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Automated evaluation of performance, certification and maintenance aspects of aircraft on-board system architectures during preliminary design stages

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On-board systems are key for the correct and safe operation of the aircraft. They constitute a significant part of an aircraft having a remarkable impact on performance since they directly affect the aircraft mass and fuel consumption. Their impact goes beyond when considering also other stages of the aircraft life cycle. On-board system architectures are defined during early design stages and have a huge impact on the final product. They are characterized by the different subsystems, components and connections among them. The total amount of possible feasible architectures for a system is huge, which usually leads to a big architectural design space. Automation is hence required in order to properly explore such design space. This study aims at providing a methodology to assess performance, maintenance and certification aspects of on-board system architectures during early stages of design. The proposed methodology allows to evaluate innovative on-board systems architectures, connecting in an automated manner their design space model to a multi-objective and multi-disciplinary evaluation framework. Such framework manages to filter out the architectures that are not preliminary certifiable before they are further evaluated, this narrows down the huge architectural design space and saves computational time as a result. An example with the roll control function of a flight control system is shown to better understand the scope and capabilities of the presented methodology. Results show that the proper filtering of the design space successfully identifies the most promising architectures and reveals interesting trade-offs. This supports the engineer during the decision making process of on-board systems design.

Nomenclature

AEA	=	All-Electric Aircraft
APU	=	Auxiliary Power Unit
EHA	=	Electro-Hydrostatic Actuator
EMA	=	Electro-Mechanical Actuator
FCS	=	Flight Control System

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HSA = Hydraulic Servo Actuator
MEA = More-Electric Aircraft
MMH = Maintenance Man Hours
MPD = Maintenance Planning Document
$MTOM$ = Maximum Take-Off Mass
OBS = On-Board Systems
PTU = Power Transfer Unit
RAT = Ram Air Turbine
RBD = Reliability Block Diagram

I. Introduction

The aviation industry is facing the challenge of reducing fuel consumption in the near future. New aircraft concepts are now being explored to fulfill this objective. New on-board systems (OBS) technologies are also being investigated to achieve the fuel reduction. For instance, more-electric and all-electric aircraft leverage new electrified concepts of on-board systems that can potentially reduce the direct operating cost of the airplane [1]. Hydrogen propelled aircraft need new fuel system concepts to store and provide the new fuel. Hypersonic vehicles need new systems, such as thermal control, that were not present in previous aircraft [2]. Some of these new aircraft concepts might establish the new generation of future vehicles and they all require innovative systems. On-board systems represent a noticeable part of an aircraft and their impact affects several aspects, such as mass, power off-takes or fuel consumption, among others. All of them affect the direct operating cost. New systems might bring benefits like better performance, higher reliability and/or lower cost, among others. Aircraft OBS are essential to fulfill the mission being responsible for functions like communication, navigation or flight controls [3]. They are considered critical systems and must be certified and properly maintained. OBS include the power generation, power distribution and power consuming systems.

One issue that arises when designing on-board system architectures is the big amount of possible solutions that exist. This creates an enormous architectural design space (i.e., millions or even billions of possible solutions). In order to explore such design space some degree of automation and filtering is required. A system architecting approach is suggested since it allows to properly create and explore all the different architectures. In terms of evaluation, three different disciplines are considered in this analysis: performance, maintenance and certification. A multi-disciplinary analysis like this can potentially give a better understanding of the real impact of each of the architectures since several stages of the product life cycle are being assessed [4]. Some stages such as manufacturing or disposal are left aside for further analyses. This concept also connects with concurrent engineering. It is a methodology which objective is to improve the product development time, which is a priority in the aerospace sector. It does this by creating a multidisciplinary framework with all the disciplines involved in the design process, all of them explored in parallel [5]. Some key aspects of this include dealing with complexity by separating the development into domains [6] (e.g., supply chain, manufacturing, maintenance...).

Summarizing, the main objective of this paper is to present a methodology that allows to simultaneously evaluate performance, certification and maintenance aspects of on-board systems architectures during preliminary design. All automated and created following a system architecting approach to guarantee a non-biased generation of architectures and traceability in the results. Sub-chapters I.A, I.B and I.C further explain the concepts of system architecting, on-board systems for aircraft and more-electric aircraft. Chapter II contains the state of the art regarding on-board systems evaluation in the three disciplines of interest. Chapter III shows the proposed methodology. Chapter IV demonstrates the methodology through an application case. Lastly, chapter V states the conclusions of this work.

A. System Architecting & Modelling

The architecture of a system is one of the first decisions to be taken while designing it [7]. The architecture of the on-board systems is already defined during conceptual design stages. The details, exact components and characteristic are determined at later stages. OBS architectures are characterized by the different subsystems, the components that build them and the different connections among them. The architectural design space represents all the possible different architectures that can compound a system and fulfill its functionality. Modelling such vast design space can be a difficult task. For that, a system architecting approach is used. A system architecture describes the behavior and structure of a system [7]. Decomposing it into functions (instead of components directly) helps making it more generic. This functional breakdown does not suggest any particular solution and removes possible bias from the designer. Traditionally,

the definition of the architecture of a system was made based on experience or from trade-off analysis in which a small amount of alternatives were evaluated and rated with semi-quantitative metrics [7]. However, these methods, do not provide a proper description of the actual performance of the architecture. This conflict is commonly known as the knowledge paradox: during early design stages a lot of freedom is available to change the existing design, but with the cost of not having much knowledge of the system [7, 8]. More effectively exploring the design possibilities in the initial stages aids in addressing this paradox and yields more detailed outcomes during conceptual design, facilitating the decision-making. Although formalizing a design space and an architecture can be challenging, various existing methods support the definition and exploration, ultimately leading to the identification of optimal solutions for the given problem [9].

B. On-Board Systems

This section explains more in depth the concept of on-board systems. Aircraft OBS can be categorized based on their functionality [3]. Systems designed to achieve a specific mission objective, such as de-icing the wings or transferring fuel to the engines, are referred to as power consuming systems. These systems require a power source to function. Power is generated by power generation systems and is subsequently transformed and distributed through power distribution systems [10, 11]. The interconnections among these subsystems define the architecture of the on-board systems. A comprehensive architecture definition contains all components, starting from the power source (e.g., APU) to specific devices (e.g., actuators, compressors). This distinction is now further explained, with a focus on aircraft systems.

1. Power Generation Systems

The origin of all required power for the users comes from the power generation systems, also referred to as prime movers. Primarily, engines serve this function, although additional components may serve as backups (e.g., ram air turbine (RAT) or auxiliary power unit (APU)). Other alternative sources such as fuel cells are also now being explored. Some power sources are only present during specific mission phases, for instance the batteries can provide electrical power during emergency phases for a limited amount of time.

2. Power Distribution Systems

These systems distribute and transform the energy (i.e., electrical, hydraulic and pneumatic) from the power generation systems to the users. Three subsystems are generally seen on aircraft:

- Electrical System: carries the electrical power and gives it at the correspondent voltage to each of the users (e.g., avionics or fuel pumps). Some examples of components included in this system are the cables, transformers, rectifiers, primary and secondary distribution units.
- Hydraulic System: transforms the power into hydraulic power through the utilization of hydraulic pumps. The fluid is typically stored in tanks and distributed through pipes. Other examples of components that belong to this system are filters, valves and accumulators.
- Pneumatic System: takes hot and compressed air from a source and provides it to the users (e.g., environmental control system or ice protection devices). The source of this air can be from a engine bleed or external compressors. Some other components of this system are the valves and pipes.

Some mechanical distribution systems are also present for example in the flap and slat systems. They are not considered as central distribution systems since they only provide support to one specific system. In this case they are considered as part of the flaps and slats themselves. The same happens with flight control systems that are connected by cables and pulleys.

3. Power Consuming Systems

These systems perform a specific function for the aircraft that is needed for the fulfillment of the mission. They receive the correspondent power from the distribution systems. The most typical power consuming systems of an aircraft can be listed as: Flight control system (FCS), landing gear (including extension, retraction, steering and braking), environmental control system, ice protection system, avionics and fuel system. Other less impactful systems are for example the water waste or lights. New aircraft concepts might need other systems such as thermal management [2].

C. More-Electric Aircraft (MEA) & All-Electric Aircraft (AEA) Concepts

One objective for the next generation of aircraft is to substitute the main subsystems that are currently non-electrical (e.g. environmental controls or engine start), with new electrical ones. This might potentially have some benefits in several fields, such as less emissions, higher performance, lower maintenance costs and/or higher reliability [12]. The benefits in terms performance have already been assessed in different studies [1, 13]. However further analysis should be carried out in order to fully assess the potential. Figure 1 shows three schematics of three different on-board system architectures. It can be seen how the architecture on the left has the three different power distribution systems previously commented. This kind of architecture is found in the Airbus A320 where some of the systems are fully hydraulic (i.e., FCS and landing gear). The central architecture represents a more-electric concept in which the hydraulic users have been fully electrified. The right architecture shows an all-electric concept in which the pneumatic users receive the air from external electric compressors instead of from an engine bleed, achieving a full electrification of the OBS.

The electrification of the flight controls is used as an application case in this study and it can be seen in figure 1 that this has an impact in the distribution and power generation systems. In this case, it is interesting to comment the different actuator technology. Conventional architectures use classic hydraulic servo actuators (HSA) [14]. These actuators need to be connected to central hydraulic lines to be powered. More-electric concepts include for example the electro-hydrostatic actuators (EHA) or electro-mechanical actuator (EMA). EHAs are still hydraulically powered but have their own smaller and local hydraulic circuit so they do not need a hydraulic system [15]. These actuators are connected to the electrical lines that power the local pumps that move the hydraulic fluid to create the necessary motion, hence are considered as more-electric components. EMAs are fully electrified actuators that create the movement thanks to a local electric motor [16]. It is important to notice that when changes on the users are made, this impacts the distribution and power generation systems as well. Single changes in power consuming systems have an impact on the power distribution and power generation systems, and this must be accounted for.

