A SIMULATION FRAMEWORK FOR AIRCRAFT POWER SYSTEMS ARCHITECTING

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Abstract

Today, the preliminary design process of power system architectures of civil aircraft is usually characterized by the separation into ATA (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 regards to the overall aircraft efficiency is to be achieved.

The development of a dedicated methodology, a simulation framework, and adapted modeling techniques is the objective of the presented research. This article focuses on the dedicated modeling approaches that are developed in order to analyze systems at aircraft-level. Three different modeling techniques illustrate on the 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 systems simulation to a global aircraft thermal model.

Abbreviations

APU	Auxiliary Power Unit
ATA	Air Transport Association
CCS	Commercial Cabin Systems
ECS	Environmental Control System
EOP	Extent Of Protection
EPS	Electric Power System
ETOPS	Extended-range Twin-Engine Operational Performance Standards
ENG	Engine
GEN	Generator
IFE	In-flight Entertainment
ISA	International Standard Atmosphere
RAT	Ram Air Turbine
WIPS	Wing Ice Protection System

1 Introduction

The increasing complexity of modern civil aircraft in a constantly evolving, ultra concurrently environment of technological, regulatory, economic and ecological challenges leads the aircraft manufacturers to seek for more and more optimized solutions for aircraft architectures. A global 'aircraft level' approach is seen as the most promising, overcoming the today's system per system optimization.

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

The aircraft power system architecture is a complex network of interacting systems fulfilling all different functions. In order to structure in this difficult task, the so-called ATA-chapters classification, established in 1936 by the ATA Air Transport Association is used to identify the sub-system 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, while the technology is available to change the system architecture in a revolutionary way, the cemented ATA breakdown reveals its weakness: the efficient integration of new technologies is only possible at multi-ATA level; the conventional interfaces change or disappear. This impacts the system design in the same way as the organizational structure: emerging topics like power and heat management are only solvable at multi-ATA and multi-domain (Systems, Structure, Power-plant) level. A functional approach is clearly the most promising solution [1], [2]. Especially with regards 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, bleed-less 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 aircraft level (mass, drag, fuel consumption) and the impact of aircraft level changes (e.g. certification, safety or ETOPS requirements) on the system design. A model-based, parametric pre-design process that allows the quantification and minimization of design margins and the better understanding of interdependencies between the systems with regards to the power architecture would be of great benefit for the aircraft manufacturers in its role as architect and system integrator.

To cope with these challenges is the objective of an Airbus internal R&T 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.

2 Methodology & Prototype Implementation

The aircraft power system architecture is a system of interacting sub-systems with a high level of functional couplings (Fig. 1). The systems are coupled via their energy exchanges (electric, hydraulic, pneumatic, mechanical, thermal, 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) as well as on 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 depends on aircraft level design parameters, e.g. number of passenger seats, aircraft geometry, mission profile, and on system / technological parameters, e.g. the power supply type (electric, hydraulic or pneumatic), pressure level in the hydraulic circuits, voltage level etc.

Regarding the increasing complexity and the changing interfaces for e.g. more electric architectures, the developed methodology [4] is based on a formalization of the design process (*Inverse Engineering Principle*) of the overall architecture (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 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:

- **Power Generation System**, like engines, auxiliary power unit (APU) for ground operations and a ram air turbine (RAT) for emergency cases. Fuel cells are candidates for future solutions.

- **Power Transformation and Distribution Systems**, which 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.
- **Power Consuming Systems,** which fulfill the different functions of the aircraft: e.g. the flight control system, wing ice protection system (WIPS), environmental control system (ECS), fuel system, fuel tank inerting system, commercial cabin systems (CCS), landing gear systems, primary flight control systems, high-lift system, equipment cooling systems.

