The All-Electric Regional Aircraft – A New Design Methodology for Vehicle-Level Systems Architecture Design

Alexander Schneegans
PACE Aerospace Engineering and Information Technology GmbH,
Berlin, Germany, alexander.schneegans@pace.de, +49 (30) 293-620

Abstract

With the complexity and energy demand of aircraft subsystems rapidly increasing, systems architecture design has become a key activity in aircraft development. The high interdependence of systems in today's aircraft means that systems cannot be analyzed in isolation, but must always be considered in the light of interaction with other systems, and as making a contribution to the performance of the aircraft as a whole.

An efficient, holistic approach to systems design is particularly important in the development of regional aircraft because of the comparatively higher significance of the operating empty weight with regards to fuel consumption and emissions and the more restrictive volumetric packaging requirements.

The paper presents a new design methodology for aircraft-level systems architecture design and its implementation in an integrated conceptual design tool developed under the European Clean Sky research initiative. The software supports the Green Regional Aircraft technology domain in validating and demonstrating the feasibility of bleedless architectures suitable to meet the pollution and noise reduction targets set for regional aircraft that will enter the market in the 2020s.

Introduction

With global air traffic expected to continue its growth over the next decades, the aviation industry's greatest challenge is to mitigate its impact on the environment. Addressing this challenge, the European Union has launched the Clean Sky initiative, a massive research program which brings together a wide range of industrial players and academic institutions to accelerate the introduction of green technology and advance sustainability in aviation.

The Clean Sky research activities are organized in six divisions, or *Integrated Technology Demonstrators* (ITDs), which focus on different segments of the air transport system. Three of the ITDs are vehicle-specific looking at large and regional fixed-wing aircraft or helicopters, respectively; a further two provide transverse technologies regarding engines and flight operations for application across all aircraft classes; and lastly, a life-cycle ITD develops cradle-to-grave strategies which are propagated to all of the other five. Each ITD works under the leadership of two major European manufacturers or research institutions.

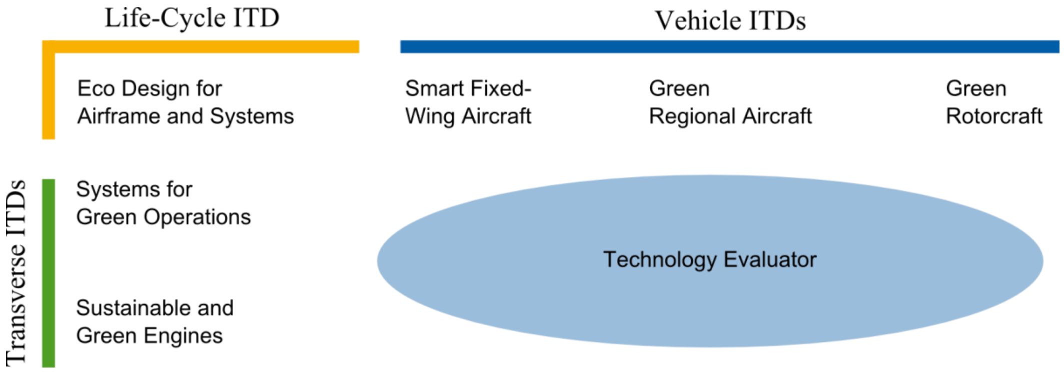


Figure 1: Research structure of the Clean Sky initiative

Clean Sky’s Green Regional Aircraft ITD explores ways of improving the environmental performance of short-haul air transport, examining a wide range of contributing factors from composite aerostructures to mission and trajectory management. Regional carriers account for a significant portion of the global commercial fleet and aircraft movements, a portion which is expected to strongly increase in the mid-term future, with average annual growth rates of around 6%.

The specific operational characteristics of regional aircraft – short range, large number of take-offs/landings and a proportionally higher empty weight – call for additional efforts to minimize harmful effects, for example through the development of low-weight, low-noise aircraft and more efficient flight operations.

One of the key concepts in the design of innovative, environmentally friendlier aircraft is the application of more-electric systems architectures. Thus, a dedicated research team within the Green Regional Aircraft ITD is tasked to evaluate all pneumatically or hydraulically driven systems installed in today’s aircraft as to their potential for being replaced by more energy-efficient electrical versions.

The aircraft functions contributing most significantly to the overall power demand, and hence engine power extraction, are electrical power generation and distribution, power electronics, electrical engine starting, cooling, heating and compression (ECS, ice protection and equipment cooling), and electro-mechanical actuation (landing gear system, flight controls).