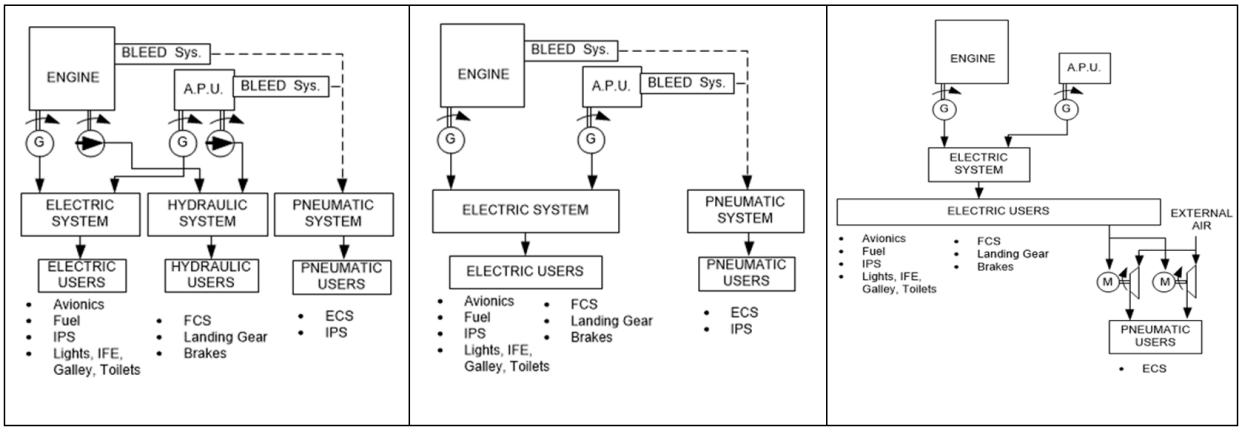


Fig. 1 Example diagrams of on-board system architectures, from [13]. Left: conventional architecture concept. Center: more-electric architecture concept. Right: all-electric architecture concept.

II. State of the Art: On-Board Systems Evaluation

This paper aims at providing a methodology to evaluate many (i.e., thousands, millions or more) on-board systems architectures in three disciplines at the same time. These disciplines are performance, maintenance and certification. The assessment of performance is the more common of all three and usually the first to be carried out to check the feasibility of new concepts. If an architecture does not perform well (e.g., creates more emissions than the conventional one) it does not make sense to further evaluate it. Hence, performance differences among architectures are usually checked during preliminary design phases of on-board systems [10, 11], and numerous tools and methodologies exist in both industry and literature (e.g., [17]). Some studies focus on the advantages of moving towards more-electric concepts on just one or two systems at a time, such as FCS [18] or environmental control system [15].

The challenge comes when new disciplines are added. Certification aspects are difficult to assess during early design stages since the components are not fully sized and located. Their positioning, characteristics and details are yet unknown. Only the architecture is defined. Same issue arises while estimating maintenance cost. Some documents such

as the maintenance planning document (MPD) focus on the scheduled maintenance of the active components. But this document only exists for conventional or existing architectures. If new components or architectures are evaluated, some assumptions are needed and as a result some information might be missed. Unscheduled maintenance is applied to other components but deciding which strategy to apply is a tough task when a detailed list of component parts is not available. Other additional issue is the huge architectural design space that comes when defining the OBS architectures. The vast amount of possible feasible solutions (i.e., thousands, millions or even more) makes it difficult to evaluate and assess all of them. Automation is needed for the generation of architectures and for the evaluation of the three previously discussed disciplines.

Regarding the certification discipline some different analysis should be carried out such as safety analysis, reliability or compliance with the certification specifications. The relevance and need of considering it during early design stages has been highlighted in other studies [10]. The first step for certification evaluation is checking the compliance with the certification specifications, such as the CS25 for instance. Most of the requirements in these documents refer to component specifications (e.g., maximum temperatures or loads), however at early stages of design this information is not available so the objective is to focus on the requirements that have an impact at an architecture level. Authorities establish a minimum reliability threshold for a system which has to be guaranteed through the usage of redundancies. These redundancies and connections significantly impact the final architecture of on-board systems. While certification authorities provide guidelines and requirements for the proper functioning of systems, specifics about connections are not explicitly defined in a dedicated section. Some of these connectivity rules can be inferred from other system requirements or located in appendices. A thorough examination is key to verify compliance with all these conditions. Some RAMS (Reliability, Availability, Maintenance and Safety) methods focused on safety analysis can be found in technical standards such as the like ARP4761 or ARP4754. These provide specific methods to evaluate the safety of the systems. For example, FMECA (Failure Modes, Effects and Criticality Analysis) identifies possible occurring failures for each component. FTA (Fault Tree Analysis) defines the architecture and its mechanisms of failure. FHA (Functional Hazard Assessment) identifies failure modes, severity and risk associated for each system. The results from different analysis converge into a final safety assessment, applied to the whole system [19]. However, these methods are not easy to automate nor to be applied during early design stages. For this reasons they are not considered for this study. The reliability block diagram (RBD) technique however has already been automated [20] and only requires the list of components, their failure rates and how they are connected in order to be used. Moreover, this approach yields quantitative outcomes, specifically in terms of system reliability, enhancing its suitability for integration into an optimization framework. Thus, the RBD seems to be the most promising method to preliminary estimate the reliability of an architecture and to provide some quantitative results in the certification discipline. Other qualitative requirements can also be used to assess the architectures. As a summary, the exploration and utilization of the certification discipline during early design stages is a current gap in literature, and one focus of this study. Other recent studies are approaching this line of research as well [21]. Taking certification aspects into account in the initial design phases can function as a filter, reducing the valid design space and allowing the assessment of only those architectures with valid potential for certification. The architectures that are not preliminary compliant with the minimum reliability established in the certification specifications are hence discarded. Also, no further calculations are required for the architectures that are discarded, leading to a savings in terms of computational time.

Regarding the maintenance discipline the main difficulty comes from the fact that the maintenance strategy for each component is still unknown (i.e., reactive, predictive or preventive maintenance). Some components are removed before failing while others are replaced once the failure has been detected. The maintenance planning document contains the activities that need to be done in order to perform the scheduled maintenance. This maintenance activities ensure that the specific components are repaired or replaced before failing. However, this document does not represent the complete maintenance plan employed by an aircraft operator. It serves as a basis for formulating a maintenance program outlining the specific preventive maintenance tasks for the aircraft along with their scheduled timing [22]. As an example, flight control system actuators are replaced before failing. Depending on the actuator type (e.g., hydraulic or electro-hydrostatic) the time required until the replacement can change, since the failure rates of each type are different. Also, the time to replace the component changes and this has an impact on the maintenance time. For the hydraulic system some components need to be checked during scheduled maintenance activities, and hence are found in the maintenance planning document. The emergency line is required to always work properly and hence must be properly maintained while other components in the main lines (e.g., redundant electric motor pump) might not be safety critical and can be replaced with unscheduled maintenance after failure [22]. This generates problems to properly estimate the maintenance cost of an architecture during early design stages. Some studies aboard this problem by creating regressions to estimate the maintenance cost of different aircraft reaching subsystem level [23]. However these methods

rely on statistics and as a result cannot properly assess new technologies with different components or on-board system architectures. Other studies aim at covering this gap and assess the maintenance cost of new technologies [24], however these methods stay at a concept level creating some quantitative indexes from qualitative opinions. This does not allow the methods to properly reach an architecture level for the on-board systems. A method that allows to properly catch the effect of architectural changes of the on-board systems and assess their impact on maintenance cost is still a gap in literature. As an example, a reference value of 1% reduction in maintenance cost was estimated in [24] when changing the actuators from pure hydraulic (HSA) to electro-hydrostatic (EHA). But this effect comes from the change in maximum take-off mass and fuel consumption, not from the architectural choice itself. Considering both effects can potentially better evaluate the feasibility of new architectures.

Concluding, the objective of this work is to provide a methodology that allows to automatically evaluate on-board systems architectures in terms of performance, certification and maintenance during early design stages. The methodology should cover the biggest gap in literature at the moment, being sensible to architectural (an component) changes in all three disciplines. It should also be automated to be able to solve the problem of having huge design spaces.

III. Methodology & Implementation

The proposed methodology consists of five parts. Figure 2 shows the general scheme in a diagram. The five parts are: modelling and generation of the architectures, filtering through certification aspects, sizing and performance evaluation, maintenance evaluation and optimization within the framework. Each part is now developed into more detail in the following sections.

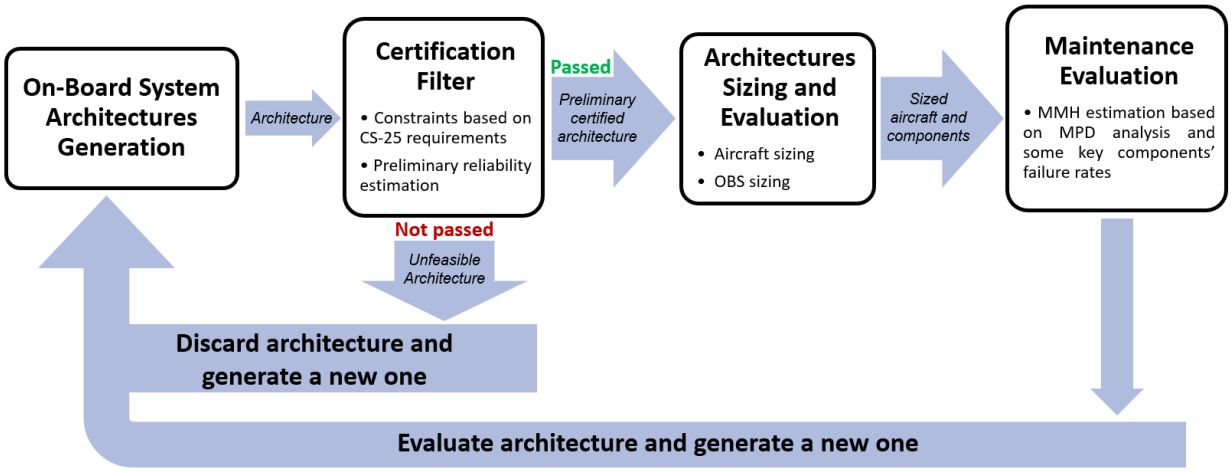


Fig. 2 Methodology schema.