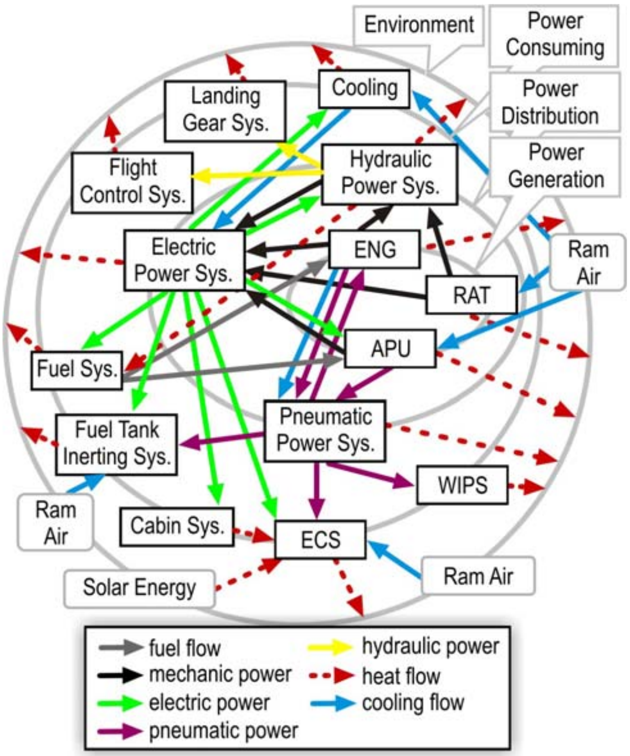

Fig. 1: Energy Coupling of a Conventional Aircraft Power Systems Architecture

The architecture sizing process starts from the functional requirement of the Power Consuming Systems. After their definition and choice of technology, the sizing requirements of the Power Transformation & 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 so defined architecture can be assessed for different off-design mission profiles.

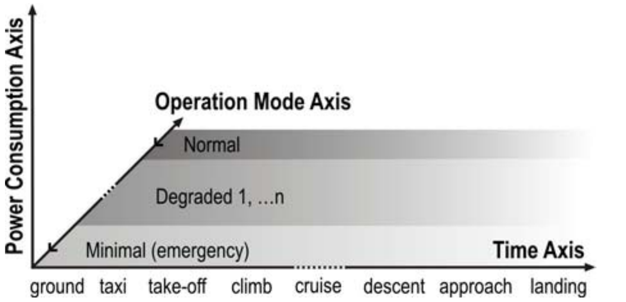

Fig. 2: Three-dimensional definition of the power-exchange interfaces of the power system modules

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 mission, corresponding to the fuel consumption, (to be assessable in the performance process).

Schematically, this calculation principle is depicted in Fig. 4-a.

2.1 Power System Modules

In principle, each system of the power systems 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)
- Operational Parameters (describe the off-design characteristics of a system).

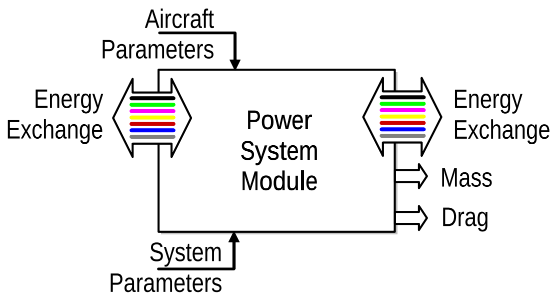

Fig. 3: General Power Systems Module

Some of these parameters can be varied and build thus the variable-space for optimization and trade-offs.

The bidirectional energy interfaces schematize the two different calculation modes required for each module:

- **Sizing Mode:** sizing characteristics like number of required components, duct diameters, generator sizes are outcome of analysis of computation results for one or more sizing scenarios (ambient conditions, failures case etc.).
- **Performance Mode:** the module calculates the dedicated output variables (mainly the energy flow) for different off-design 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 e.g. the required cooling demand or heat rejection to the environment. This aspect becomes crucial for more electric or bleed-less architectures. In this case those "parasitic" couplings of systems, which lead to snowballed effects on aircraft level, are often neglected as out of responsibility of one system domain. One example is the increased cooling demand that leads to higher ram air demand, which increases the aircraft drag and thus the fuel consumption. Or, when cooling requirements are fulfilled via a liquid cooling system, the weight of this system and the snowballed weight of power supply and thus fuel consumption via increase power off-takes on the engines have to be considered.

