, are considered in this case.

An electrical IPS constitutes the main peak power consumer of a MEA architecture. Thus, if a more electric engine secondary power extraction is chosen, hybrid use of bleed air and MTC will be investigated to enhance engine power extraction efficiency.

For the baseline systems architecture, the following system variants are selected:

- Bleed-air supplied ECS with bootstrap air cycle machines
- Thermal bleed-air WIPS and electrical heating for cockpit windows

## 4.3 Flight control system

The control surface layout resembles a conventional split of primary and secondary flight controls for the AVACON baseline and target aircraft. It is defined by the responsible OAD work package. However, the selection of actuation concepts and their allocation to the power supply are part of system design activities.

*Primary flight control system (PFCS).* The main func-

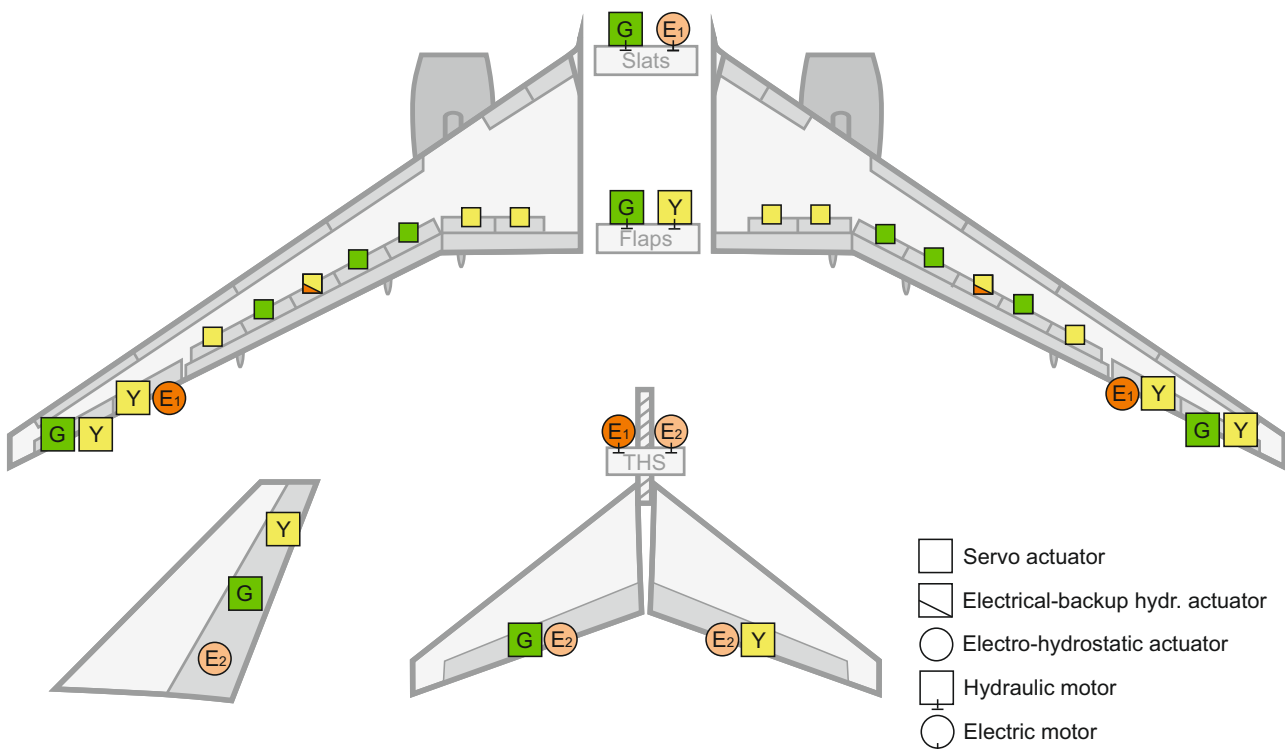


FIGURE 8: FCS baseline architecture of AVACON with allocation to electrical (E1,E2) and hydraulic (G,Y) power supply

on of the PFCS is to provide roll, pitch, and yaw control during flight. In addition, load-alleviation systems have been developed to relieve structural loads for maneuvering and gust turbulence, which enables certification for higher maximum takeoff weights. Since the entire FCS has to be designed for fault-tolerant operation, flight control actuators have to be allocated to independent power sources (e.g. to multiple circuits of a power type) to comply with safety requirements.

