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Simulation Framework for Aircraft Power System Architecting

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Today, the preliminary design process of power system architectures of civil aircraft is usually characterized by the separation into Air Transport Association chapters. However, the complexity of an aircraft energy network, the large number of influencing design parameters, and system interfaces require a common and transparent process if a meaningful evaluation of different system architectures with regard to the overall aircraft efficiency is to be achieved. The development of a dedicated methodology, a simulation framework, and adapted modeling techniques are the objectives of the presented research. This paper focuses on the dedicated modeling approaches that are developed to analyze systems at the aircraft level. Three different modeling techniques illustrate, on one hand, the effort required to develop adapted models to fit in the proposed analysis environment. On the other hand, the added value of such an integrated modeling approach is demonstrated with the examples of the electric generator sizing analysis and the link of power system simulation to a global aircraft thermal model.

I. Introduction

THE increasing complexity of modern civil aircraft in a constantly evolving, very competitive environment of technological, regulatory, economic, and ecological challenges leads the aircraft manufacturers to seek increasingly optimized solutions for aircraft architectures. A global aircraft-level approach is seen as the most promising, overcoming the system-per-system optimization used today.

Energy saving is one of the most important aspects in a highly competitive market with increasing fuel prices and the growing importance of environmentally friendly transport. Thus, the optimization of the aircraft power system architecture with regard to energy consumption is an important issue [1], in addition to the improvement of the aircraft engine and aerodynamic performance.

The aircraft power system architecture is a complex network of interacting systems, all fulfilling different functions. To structure this challenging task, the so-called Air Transport Association (ATA) chapter classification, established in 1936 by the ATA, is used to identify the subsystem responsibilities and define interfaces between design teams. The ATA breakdown is based on a conventional system architecture, which has not changed significantly until the need for optimization arrived at the system-architecture level. Today, although the technology is available to change the system architecture in a revolutionary way, the ATA breakdown reveals its weakness: the efficient integration of new technologies is only possible at the multi-ATA level; the conventional interfaces change or disappear. This impacts the system design in the same way as the organizational structure: emerging topics such as power and heat management are only solvable at multi-ATA and multidomain (systems, structure, power plant) levels. A functional approach is clearly the most promising solution [1,2]. Especially with regard to the comparability of different solutions, a functional approach will enable to open the design space and to start to shift from an evolutionary design to more revolutionary solutions.

The variety of possible solutions and new technologies (e.g., more electrical aircraft systems and bleedless power system architectures) and the large number of influencing design parameters require an efficient tool enabling the system designer or aircraft architect to analyze the impact of system-architecture changes at the aircraft level (mass, drag, and fuel consumption) and the impact of aircraft-level changes (e.g., certification, safety, or extended-range twin-engine operational performance standards requirements) on the system design. A model-based parametric predesign process that allows the quantification and minimization of design margins and a better understanding of interdependencies between the systems with regard to the power architecture would be of great benefit to aircraft manufacturers in their role as architects and system integrators.

Coping with these challenges is the objective of an Airbus internal research and technology project (part of the Common Virtual Bird initiative [3]), started in 2005. A methodology has been developed [4] and implemented into a simulation framework prototype [5]. The present paper aims to illustrate selected modeling techniques and to demonstrate the added value of this approach via two application examples.

II. Methodology and Prototype Implementation

The aircraft power system architecture is a system of interacting subsystems with a high level of functional couplings (Fig. 1). The systems are coupled via their energy exchanges (electric, hydraulic, pneumatic, mechanical, thermal, and fuel flow). Additionally, the energy flow depends on the time axis (different flight phases), the operation mode (normal, degraded, or failure mode), the chosen technology (power type and power consumption characteristics), and the safety requirements (installation of redundant systems, etc.). The aircraft power system architecture is linked to the overall aircraft performance via its contribution to mass, drag, and fuel consumption.