2.2 Implementation

A prototype of a simulation framework that corresponds to the above-described requirements has been developed (see Fig. 4) in a Matlab/Simulink/Stateflow® environment. Additional code is coupled, depending on the systems module. E.g. C-code is used for the Engine-Model, a java application for the aircraft performance tool, Dymola/Modelica® import is achieved for the ECS module.

The simulation framework contains the parametric power system modules as listed above embedded in the integrated automated sizing and performance calculation process (Fig. 4-a). The process is guided via a graphical user interface (Fig. 4-b). For the coupling to the aircraft level, the power systems computation is linked to an Airbus in-house mission and performance tool (Fig. 4-c). Common parameters (Fig. 4-d,e), e.g. environmental

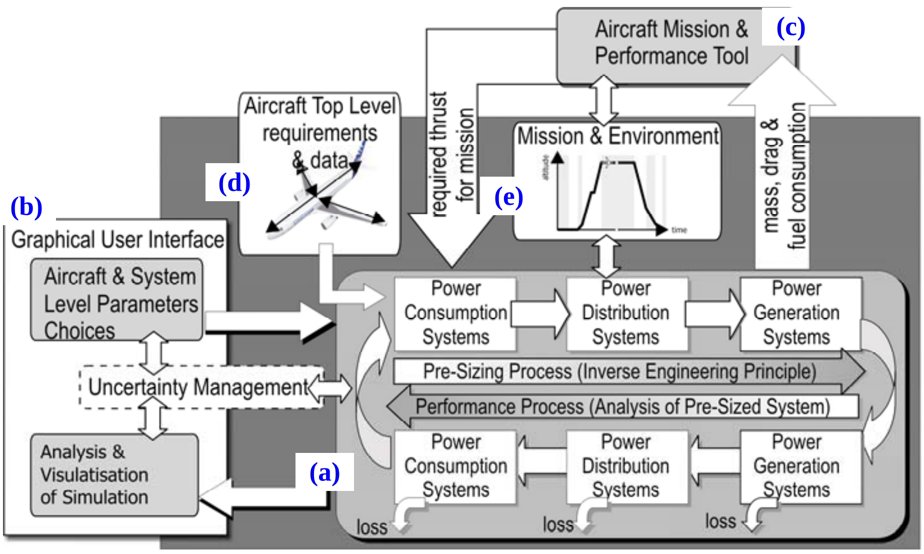

Fig. 4: Simulation Framework Overview

conditions, mission profile data and aircraft data, are made available for all systems in order to ensure consistency.

3 Modeling Approaches of Selected Systems

In the following section the modeling principles of selected systems are presented. These systems are chosen in order to illustrate the different modeling principles used for the implementation: a functional/deterministic approach for the WIPS, a statistical approach for the CCS, a logic approach for the EPS. The analysis capabilities offered by these modeling approaches within the simulation framework are illustrated in the use-case example developed in Section 4.

3.1 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 even during icing conditions (descent or climb through clouds).

Different candidate technologies exists to fulfill the ice protection function: e.g. pneumatic thermal anti-icing, electro-thermal anti-icing, electro-thermal de-icing, electro-mechanic de-icing. Hybrid solutions (e.g. combined anti- and de-ice [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 one side from the wing geometry and on the other side on the chosen Ice Protection technology principle (anti-ice or de-ice, thermal or impulse).

In a second step, the power required at the slat-surface to proceed anti- or de-icing has to be determined, which could be done with e.g. 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. It depends on the system technology if the power demand in off-design conditions can be modulated or not. Conventional pneumatic ant-ice systems do not modulate the power demand (on/off valve).