A. On-Board System Architectures Generation (Design Space Modelling)

The initial step involves modelling the design space for the system of interest. The primary aim is to subsequently generate architectures from it. This design space is shaped based on established principles of system architecting, it represents the architectural decisions that are involved in the later optimization problem. The process entails identifying the main function (i.e., top function) that the system must fulfill. Subsequently, various component options are assigned with this function, and new functions are derived and connected to these components, necessitating further derivation of new induced functions. Also, additional information about components, such as the number of instances and attributes, can be assigned. As a result, the design space is created from a functional perspective, leaving no space for biased solutions. For more details on how to model a design space, readers are directed to [7, 9].

This part of the methodology is implemented with ADORE [9], an in-house tool developed at DLR. It enables the graphical modelling of the design space, providing essential support for the design process while establishing a connection between the design space and the optimization problem, as presented in [25]. Following the previous methodology, functions are modeled, and diverse components can be introduced as potential fulfillers of these functions. When a function can be satisfied by two or more components, a decision node is introduced to represent the selection of

architectures. In this manner, the architectural design space takes shape by incorporating decision nodes in specific scenarios. Decisions are automatically identified and directly linked to the architecture decisions within the optimization problem. This approach allows the modeling of complex concepts. From this designed space, all conceivable physical architectures for the system can be derived. Hence, once the design space is created, the generation of architectures becomes an automated process.

B. Certification Filter

This part of the methodology receives an architecture as an input and decides weather or not this architecture is potentially certifiable based on certain certification specifications. CS25 is chosen for this analysis but any other standards can be selected following the same methodology. Three main requirements are extracted from the CS25. These requirements can be assessed at an architecture level and highly impact it [20]. The first one states that the single failure of a single component (i.e., single failure) must never lead to the failure of the whole subsystem (extracted from CS 25.1309(b)(1)(ii)). This implies the necessity for redundancies in components and power lines. This requirement is underscored in subsequent paragraphs though the whole CS25 [20]. The second requirement comes from CS 25.671(d). It says that there must be at least one back-up system to guarantee the correct functioning of the landing gear and flight control system in case of loss of all engines. This leads to the need for the installation of at least one auxiliary power unit (APU), a ram air turbine (RAM), or another power source that is independent of the aircraft's engines. The third requirement comes from a combination of two. CS 25.1309(b)(1)(i) specifies that catastrophic failure conditions (e.g. loss of one subsystem functionality) must be extremely improbable. AMC 25.1309(7.c)(1)(iv)) gives a numeric value to the "extremely improbable" statement, providing an average probability of failure lower than 1×10^{-9} per flight hour. This last requirement needs calculations in order to be verified. The reliability block diagram technique is used since it can be automated an provides a fast evaluation of the reliability of an architecture [20]. The reader is referred to some standards for more information on how to solve a reliability block diagram (RBD) [26]. One issue arises here. The generated on-board system architectures represent physical architectures, but these are not the same as in a reliability block diagram. An automated translation between both is needed. A previous study already handled this problem [27]. It provides a methodology to automatically translate a physical architecture into a RBD configuration. This allows to calculate the probability of failure and compare it with the one given by the normative.

The final result of the certification filter is a check on each of the three requirements: single failure condition, back-up systems and minimum reliability. If just one of the three is not fulfilled the architecture is considered as not preliminary certified and is discarded. This allows to not evaluate the following steps of the methodology when an architecture fails this filter, saving computational time. The third requirement can be fulfilled with a certain margin since it is not a boolean condition. An architecture can be for instance a 10 percent safer than the minimum or a 100 percent safer. This result of probability of failure is kept as a later optimization objective of the certification discipline. The implementation of this part of the methodology is done with a python-based tool (ACOBS - Automated Certification of aircraft On-Board Systems) developed specifically for this analysis that can be easily and automatically connected to the rest of the framework.

C. Architectures Sizing and Evaluation

This part of the methodology focuses on the sizing of the architectures. Each architecture has certain components that carry a certain weight and power requirement. The proper estimation of these parameters is key to identify which architectures perform better (i.e., achieve a fuel consumption reduction). Once the systems have been sized they must be installed on the aircraft. For this, an aircraft baseline must be selected. The effect that a certain architecture has can be different from one aircraft to another. Furthermore, the increase in mass and power that a system has can represent a higher increase when installed. This comes from the fact that when the system is heavier, more fuel and structural elements are also needed. This is known as the snowball effect and it is important to include it in the analysis and not stop the analysis at a system level [13]. Also, if the required power increases, this will require higher engine off-takes and the fuel consumption is penalized. Consequently, reaching aircraft level is required and finishing the analysis at a subsystem level can lead to non-accurate and non-representative conclusions. Some studies asserted this error and reported approximately and deviation of a 40% error in the results when these mass and power off-takes effects where not considered [13].

Different tools are used for the implementation. ASTRID [17], a tool for on-board systems sizing developed at Politecnico di Torino is used for the evaluation of the architectures. However, one issue arises. The application case is focused on flight controls. The huge amount of architectures that are generated from the design space generates

non-conventional configurations that cannot be easily linked with ASTRID's input. For this reason, a dedicated code needs to be developed to handle these architectures. In this case, a specific python code is developed in order to fully assess the flight control system impact following the methodology proposed in [18]. This way, the flight controls are fully assessed by this tool while the rest of the on-board systems are calculated by ASTRID. Once the on-board systems are sized they can be installed in a specific aircraft. The overall aircraft design is performed with OpenAD [28], another DLR in-house tool. It allows to estimate key parameters of the aircraft such as fuel consumption or maximum take-off mass, among much others. The running order of the tools is as it follows. First, OpenAD to generate a baseline and obtain the necessary parameters for the next tool (i.e., initial estimation of the masses, wing size and tail size). Secondly, the dedicated FCS tool which provides precise values on the masses and power required by this system. Thirdly, ASTRID that calculates the results of the rest of the OBS. It can be run in parallel with the previous tool. Lastly, another run with OpenAD is needed in order to consider the previously mentioned snowball effect. This toolchain can be run several times until convergence in mass is achieved. However depending on the specific application case the workflow can be simplified in order to reduce computational times, an example of this can be found in [29]. This is also shown in section IV with the correspondent example.

D. Maintenance Evaluation

The maintenance evaluation can be performed once the architecture is defined and sized. Some other top level aircraft requirements are also needed, such as the fleet size, daily utilization of the aircraft, thrust or cabin length. Previous maintenance models do not reach component level [23], however they can be enhanced to do so. The main issue is how to properly estimate the different parts of the maintenance cost (i.e., direct and indirect, scheduled and unscheduled). Some documents such as the MPD focus on the scheduled maintenance of the active components. Unscheduled maintenance is applied to other components but deciding which strategy to apply is a tough task when a detailed list of component parts is not available. This differentiation is even more difficult considering that each company creates their own final maintenance planning depending on their policies. A model covering all the different parts of the maintenance cost becomes untenable at this level, hence this analysis focuses on estimating the maintenance man hours (MMH) of the different OBS architectures. More specifically it aims at calculating the difference in MMH with respect to a reference conventional architecture. The methodology used is the one presented in [30]. This study provides quantitative equations to estimate the MMH of different OBS for a reference aircraft. These equations can be used for each of the subsystems separately, giving flexibility and allowing to isolate the different effects of each of them. In order to obtain these equations two methods are mixed: MPD analysis and expert interviews. The MPD analysis consists of going through all the scheduled tasks in the document and remove or modify the ones that change when a new OBS architecture is installed. This reaches component level and task level, providing very detailed results. The A320 is used for this analysis as a baseline. If a different OBS architecture is selected some tasks disappear and others are substituted by new ones. If they disappear, the MMH corresponding to that task are not present anymore and can simply be removed. If the task changes, the MMH are updated with a proportion equal to the failure rate ratio between the new component and the one removed [22]. These failure rates can be approximated by a constant value, as suggested in [31]. This provides a new estimation of MMH of the new task by knowing only the ratio between the new and old component. The sum of all the MMH from the different tasks through all the different maintenance checks (i.e., A-checks and C-checks) within their correspondent intervals provides a total amount of hours that can be compared to the reference one, hence obtaining the final change in MMH. These results are mixed with the ones obtained during the expert interviews, providing more realistic and mitigated results. Several architectures were analyzed and a surrogate model is created per each of the systems. For more details the reader is referred to [30]. Some small adjustments to the model are needed since the architectures generated in this analysis need a higher level of sensitivity than the one provided by this method. These adjustments are covered directly in section IV when the application case is presented.