Additionally, the design and thus the power requirements and interaction between systems depend on aircraft-level design parameters (e.g., number of passenger seats, aircraft geometry, and mission profile) and on system/technological parameters [e.g., the

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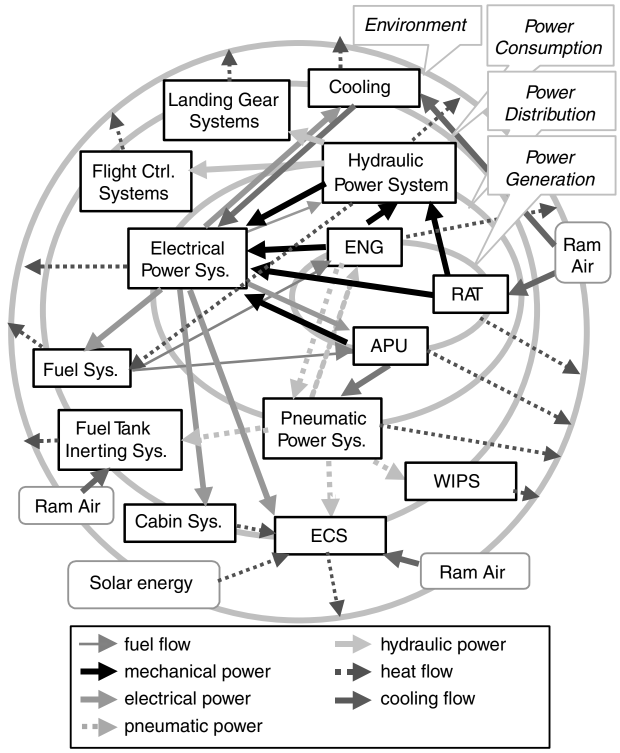

Fig. 1 Energy Coupling of a conventional aircraft power system architecture.

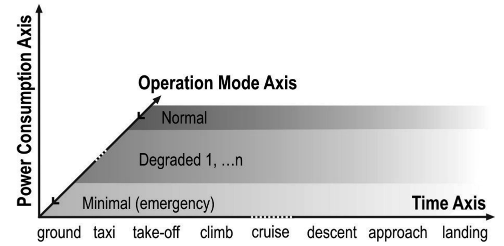

Fig. 2 Three-dimensional definition of the power-exchange interfaces of the power system modules.

power supply type (electric, hydraulic, or pneumatic), pressure level in the hydraulic circuits, voltage level, etc.].

Regarding the increasing complexity and the changing interfaces, especially for more electric architectures, the developed methodology [4] is based on a formalization of the design process (inverse engineering principle) of the overall architecture (and thus of the integrated design processes of each system within the architecture of systems) following a functional approach. This approach allows technology choices at the end of the decision chain and enables the highlighting of key parameters that are interesting for analysis on the aircraft level. The functional approach also enables the implementation of a generic process, which then allows the comparison of different architectures or of aircraft-level parameter sets in a *consistent* way.

It is proposed to classify the systems of aircraft power system architecture, as depicted in Fig. 1, according to their major function within the power architecture:

1) The group of "power generation systems" comprises engines, an auxiliary power unit (APU) for ground operations, and a ram air turbine (RAT) for emergency conditions; fuel cells are candidates for future architectures.

2) The group of "power transformation and distribution systems" comprises the systems that transform and distribute the secondary power provided by the power generating systems to the consumer system. Conventionally, the electrical power system (EPS) and the hydraulic power system transform the mechanical power of the engine into electric and hydraulic power. Pneumatic power is distributed to the dedicated systems after temperature and pressure control.

3) The group of "power consumption systems" comprises the systems, which fulfill the different primary functions of the aircraft. For example, the flight control system, the wing ice- protection system (WIPS), the environmental control system (ECS), the fuel system, the fuel tank inerting system, the commercial cabin systems (CCSs), the landing gear systems, the primary flight control systems, the high-lift system, and the equipment-cooling systems.

The architecture sizing process starts from the functional requirement of the power consumption systems. After their definition and choice of technology, the sizing requirements of the power transformation and distribution systems can be derived from the simulation of the three-dimensional power profiles (Fig. 2). Then the required, versus the available, power from the engine and other power generating systems can be derived.

In a second step, the performance of the thus-defined architecture can be assessed for different offdesign mission profiles.