In a last step, the actual technology solution is regarded: represented by an efficiency $\eta_{WIPS,i}$. The power demand from the dedicated Power Distribution System (Eq.1), here electric or pneumatic, can be computed for the design point. As well, the systems mass can be defined.

$$P_{WIPS} = P_{perEOP,i} \cdot l_{EOP} \cdot \frac{1}{\eta_{WIPS,i}} \tag{1}$$

With:

P_{perEOP}	[W/m]	required power at slat surface per m-spanwise extension
l_{EOP}	[m]	spanwise length of EOP
$\eta_{WIPS,I}$	[-]	technology efficiency factor
i	[-]	technology index

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

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

- maximum altitude for icing conditions, which depends on the ambient conditions – on hot days, icing can occur up to higher altitude as for International Standard Atmosphere (ISA) normal or cold day conditions;
- WIPS operation definition (e.g. only for climb, descent and approach but not for take-off or on ground), which depends on the aircraft-level sizing philosophy.

As an example, Fig. 6 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 electro-thermal concept with de-ice function for failure case or high altitudes increases the operational flexibility. However, a combined anti-ice de-ice system has higher weight due to the increased EOP. The impact of these choices on the electric generator sizing will be discussed in Section 4.

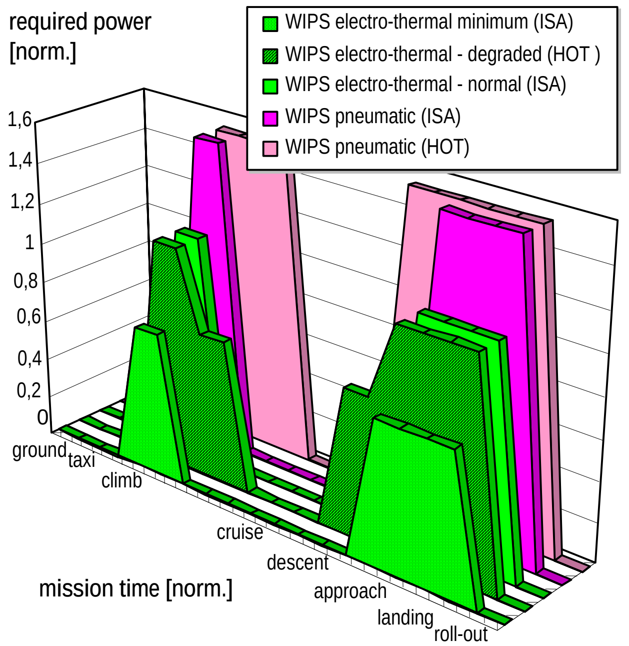

Fig. 6: WIPS Operational Power requirements for different system configurations.

3.2 Commercial Cabin Systems

The passenger comfort requirements drive the sizing of the CCS, such as lighting (cabin light, individual reading lights), galleys (e.g. ovens, refrigerators, beverage makers) and In-flight Entertainment (IFE).

As air transport becomes more and more 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 CCS, not essential for the flight mission, impact differently the failure cases analysis (refer to Section 4).

With regards to the power architecture synthesis the CCS impact the design of the following systems significantly:

- Environmental Control System (ECS): all heat dissipated in the cabin builds a heat-load that impacts the air-conditioning and especially the temperature control design.
- Electric Power System (EPS), which 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 depends significantly on the type of aircraft (long range, short range) and the operating airline (low cost, luxury liner) as well as on the final passenger behavior (leisure travel, business travel, etc.).

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

The number of components e.g. reading light, IFE units depends on the number of passengers, 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. 7 for the example of beverage makers (part of the galley equipment).

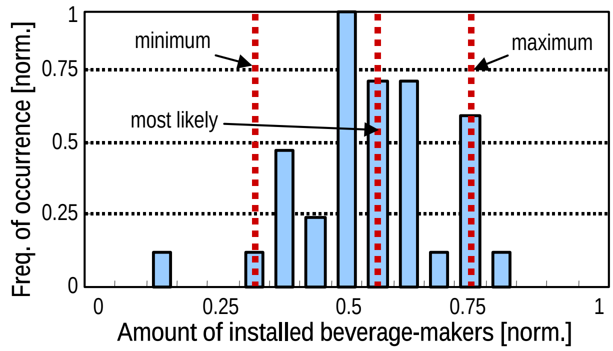

Fig. 7: Example for statistical distribution of installed cabin system equipment [8].

