Environmental & Flight Control System Architecture Optimization from a Family Concept Design Perspective

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One method an Original Equipment Manufacturer (OEM) can apply to reduce development and manufacturing costs is family concept design: each product family member is designed for a different design point, but a significant amount of components is shared among the family members. In this case, a trade-off exists between member performance and commonality. In the design of complex systems, often many different architectures are possible, and the design space is too large to explore exhaustively. In this work, we present an application of a new architecture optimization method to the design of a family of passenger transport jets, with a focus on the sizing of the Environmental Control System (ECS) and Flight Control System (FCS). The architecture design space is modeled using the Architecture Design Space Graph (ADSG), a novel method for constructing model-based system architecture optimization problems. Decisions are extracted and the multi-objective optimization problem is automatically formulated. Objectives used are commonality, representing acquisition costs, and fuel burn, representing a part of operation costs. These metrics are evaluated using a cross-organizational collaborative multidisciplinary analysis toolchain, and the resulting Multidisciplinary Design Optimization (MDO) problem is solved using a multi-objective evolutionary optimization algorithm. The results show that the trade-off between commonality and fuel burn is only present above a certain commonality level.

I. Nomenclature

ACM = Air Cycle Machine
ACU = Air Conditioning Unit
$ADSG$ = Architecture Design Space Graph
BC = Bootstrap Cycle
$CPACS$ = Common Parametric Aircraft Configuration Scheme
DOC = Direct Operation Costs
ECS = Environmental Control System
EHA = Electro-Hydrostatic Actuator
EMA = Electro-Mechanical Actuator
FCS = Flight Control System
HSA = Hydraulic Servo Actuator
OAD = Overall Aircraft Design
OEM = Original Equipment Manufacturer

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PCI = Product Line Commonality Index
$PIDO$ = Process Integration and Design Optimization
RCE = Remote Component Environment
SFC = Specific Fuel Consumption
$TLAR$ = Top-Level Aircraft Requirement
$XDSM$ = Extended Design Structure Matrix

II. Introduction

In aircraft design, performance improvements in terms of fuel burn reduction are pursued to reduce operating costs and environmental impact. One way of achieving such performance improvements, is by developing innovative system architectures by recombining existing components and technologies. However, due to the combinatorial explosion of alternatives, the design space spanning all possible architecture alternatives usually is too large to enumerate exhaustively. To enable successful design space exploration and the discovery of innovative, performance-improving architectures, numerical optimization methods are needed.

Another problem is that developing a new aircraft takes a long time and needs a large upfront investment. As a result, new aircraft models are usually modifications of previous versions, for example with new engines, added winglets, or a modified fuselage. The original aircraft and its modifications can be seen as an aircraft family (e.g. Airbus A320 family consists of the A318, A319, A320 and A321 models). In the past, the main aircraft was usually optimized and after some time modifications were made to extend the market coverage of the family. The problem is that this way of designing does not optimize the whole aircraft family, since the optimum point of one product differs from the optimum point of a product family. New design methods are needed to take this effect into account from the start and to design an aircraft family concurrently. Previous studies have focused on how to estimate commonality [1, 2] but in this paper we would also like to check how the commonality affects the family performance.

In this work, we consider the design of an environmental control system (ECS) and the flight control system (FCS) for a family of aircraft. To do this, a novel system architecture optimization method will be applied, and a collaborative Multidisciplinary Design Optimization (MDO) problem will be formulated to assess architecture performances. Since product family design contains an inherent trade-off between member performance and commonality, the formulated optimization problem will be a multi-objective problem with two objectives: acquisition cost, representing the costs an OEM makes to develop and produce a new aircraft family, and operating costs, representing the aircraft performance (i.e. efficiency and maintenance). The multidisciplinary toolchain will contain an Overall Aircraft Design (OAD) tool, disciplines specific to the analysis of the on-board systems, and disciplines related to the assessments of the two metrics. Data is communicated between tools using CPACS, an XML-based aircraft parameterization format, as the common language [3, 4].

The following sections explain some of the concepts involved in the posed design problem in more depth.

A. Family Concept Design

Family concept design is a way of covering a certain market area with several similar products at the same time. The advantage of it is that the development and production cost (and hence the acquisition cost) can be reduced if some parts or processes are shared among the different products. It also has advantages to the airlines in terms of maintenance and pilot training cost reduction. This is called commonality among members [5–8] and it is in the interest of the aircraft OEM to maximize it in order to reduce costs. Family concept design treats the design of several similar products which can use common components or manufacturing processes to cover a certain market area as a concurrent design problem. The objective is designing multiple versions of a product at the same time to look for more optimum designs; this is also known as set-based design [7].

In the aviation sector, when designing an aircraft family, the main differences among members are often in the fuselage length and the engine types. Later some subsystems might need to be modified, like tail or control surfaces, in order to fulfill certification requirements. As an example, an aircraft family could consist of a regular member, a short range version and a long range variation. With these family members a certain market region is covered, and covering that region with good performance means that more aircraft can be sold. In commercial aviation, market regions are often specified as payload-range (PL-R) diagrams. This means that the expected operational points can be represented by points in the diagram with some associated frequencies that the aircraft will have to cover [9–11]. Aircraft need to supply different routes, this means that they often fly in off-design conditions. The aircraft family optimization will consist of where to position each member in the (PL-R) diagram and the degree of commonality among the members.

B. Collaborative System Architecture Design and Optimization

In the early design stage, the system architecture is defined. Traditionally, this has been either done based on experience, or by considering only a small amount of alternatives and scoring them based on semi-quantitative metrics, that were usually also based on experience. Such metrics, however, do not offer a detailed description of the real performance of the architecture. This conflict is known as the knowledge paradox: in the early design stage much freedom is available to modify the existing design, but not much knowledge of the system is available [12, 13].

A move towards better methods for quantifying architecture performance has opened the way for analyzing more architecture alternatives in a more detailed manner. The number of possible alternatives, however, can grow so large that analyzing all alternatives is infeasible. Optimization methods are therefore needed to find optimal architectures.

One promising area for the evaluation of product performance is collaborative MDO. Multidisciplinary Design Optimization (MDO) deals with the coupling between different engineering disciplines and how to integrate them in order to perform successful design optimization. Collaborative MDO realizes that in order to perform more elaborate design analysis, it is not practically feasible to have one person setup and execute an MDO problem. Rather, there exists a separation between the disciplinary experts and their analysis tools. The integrator that has an overview of the design problem collects tool specifications, arranges access to tool execution, and executes the problem. To reduce the amount of data interfaces that need to be implemented between tools, a common data exchange format is needed: a common language. In the field of aircraft design, CPACS [3, 4] has been established as such a common language, and will be used in this work.