Summarizing, the two following steps are proposed to allow the elaboration of aircraft-level energy-balanced system architectures: The power to be installed, corresponding to the weight (outcome of the sizing process taking into account various security margins and other requirements) has to be balanced against the power actually consumed during a flight, corresponding to the fuel consumption (to be assessed in the performance process).

A. Power System Modules

In principle, each system of the power system architecture can be represented in the form of a general power system module (Fig. 3). The main interfaces between the system modules are the power interfaces. Each system depends on different types of parameters: aircraft parameters (global parameters), system design parameters (local parameters that can influence neighboring systems), and operational parameters (which describe the offdesign characteristics of a system).

Some of these parameters can be varied. Thus, these parameters build the optimization and tradeoff space. The bidirectional energy interfaces represent the two different calculation modes required for each module:

1) In sizing mode, the sizing characteristics such as the number of required components, duct diameters, and generator sizes are the outcome of analysis of computation results for one or more sizing scenarios (ambient conditions, failures case, etc.).

2) In performance mode, the module calculates the dedicated output variables (mainly the energy flow) for different offdesign conditions with fixed characteristics from the sizing mode for the whole mission profile.

Each system module is developed to ensure the energy-balance principle. This allows automatic assessments of the required cooling demand or heat rejection to the environment, for example. This aspect becomes crucial for more electric or bleedless architectures, in which parasitic couplings of systems, which lead to rapidly accumulating effects on the aircraft level, are often neglected as being out of the responsibility of one system domain. One example is the increased cooling demand that leads to a higher ram air need, which increases the aircraft drag and thus the fuel consumption. Or, when cooling requirements are fulfilled via a liquid cooling system,

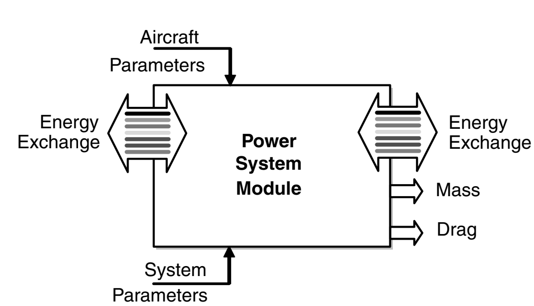

Fig. 3 General power system module.

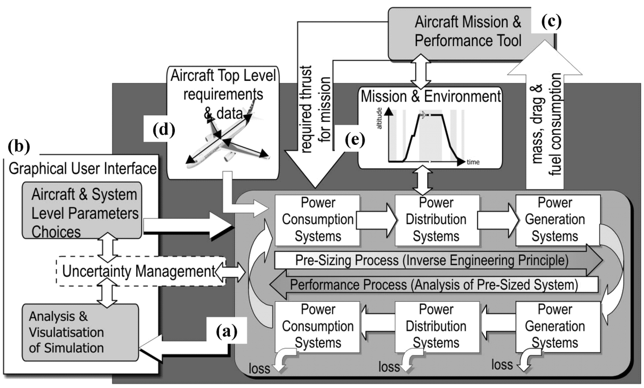

Fig. 4 Simulation framework overview.

the weight of this system and the additional weight due to fuel consumed as a result of power demand by this system have to be considered.

B. Implementation

A prototype of a simulation framework that corresponds to the preceding requirements has been developed (see Fig. 4) in a MATLAB/Simulink/Stateflow® environment. Additional code is coupled, depending on the systems module. For example, C-code is used for the engine model; a Java application is used for the aircraft performance tool, and Dymola/Modelica® import is achieved for the ECS module.

The simulation framework contains the parametric power system modules (as listed previously) embedded in the integrated automated sizing and performance calculation process [(a) in Fig. 4]. The process is guided via a graphical user interface [(b) in Fig. 4]. For the coupling to the aircraft level, the power system computation is linked to an Airbus in-house mission and performance tool [(c) in Fig. 4]. Common parameters [(d) and (e) in Fig. 4] such as environmental conditions, mission profile data, and aircraft data are made available for all systems to ensure consistency.