E. Optimization Loop & Whole Workflow

The last step is to connect the results with the design variables through optimization algorithms. Three optimization objectives are selected, one per discipline. Regarding the certification discipline, the probability of failure of the architecture is chosen. The value is normalized by a reference one, for this application case the A320 is chosen. This idea is further explained with an example in the application case section. Furthermore, three design constraints are added and allow to perform as the certification filter. These constraints are the three previously commented requirements: single failure, back-up systems and minimum reliability. If one of these is not met, the following parts of the methodology are skipped and the architecture is directly discarded. Concerning the performance discipline, the aircraft maximum

take-off mass is taken as the main metric. It allows to properly measure how good or bad an architecture performs. For the maintenance discipline, as discussed before, the reduction in maintenance man hours is selected.

ADORE [9] is used for the optimization process. It automatically reads the optimization objectives and creates the new design vector containing the next architecture to be evaluated. Genetic algorithms are used owing to the nature of the problem with discrete design variables. ADORE contains libraries with different optimization algorithms that can be used, the exact ones are shown and explained in the application case section.

The whole workflow is shown in figure 3. The diagram is an extended design structure matrix (XDSM) and it has been created with MDAx [32], a DLR in-house tool used to automatically create multi-disciplinary design optimization workflows. Blocks represent the different tools. Inputs are contained in the vertical lines, outputs in the horizontal ones. A step by step guide is now commented to support the understanding of the diagram. The initial block is the optimizer, this generates the design variables that are automatically transformed into an architecture by ADORE. Then the whole toolchain is run and the three optimization objectives (MMH - maintenance man hours, MTOM and PF - probability of failure) and constraints are given back to the optimizer, which starts the next iteration with new design variables. The following block is the overall aircraft design initialization, this block is run only once to generate the correspondent aircraft baseline and does not need to be re-run on each iteration. The certification filter is run for every optimizer iteration and decides if the associated architecture is potentially certifiable or not. If not, constraints are activated and the rest of the workflow is skipped. This saves computational time. The rest of the tools are hence run only if the constraints are fulfilled. The next block is a converger that evaluates the performance discipline. Inside of it three tools are found. First, the flight control system is evaluated. Then the rest of OBS are sized. Lastly, the aircraft baseline is updated with the values provided by the two tools and another run of the overall aircraft design tool is performed. This provides a new value of the aircraft MTOM, which can be compared with the initially estimated one, giving feedback to the convergence loop. This exact loop has already been utilized in previous studies [15]. This three-tools toolchain is run until convergence in MTOM is reached. Finally, the maintenance discipline is evaluated by the dedicated tool

IV. Application Case: Airbus A320neo roll control

The roll control of the Airbus A320neo flight control system is chosen as a system of interest. Some of the most relevant parameters used as input data for this aircraft are shown in table 1. These initial parameters are needed for the initialization of the tools.

Table 1 A320neo input data and assumptions

Parameter	Units	Value	Parameter	Units	Value
Maximum Take-off Mass	kg	78981	Fleet size	-	890
Engine model	-	PW1133	Utilization	Flight hours per year	2800
Static thrust (ISA)	kN	147.3	Seats	-	180
Fuselage length	m	37.57	Flight hours per flight cycle	-	2.59
Wing area	m^2	124.78	Design range	nm	2935

The A320 architecture is used as a reference and is shown in figure 4. It contains five spoilers per wing from which four are used in flight for roll control. Each spoiler is actuated by a hydraulic actuator connected to one hydraulic line from the three existing ones (green, yellow and blue). The connection to the lines is symmetrical, which means that both right and left spoilers are connected to the same line. If one spoiler actuator fails (e.g. spoiler four right) the associated pair is not used (i.e. spoiler four left) in order to guarantee the symmetry of the roll. It can be noticed how the users (actuators) require certain distribution systems (hydraulic system). A full conversion of the spoilers into a more electric concept using EHAs would remove the need of a hydraulic system, at least for the spoilers. In that case the actuators would be connected to electrical lines to receive the required power. The same logic applies to the ailerons, however these surfaces have two actuators in redundancy connected to them. One actuator is active while the other stays in stand-by mode [31]. When the active one fails the redundant one takes over.

Regarding the distribution systems, both the hydraulic and the electrical can be connected to the spoiler and aileron actuators depending on the actuator type. The A320 power distribution system schemes are shown in figure 5. Figure 5a represents the hydraulic system and three lines are present. The green line is powered by an engine pump connected to one engine. The yellow line is also connected to an engine pump, but this time connected to the other engine.

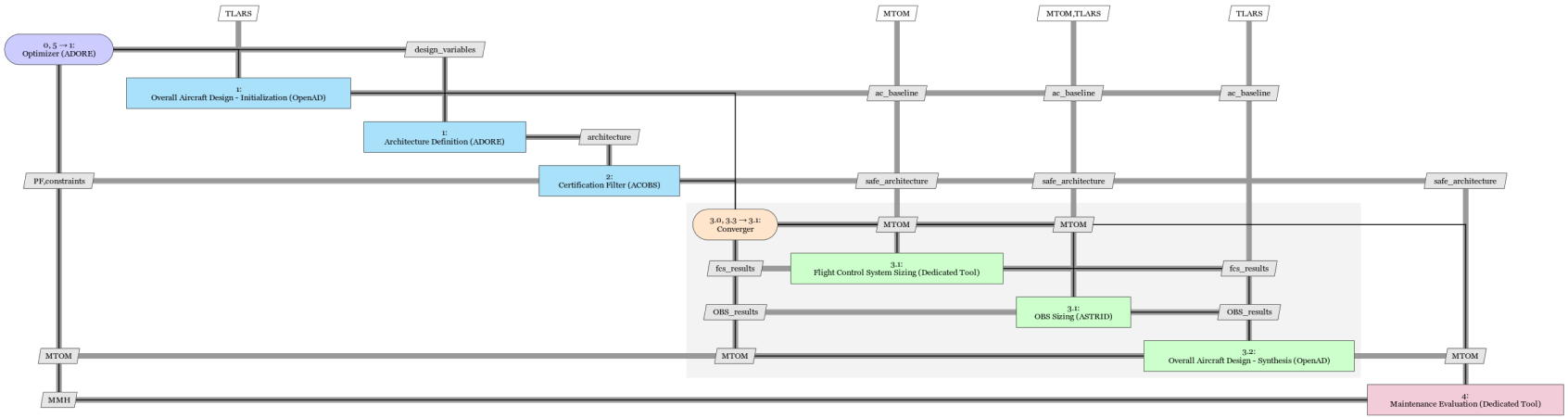


Fig. 3 Extended Design Structure Matrix of the whole workflow.

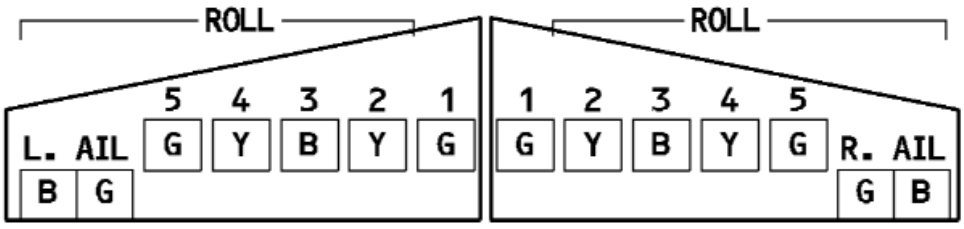
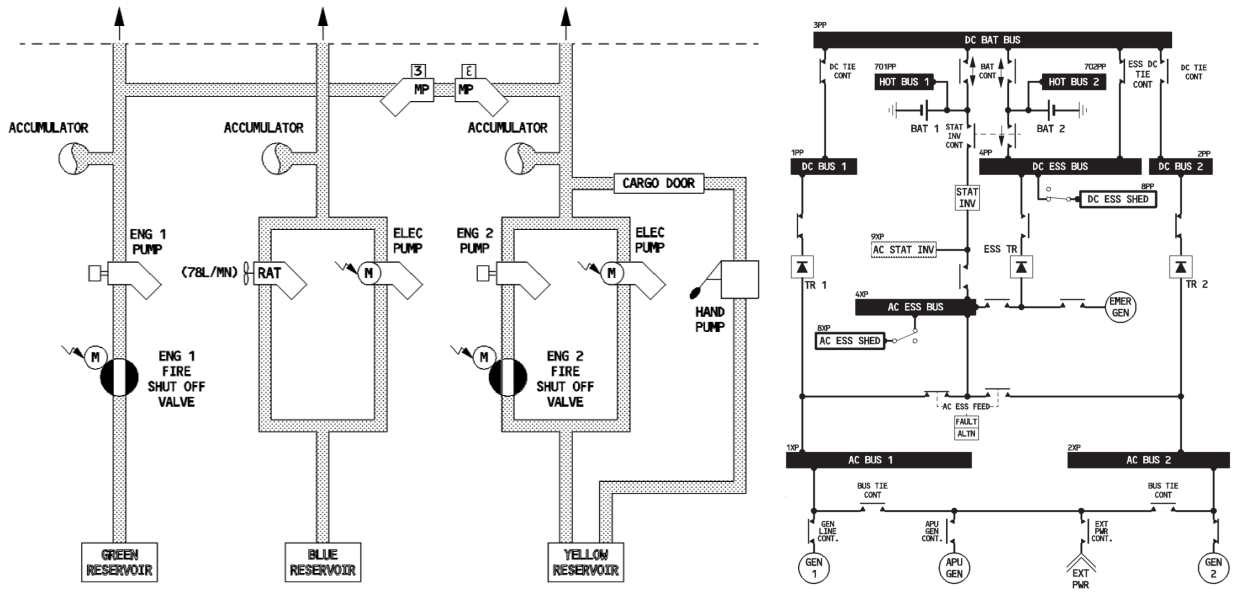


Fig. 4 A320 ailerons and flight spoilers schema, from [33]. Used as a reference architecture.