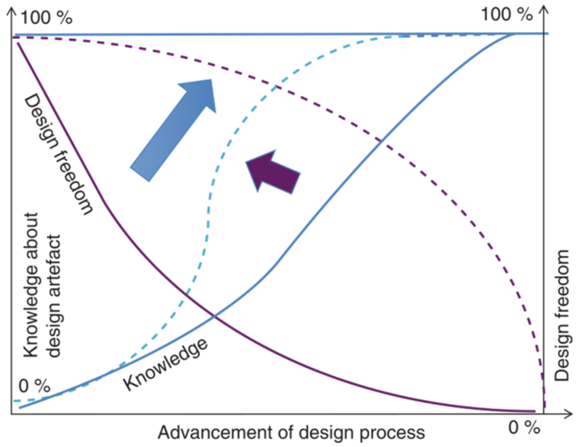


Fig. 1 Mitigating the knowledge paradox, from [13].

By connecting system architecting with collaborative MDO, the knowledge paradox is partly mitigated: large design freedom is present, however at the same time design performance can be quantified using relatively high-fidelity multidisciplinary analysis, as shown in figure 1. Additionally, by decomposing the architecture in terms of its functions to be fulfilled, as is done in system architecting, extra benefits are achieved: the functional breakdown is generic to any architecture alternative, it does not suggest any architecture concept, and it suggests solution types rather than specific technologies. This results in a framework that is not prone to expert bias, and therefore is suitable for finding innovative new architectures.

C. Environmental Control System

The environmental control system ensures that cabin air conditions are adequate for meeting the physiological needs of passengers and crew. The minimum and maximum temperatures, humidity and pressure levels that need to be achieved are determined by regulatory authorities. For instance, in FAR25 and CS-25 a minimum of fresh air mass flow of 4.16 grams per passenger and second are required [14], but aircraft manufacturers usually exceed this minimum. The functioning of the environmental control system can be divided into several subsystems: the air is extracted by the

Bleed Air System and then delivered to the Air Conditioning System, which regulates the air conditions (i.e. pressure, temperature and humidity) and delivers it to the cabin. In order to do this, the air is passed through a primary heat exchanger, then a compressor, a main heat exchanger and finally through a turbine. The heat exchangers cool down the air with more air provided by a ram air inlet below the fuselage. Once the air is delivered into the cabin, the pressure is controlled by the Cabin Pressure Control System.

One of the main decisions about the ECS architecture is how to extract the air from the atmosphere. Almost all passenger transport aircraft use bleed air extracted from the engines. An exception is the Boeing 787, which uses inlets positioned below the fuselage, and then compresses the air with electrically driven compressors. These compressors require a small amount of fuel, but this amount is low compared with a traditional bleed system. This way the fuel consumption decreases, but the fans' weight is higher than the bleed air system's weight, so there is a trade-off between both decisions [15, 16].

The second main design choice is on which type of Air Conditioning System to use, which is decomposed into two further decisions. The first one is about the Air Cycle Machine (ACM), which determines how to link the compressor, the turbine and the fan. In this research three different bootstrap cycles are considered, they can be seen in figure 2. The bootstrap cycle (called BC, or two wheel BC) consists of the turbine moving the compressor, but in ground conditions the ram air has to be provided by an external ground fan. The three wheel BC solves this by linking a fan to the turbine-compressor shaft so the ground ram air is provided by this fan and the system is auto-contained (i.e. does not need external components in order to function). A drawback of the three wheel BC is that the turbine is less efficient since it has to provide power to an additional component. The four wheel BC links the compressor to a high pressure turbine and the fan to a low pressure turbine, which means that each component consumes the exact power needed and the efficiency increases, but as a result there are more components and a higher weight.

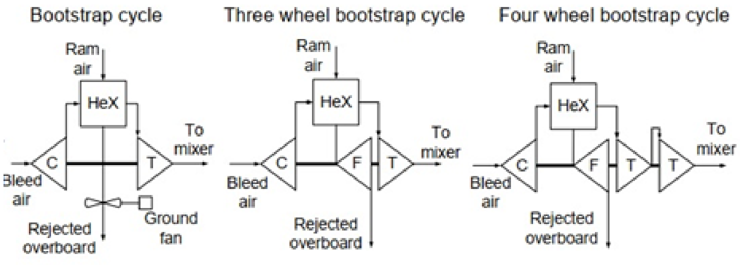


Fig. 2 Types of bootstrap cycles, from [17]

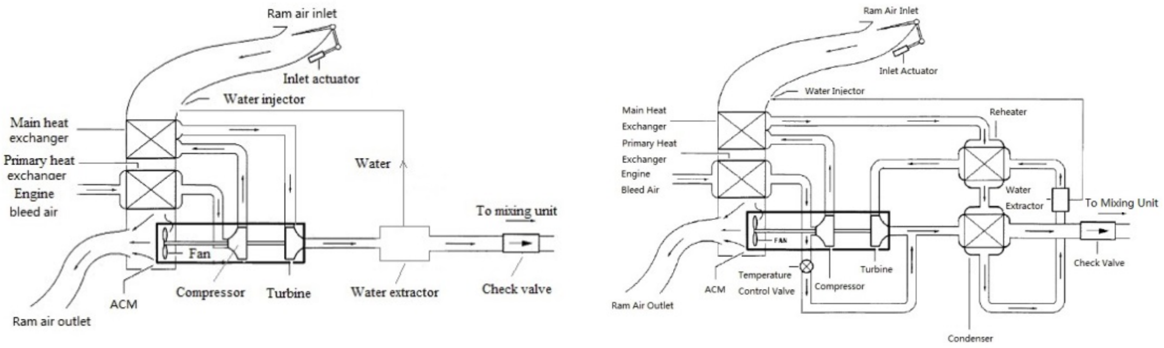
The second design choice about the Air Conditioning System is about when to extract the water from the air in order to control the humidity, this will affect the minimum temperature reachable in the turbine. The water extraction can be done after the turbine (low pressure water extraction system, also called non-subfreezing ACU) or before the turbine (high pressure water extraction system, also called subfreezing ACU). The advantage of extracting the water before the turbine is that this component can work at temperatures below zero, and hence the performance increases. However, extra components need to be added in order for this to function: a re-heater and a condenser. In figure 3 a three wheel BC with both configurations can be seen.

Twelve different ECS configurations will be considered for this analysis. They come from all the combinations for the decisions: bleedless or conventional way to take the air, using two, three or four wheel BC, and having a low or high pressure water extraction system. Some of the combinations can seem to be inefficient (like a 4 wheel BC with low pressure extractor), but they will be considered and discarded by quantitative performance evaluation, not by experience-based pre-selection. This way more possible configurations are checked.

Depending on the configuration, the system will have different weight, specific fuel consumption (SFC) and reliability. It is known that the wing anti-ice system strongly depends on the ECS, and for this reason its effects will be taken into account. For instance, with bleed-less architectures it is better to install electric anti-icing devices and the correspondent change in weight is considered.

D. Flight Control System

The flight control system is in charge of the safe control of the aircraft. Control is achieved using the primary (rudder, elevator and ailerons) and the secondary (spoilers, high lift devices) control surfaces. Other components include



(a) Low pressure BC

(b) High pressure BC

Fig. 3 3 Wheel Bootstrap Cycle, from [18]

the actuators, hydraulic circuits, electric components and flight control computers. Architecture choices considered in the design of the FCS will relate to the selection of the control surfaces and actuators. FCS computers and avionics are not considered.