To avoid the common pitfalls of optimizing systems components in isolation of each other and the total system, the All-Electric Aircraft group has opted for a holistic, aircraft-level approach to systems architecture design, which will supply key aircraft systems data for the preliminary assessment of different regional aircraft configurations from the very start.

The paper will describe the design methodology and its implementation in the SysArc software, which supports the research activities of the All-Electric Aircraft workgroup.

New design methodology

Traditional development processes typically follow the V-model, which has been established since the 1960s. It is characterized by a top-down approach to system design (decomposition) and a bottom-up approach to system integration. Although successful in defining tangible phases of the process, this simple model does not account for the complexities involved in the design of systems architectures.

The most frequently encountered problems include:

- Systems are decomposed into sub-systems along arbitrary, mostly engineering-domain specific lines; subsequent detailed design phases follow this decomposition scheme.
- The resulting architectures are isolated designs with little understanding of or visibility to their neighboring domains.
- The un-modeled interactions between sub-systems lead to design inconsistencies and unforeseen behavior during the integration phases

Adhering to a dated, inflexible design approach, system components are optimized in isolation of the total system, which will result in sub-optimal systems solutions particularly when looking for new architectures which have no precedents. Thus, there is an urgent need for breaking tradition and introducing a new paradigm that integrates vehicle design with the development of its systems architectures from early concept through the detailed design phase.

The enabling technology for modeling, analyzing and sizing all major systems at the aircraft-level is provided by SysArc, a software tool which was developed for the Green Regional Aircraft ITD. With a flexible, modular architecture, SysArc is capable of evaluating conventional systems architectures but also entirely novel solutions which may emerge in the course of the project.

Modular architecture

The SysArc solution was built on the knowledge-based engineering design platform Pacelab Suite and its conceptual aircraft design module APD. In combination, they provide a fully-fledged aircraft design environment in which to conduct systems architecture investigations. To this, an additional functional layer was added to provide systems-specific functionality.

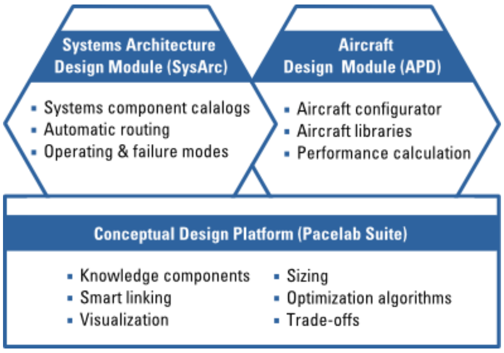


Figure 2: Structure of the SysArc software

The Pacelab Suite platform supplies the basic functional and procedural infrastructure for early-stage product design such as the ability to parametrically model, analyze and size complex technical systems. Pacelab Suite uses a consistent, object-oriented knowledge modeling approach which clusters parameters and methods in generic, reusable building blocks (Knowledge Components) and supports their assembly into complex systems by automatically generating mathematical relations between them (Smart Linking).

The exploration of the resulting model, whether performed manually by the user or through the application of numeric sampling or optimization techniques, is controlled by Pacelab Suite's solving engine, or Resolution System. The Resolution System automatically analyzes the non-linear equation system underlying the parametric model, the methods linking the parameters and the calculation direction (i.e. which parameters are input, which are output). The analysis results in the automatic identification of a solving sequence which satisfies all relations. The solving sequence typically involves complex cyclic dependencies which require iterative, numeric solving; it is applied automatically every time a parametric value is modified.

The solving engine's inherent knowledge of the mathematical system's topology is unique to Pacelab Suite and has two important advantages in addition to its ability to automatically solve user-specified models. Firstly, it allows an incremental or partial update of the system, which significantly improves the runtime performance of the application. Secondly, it enables users to flexibly swap the input or output status of parameters, i.e. to enter a target value and calculate the required inputs instead of manually tweaking input values to arrive at a given result. Consequently, the versatility of the product model is greatly increased, because it can be configured to a specific view of the engineering problem without the need to rebuild it from scratch.

To this, the aircraft design module APD provides an additional functional layer that supports the specific tasks of aircraft conceptual design. The APD module supplies libraries of geometric aircraft components such as lifting surfaces, fuselage or engine models, mass and aerodynamic estimation modules, and a comprehensive performance calculation kernel to analyze design and off-design missions. APD also provides a standard set of analysis methods for weight, high-speed and low-speed aerodynamics, flight performance, and static stability which can be flexibly replaced with proprietary and higher fidelity methods.