To satisfy these requirements, several actuation technologies are available, which are described in detail by Maré and Fu [67]. Next to traditional hydraulic servo actuators (SA), electro-hydrostatic actuators (EHA) are considered in the course of AVACON. Hereby, the actuator's position is controlled by an electro-hydraulic motor-pump unit. A hybrid solution of EHA and SA is the electrical backup hydraulic actuator (EBHA). It is connected to both electric and hydraulic circuits. In addition, the use of electro-mechanical actuators (EMA) for front-line operation, which are connected to the electrical power supply system, will be examined.

*Secondary flight control system (SFCS).* The main functionality of the high lift system is to augment lift during takeoff and landing. More advanced systems also provide differential flap setting and variable camber for performance optimization, especially during cruise, as it has been developed for the Airbus A350 XWB-900 [68]. Hence, the high lift actuation system has to be designed to assure safe control surface motion respecting maximum hinge moment, maximum deflection rate, available installation space, and control surface kinematics. To this end, the SFCS can either be realized as a centralized architecture, where a central drive unit (power control unit, PCU) drives the control surfaces via a mechanically-driven shaft transmission system, or a distributed actuation concept, for which the actuation can be fulfilled by distributed mechanical, electro-hydraulic or electro-mechanical power trains [69]. If differential flap setting functionality is a system requirement for centralized mechanically-driven flaps, an active or passive differential gear box has to be considered to enable a controlled asynchronous flap movement of adjacent surfaces.

An UHBR engine and HLFC technology installation implies additional design constraints. Due to its large engine diameter, a close mounting of the engine under the wing is inevitable. This may cause premature separation of the air flow and calls for employment of flow control devices [70]. In addition, the slat mechanism has to be selected such that its functionality is not affected by the nacelle. A gapless droop nose device for inboard slats will be taken into account instead of *rack and pinion* or *Shielded Krüger* kinematics for inboard slats. This also minimizes noise production [68]. The jet wake may also impact the load on the flap, which may favor new moveable concepts with me-

chanically decoupled flaps [70]. If an over-wing engine configuration in conjunction with a HLFC system is considered, their laminarization effects may facilitate the design for thin aircraft wing profiles. Thus, installation space for flight control actuation can be limited. Moreover, the HLFC technology requires *Shielded Krüger flap* kinematics for the leading-edge high lift system. Thus, *Shielded Krüger flaps* will be assumed as an additional kinematics concept for outboard slats in future studies.

As stated before, a 2H2E-configuration is selected for the baseline systems architecture considering two hydraulic circuits (G,Y) and two electric circuits (E1,E2). The baseline flight control system architecture with corresponding allocation to the supply system is depicted in Figure 8. Hereby, flaps with dropped-hinge kinematics are assumed. For the inboard slats, gapless droop nose devices driven by geared rotary actuators. Rack and pinion kinematics with sealed slats for the outboard leading-edge high lift devices are assumed.

#### 4.4 Landing gear system

An over-wing configuration of UHBR engines is considered for the AVACON target aircraft. This configuration enables the integration of unconventional landing gear concepts, which will be examined in a dedicated AVACON work package. The related methodology, concepts and requirements are outlined in detail by Kling et al. [71]. However, for the AVACON baseline systems architecture, a wing-mounted landing gear with redundant 2H-supply for braking functionality and a 1H-supply for wheel steering and for extension/retraction functionality is considered.

## 5 CONCLUSION AND OUTLOOK

In this paper, a methodology for system design and assessment of aircraft systems architectures for the AVACON baseline and target aircraft has been described. It combines expertise of partners contributing to system design activities with design and assessment methods ranging from low to high fidelity. To this end, an empirical method for all-electric system architecture sizing, an overall system architecting, sizing and assessment tool chain, and a dedicated HLFC system sizing and assessment approach of contributing system design partners have been presented. Based on a comprehensive literature review of available approaches to aircraft conceptual system design, a list of directions for methodological improvements in future research has been proposed.

A majority of these points will be addressed within the scope of the AVACON project. In addition, technology trade studies will contribute to derive a holistically op-

timized aircraft systems architecture for the AVACON target aircraft. As a next step, the AVACON baseline system architecture will be sized with improved low to medium-fidelity methods using state-of-the-art technology factors. Starting from this baseline, selected system-specific trades will be conducted to iteratively converge at a dominant system architecture. This comprises studies to optimize more-electric power supply systems. In this regard, the identification of coupling effects between system and engine sizing in the light of conventional and all-electric engine power extraction will be considered.

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