The trend in FCS design is to move towards more-electric concepts. This means removing or reducing the number of hydraulic circuits in the aircraft that have been used in the past, and substitute them with electric components. Even so, redundancies need to be taken into account. For instance, primary surfaces usually have one main actuator and a second one that operates in case of failure [19]. So in order to reduce the usage of hydraulic actuators, one possibility would be to have one hydraulic and one electric actuator, or directly having two electric ones. As an example, the A320 model has three hydraulic circuits to supply all of its hydraulic actuators [20], whereas the A380 removed one of these circuits and implemented new more-electric actuators in place [21].

Three types of actuators are considered for the analysis in this paper. The first one is the classic conventional hydraulic servo actuator (HSA), which is electrically controlled but hydraulically moved. It relies on a central hydraulic circuit that provides the power. Its main disadvantage is that this global hydraulic circuit need many pipes, pumps and other hydraulic equipment that increase the system's weight. Two new more-electric actuators are being used currently. Their main advantages are that they remove these heavy hydraulic circuits and they reduce maintenance costs since electric components are more reliable than mechanic ones. One is the electro-hydrostatic actuator (EHA) and consists of a hydraulic actuator with a local hydraulic circuit. This local deposit is used only for that specific actuator and is powered by an electrically driven motor. The way the servo-actuator functions is the same as in the case of an HSA but the central hydraulic supply lines are no longer needed. The other more-electric actuator type is the electro-mechanical actuator (EMA). This servo replaces all hydraulic components and is based on an electric motor and a gearbox assembly to move the actuator. EMA is a more-electric version of the usual screw-jack actuators. They resist bigger loads but are not able to achieve large angular rates, so they are usually used for high lift devices [22–24]. Figure 4 represents the principle of the three types.

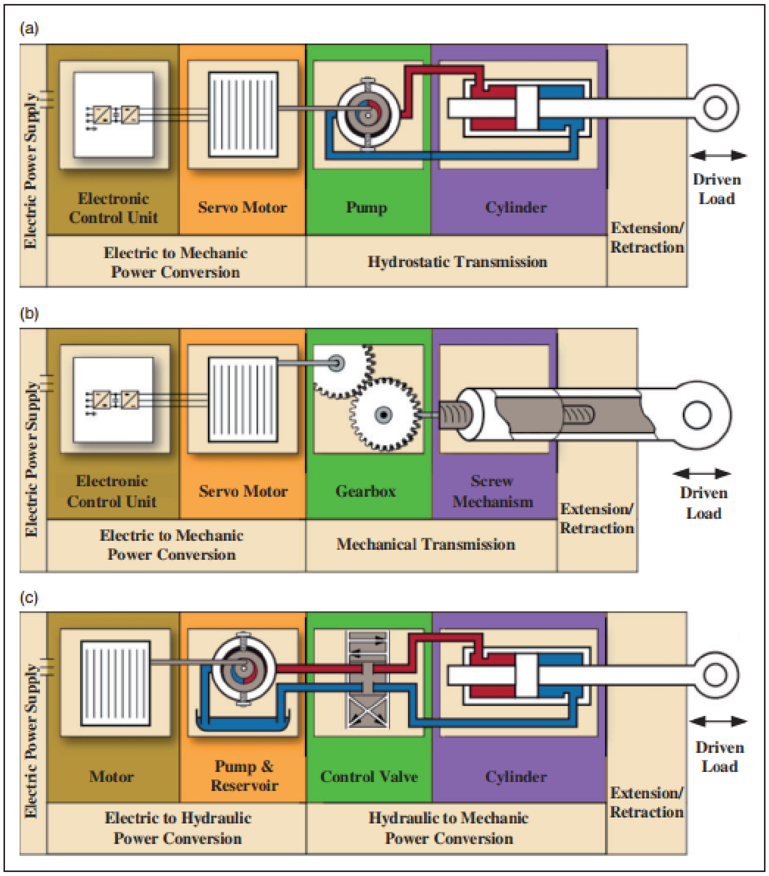
The FCS layout that was chosen, it is based on the A320 and consist of:

- 2 ailerons, with two actuators each
- 2 elevators, with two actuators each
- 1 ruder, with three actuators
- 10 spoilers, with one actuator each
- 1 flap and 1 slat central power control unit, with two servos each

The software used for the FCS sizing (ASTRID) considers two options, all hydraulic or all electric. In the case of all hydraulic it simply calculates everything considering HSA actuators. In the case of all electric it considers EHA for ailerons, elevators, ruder and spoilers and EMA for the flaps and slats.

III. Optimization Problem

The ECS and FCS architectures will be optimized for two objectives: commonality and fuel burn, both of which are attempted to be minimized. Supposing a certain market region input given by historical flight data, the OEM should



. Power-by-wire actuators and HSA composition. (a) EHA, (b) EMA, and (c) HSA.

Fig. 4 Actuators comparison, from [22]

design an aircraft family to cover some part of the market in terms of Payload-Range. For a given aircraft sales price, the more capital the aircraft manufacturer needs to invest in order to develop and produce it, the less profit it will make. On the other hand, the better the product performs, the less the operation costs will be for the airline. To improve performance, however, aircraft manufacturer should spend more effort in making every family member work on its optimum point. Introducing commonality can be a way to mitigate this conflict: the larger the commonality among members, the cheaper it will be to develop and produce (more similar product facilities, less design and certification effort, etc.). However, the members will operate away from their design point for a larger share of the time and thus overall performance will be penalized.

The main costs for the operator (airline) are all summarized in the DOC (Direct Operation Costs). This cost is divided into several parts and it is highly affected by fuel burn. In this analysis the architectures are being studied, so only those parameters related to the costs that are directly affected by the ECS and FCS performance will be estimated. The model proposed is that the operating cost strongly depends on the fuel consumption and the maintenance cost, among others. The fuel burn is directly dependent on the SFC, the weight, and the estimated distribution of operating points. The maintenance cost depends on the reliability and number of components and is directly related to the architecture chosen: for example, reducing the number of components and increasing the maintainability (i.e. avoiding hydraulic fluid) may produce a reduction of the maintenance cost.

The main costs for the OEM are the design, manufacturing, and certification costs. If there are more common components, the costs of producing, testing, and certificating will be lower so it is highly affected by commonality.

Due to the presence of multiple conflicting objectives, it is not expected to find one best architecture, rather a Pareto set of optimal architectures is expected to be found. The Pareto optimal set is the set of architectures that are not mutually dominating, however they do all dominate the remaining architectures. An architecture dominates another architecture if its performance is better for all considered objectives. The Pareto optimal set therefore consists of architectures that are not objectively better than one another, because an improvement of performance in one objective (i.e. commonality) necessarily is accompanied with a reduction of performance in one or more other objectives (i.e. fuel burn).