The main development effort for the Green Regional Aircraft ITD is devoted to implementing and integrating the following systems-specific capabilities:

- Creation of a system component catalog for all systems under investigation, with specific emphasis on power demand
- Graphical-schematic build-up of architectures using above system component catalogs
- Definition of physical installation areas (i.e. compartments) to control the geometric position of system components and to analyze the thermal impact

- Automatic transfer of logical system connections into the physical space of the aircraft, providing their physical properties such as length or mass as well as the associated power losses (electric voltage or hydraulic pressure).
- Load analysis as a function of flight phase and/or system failure modes
- Feeding system mass estimations and power off-take requirements to the aircraft design module for instant assessment of their impact on key performance parameters (e.g. climb capability or fuel consumption)

These capabilities and their associated workflows are described in detail in the sections below.

Workflow

Depicted below is the basic workflow for a holistic investigation of aircraft systems architectures. The SysArc solution covers all process stages, but additional tools, methods, models etc. can be plugged in if and when required. Moreover, the application does not impose a particular workflow on the user but flexibly adapts to team-specific task distributions.

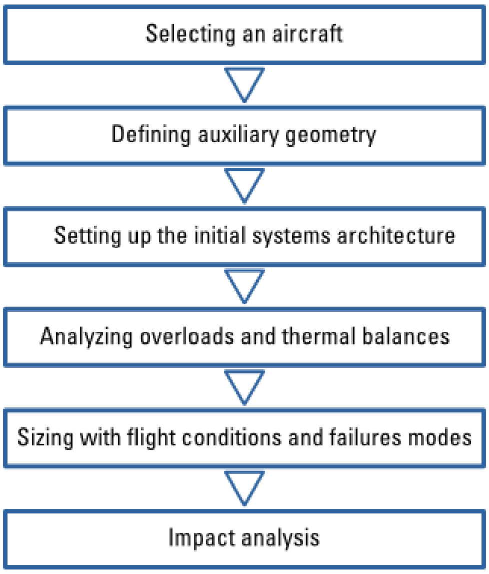


Figure 3: Systems architecture design workflow

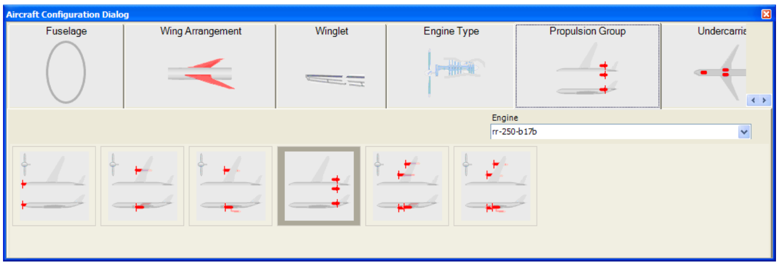
1. Selecting an aircraft

The quickest way of setting up an aircraft configuration is to derive it from an aircraft model retrieved from the resident library. For the Green Regional Aircraft ITD, the library has been extended with dedicated models for turboprop and jet engine aircraft with 90-130 seats and a range up to 3000 NM. Due to their full parameterization, these aircraft models can be easily modified by adjusting high-level design parameters such as number of passengers, engine types, engine installation, wing configuration, fuselage shape, etc.

After values have been assigned to key geometry parameters such as wing area, aspect ratios, and general aircraft dimensions, the SysArc solution calculates the mass and aerodynamic properties of the current aircraft configuration. With pre-defined calculation scenarios, that is, sets of parameter input/output settings, the system can be calibrated to meet known results or to account for technology factors, for example.

Mission and airfield performance are calculated from the aircraft's aerodynamic and engine properties based on user-specified design missions. Subsequently, parameters and calibration factors can be iterated and fine-tuned until they meet the targeted objectives. This is supported by trade studies and built-in optimization algorithms, which automate the exploration of the design space.

For the systems architecture design module, the propulsion system characteristics provided by the APD module are refined in order to supply engine data such as shaft speeds or bleed air parameters, in addition to the standard thrust and fuel flow data required for mission analysis.