This line also has an extra redundancy since power can come from a electric pump. Both green and yellow lines are linked through a power transfer unit that allows one line to provide power to the other one. Lastly, the blue line also has a double redundancy. Power can come from an electric pump or from the ram air turbine. Figure 5b represents the electrical system of the A320. Two main lines and one essential are seen. The main ones are connected to the engines and auxiliary power unit. They provide alternate current and can be transformed into direct current through transformer-rectifiers. Both can also provide power to the essential line if needed. The essential line can also be powered by an emergency generator connected to the ram air turbine. If needed, the batteries can give power to this line for a certain period of time through the DC essential bus and another transformer-rectifier. It can be noticed how the redundancies ensure a correct and safe functioning of the systems. If the actuators change, this has an impact on the power distribution systems architecture and safety must still be ensured.



(a) Hydraulic system schema **(b) Electrical system schema**

Fig. 5 A320 distribution systems schema, from [33]. Used as a reference architecture.

A. Design Space Model

The first step is to model the design space with all the possible architectures for the system. The ailerons and flight spoilers system is modelled with ADORE. Figures 6 and 7 show the whole compact design space split into three parts for visualisation and clarity purposes. The three models are however connected and represent a single united model. Figure 6 shows the flight control system part. The top function is defined following the system architecting principles, being "control roll". Then the user can decide among having three to five flight spoilers (note that the ground spoiler is out of the decisions but it is always present). There is always one aileron pair with two actuators each. This decisions is generic for any aircraft and the exact number can be fixed for later runs, but this application case is focused on the A320.

The decision of how to move each spoiler comes from the selected actuator type. Two options are possible, classic hydraulic servo actuator (HSA) or electro-hydrostatic actuator (EHA). The HSA requires a function to work, "provide hydraulic power to spoiler" and connects the actuator with the hydraulic system. The EHA needs the function "provide electric power to spoiler" and connects the actuator with the electrical system. It can be noticed how the decisions here are hierarchical. This means that if for instance all actuators are EHAs, then the hydraulic system is not needed at all and the decisions linked to the hydraulic system are not meaningful. This design space is modelled from a functional reliability approach. Meaning that some components are forced to be connected directly in order to function.

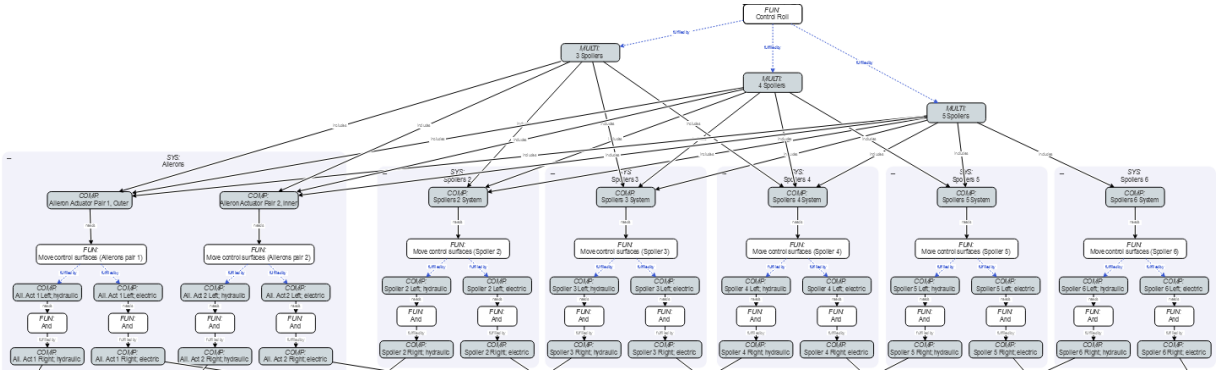


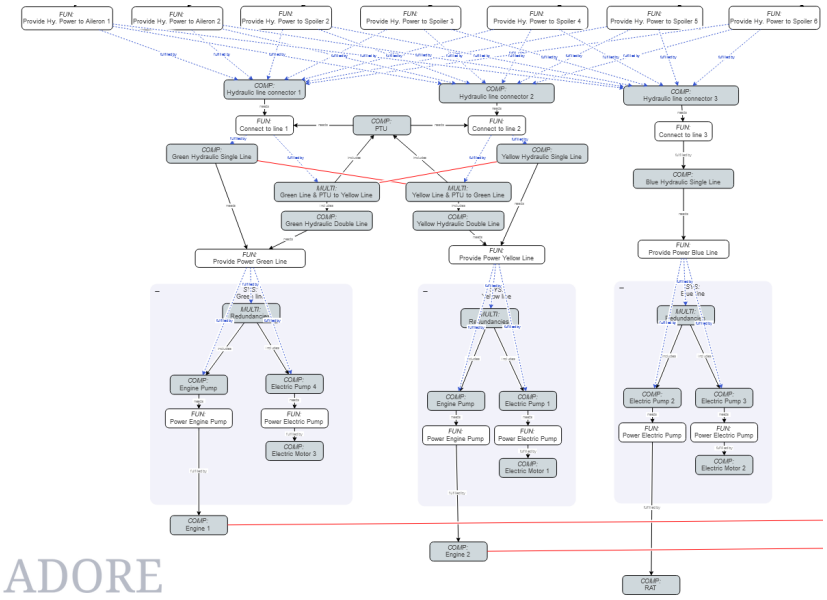
Fig. 6 Design space modelled with ADORE, zoom in the flight control system.

Figure 7a shows the modelling of the hydraulic system. Here a maximum of three hydraulic lines are allowed. Two of the lines can be connected through a power transfer unit (PTU) and can be powered by an engine pump, an electric pump driven by an electric motor, or both. The other line represents a classic emergency line and can be connected to an electric motor or the ram air turbine (RAT). Figure 7b represents the electrical system. Three main lines are also imposed. Two main ones and a emergency one connected to the ram air turbine or a generator linked to an external motor (hydraulic or pneumatic). Both main lines can be powered by one of the engines and/or the auxiliary power unit (APU) and can have one or two generators per engine. The presence of the PTU and APU create non-conventional reliability block diagrams that were solved in previous studies [20, 27]. Automation is guaranteed.

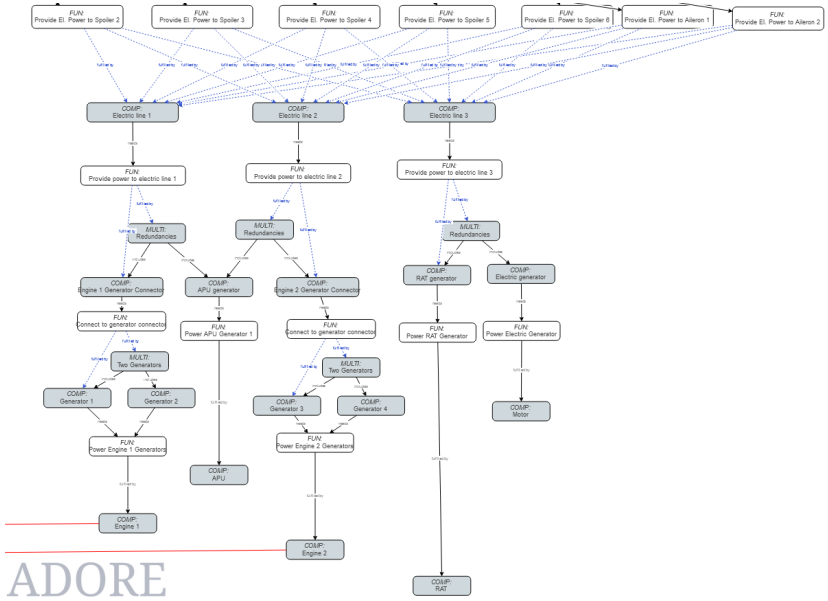
With this design space the total amount of decisions reaches 32. The total amount of possible architectures goes beyond 6 billions (the exact number is 6 347 497 291 776). Assuming and average evaluation time per architecture of 1 minute, it would take more than 12 million years to evaluate all of them. This shows the origin of the problem. Optimization is needed in order to find the best architectures without evaluating all of them. Furthermore, the certification filter provides an extra layer of computational savings allowing to discard architectures without needing to evaluate them, and hence reducing the average run time per architecture. ADORE allows to visually check the results and check which architectures did not passed the certification filter if one or more of the constraints were not satisfied. Each of the constraints can be individually controlled. The number of non-passed architectures always highly overcame the number of passed ones in all runs. There is one last input required, the estimated failure rate for each component. These were obtained from the Quanterion Automated Databook, more specifically from the NPRD-2016 publication and are shown in table 2.

B. Workflow Adjustments

The whole framework can be executed after the design space has been modelled. The general version of the workflow has already been shown in figure 3, however some simplifications can be made for this specific application case. This reduces computational time and helps with convergence. A relevant simplification can be done to ASTRID, keeping it outside of the convergence loop. This can only be achieved if the aircraft is fixed. In this case the A320 is selected, this allows to carry out some preliminary work to create baselines for different OBS architectures. The only system that is sensitive to the design variables is the FCS. This system already has a dedicated tool which results are sensitive to such design variables. This allows to substitute the rest of the OBS by previously run results on every iteration. This does not mean that ASTRID is not run. It is run outside of the loop to generate several baselines that can be later used inside of the loop. However, this adjustment allows to highly reduce the computational time since one tool is substituted by just a file containing different results. ASTRID run time can vary from some seconds to some minutes depending on the



(a) Design space modelled with ADORE, zoom in the hydraulic system.



(b) Design space modelled with ADORE, zoom in the electrical system.

Fig. 7 Design space modelled with ADORE, zoom in the distribution systems.