There are some fixed inputs to the optimization problem. One is the market segment the family is to be designed for. This information will be provided as a span of payloads and ranges. As aircraft do not operate one single route, a distribution of relative flight frequency over the points in the payload-range segment is needed. The mission profile is separated into 20 different segments (e.g. taxi-in, climb, cruise, descent...). For each segment the Mach number and average altitude is specified. The mission profile is used for sizing the power needed by the subsystems and for calculating average fuel burn. Also, three family members will be considered in this analysis.

The design variables are those parameters that the optimization algorithm can vary in order to find the optimum points and obtain the Pareto front. These variables shall represent the different architectures and the family concept. The design variables are the following:

- FCS architecture, for each aircraft. Discrete variable that selects electric or hydraulic.
- ECS architecture, for each aircraft. Discrete variable that selects: conventional or bleedless concept, high or low pressure bootstrap cycle and number of air conditioning unit wheels.
- Decision about using in aircraft 2 the subsystems from aircraft 1. Discrete yes or no variable.
- Decision about using in aircraft 3 the subsystems from aircraft 2. Discrete yes or no variable.

Here we can see that the aircraft 1 is the sizing aircraft, as it is the biggest of the three.

IV. Modeling the Architecture Design Space

To determine the architecture decisions involved in the optimization problem, the architecture design space is modeled first. A novel methodology that enables modeling the design space from a functional perspective is used [25]. This methodology models the architecture design space using the Architecture Design Space Graph (ADSG), which maps functions to components. Additionally, component characterization choices (e.g. related to the number of instances, or to component attributes), and component connection choices are modeled. Decisions are automatically identified, and these decisions are subsequently mapped to the architecture decisions in the optimization problem.

The ADSG is a directed graph where nodes represent architecture elements and edges normally represent derivations: if the source node exists, then the target node exists as well. The architecture design space is modeled by inserting decision nodes in certain situations. A decision node represents an architecture decision, and its outgoing edges point to the decision options, rather than representing node derivations. One assumption made in the ADSG methodology is that in architecture instances, generated from the architecture design space by resolving the decisions, only one component can fulfill a function (i.e. a function node can point to only one component node). Therefore, if the ADSG contains a function node that points to two or more components, a decision node is inserted to represent the choice of architectures. For more details on the ADSG and its architecture decision mechanisms, the reader is referred to [25].

Figure 5 shows the environmental control system function breakdown modeled with the ADSG. It is done from a subsystems level perspective. First, it specifies the neutral function of the system, which is delivering air to the cabin and making it suitable to the passengers and crew. In order to do this, the ECS is divided in three main subsystems (as discussed in chapter II.C). The Bleed Air System extracts the air from the atmosphere and has an attribute that represents if this is done with a conventional bleeding or from a more electric plane perspective. The Air Conditioning System has two attributes that represent the type of Air Conditioning Unit (ACU) and the type of water extractor. The Cabin Pressure Control System only controls the cabin pressure and has no design decisions associated.

The Flight Control System's architecture design space graph is simpler since it only has one design variable to decide whether the actuators would be hydraulic or electric. The ADSG for this subsystem is shown in figure 6.

The actual system's model goes more in depth into a component level. The functions specified are decomposed into more specific ones which can be fulfilled with different components. For instance, one function is "provide ram air on ground" and can be fulfilled by two different components which are an external ground fan or a fan joined to the ACU. If the first one is chosen then the final architecture is what we call two-wheel bootstrap cycle. However, if the second one is selected then a new function appears, which is: "move fan". Depending on the component that fulfills this new function the final result can be a three-wheel or a four-wheel cycle.

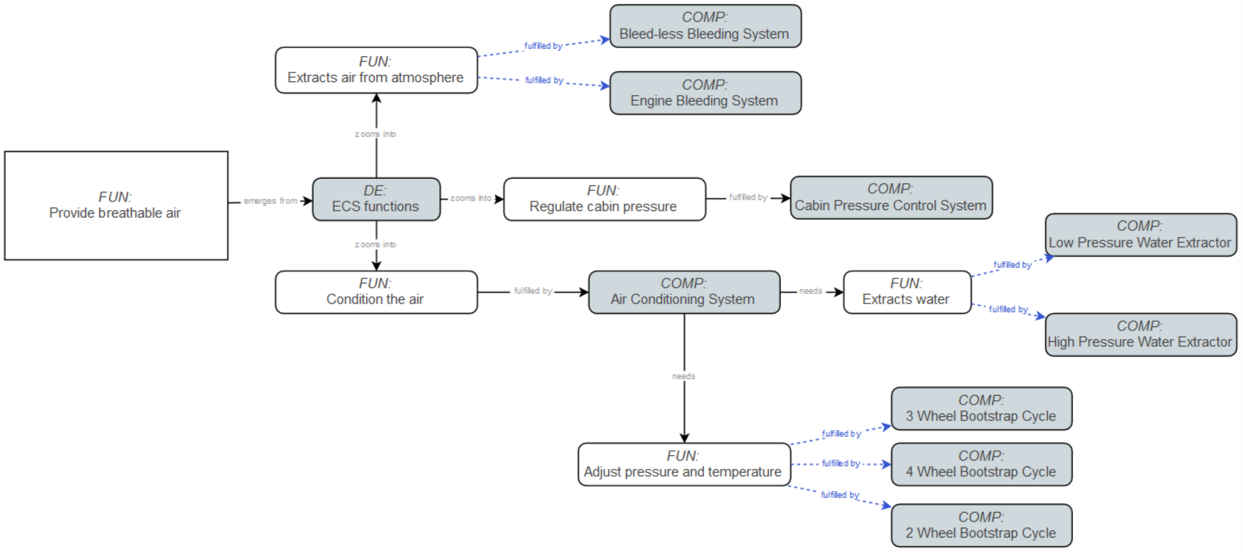


Fig. 5 Architecture Design Space Graph (ADSG) of the Environmental Control System (ECS)

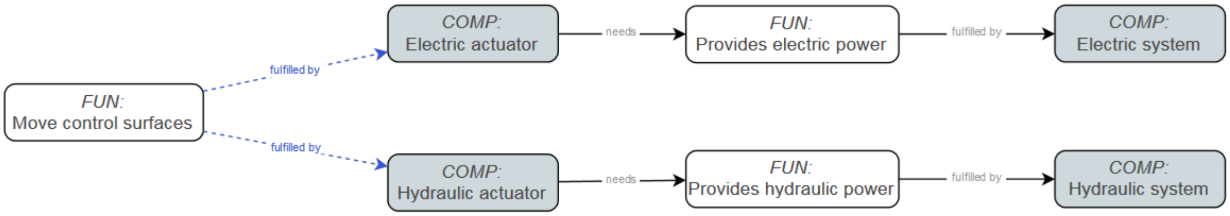


Fig. 6 Architecture Design Space Graph (ADSG) of the Flight Control System (FCS)

V. Multidisciplinary Analysis Toolchain

To solve the problem presented in this paper, a multidisciplinary analysis toolchain is constructed. The developed toolchain is represented as an XDSM (eXtended Design Structure Matrix) diagram [26] in figure 7. Note that this is a reduced version that summarizes the diagram since the actual one converges the three aircraft separately. This is due to the fact that one loop has to wait to the previous aircraft to be sized to share or not the subsystems with it. The detailed version of the XDSM is shown in figure 11 in the appendix.