Engine: rr-250-b17b

Figure 4: Aircraft configuration dialog

2. Defining auxiliary geometry: Compartments and pathways

In order to facilitate the layout of systems architectures, the aircraft model can be equipped with auxiliary geometries including a flexible compartment model and pathway model for connections between systems components such as cables, ducts, or pipes.

Compartments can be defined in all major geometric aircraft components including fuselage, wing, horizontal or vertical tail. The user interface provides visual aids to support the shaping and positioning of the compartment within the aircraft. The shape can be defined flexibly and also permits the definition of non-symmetric volumes such as avionic bays. Once the compartments are in place, they provide comprehensive geometric data, including volumes and adjacent surfaces, which can be directly linked to internal thermal analysis models or external analysis tools.

Pathways allow the definition of permissible connection routes between components and are prerequisite to applying the automatic routing algorithm.

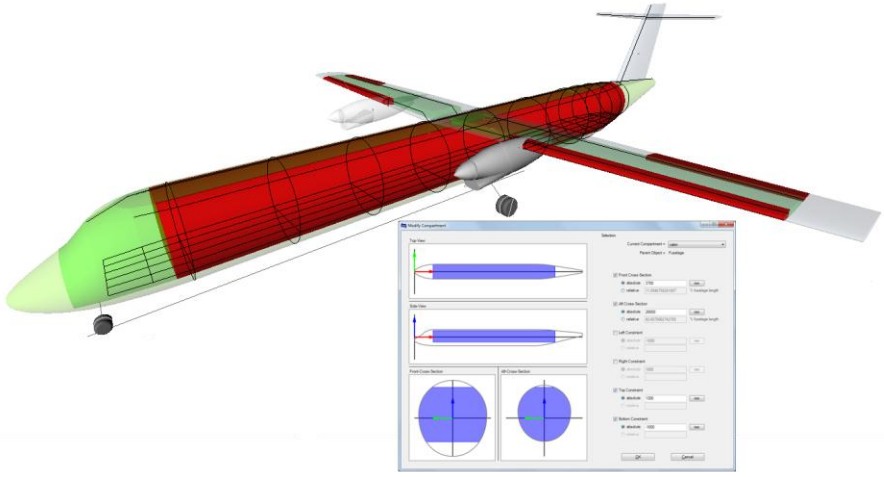


Figure 5: Auxiliary aircraft geometry: Compartments and pathways

3. Setting up the initial systems architecture

Reflecting Pacelab Suite's building-block approach to modeling, the basic procedure for setting up systems architectures entails selecting the required systems components from the component catalog and graphically establishing their connections in a dedicated schematic view.

The component catalog provided by the SysArc solution contains generic models of system components. The initial deployment encompasses basic parametric component models covering systems from Flight Control (FCS) and Environmental Control Systems (ECS) to Electrical Power

Generation and Hydraulic Systems. The models are either derived from public-domain sources or implementations of external models which have been supplied by the industrial partners of the Green Regional Aircraft ITD. The component catalog is fully extensible and more systems will be added as the project progresses. In addition, supplier data for systems components can be imported from spreadsheet or database programs for rapid build-up of supplier-specific component catalogs.

Systems components are described by both geometric-physical and non-physical parameters. Of the latter, those related to cost aspects are part of the main metrics in order to balance the level of technological innovation and ready market acceptance.

Each component can be accompanied by an in-depth hypertext documentation detailing design intent, parameter descriptions and suggested usage to help systems engineers select the appropriate building blocks for their investigation.

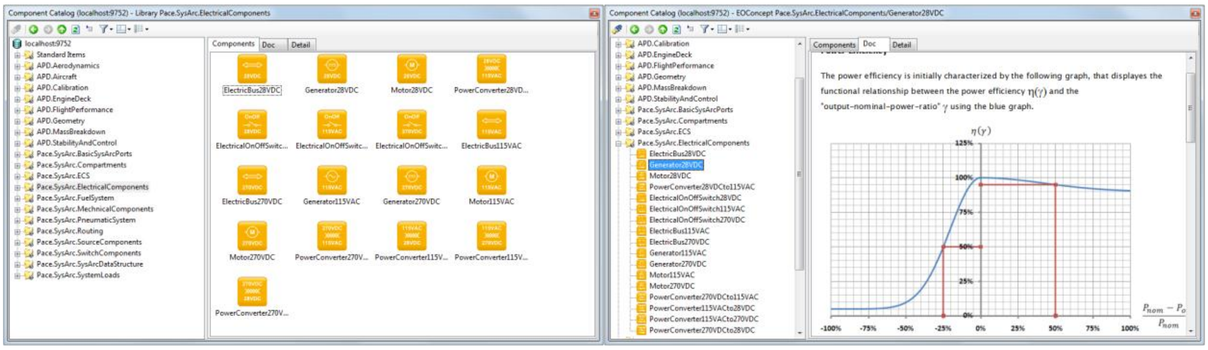

The power efficiency is initially characterized by the following graph, that displayes the functional relationship between the power efficiency $\eta(\gamma)$ and the "output-nominal-power-ratio" γ using the blue graph.