III. Modeling Approaches of Selected Systems

In the following section, the modeling principles of selected systems are presented. These systems are chosen to illustrate the different modeling principles used for the implementation: a functional/deterministic approach for the WIPS, a statistical approach for the CCSs, and a logic approach for the EPS. The analysis capabilities offered by these modeling approaches within the simulation framework are illustrated in the example developed in Sec. IV.

A. Wing Ice-Protection System

The function of the WIPS is to protect dedicated surfaces against ice accretion. In this way, the maneuverability of the aircraft will be ensured during icing conditions (e.g., descent or climb through clouds). Different candidate technologies exist to fulfill the ice-protection function (e.g., pneumatic thermal anti-icing, electrothermal anti-icing, electrothermal deicing, and electromechanical deicing). Hybrid solutions (e.g., combined anti- and deice [6]) are possible as well.

The first step in the design process is the definition of the so-called extent of protection (EOP). The EOP depends on both the wing geometry and the chosen ice-protection technology principle (anti-ice or deice, thermal, or impulse).

In a second step, the power required at the slat surface for anti- or deicing has to be determined, which could be done with more detailed simulation or test data. The design point of the WIPS is driven by certification requirements: 45 min holding flight under icing conditions [7], which defines the required power. Whether or not the power demand in offdesign conditions can be modulated depends on the system technology. Conventional pneumatic anti-ice systems do not modulate the power demand (on/off valve).

In a last step, the actual technology solution is regarded and represented by an efficiency $\eta_{\mathrm{WIPS},i}$. The power demand from the dedicated power distribution system [Eq. (1)], electric or pneumatic here, can be computed for the design point. In addition, the system's mass can be defined:

$$P_{\mathrm{WIPS}} = P_{\mathrm{perEOP},i} \cdot l_{\mathrm{EOP}} \cdot \frac{\mathbf{1}}{\boldsymbol{\eta}_{\mathrm{WIPS},i}} \tag{1}$$

where P_{perEOP} (in watts/meter) is the required power at the slat surface per meter of spanwise extension, l_{EOP} (in meters) is the spanwise length of the EOP, $\eta_{\mathrm{WIPS},I}$ is the technology efficiency factor, and i is the technology index.

According to the system technology, additional design parameters can be chosen; for example, for the case of a conventional pneumatic thermal anti-icing system, the trade can be made between temperature, pressure, and airflow provided to the slat surface.

To build up the performance mode, the power demand of the WIPS is computed based on the operational parameters:

1) The maximum altitude for icing conditions, which depends on the ambient conditions, impacts the WIPS power demand profile. For example, on hot days, icing can occur up to higher altitudes than for International Standard Atmosphere (ISA) normal or cold-day conditions.

2) The WIPS operation definition (e.g., operation of the WIPS only for climb, descent, and approach, but not for takeoff or on ground), which depends on the aircraft-level sizing philosophy, also impacts the WIPS power demand profile.

As an example, Figure 5 shows the power demand of two different technologies for different mission conditions and operation modes. The conventional WIPS (pneumatic) enables no load shedding in failure cases, whereas an electrothermal concept with a deice function for a failure case or high altitudes increases the operational flexibility. However, a combined anti-ice/deice system has higher weight due to the increased EOP. The impact of these choices on the electric generator sizing will be discussed in Sec. IV.

B. Commercial Cabin Systems

The passenger comfort requirements drive the sizing of the CCSs, such as lighting (cabin light and individual reading lights), galleys (e.g., ovens, refrigerators, and beverage makers), and in-flight entertainment (IFE). As air transport became increasingly widespread, the requested operational reliability of these systems increased and most of the airlines have changed their requirements significantly. In terms of power architecture design, this means that CCSs, not essential for the flight mission, impact the failure cases analysis differently (refer to Sec. IV).

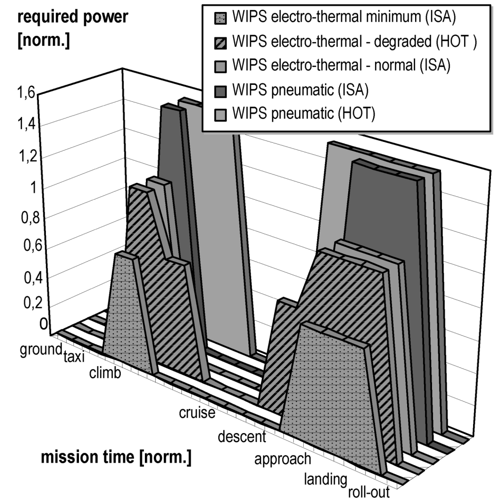

Fig. 5 WIPS operational power requirements for different system configurations.