The different disciplines communicate their data using a common language: all tools read from and write to a common format to reduce the amount of data interfaces to be implemented. The language used in this project is CPACS: a common language used for aircraft design [3, 4]. Disciplinary tools are integrated in RCE (Remote Component Environment), a PIDO (Process Integration and Design Optimization) environment developed by the DLR [27]. An in-depth explanation of the different blocks, steps, and loops is presented next.

A. Optimizer

This block creates the new design variables and receives the solutions from the optimization objectives, which are the fuel burn and commonality. The genetic algorithms make this process converge to the optimum solutions in less iteration than exhaustively enumerating the design space. All the variables have their corresponding boundaries and are written into CPACS so all the other tools can properly read them. The algorithm used in this work was the Dakota Multi Objective Genetic Algorithm [28].

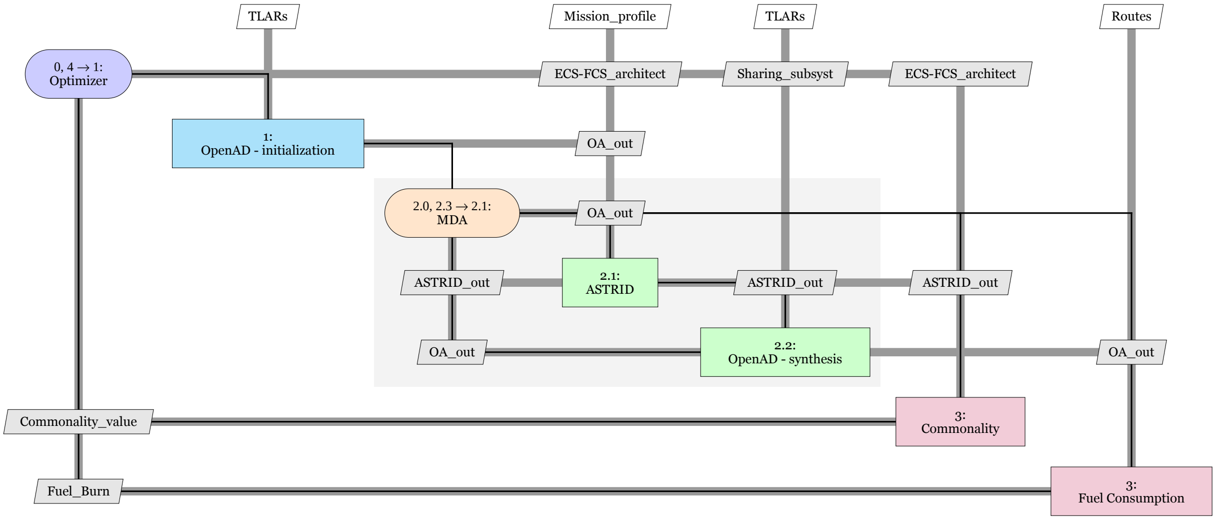


Fig. 7 Notional version of the XDSM diagram

B. OpenAD - Overall Aircraft Design

This block sizes the aircraft based on the information from the TLARs. OpenAD (previously called VAMPzero) is used for this analysis. It is a tool for conceptual aircraft design [29, 30] and it was developed in DLR to analyze and generate CPACS files. The aircraft sizing methods are based on handbook and empirical methods from literature.

C. ASTRID - On-Board Systems Analysis

ASTRID (Aircraft on Board Systems Sizing and Trade-Off Analysis in Inital Design) is a tool developed by the Polytechnical University of Turin [31]. This tool is used for aircraft on-board systems sizing and its inputs are the aircraft TLARs, the mission profile, geometry and masses, among others.

The software sizes the utility systems and then sizes the electric and hydraulic system depending on the requirements given from them. Subsystems considered are: avionics, flight control system, landing gear, ice protection system, environmental control system, bleed system and fuel system. The furnishing systems' weight is taken from OpenAD output. The output of ASTRID is a detailed list of characteristics for each of the subsystems. Relevant for the optimization problem of this work are the masses (for each system and the global system mass), and data about the engine bleeding and the power budget of the aircraft (per mission segment).

D. BRICS - Cross-organizational communication of analysis results

The development of the toolchain is done at the DLR in Germany, and due to intellectual property rights it is not possible to run ASTRID locally. This problem is solved using an intermediate tool called BRICS.

BRICS is a tool developed by the NLR (Royal Netherlands Aerospace Centre) that can be implemented into RCE workflows and allows the remote excecution of a tool [32]. In this workflow BRICS was in the exact position were ASTRID should be. It receives the input file, sends it to Polythechnic Univerity of Turin and waits for the output. The workflow continues once it receives output from ASTRID, all automatic [33].

E. OpenAD synthesis and mass convergence (MDA converger)

The objective of the second OpenAD block is to resize the aircraft now that more precise information is available. ASTRID provides a value of the on-board systems masses, bleeding air and mechanical power off-takes. Giving this information back to OpenAD the masses and specific fuel consumption can be updated. If the subsystems are shared then this block takes ASTRID's output from the previous converged aircraft.

This methodology takes into account the snowball effect that characterizes aircraft design. This effect consists of the increase in mass that the MTOM suffers when the mass of a component also increases. It could seem like both increases are the same but this is not true since when a component's mass increases then more elements need to be added, or the previous ones need to be reinforced to support the loads and this effect spreads all over the aircraft. Therefore, if a subsystem weights more, the MTOM increases in a quantity bigger than the subsystem's mass increase. The same happens in the other direction: reductions in subsystems' masses result in bigger reductions in the total mass.

F. Fuel Burn Tool

This tool was specifically developed for this analysis and workflow. As input it takes information about flown routes and a CPACS file with the aircraft characteristics. The routes data was taken from the USA Bureau of Transportation Statistics [34]. Several A320-like aircraft routes were considered making a total of 139 028 different routes. All these routes are represented in figure 8, where colors show the frequency that each route is flown. The main objective of this tool is to assign each route to one of the three aircraft, calculate the fuel needed to fly it, sum all the fuel tons and calculate an average fuel consumption per route per aircraft. This result is an index of how efficiently the aircraft family performs that market segment in terms of fuel. There are two main aspects for this tool. One is the criteria to assign the route to one aircraft or another one. The other is the fuel consumption model.