Figure 6: Catalog of electrical components and their documentation

Part of the parametric description of system components are connector points, or Ports. Ports constitute a specific implementation of Pacelab Suite's Smart Linking technology and support the interactive build-up of architectures and configurations. Users can graphically define physical and abstract connections between components, which are automatically translated into mathematical relations. If the user draws a line between two electrical components, SysArc will create the required power summation formulas or propagate voltages and automatically take into account the voltage drops induced by the resistance of the physical cable connection.

When building the system architecture, the user has to specify primary and alternative power supplies for the loads, the latter of which will be used in case of major power sources failure. Through activation or de-activation of primary and alternative connections, the system can be analyzed for specific failure scenarios, which are described in more detail below.

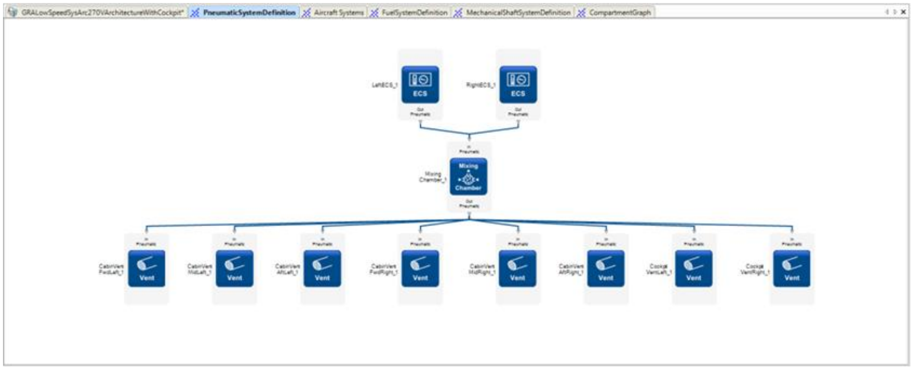


Figure 7: Schematic view of ECS systems incl. logical connections

When the logical connections between the components have been defined, the automatic routing can be triggered. The routing creates the physical counterparts of the logical connections, automatically adding weight, gauging electric or hydraulic losses, etc. The routing algorithm (Dijkstra's algorithm for electric, Steiner tree algorithm for hydraulic connections) seeks the shortest possible route between two system components along the previously defined pathways. An initial sizing selects cables, pipes and ducts with suitable diameters from a list of standard parts.

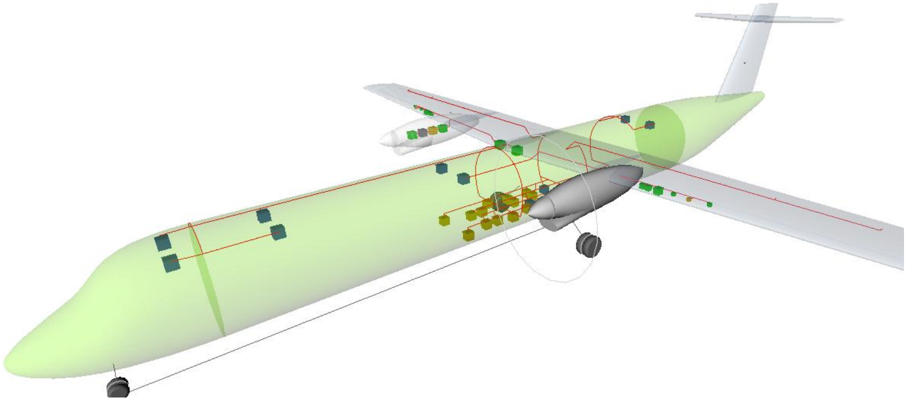


Figure 8: Results of auto-routing

4. Analyzing overloads and thermal balances

When the initial architecture is complete, it can be analyzed in terms of overloads and thermal balances. SysArc monitors main parameters such as power (electrical, mechanical, hydraulic), mass flow (pneumatic, fuel systems) or pressure required by subordinate components. The software automatically detects accumulated demands that exceed the capability of the provider and highlights the overloaded component in the layout.