The number of components corresponding to *minimum* can be found in equal or less than 10% of the examined aircrafts. More equipment than on the *maximum* line was found in equal or less of 10% or the airlines. The *most likely*-value represents the average number of components counted in the aircraft test examples.

The user can chose between these three values, which are then representing a dedicated level of airline comfort standard: minimum corresponds to charter airline with e.g. low catering standards, 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, as well, most probable statistical data are available.

Summarizing, the following Eq.(2) defines the power-space of the CCS.

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

With:

n	[-]	number of different cabin sub-systems
$c_{usage,i}$	[-]	usage factor, depending on the flight phase
$P_{nom,i}$	[W]	nominal power per sub-system i
$c_{OM,j}$	[-]	operation mode factor to be defined for each operation mode j (1=normal, 0=minimal).

The application of this statistical modelling approach within the PWR-Platform is illustrated in Section 4.1.

3.3 Electric Power System

The EPS is a key system in the aircraft power system architecture and becomes more and more important as the amount of required electric power increases and especially for more electric architecture concepts. From a functional point of view, the electric power system

- *generates* electric power in different forms (AC, DC, different voltage levels) from transformation of mechanic power (engines, auxiliary power unit (APU), Ram Air Turbine (RAT)),
- *modulates* electric power in different forms and voltage levels (AC to DC, DC to AC),
- *stores* electric energy in batteries (e.g. for emergency use or APU starting) and
- *distributes* electric power to the dedicated consumer systems.

As well, electric power can be provided directly, via an external supply (for ground operations) or via e.g. a fuel cell system, which generates electric power.

The power interfaces of the EPS-module are the electric power demand of the consumer systems, the electric power sources, mechanic 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, beside the EPS architecture itself, the power required by the electric power consuming systems. For conventional architectures, the most important are the CCS, the different *technical loads* (fuel system pumps, ECS partly, avionics, more electric actuation systems). For bleed-less architectures the WIPS and the ECS are the major consumers.

The key sizing parameters of the EPS are the number of generators (GEN) 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 trade-off between voltage drop, feeder-temperature and diameter.

In order 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. 8) in this article.

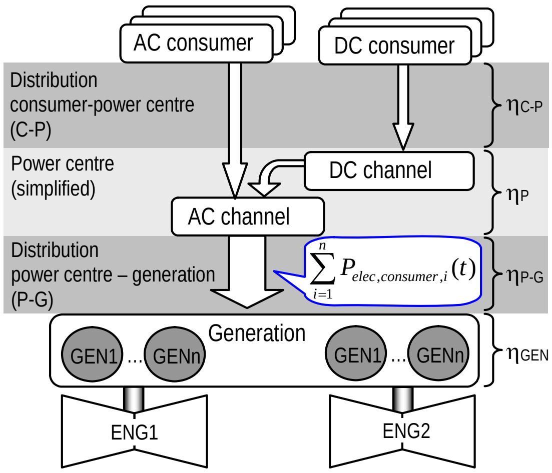

Fig. 8: Schematic of example architecture of the main channel of the electric power system.

The Fig. 8 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 electric power.

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

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

With:

$P_{elec,cons,i}(t)$ [W] electric power of consumer systems at the generator input, function of time

N_{GEN} [-] number of generators

n [-] number of electric power consuming systems

m [-] number of tested operation scenarios

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

3.4 Validation

The validation of the developed models is a key step when aiming acceptance of simulation for decision-making. Here, the validation has two aims:

- Confidence-building in the modelling approaches,
- Quantification of the model uncertainty.

However, the validation of models for future system solutions cannot be done with traditional methods. As well, 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:

- System models representing a “conventional” configuration are compared with existing systems. The occurring differences are analysed taking into account the changing requirements and hypothesis.
- System models representing new system configurations are calibrated to current state of the art technology and knowledge. 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 system level tend to overestimate and this is then propagated to the aircraft level. Often, adding margins compensates lack of consistency in the design assumptions. The minimisation of design margins and the understanding of their impact is one of the major benefits of a model-based early design trade-off phase.