With regard to the power architecture synthesis, CCSs impact the design of the following systems significantly:

1) In the ECS, all heat dissipated in the cabin builds a heat load that impacts the air conditioning and, especially, the temperature control design.

2) The EPS delivers the required energy to the cabin systems.

The amount of installed equipment and thus the amount of power required and the amount of heat dissipated depend significantly on the type of aircraft (long range and short range) and the operating airline (low-cost and luxury liner) as well as on the final passenger behavior (leisure travel, business travel, etc.).

Taking into account the preceding described characteristics of theses systems, the model is based on statistical and technology-dependent component data.

The number of components (e.g., reading light and IFE units) depends on the number of passengers and thus on the aircraft size and cabin layout. For the cabin lights, the cabin area to be illuminated is the main design driver. Based on a statistical analysis [8] of around 30 aircraft of different airlines, the statistical distribution of installed components for the following cabin configurations can be defined: minimum, most likely, or maximum. This approach is illustrated in Fig. 6 for the example of beverage makers (part of the galley equipment).

The number of components corresponding to minimum can be found in less than 10% of the examined aircraft (30 aircraft have been examined in [8]). More equipment than the maximum was found less of 10% of the aircraft. The most likely value represents the average number of components counted in the aircraft test examples.

The user can chose between the three values of minimum, most likely, and maximum, which represent a dedicated level of airline comfort standard. Minimum corresponds to a charter airline with low catering standards, and maximum represents long-range or high catering/comfort standards. The nominal power demand and the weight of the installed systems are defined by those choices.

For the operational power demand, so-called usage factors are defined per system and per flight phase. For these usage factors, defined between 0 and 1, the most probable statistical data are available.

Summarizing, Eq. (2) defines the power space of the CCSs:

$$P_{\mathrm{elec,CCS}}(t) = \sum_{i=1}^{n} c_{\mathrm{usage},i}(t) \cdot P_{\mathrm{nom},i} \cdot c_{\mathrm{OM},j} \tag{2}$$

where n is the number of different cabin subsystems; $c_{\mathrm{usage},i}$ is the usage factor, depending on the flight phase; $P_{\mathrm{nom},i}$ (in watts) is the nominal power per subsystem i; and $c_{\mathrm{OM},j}$ is the operation-mode factor to be defined for each operation mode j ($1 =$ normal and $0 =$ minimal). The application of this statistical modeling approach within the presented simulation framework platform is illustrated in Sec. IV.A.

C. Electrical Power System

The EPS is a key system in the aircraft power system architecture and becomes increasingly important as the amount of required electrical power increases and especially for more electrical architecture concepts. From a functional point of view, the electrical power system *generates* electrical power in different forms (ac, dc, and different voltage levels) from transformation of mechanical power (engines, APU, and RAT), *modulates* electrical power in different forms and voltage levels (ac to dc and dc to ac), *stores* electrical energy in batteries (e.g., for emergency use or APU starting), and *distributes* electrical power to the dedicated consumer systems. Electrical power can also be provided directly, via an external supply (for ground operations) or via, for example, a fuel cell system, which generates electric power.

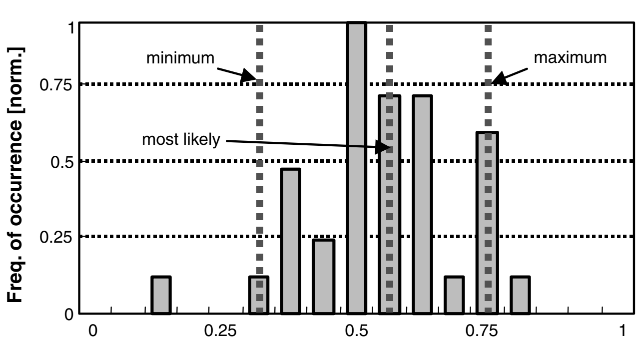

Fig. 6 Example for statistical distribution of installed cabin system equipment [8].