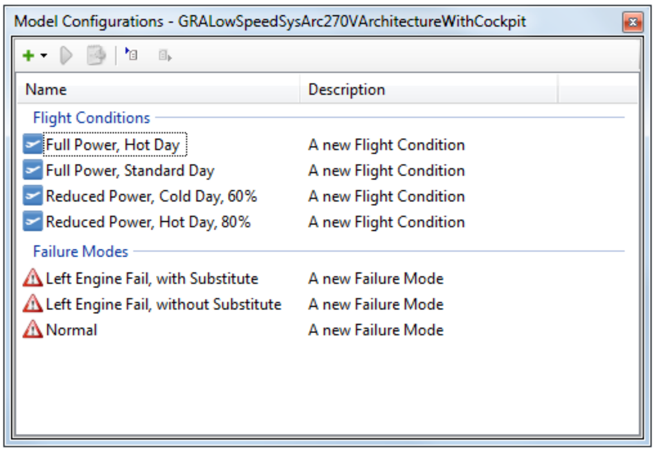
The objective of the thermal management is to determine the volume, or mass flow, of the circulated air required to achieve a target ambient temperature. The ambient temperature can be defined individually for each compartment.

The required mass flow is basically calculated from the outlet temperature of the ECS component, the recirculation ratio of the mixing chamber and the target ambient temperature of the compartment. The compartments' demand of air cooling takes into account the heat emanating from passengers, crew and systems components and the performance parameter of the fresh-air vents. Additional pneumatic components like valves and fans can be added to fine-tune the flow model of the air stream.

5. Sizing with flight conditions and failures modes

Flight conditions and failure modes help to identify critical cases and limiting values and thus to establish the sizing conditions of a given systems architecture. Flight conditions account for systems components' changing operational states during the course of a flight mission and allow calculating the power and cooling requirements of the aircraft systems under a specific set of conditions. Each flight condition is associated with a flight segment and described by (a) a set of environment parameters such as altitude, pressure, velocity or ISA deviation, and (b) the power consumption rate of all consumers at this point (expressed as a percentage of the nominal value). The required engine data is retrieved from the propulsion model. Applying a flight condition will automatically adjust the parameter values and trigger a recalculation of the mathematical system.

Failure modes, on the other hand, represent typical failure scenarios and are defined by a set of failed electric or hydraulic providers such as sources, generators, converters or distribution elements. Applying a failure mode to a systems architecture will result in a number of unsupplied consumers and prompt a switch to the alternative providers if previously defined in the architecture setup.



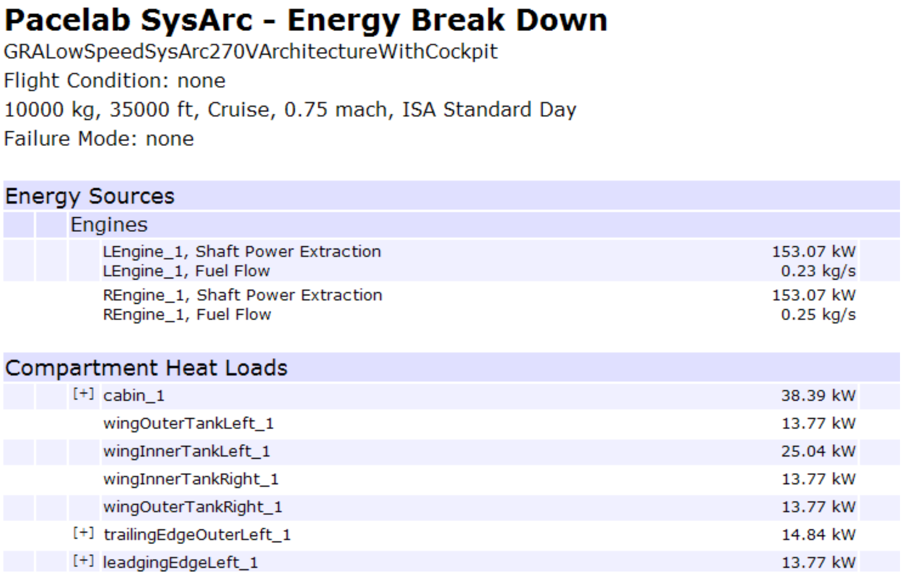
Model Configurations - GRALowSpeedSysArc270VArchitectureWithCockpit