The fuel consumption model is based on the Breguet equation (eq. 1), with several additional assumptions:

- Jet engines are used
- The flight is modeled as cruise-only from the origin to the destination
- The drag polar is modeled as a quadratic equation plus wave drag contribution

From these assumptions, equation 2 follows. The final lift coefficient can be expressed as (eq. 3). Hence, the only unknown is the initial lift coefficient which contains the value of fuel tons.

$$R = \int_{t_1}^{t_2} \frac{dR}{dt} dt = \int_{m_2}^{m_1} \frac{V}{f_{cons}} dm \tag{1}$$

$$R(km) = \frac{2VE_{\max}}{gSFC} \left[\text{atan}\left(\frac{C_{Li}}{C_{Lopt}}\right) - \text{atan}\left(\frac{C_{Lf}}{C_{Lopt}}\right) \right] \cdot 1000 \tag{2}$$

$$\text{mass}_{\text{final}} = LW = \frac{OEW + PL}{1 - \alpha} \tag{3}$$

Routes are assigned to aircraft as follows: the smallest aircraft is selected and it will perform all the routes that are below its maximum payload and its maximum range with maximum payload. These routes are removed and the second aircraft will fly the remaining routes which are also below its maximum payload and its maximum range with maximum payload. The biggest aircraft will then fly the remaining routes that have not been selected for the other two members. This requires an a-priori analysis where it should be confirmed that the biggest aircraft can actually fulfill all the routes. Figure 8 shows this criteria. The black lines separate the areas that each aircraft will perform.

G. Commonality Tool

The inputs for this tool are the results from ASTRID and design variables. The output is an estimated value of the commonality index reached by that aircraft family. The tool needs to consider three possibilities: aircraft that share the exact same subsystems, aircraft with the same architectures but different sized subsystems, and aircraft with different architectures. The model proposed is the Product Line Commonality Index (PCI), a metric for evaluating design commonality in product families [2].

The model is based on reducing the system into components and checking which ones are shared among architectures and which ones are not. The index is defined in equation 4:

$$\text{PCI} = \frac{\sum_{i=1}^{P} \text{CCI}_i - \sum_{i=1}^{\text{P}} \text{Min CCI}_i}{\sum_{i=1}^{\text{P}} \text{Max CCI}_i - \sum_{i=1}^{\text{P}} \text{Min CCI}_i} \times 100 = \frac{\sum_{i=1}^{P} n_i \times f_i - \sum_{i=1}^{P} \frac{1}{n_i^2}}{(P \times N) - \sum_{i=1}^{P} \frac{1}{n_i^2}} \times 100 \tag{4}$$

The index i refers to the components and goes from 1 to the total amount of components which is P. While N is the number of products in the product family, which is three in this analysis (three aircraft). The parameter n_i is the number of products in the product family that have component i. And f_i is a size factor for component i. This size factor is used to differentiate aircraft with the same architectures but optimized for different aircraft, hence they will have different masses and dimensions.

In the case of the ECS, eight components are selected: compressor plus turbine, primary heat exchanger plus main heat exchanger, second turbine, ground fan, ACU fan (fan joined to the turbine), re-heater plus condenser, electric fan

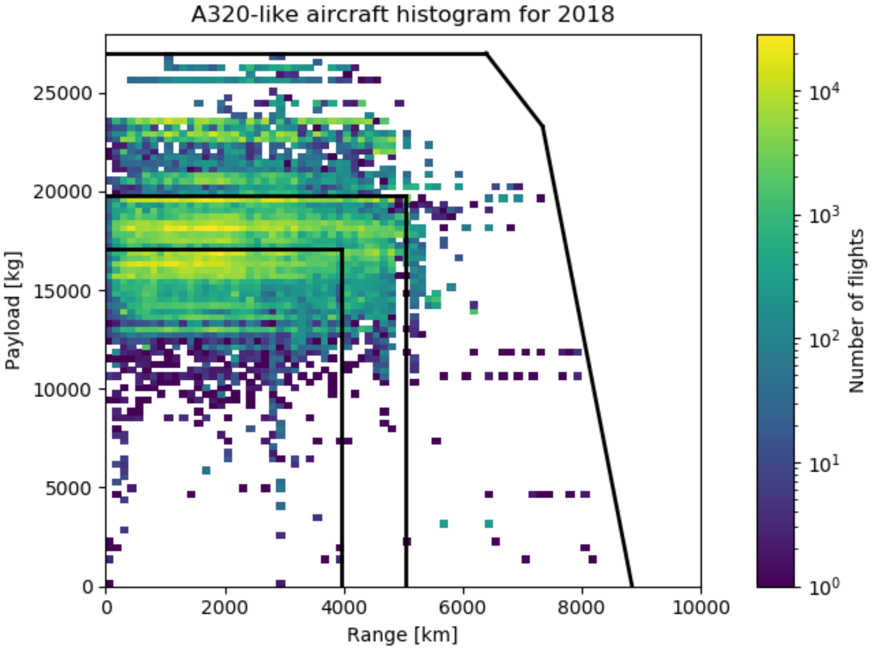


Fig. 8 Diagram with the routes and the selection criteria for each aircraft.

and fuselage inlets. The compressor, turbine and heat exchangers are common to all the architectures. The ACU fan is present in 3 Wheel BC and 4 Wheel BC, whereas in the 2 Wheel BC the ground fan substitutes this component. The second turbine is only used for the 4 Wheel BC. The re-heater and condenser are components which are used in sub-freezing (also known as high pressure) architectures. And finally the electric fan and fuselage inlets are specific for the bleed-less concept architectures since they need this extra inlet plus fan to substitute the engine bleeding.

The sizing factor is applied to the components whose size depends on the ACU mass flow. These ones are all the heat exchangers, including the condenser and re-heater, the compressor and the two turbines. Hence this factor was modeled as the Average Absolute Deviation of the mass flows. On each case these mass flows refer only to the common components, this means that it can be done between two or three aircraft depending exactly on which ones share that component in particular. Equation 5 shows the expression for the sizing factor.

$$\text{Sizing factor} = 1 - \frac{\frac{1}{n}\sum_{i=j}^{n}\left|x_j - m(X)\right|}{m(X)} \tag{5}$$

The lower the value of this factor, the lower the commonality index.

In the case of the FCS, the situation is more simple since there are only two architecture options: electric or hydraulic. It is important to also differentiate when two aircraft share the subsystem from when they just share the architecture. The PCI model without sizing factor and a low amount of components is used and the results are that when two aircraft share the FCS the commonality is 1, if they just have the same architecture the value is 0.75 and if they don not share architectures the value will be 0.325. Hence there are only five different cases, the commonality values for each of them made with the PCI are as follows:

- **Case 1:** The three aircraft share subsystems. The value is 1.
- **Case 2:** Two aircraft share subsystems and the other one has the same architecture. The value is 0.834.
- **Case 3:** Two aircraft share subsystems and the other one has a different architecture. The value is 0.55.
- **Case 4:** Aircraft do not share subsystems but the three have the same architecture. The value is 0.75.
- **Case 5:** Aircraft do not share subsystems and just two have the same architecture. The value is 0.467.

The final commonality value is the average of both subsystems.

VI. Results

The result is the Pareto front between fuel consumption and commonality. The trade-off between these variables is the origin of this analysis. Different degrees of commonality and fuel burn were be obtained for each configuration.

The optimization was done in two steps. First, in order to check values and sensitivities to the design variables a DOE (Design of experiments) was done. It consists of running the whole workflow with some pre-defined design variables. The first runs were made changing the architecture and using it for the three family members. Then, some runs with active sharing variables were also made. These points can be seen in figure 10. Once the DOE results are validated the optimization process is done. Several runs were made with different initial points. The obtained points and Pareto front is shown in figure 9. This graph specifies which architectures allow the biggest degree of commonality and which one performs better from a fuel consumption perspective, as well as all the intermediate points that represent the Pareto front.