The power interfaces of the EPS module are the electrical power demand of the consumer systems, the electrical power sources, mechanical power demand from the engines, APU or RAT, and thermal exchange (heat load for cooling systems). The latter is of increasing importance for high-voltage and high-power EPS architectures.

The key driver for the EPS sizing is, in addition to the EPS architecture itself, the power required by the electrical power consumption systems. For conventional architectures, the most important are the CCSs, the different technical loads (fuel system pumps, ECS partly, avionics, and more electric actuation systems). For bleedless architectures, the WIPS and the ECS are the major consumers.

The key sizing parameters of the EPS are the number of generators (GENs) per engine (ENG), the chosen voltage level for ac and dc, and the location of the power centers. The latter mainly influences the mass of the feeders, which is linked to the tradeoff between voltage drop, feeder temperature, and diameter.

To illustrate the modeling principle that allows automated sizing of the generators, a simplified approach of the main channel of the EPS is presented (see Fig. 7) in this paper.

Figure 7 shows the example of an aircraft with two engines and two ac generators per engine. However, the principle is valid for any number of generators or engines when a symmetric architecture is chosen. The following assumption is made: all consumer power is equally distributed between the available sources of electrical power.

The generator size is defined in Eq. (3). Safety and reliability issues mainly drive the sizing of the EPS and thus of the generators:

$$P_{\mathrm{GEN,sized}} = \max_{j=1}^{m} \left\{ \frac{1}{N_{\mathrm{GEN},j}} \left(\sum_{i=1}^{n} P_{\mathrm{elec,cons},i}(t) \right)_j \right\} \tag{3}$$

where $P_{\mathrm{elec,cons},i}(t)$ (in watts) is the electrical power of consumer systems at the generator input as a function of time,N_{GEN} is the number of generators, n is the number of electrical power consumption systems, and m is the number of tested operation scenarios.

Therefore, Eq. (3) has to be analyzed for the major sizing scenarios (e.g., normal conditions, one GEN failure, and one ENG failure). For each failure scenario j, the possible frequency of

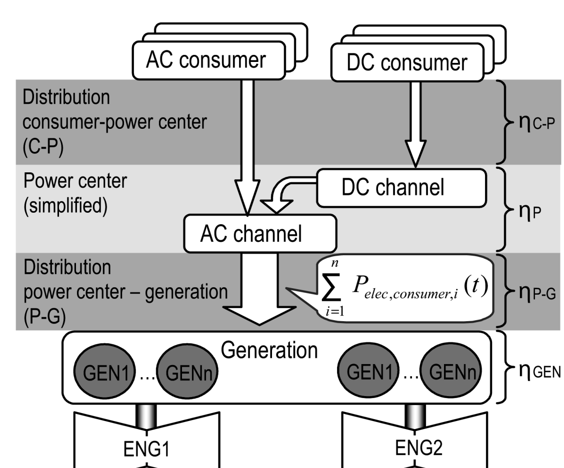

Fig. 7 Schematic of example architecture of the main channel of the electrical power system.

Table 1 Power system architectures used for the test case

System	Architecture 1 (A1) conventional	Architecture 2 (A2) bleedless
ECS	Pneumatic (electric recirculation fans)	Electric
WIPS	Pneumatic anti-ice	Electrothermal anti- and deice
Actuation	Hydraulic	Electro/hydraulic
EPS	2 generators	4 generators

occurrence induces dedicated power requirements of the consumer systems. These dedicated load profiles of the consumer systems (defined in the 3-dimensional power space) are combined with the number of available generators to identify the sizing case.

D. Validation

The validation of the developed models is a key step when attempting to get acceptance of simulation for decision-making. Here, the validation has two aims: 1) confidence-building in the modeling approaches and 2) quantification of the model uncertainty.

However, the validation of models for future system solutions cannot be done with traditional methods. Also, the comparison of the simulation with existing architectures is not obvious, as design paradigms as well as component technology have changed. Therefore, a hybrid approach is taken here:

1) System models representing a *conventional configuration* are compared with existing systems. The occurring differences are analyzed, taking into account the changing requirements and hypothesis.