Name	Description
Flight Conditions	
Full Power, Hot Day	A new Flight Condition
Full Power, Standard Day	A new Flight Condition
Reduced Power, Cold Day, 60%	A new Flight Condition
Reduced Power, Hot Day, 80%	A new Flight Condition
Failure Modes	
Left Engine Fail, with Substitute	A new Failure Mode
Left Engine Fail, without Substitute	A new Failure Mode
Normal	A new Failure Mode

Figure 9: Flight conditions and failure modes

To enable the alternative providers to deal with the extra loads, SysArc allows switching the affected electrical loads to voltage-modulated operation. In modulated operation, a reduced voltage is supplied to subordinate systems, which restricts their power consumption to the working minimum and prevents an overload of the provider.

In order to determine the exact sizing conditions, the solving engine iterates over all possible combinations of flight conditions and failure modes, while monitoring key parameters such as power consumption, size and weight. The results are displayed in a ranked matrix so that the extremes can be identified. The flight condition with the highest power consumption can be used for the final sizing of the systems architecture. The sizing results can be presented in an energy breakdown report.



Pacelab SysArc - Energy Break Down

GRALowSpeedSysArc270VArchitectureWithCockpit
Flight Condition: none
10000 kg, 35000 ft, Cruise, 0.75 mach, ISA Standard Day
Failure Mode: none

Energy Sources	
Engines	
LEngine_1, Shaft Power Extraction	153.07 kW
LEngine_1, Fuel Flow	0.23 kg/s
REngine_1, Shaft Power Extraction	153.07 kW
REngine_1, Fuel Flow	0.25 kg/s

Compartment Heat Loads	
[+] cabin_1	38.39 kW
wingOuterTankLeft_1	13.77 kW
wingInnerTankLeft_1	25.04 kW
wingInnerTankRight_1	13.77 kW
wingOuterTankRight_1	13.77 kW
[+] trailingEdgeOuterLeft_1	14.84 kW
[+] leadgingEdgeLeft_1	13.77 kW

Figure 10: Principle view of the energy breakdown

6. Impact analysis

In addition to providing the geometric host platform for the systems architecture design module, the APD module is used to assess the impact of the chosen architecture on the overall aircraft characteristics and performance. The two most important intersections between the system architecture module and APD in this respect are the mass chapter and the propulsion module.

The total systems architecture mass, i.e. the summed masses of individual system components and their connections, is mathematically linked to the APD module's respective mass chapter entry (e.g. electrical systems mass, hydraulic systems mass). Consequently, every modification of the systems architecture is propagated to the aircraft mass chapter and can, if so wished, automatically trigger a recalculation of the overall mass chapter (including centers of gravity), the performance and all other areas affected.

At the same time, the propulsion module considers power off-takes as a function of the flight phase, assuming normal operations of all systems. The remaining engine power is then used for propulsion of the aircraft. Hence, modifications of the architecture may lead to modified performance capability (e.g. reduced or increased ceilings) or simply to lower or higher fuel consumption.

Through the integration with the APD module, the user is enabled to study complex questions very efficiently, while focusing on the principle task of designing systems architectures. The functionality provided by the SysArc tool can be applied to a range of use cases, from the design of new aircraft (which is the primary purpose in the scope of the Green Regional Aircraft project) to the modification of specific aspects of existing systems architectures.

Conclusion

The SysArc solution represents a novel technical approach to aircraft-level design and analysis of aircraft system architectures, which unites the logical definition of systems architectures with the physical layout of system components and their connections in the aircraft geometry. The software draws on the strength of object-oriented programming and knowledge-based engineering techniques to speed up modeling and analysis. The tight, yet runtime-efficient integration of systems architecture configuration within the conceptual aircraft model allows an instantaneous investigation of the impact of system architecture modifications on the aircraft characteristics and overall performance.

Thus, the software provides a comprehensive platform for the holistic investigation of modern, more-electric architectures which helps avoid errors that are the result of overlooking possibly penalizing side-effects of the new technologies applied. The assumptions made about the suitability and scalability of the underlying platform at the start of the project have proven correct – to date, the level of detail addressed in the current project are readily achieved by the SysArc solution, and there is clear potential for further scaling the tool's functionality to cover additional systems as well as to increase the depth of analysis.