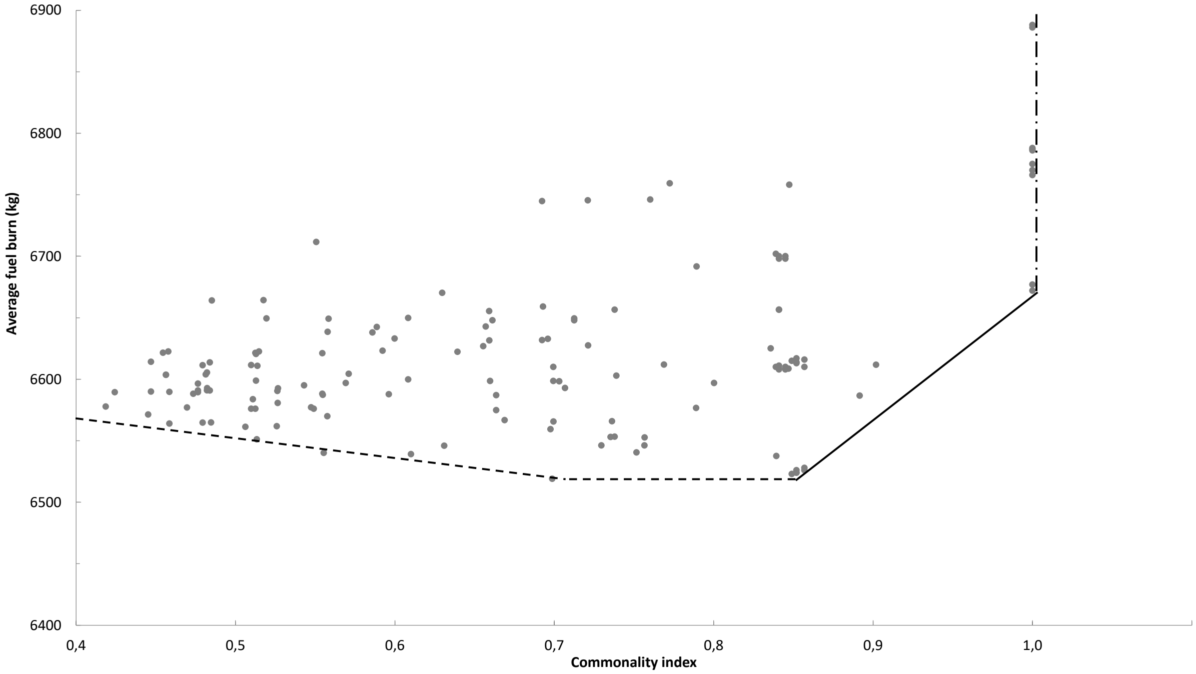


Fig. 9 Pareto front

Three different areas are seen in the Pareto front. The first one, represented by a dashed line, it is observed that the average fuel burn decreases as the commonality increased. The second one, represented with a continuous line, that has the opposite behavior as the previous one. And the dotted line, that represents the maximum commonality index reached.

The first area is affected by the fact that the minimum fuel burn is reached with a certain architecture. If the three aircraft have different architectures it's very likely that at least one of them will poorly perform in terms of fuel burn and as a result raise the average fuel tons. If the three architectures are different, the commonality value is low. Hence as we raise the commonality value, the minimum possible fuel burn decreases.

The second area has the opposite effect. The initial point starts were the three aircraft have the same architecture with the minimum possible fuel burn. This is the point of minimum fuel consumption of all architectures. Each of the aircraft has its own sized subsystems. The commonality obtained with this configuration is limited, and in order to increase it some subsystems shall be shared among members. The sizing aircraft in case of sharing is always the bigger one, this causes that if components are shared the weight and specific consumption would increase, hence the family will perform worse on average. This trade-off between commonality and fuel consumption is common to family design problem.

The third area is a vertical line that represents the maximum commonality index, which can be only reached when the three family members share the subsystems among them. This means that the first aircraft is sized and the other two are using its same subsystems. This causes the second member to be slightly over-sized. The third member is highly over-sized and out of its optimum design. This causes the fuel burn to substantially increase.

Figure 10 shows a detailed view of the Pareto front. Some interesting points have been highlighted.

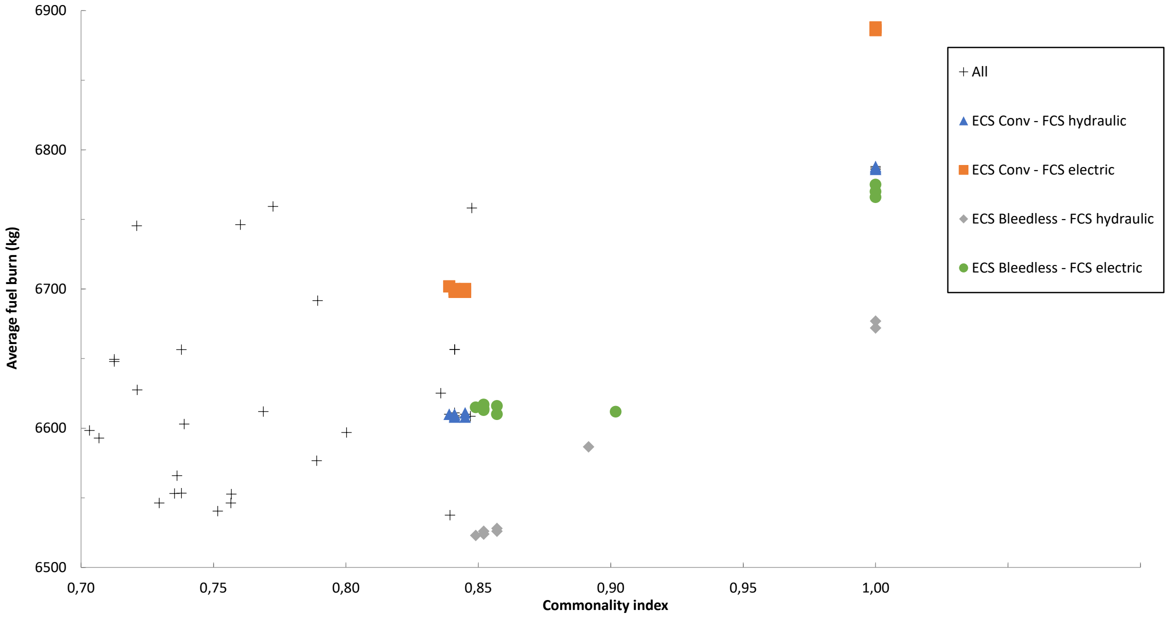


Fig. 10 Detailed view of the Pareto front with architectures

The architecture that reaches the lowest fuel burn values corresponds to the bleedless ECS with hydraulic FCS. The bleedless ECS has the lowest specific fuel consumption and compensates its mass increase. The electric FCS had a bigger mass increase than SFC reduction in terms of fuel burn. This result can be related to the fact that all the FCS actuators had the same architecture, a mix between electric and hydraulic FCS could reach better results.