4 Application Examples

The developed simulation framework allows a broad field of possible application: e.g. the comparison of the fuel consumption between two different system architectures taking into account all snowball-effects and propagated changes (mass, drag, aircraft mission-re-evaluation), the sizing analysis of aircraft family concepts, and many more. In the following sections, two examples of closer interest for more electric aircraft are focused: the generator sizing example and the global thermal analysis.

4.1 Electric Generator Sizing Analysis

As an example, the impact on the generator sizing is described in this chapter for two different power system architectures, summarized in Tab. 1.

Tab. 1: Power Systems Architectures used for Test Case

System	Architecture 1 (A1) “Conventional”	Architecture 2 (A2) “Bleed-less”
ECS	Pneumatic (electric recirculation fans)	Electric
WIPS	Pneumatic anti-ice	Electro-thermal anti- and de-ice
Actuation	Hydraulic	Electro/hydraulic
EPS	2 generators	4 generators

The simulation results are depicted in Fig. 9, showing the profile of total required power per GEN for different operation scenarios (normal, one GEN failed, one ENG failed) for the conventional architecture (a) and the bleed-less architecture (Fig. 9-b). The load shedding applied to the CCS and ECS is identical for both architectures, in the case one GEN failed, only

CCS loads are shed. Due to the different numbers of generators, the GEN failure is the sizing condition for the A1. For A2, the ENG failure is sizing as only two GEN instead of three are left to carry the load.

A detailed look on the sizing case for A1 is given in Fig. 9-c. As ECS and technical loads are not to be shed in this failure case, the CCS shedding philosophy drives directly the generator sizing. As the design point is in cruise conditions, load shedding in this phase of the mission would be difficult to accept by airlines. An EPS architecture with four GEN would be an option, adding more operational flexibility but adding also complexity and probably weight.

For A2, the ENG failure is the sizing case, as only two of four GEN remain. Significant is the contribution of the WIPS to the GEN size. It is obvious, that load shedding strategies, e.g. the here chosen switch to a de-ice mode, downsize the generator. As well, the further load shedding of the CCS only during WIPS operation phases would bring benefit with only low impact on passenger comfort.

Summarizing, this detailed view on the system power consumption, here only showed for few selected subsystems of one energy type, and contribution to sizing brings benefit when setting the sizing scenarios and enable the implementation of dedicated power management strategies.

4.2 Aircraft Thermal Analysis

Beside 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. 10-a) 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