Table 2 Failure rates values taken from: Quanterion Automated Databook (NPRD-2016)

Component name (in ADORE; from database)	Failure rates (per hour)	Quality	Environment
Spoiler Actuator (H); Actuator Hydraulic Linear	9.51×10^{-5}	Commercial	Airborne Uninhabited Cargo
Spoiler Actuator (E); Actuator Electric Linear	5.89×10^{-5}	Commercial	Airborne Uninhabited Cargo
Power Transfer Unit; Two series: Pump Hydraulic	8.52×10^{-5}	Commercial	Airborne Uninhabited Transport
Engine Pump; Pump Hydraulic, Engine Driven	2.19×10^{-6}	Military	Airborne Cargo
Electric Motor Pump; Pump Hydraulic, Motor Driven	1.70×10^{-5}	Military	Airborne Uninhabited Fighter
Engine; Engine, Turbofan	7.74×10^{-6}	Military	Airborne Uninhabited Attack
Electric Motor; Motor AC	2.39×10^{-6}	Military	Airborne Cargo
Ram Air Turbine; Turbine Unit Assembly	3.49×10^{-7}	Military	Airborne Cargo
Generators; Generator AC	3.30×10^{-6}	Military	Airborne Attack
Auxiliary Power Unit; Power Unit, Aircraft	5.47×10^{-6}	Military	Airborne Uninhabited Cargo

architecture that is being evaluated, the computational time savings are not negligible. The question that arises now relies on the number of OBS baselines that are needed, and on how to decide which one to choose on each iteration. Three baselines are generated. One for conventional architectures, used if all the actuators are conventional HSA. One for the all-electric architectures, in which all actuators are electrified. One for more-electric architectures in which actuators from both typologies are selected. A description of the three OBS baselines is now provided.

The conventional OBS architecture is based on the A320. It uses HSAs for all the flight control surfaces and ball-screw actuators connected to a hydraulic central power drive unit for the high lift devices. The environmental control system is conventional based on bleeding as well as the ice protection system. The landing gear uses hydraulic actuators for all its functions. A central hydraulic system with three lines is present, two of them connected through a power transfer unit and an emergency line powered by a ram air turbine. The electrical system generates and distributes electric power from two integrated drive generators connected to the engines and a conventional pneumatic system is also present. The all-electric architecture represents a case in which all the systems are fully electrified. Flight controls are powered by EHAs and high-lift devices by electric power drive units. The environmental controls are based on bleed-less technologies, using two external compressors to compress the air before conditioning it in the packs. Wing ice protection utilizes thermal blankets while nacelles contain anti-ice valves connected directly to the engine flow. The landing gear uses electric actuators for all its functions. Engines start is performed by starter-generators. Hydraulic and pneumatic systems disappears since are not needed anymore. The electrical system remains as the only power distribution system with several lines connected to the generators and the ram air turbine. Lastly, the more-electric baseline is a middle point between the two previous ones and is based on the A350 architecture. Flight controls are mixed, having HSAs and EHAs at the same time. High lift devices, environmental controls, ice protection and landing gear are the same as in the conventional case. The hydraulic system now only has two lines and the electrical system is now connected to variable frequency generators and needs to power more users than in the conventional case. The results for the three architectures are shown in table 3. The main effect of changing the architecture affects mainly the flight controls and distribution systems, as expected. Flight controls mass increases with the usage of electric actuators, since these are heavier. However the removal and/or reduction of the pneumatic and hydraulic systems compensates this effect. The electrical system is lighter for the all-electric case since it integrates a new technology that generates power at 230 Volts in alternate current. Increasing the current manages to reduce the size of some components (e.g., rectifiers, power distribution units, transformers, cables...) and consequently the overall mass of the system is slightly reduced even if the power budget is higher with respect to the conventional architecture.

However, these are just the baselines for the OBS architectures. Some further modifications are needed to make the model sensitive to all the design variables. Some non-conventional architectures can be generated from the design space. For example, a more-electric architecture with three hydraulic lines, an electric ram air turbine and no power transfer unit is possible, at least in terms of design variables. These architectures need to be assessed as well. For that some small adjustments are made after the OBS baseline is selected. It should be noted that they affect only the hydraulic and electrical systems, since those are the systems impacted by the architectural decisions. Regarding the hydraulic system, some key components must be analyzed. The first one is the power transfer unit. It should be possible to assess the difference in terms of mass between one architecture with it and one without it. The certification filter decides if the architecture is actually feasible or not, but the models needs to be able to evaluate such architecture. The same effect happens with the possibility to have, or not have, engine driven pumps and pumps driven by electric motors. For the

Table 3 ASTRID results for the three OBS baseline architectures.

	Conventional [kg]	More-Electric [kg]	All-Electric [kg]
Avionics	781	781	781
Flight Control System*	846	908	1008
Ice Protection System	73	73	105
Environmental Control System	480	480	589
Fuel System	344	344	344
Landing Gear	2176	2176	2320
Fire Protection	95	95	95
Lights	341	341	341
Oxygen	112	112	112
Water Waste	302	302	302
APU	138	138	122
Pneumatic System	169	169	0
Hydraulic System	1022	649	0
Electrical System	1443	1539	1395
Total	**8322**	**8107**	**7513**

* Calculated with the dedicated FCS tool, not with ASTRID

electrical system the same issue appears. The number of generators becomes a design variable, as well as the possibility to have an extra redundancy in the emergency line. This redundancy is achieved thanks to a generator connected to a motor. This motor can be hydraulic or pneumatic, the specific case is not relevant to this application case since they cannot be differentiated in terms of mass or failure rates at this level. However, these decisions must have an impact in terms of performance. The reference architecture values for the OBS baselines are represented in table 3 and on top of these values some additions or subtractions are done depending on the extra components that are found on the architecture. These values should not be taken as precise, but serve more as an initial estimation to provide sensitivity for the model to the design variables. The estimations for this application case (i.e., A320) are as follow:

- Estimated extra mass for a power transfer unit: 37.07 kg
- Estimated extra mass for a extra engine driven pump: 23.18 kg
- Estimated extra mass for a extra electric motor pump: 13.06 kg
- Estimated extra mass for a extra conventional engine generator: 60.53 kg + 12% more for the generator control unit
- Estimated extra mass for a extra all-electric engine generator: 67.28 kg + 12% more for the generator control unit
- Estimated extra mass for a extra motor in the electrical emergency line: 23.18 kg

The same effect happens in the maintenance domain. The method explained in section III.D is able to estimate most of the architectures but it is not sensible to all the design variables. The same adjustment as for the masses is done. The baseline OBS architecture is evaluated obtaining the reference value of MMH reduction, and some additions or subtractions are added depending on the design variables. These calculations are obtained by checking the correspondent tasks in the A320 MPD and calculating the total amount of hours through all the maintenance checks. The values can then be directly summed to the total MMH result and are shown here:

- Estimated extra MMH for an extra HSA spoiler: 2.42 h
- Estimated extra MMH for an extra EHA spoiler: 1.5 h
- Estimated extra MMH for an extra integrated drive generator: 25.625 h
- Estimated extra MMH for an extra variable frequency generator: 24.09 h
- Estimated extra MMH for an extra redundancy in the electrical emergency line: 31.62 h

C. Design of Experiments

A design of experiments with some relevant and interesting architectures has been performed in order to obtain some preliminary conclusions. The whole workflow is executed for eleven architectures that are manually generated with the ADORE user interface. The execution is done in python, running all the tools as explained before in section III.E. The evaluated architectures are:

1) A320-baseline: this is merely the A320 architecture without any changes. Three hydraulic lines are present, conventional flight controls and same electrical system.

2) AEA: this is the all-electric version of the A320 but without changing the electrical system. No extra generators or lines are added. The actuators of the FCS change to EHAs and are direcly connected to the existing electrical lines.
3) MEA-1: a more-electric architecture in which the HSAs that were connected to the blue hydraulic line are now transformed into EHAs and are connected to an electrical line. As a result only two hydraulic lines are needed, and they are connected with a power transfer unit. The electrical system changes to a MEA one. This architecture is similar to the one of the A350.
4) MEA-2: a more-electric architecture in which two spoilers are electrified. There are still three hydraulic lines but the power transfer unit is not needed. The electrical system is the one from the MEA baseline. This architecture is similar to the one of the B787.
5) AEA-enhanced: this all-electric architecture increases the redundancies in the electrical system with respect to the one in the A320. There are now two generators per engine and the extra redundancy in the emergency electrical line is present.
6) AEA-gens: this is the same architecture as "AEA-enhanced" but without the extra redundancy in the emergency electrical line.
7) AEA-line: this is the same architecture as "AEA-enhanced" but with only two generators per engine.
8) A320-3spoilers: this is a hypothetical case in which the A320 has only three flight spoilers, instead of four. Spoiler 2 disappears as it is.
9) A320-5spoilers: this is a hypothetical case in which the A320 has five flight spoilers, instead of four. A new spoiler appears and it is connected to the blue line.
10) AEA-3spoilers: this is a hypothetical case in which the "AEA" architecture has only three flight spoilers, instead of four. Spoiler 2 disappears as it is.
11) AEA-5spoilers: this is a hypothetical case in which the "AEA" architecture has five flight spoilers, instead of four. A new spoiler appears and it is connected to one of the main electrical lines.

Table 4 shows the relevant results for all eleven architectures. The probability of failure is calculated as the one from the correspondent architecture divided by the reference one (i.e., the one from the A320). For instance, architecture two fails 39 times more often than architecture one. Values between zero and one is the area of interest. The three constraints are also displayed in the table, their values can only be zero or one. The architectures with at least one zero in the constraints are filtered by the certification block and would not have been evaluated in the optimization problem. However they have been evaluated now for the design of experiments since it is interesting to know the results in the other disciplines. The MMH are represented as the hours reduced from the reference architecture.