2) System models representing *new configurations* are calibrated to current state-of-the-art technology and knowledge. The evolution potential is outlined.

In this way, it is possible to evaluate the level of confidence for each system separately. The complete architecture is assessed by comparing manual trade studies with the simulation results. Concluding, manual calculations at the system level tend to overestimate and this is then propagated to the aircraft level. Often, adding margins compensates for a lack of consistency in the design assumptions. The minimization of design margins and the understanding of their impact is one of the major benefits of a model-based early design tradeoff phase.

IV. Application Examples

The developed simulation framework allows a broad field of possible application: for example, the comparison of the fuel consumption between two different system architectures, taking into account all coupled effects (additional weight due to additional fuel burn, additional fuel burn due to increase overall weight, etc.) and propagated changes (mass, drag, and aircraft mission reevaluation), the sizing analysis of aircraft family concepts, and many more.

A. Electric Generator Sizing Analysis

The impact on the generator sizing is described in this section for two different power system architectures, summarized in Table 1. The simulation results are depicted in Fig. 8, showing the profile of total required power per GEN for different operation scenarios (normal, one GEN failed, and one ENG failed) for the conventional architecture (Fig. 8a) and the bleedless architecture (Fig. 8b). The load shedding applied to the CCSs and ECS is identical for both architectures; in the case in which one GEN failed, only CCSs loads are shed. Because of the different numbers of generators, the GEN failure is the sizing condition for the architecture 1 (A1). For architecture 2 (A2), the ENG failure constitutes the sizing case, as only two GENs, instead of three, are left to carry the load.

A detailed look on the sizing case for A1 is given in Fig. 8c. As ECS and technical loads are not to be shed in this failure case, the CCSs' shedding philosophy directly drives the generator sizing. As the design point is in cruise conditions, load shedding in this phase of

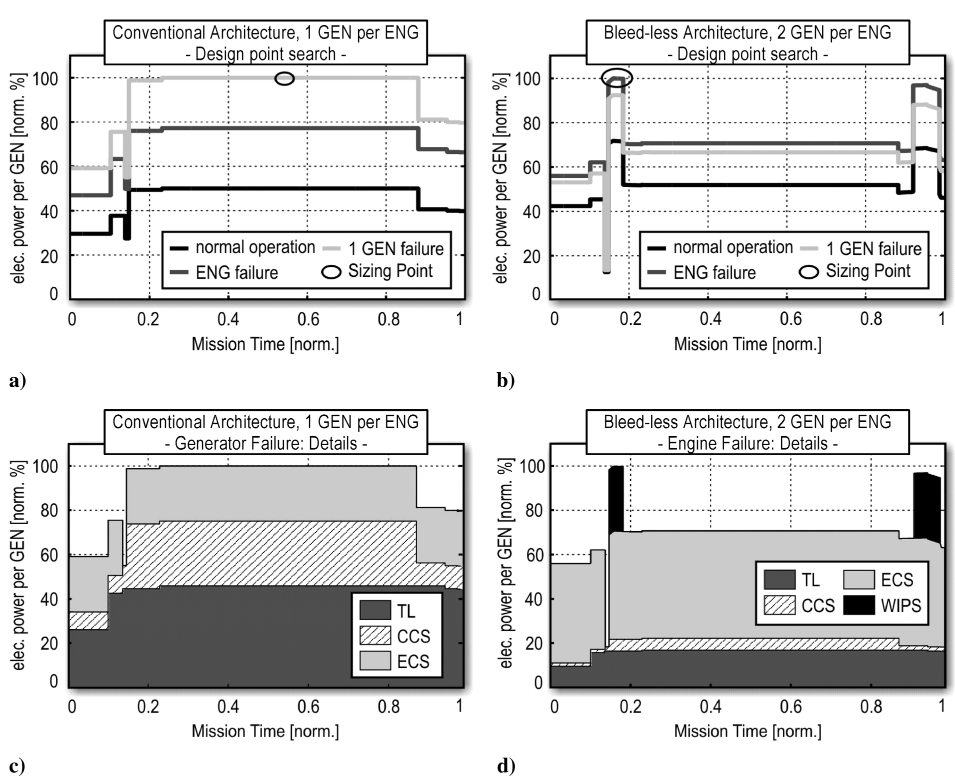

Fig. 8 Engine generator sizing analysis.