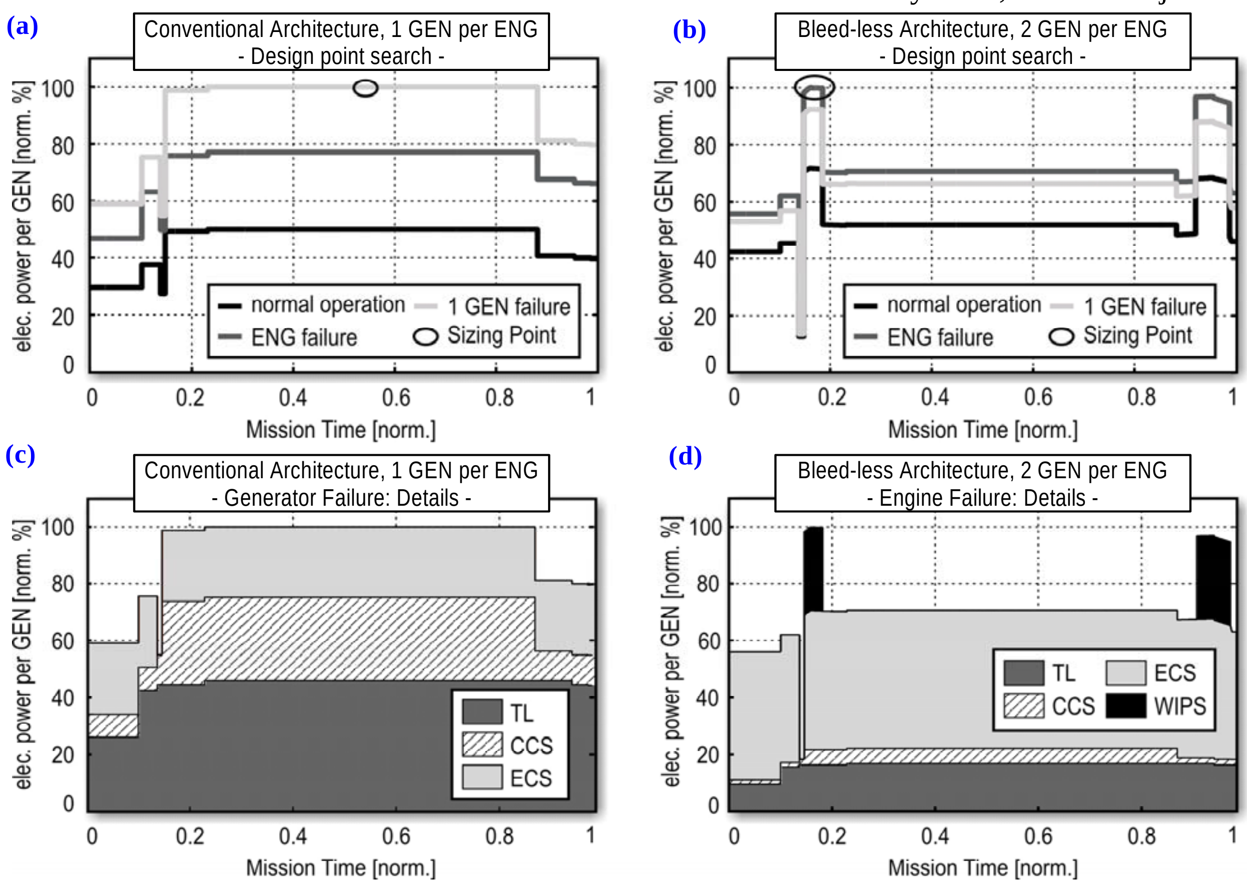

Fig. 9: Engine Generator Sizing Analysis

the systems can be computed. This enables the calculation of structure, fuel and air temperatures (see Fig. 10-b and Fig. 10-c) for two different mission points, which will be in return an input to the systems sizing calculation. The coupling of the structural and the systems module will allow the identification of thermal critical points already earlier in the design process, the development of adapted thermal management strategies and the establishing of a topological view on aircraft systems in their environment.

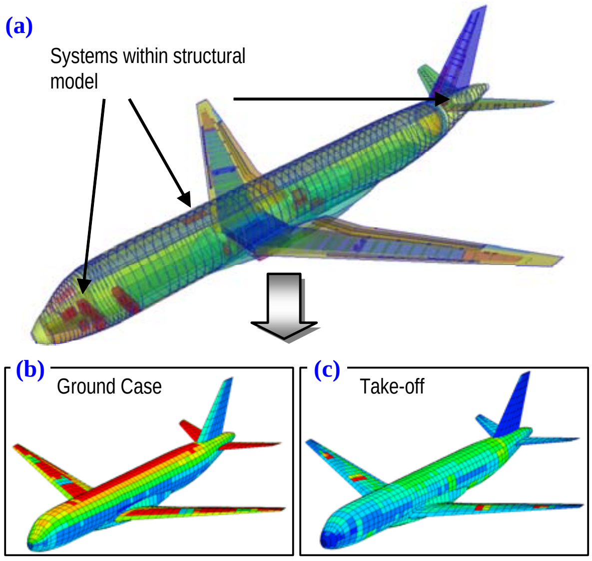

Fig. 10: Application example - analysis of systems heat rejection on the structure temperature.

5 Conclusions and Outlook

The presented simulation framework implements a methodology, which is a great asset for architecting (definition, pre-sizing and optimizing) aircraft power systems. It allows parametric studies during the preliminary design phases of modern aircraft. Different modeling methodologies (deterministic, statistics, 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, to 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 showed already the further benefit brought to the model development and the end user of this tool.

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