Table 4 Results for the eleven manually generated architectures of the design of experiments

Architecture & Name	FCS mass [kg]	Hydraulic system mass [kg]	Electrical system mass [kg]	MTOM [kg]	Fuel burn [kg]	Probability of failure [-]	Back Up [-]	Single failure condition [-]	Minimum reliability [-]	MMH [hours reduced]
1) A320-baseline	846	1022	1443	78967	19080	1	1	1	1	0
2) AEA	1008	0	1395	77511	18529	39	1	1	0	1502
3) MEA-1	908	663	1539	78656	18935	0.6	1	1	1	335
4) MEA-2	897	952	1539	79085	19134	91	1	1	0	245
5) AEA-enhanced	1008	0	1636	77883	18700	0.085	1	1	1	1422
6) AEA-gens	1008	0	1546	77744	18636	22	1	1	0	1454
7) AEA-line	1008	0	1485	77651	18593	0.15	1	1	1	1471
8) A320-3spoilers	827	1022	1443	78938	19066	2171	1	1	0	5
9) A320-5spoilers	866	1022	1443	78997	19094	0.008	1	1	1	-5
10) AEA-3spoilers	977	0	1636	77836	18678	193	1	1	0	1425
11) AEA-5spoilers	1039	0	1395	77559	18551	33	1	1	0	1499

It is noticeable how there are three main regions for the FCS mass, depending on the architecture selection. The conventional one is the lightest since HSAs are lighter than EHAs, while the AEA is the heaviest. The MEA architectures stay in a middle region. There is a small increase or reduction when a spoiler is added or removed. The hydraulic system mass is zero for all the AEA architectures. For the MEA ones it depends mainly on the number of hydraulic lines that was specified and the extra components. The electrical system has an interesting effect, its lower weight is found for architecture 2 but its higher mass corresponds to the AEA architecture 5. This is caused by the addition of generators and extra emergency lines. Even if the system is lighter for ther AEA version, when it needs to be enhanced for safety issues it becomes heavier as a result. The MTOM varies accordingly to the total systems mass and power and

bleed penalties calculated by ASTRID. Initially two design objectives were proposed for the performance discipline: MTOM and fuel burn. However, after this design of experiments, it can be seen how both variables are almost linearly dependant, so only the MTOM is left as an objective. Constraints were already commented, all of them need to be active (i.e., equal to one) so that the certification filter approves the architecture. It can be seen how only five of the eleven architectures are feasible in terms of certification.

The probability of failure results already show some interesting conclusions. Architecture 2 does not meet the minimum reliability conditions. This means that just changing the actuators type to EHAs and connecting them to the already existing electrical lines is not enough and safety can be compromised. This can be extrapolated to other FCS functions or other systems, a check in the probability of failure is needed when moving to a more-electric or all-electric concept. In this case, two possibilities are explored in order to raise the reliability levels. One is architecture 6, in which the number of generators has been doubled. This solution increases the reliability, but still does not reach the minimum required. The other solution is architecture 7, in which an extra redundancy is added in the emergency line through the use of a hydraulic or pneumatic motor connected to a generator. This extra redundancy hugely increases the reliability and leaves this architecture as a feasible one. Architecture 5 combines the two previous solutions but the extra benefits when compared with architecture 7 are not meaningful. This result does not come as a surprise, the hydraulic system of the A320 has two main lines, connected with a power transfer unit and a emergency line connected to two power sources. When changing to the electrical system two main lines are also present, and connected to the auxiliary power unit. But the emergency line has only one power source. This is just the case for the FCS since batteries are also connected to this emergency line but cannot be used in this context. The result is that if the FCS is electrified, a new redundancy in the emergency line of the electrical system must be added.

The results in terms of MMH are quite straightforward, AEA architectures have the biggest potential in terms of MMH reduction. This effect comes from the removal of the hydraulic and pneumatic systems. MEA architectures manage to reduce only around a quarter of what the AEA achieves. Depending on the exact architecture the values vary around certain areas, as seen when comparing architectures 5, 6 and 7. However, these changes are small when compared to the difference with a conventional architecture. To put numbers into perspective, the total number of MMH for the A320 can be estimated with data from aircraft commerce, as suggested in [30]. Here a sum among A-checks and C-checks estimates the total amount of planned MMH of 166750 hours, obtaining a reduction of less than 1% of the total MMH when switching to an AEA architecture for the OBS. This number might seem low but it is not negligible.

Some preliminary conclusions can already be stated. MEA architectures are generally heavier than AEA but can be more reliable since two distribution systems can be mixed. If both are enhanced the probability of failure improves massively, but also the weight and the MMH penalty. They still have better results in terms of MMH reduction than the conventional architecture. AEA architectures achieve lower MTOMs and MMH reductions, but certification can be an issue. Removing the hydraulic system adds the necessity of enhancing the electrical lines with more redundancies to reach the minimum reliability required by the CS-25. Adding or removing spoilers does not really have a good impact since it seems that improving the distribution lines has a bigger impact in the probability of failure. The implementation of these design of experiments with ADORE is shown in figure 8. Here the software provides instant feedback on each of the architectures telling the user which ones meet the constraints, and what are the results for the optimization objectives. Clicking on one also allows to properly explore the architecture ensuring traceability.

D. Optimization

An optimization process can now be started. The design variables are the architectural choices (or architectural decisions). As optimization objectives three metrics are selected: maximum take-off mass, maintenance man hour reduction and probability of failure of the architecture. The MTOM is calculated in kilograms. The MMH reduction is estimated in hours. The probability of failure is divided by the reference one, as done in the previous design of experiments, resulting in a non-dimensional variable. The parameters selected as constraints are again the minimum reliability requirement, single failure condition and back-up power source requisite.

ADORE allows to connect this optimization framework to different optimization algorithms [34]. Genetic algorithms are recommended for this analysis due to the nature of the design variables. Most of them are discrete, non-continuous and even hierarchical. This limits the feasibility of gradient based optimization methods. The specific algorithm that was used for this analysis is the genetic algorithm NSGA-II [35]. The results from the optimization process are shown in figure 9. Here, the reader can find the different 2-dimensional projections of the 3-dimensional Pareto front that comes from having 3 optimization objectives. The different trends and trade-offs that are observed in the Pareto fronts are commented in the next paragraph. For this specific study the NSGA-II algorithm was launched with 20 generations

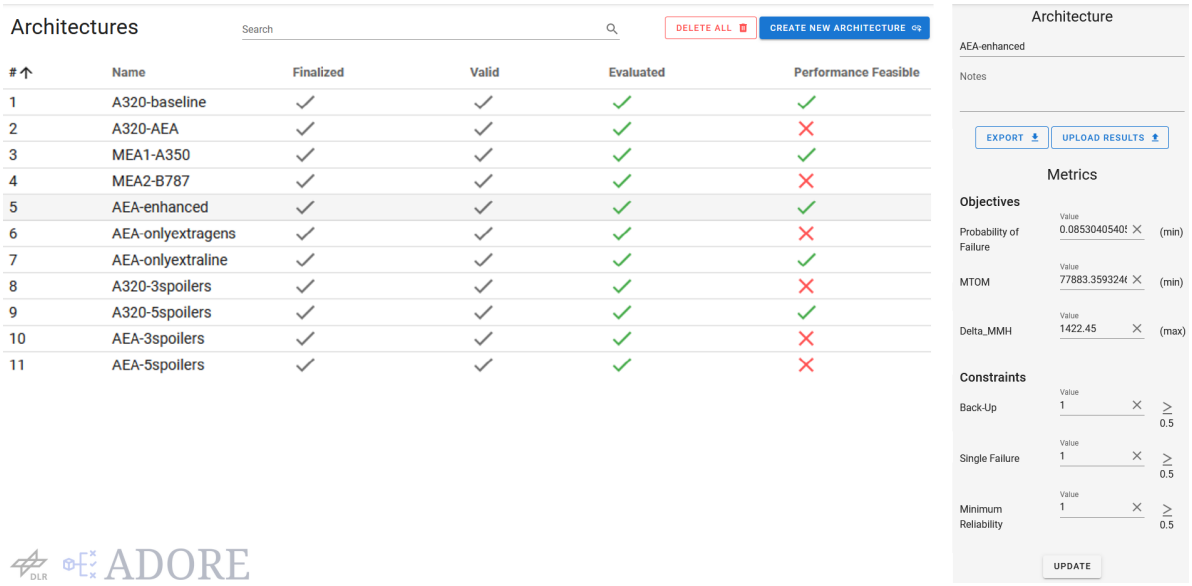
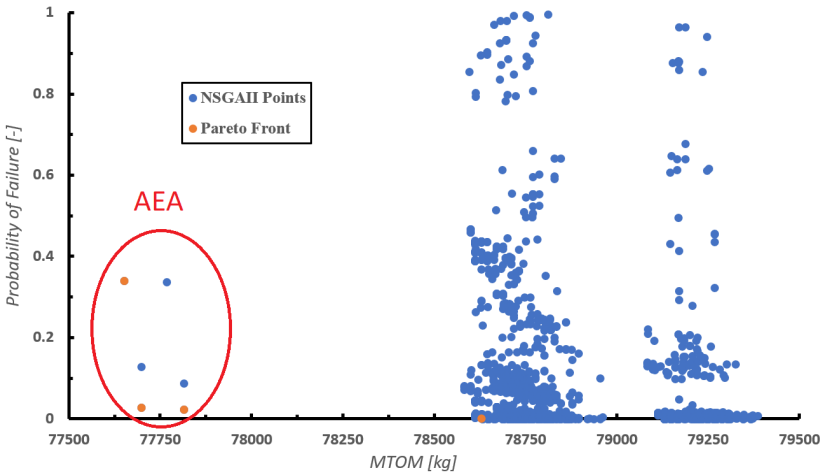