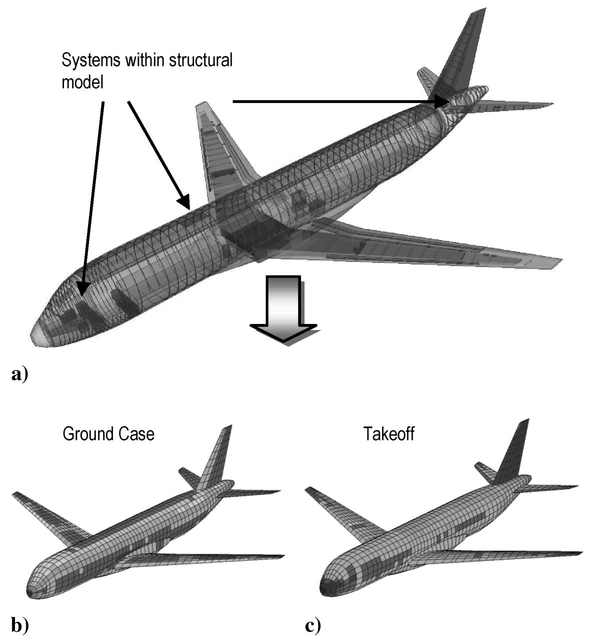

Fig. 9 Application example—analysis of systems heat rejection on the structure temperature.

the mission would be difficult to accept by airlines. An EPS architecture with four GENs would be an option, adding more operational flexibility but also adding complexity and probably weight.

For A2, the ENG failure is the sizing case, as only two of four GENs remain. The contribution of the WIPS to the GEN size is significant. It is obvious that load-shedding strategies (e.g., the here-chosen switch to a deice mode) downsize the generator. The further load shedding of the CCSs only during WIPS operation phases would also bring benefit with only low impact on passenger comfort.

To summarize, this detailed view on the system power consumption, shown here for only a few selected subsystems of one energy type, and the contribution to sizing bring benefits when setting the sizing scenarios and enable the implementation of dedicated power-management strategies.

B. Aircraft Thermal Analysis

In addition to the application illustrated in the previous section, the developed simulation framework is also conceived to fit more multidisciplinary analysis. One of these of specific interest for more electric aircraft in combination with composite structures is the aircraft global thermal analysis. In the frame of another Airbus internal research project, a global thermal model of the aircraft has been developed. This model (see Fig. 9a) enables the coupling of the systems with the aircraft environment: the structure and ambient air. The power system simulation framework presented here is used for a test-case simulation to compute the systems' heat rejection for different flight missions. Via the mass and an approximate surface of components, combined with the power loss simulation of the systems, the heat rejection of the systems can be computed. This enables the calculation of structure, fuel, and air temperatures (see Figs. 9b and 9c) for two different mission points, which will, in turn, be input to the systems' sizing calculation. The coupling of the structural and the systems module will allow the identification of thermal critical points earlier in the design process, the development of adapted thermal management strategies, and the establishment of a topological view on aircraft systems in their environment.

V. Conclusions

The presented simulation framework implements a methodology that is a great asset for architecting (definition, presizing, and optimizing) aircraft power systems. It allows parametric studies during the preliminary design phases of modern aircraft. Different modeling methodologies (deterministic, statistics, and logic) are combined in a common platform, respecting the specific characteristics of each system while helping the architect to integrate them into an energy-balanced design. The common simulation framework enables the challenging of design margins, the analysis of more different architecture configurations in less time, and the elaboration of more integrated architectures.

Efforts are still necessary to model all systems of interest following the presented principle. The coupling of probabilistic methods for uncertainty management and sensitivity analysis is in progress. Preliminary test studies already show the further benefit brought to the model development and the end user of this tool.

Acknowledgments

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