The other ECS design variables did not show a huge impact on the results as the other two. This is due to ASTRID sizing. The number of wheels does not have an impact on the off-takes since the necessary airflow comes from the analysis of the thermal loads between fuselage and cabin. The mass difference is minimum and the needed bleeding is the same one. Regarding the sub-freezing or non-subfreezing architecture, the cruise off-takes are the same in both cases since the external air is practically dry and the non-subfreezing configuration can work at minus-zero temperatures. The difference in mass and SFC were appreciable but small. As a result these two variables did not highly affect the results and only induced small variations around a certain point.

The difference between the minimum average fuel burn and the minimum reached with the maximum commonality index is approximately 150 kilograms per flight. Multiplying this value with the total amount of flights the result is a difference of 454 000 fuel tons per year for the whole family.

VII. Conclusion

An application of a new system architecting method to the design of a family of Environmental Control Systems (ECS) and Flight Control Systems (FCS) is presented. First the architecture design space is modeled and the multi-objective optimization problem is automatically formulated from this model. Then, the acquisition and operation costs are optimized using a collaborative multidisciplinary analysis toolchain. Several analysis tools are developed. An important difference compared to conventional system architecting methods is that in principle all possible system architectures are considered, and no pre-selection using expert experience is done. This way more architecture alternatives are considered by quantitative analysis, resulting in more complete knowledge about the behavior of the design space.

This setup allows the optimization of onboard system architecture for the aircraft family as a whole. Other aircraft subsystems than the ECS and FCS can be optimized this way by adding the corresponding architecture decisions and adding relevant tools to the multidisciplinary analysis toolchain.

The outputs of the multidisciplinary analysis toolchain are the family-level commonality and average fuel burn. Future improvements could include replacing these two objectives by their cost analysis counterparts: acquisition cost and operating cost, respectively. Another interesting trade-off might be present when looking at the design of more-electric architectures, where it is expected that maintenance costs are lower, but development costs are higher. Both of the improvements can be easily integrated in the current toolchain due to the modular setup and flexibility of the architecture design space modeling method.

Analysis results show that the bleed-less environmental control system reaches the lowest fuel burn from all the architectures if combined with a hydraulic flight control system. Potential improvements in analysis and design fidelity can be achieved by integrating control of the electrification degree at actuator-level instead of at system-level. This would allow to analyze intermediate design points where the SFC decrease and the mass increase that the electric actuators cause results in an average fuel burn reduction. More variables to define the ECS architecture can also be included, like control over the spacial layout of the system.

A Pareto trade-off between commonality and fuel burn was found as expected, although it was seen that for lower commonality indexes commonality and fuel burn correlated positively. The inflexion point was found to be the one with minimum fuel burn, which corresponds to a family consisting of the three aircraft with the architecture that needs the least fuel and without sharing subsystems. This effect is due to the fact that there is an architecture that has a noticeably lower fuel burn than the others. If this architecture is chosen for the three family members, the fuel burn will be the lowest possible while the commonality index will be high since the all the aircraft have the same components. If one member has a different architecture the commonality will decrease and the fuel burn will be penalized, hence the resulting point will move to the left side of the Pareto front. If one member shares subsystems with another one, the commonality index will increase but the fuel burn will also be higher since the aircraft is being over-sized. This will result in a point on the right side if the Pareto front.

Appendix

The XDSM can be seen in figure 11. It represents the information workflow among disciplines showing the inputs and outputs of each of them and the overall variables and parameters.

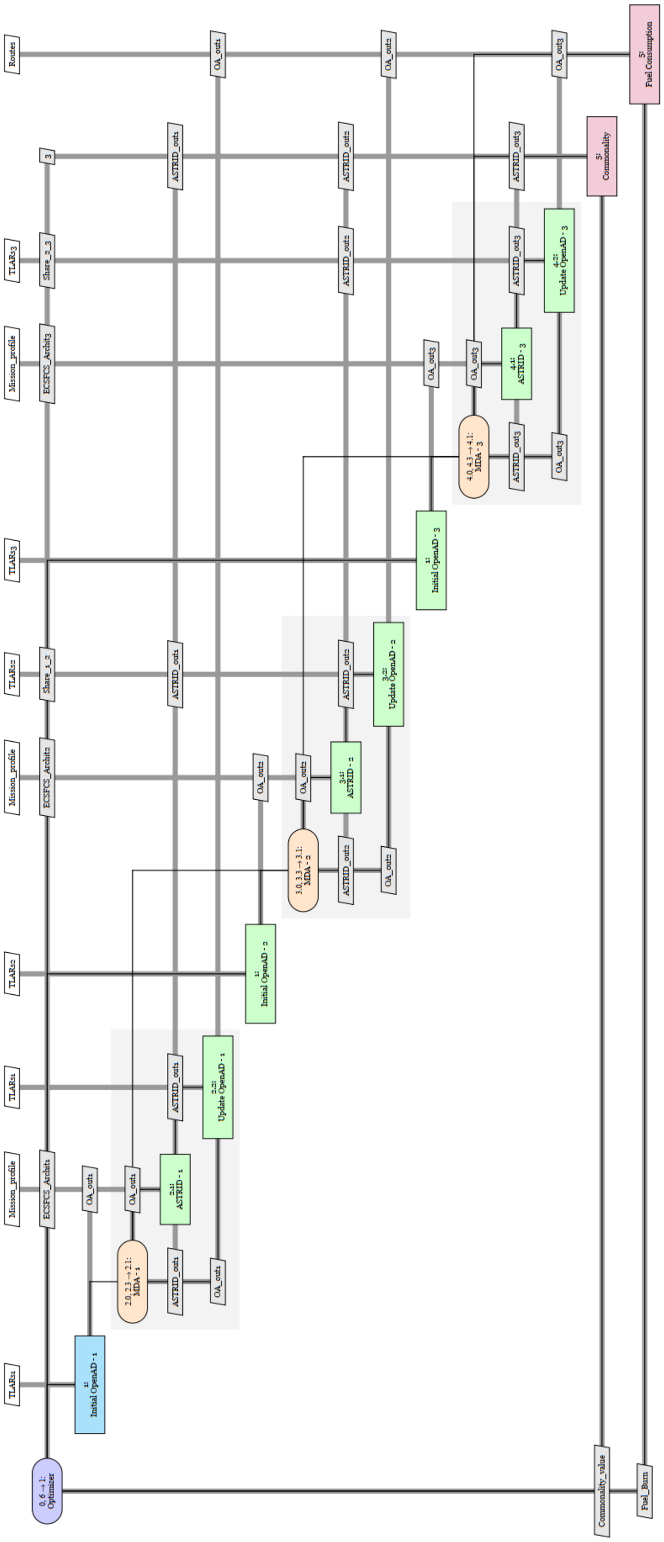


Fig. 11 XDSM diagram

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