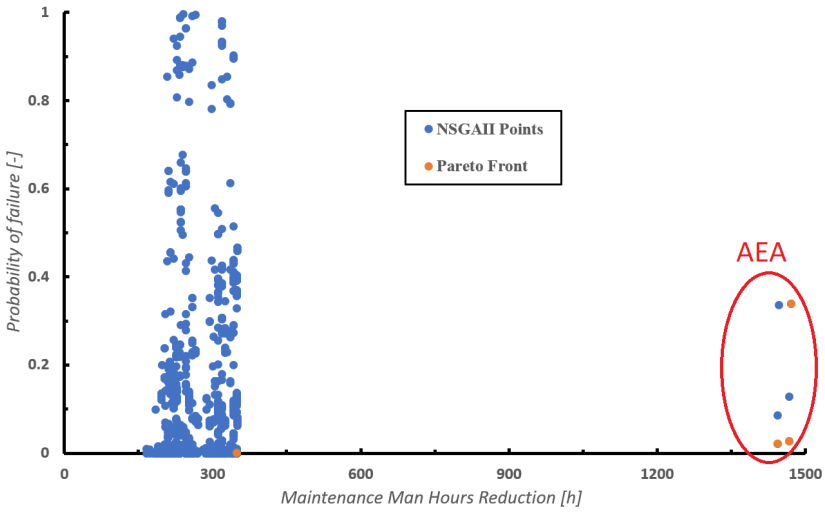
Fig. 8 Example of filtered architectures with ADORE [9] after the design of experiments run.

and a population size of 320 each, obtaining a total of 6400 points. An interesting result is that only four of these points are identified as part of the Pareto front, as represented in the figures. This specific run took a computational time of approximately three days, but more than fifty percent of the architectures were discarded by the certification filter. Without this filter, all those architectures would have been evaluated in terms of performance and maintenance, highly increasing the computational time. As a reference, the certification filter takes less than a second to evaluate the architecture, while the performance loop takes on average more than a minute.

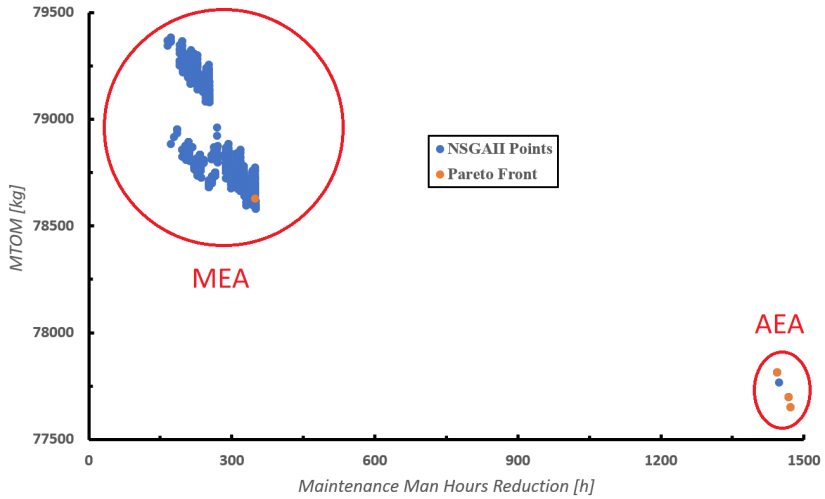
Figure 9a shows a 2-dimensional projection of the 3-dimensional Pareto front that comes from the optimization process. The two objectives here represented are the MTOM and the probability of failure. Two very separated regions can be found. All the architectures that are lighter than 78000 kg correspond to the all-electric architectures that successfully passed the certification filter. Only six are found, this comes from the effect that was seen in table 4. AEA need extra redundancies and cannot simply be certified without adding extra lines. From the six points, three of them lie on the Pareto front, these architectures are explained later. All the architectures that are heavier than 78500 kg correspond to conventional and more-electric ones. It is interesting to see the verticalily of the results, this means, some points have the same MTOM but different results for the probability of failure. This effect is easily explained, these architectures have the same components but the connections among them are more-optimized in the low-probability ones. An example of this effect is now provided with a hypothetical case. Given an architecture with four actuators (A1, A2, A3 and A4) and two lines (L1 and L2), these actuators could be connected in different ways. Probability of failure would be low if three of them (e.g., A2, A3 and A4) are connected to one line (e.g., L1), and the other actuator (A1) to the remaining line (L2). If that line 1 and actuator 1 fail, the whole system is lost. On the other hand, if the actuators are connected two-to-two (e.g., A1 and A2 to L2, A3 and A4 to L1) the probability of failure is higher. Now the system functions even if line 1 and actuator 1 are lost, since line 2 and actuator 2 still work. Both architectures have the same components, but the connections are different. This fully explains the verticallity in the results that was mentioned previously. Another conclusion that can be seen is that, in general, architectures with a lower probability of failure are heavier. Which means that there is a trade-off between MTOM and probability of failure. This can also be explained, a higher number of components would generally translate in a higher number of redundancies, which increases the reliability of the system but also the mass. Having for example more spoilers, or more generators, or more lines decreases the probability of failure, but it translates into a penalty in mass. MEA architectures have more potential in terms of reliability since they allow a really high number of lines (hydraulic and electric). An architecture with, for instance, three hydraulic lines and three electric lines connected to the different spoilers is possible from an architectural point of view. A high level of redundancy is then reached, but the mass is greatly penalized. This verticality in the results is also observed in figure 9b between MMH reduction and probability of failure. The AEA are now on the right side of the graph, while the MEA stay on the left bellow 500 hours of reduction. The explanation for this effect is the



(a) Pareto front between MTOM and probability of failure.



(b) Pareto front between MMH reduction and probability of failure.



(c) Pareto front between MMH reduction and MTOM.

Fig. 9 Pareto fronts among the three optimization objectives.

same as before, the same number of components can have different probabilities of failure but the same MMH reduction. The same trade-off as before is found. Increasing the number of components decreases the probability of failure but increases the required maintenance, hence penalizing the MMH reduction.

Figure 9c shows the Pareto front between MMH reduction and MTOM. In this case the trade-off is different as the one observed in the Paretos before. Going from a MEA to a AEA removes the hydraulic and pneumatic systems. This translates in a lighter aircraft and a more-maintainalble one. There is not really a trade-off among the variables. The optimum architecture following just these two objectives is always an AEA. It can be noticed how the algorithms did not generate further conventional architectures since they understand quite fast that these concepts have no improvement in the maintenance discipline. Hence not exploring the region around those architectures.

One interesting result to comment is that only four points are lying on the Pareto front, from a run with 6400 points in total. This paragraph provides an explanation to this. As seen in table 4, the all-electric architectures cannot be certified without increasing the level of redundancy on the emergency lines. The certification filter is directly filtering, and not representing or evaluating, these architectures. Another effect is that the total number of possible AEA architectures compared to MEA is relatively low. Summing both effects (e.g., low number of AEA plus high filtering of AEA) leaves a quite small amount of AEA left. These are the feasible AEA extracted from the analysis. Which narrows quite a lot the huge amount of architectures initially envisioned, leaving just a small number of interesting ones. This justifies quite well the purpose of this manuscript. The certification filter together with the optimization algorithms manage to reduce the design space to just a few of architectures that could be further analyzed later with higher fidelity analysis or tools. This allows to successfully remove the vast majority of non-feasible and non-interesting architectures from the design space.

Lastly, it is interesting to see which are the four architectures that are on the Pareto front. Their exact results are shown in table 5. It is important to state that this manuscript does not focus on finding the best architecture for the given flight spoilers system, but instead on the methodology behind that allows to filter such design space and supports the decision making. Interesting trade-offs can be found in this analysis and this can lead to important conclusions and outcomes. The pareto front points are now briefly commented. Point 1 corresponds to an architecture with five flight spoilers. Ailerons and spoilers are all moved by EHAs, resulting in an AEA. There are two main electric lines and an emergency one. Both ailerons are connected respectively to one of the two main lines. Three spoilers are connected to the emergency line, and the other two to different main lines. The two main lines are connected to one engine generator each, and both to the APU. The emergency line is linked to the RAT and a external motor in redundancy. Point 2 is also an AEA, however it has four flight spoilers in this case. The rest of the architecture is practically the same as in point 1. The main difference is the number of spoilers and to which line each actuator is connected. The result when compared to point 1 is a small decrease in MTOM, small improvement in MMH, but a huge increase in probability of failure. However, this architecture is still more reliable than the reference one. Point 4 is an AEA as well. It has five flight spoilers and the same number of electric lines. The main difference with point 1 relies on the connections among actuators and lines, and on the addition of one extra generator in engine 1. The rest of the architecture is the same as in point 1. It can be seen how the MTOM and MMH are slightly penalized, but the probability of failure is slightly favoured. Point 3 is different from the ones before since it represents a MEA concept. Both ailerons are hydraulically powered while all the spoilers are electric. There are two main electric lines, both connected to their respective engines through one generator, and to the APU. The emergency line of the electric system is only connected to the RAT in this architecture, since the extra redundancy is now not required. Two spoilers are connected to one of the main lines, two spoilers to the other main line, the remaining spoiler to the emergency line. The hydraulic system is conformed by two lines. Each of the ailerons is linked to one of them. both lines are powered by electric pumps connected to electric motors.

Table 5 Results of the points that conform the Pareto front.

	MTOM [kg]	**Probability of Failure [-]**	**MMH [hours reduced]**
Pareto Point 1	77699	0.0279	1468
Pareto Point 2	77651	0.3395	1471
Pareto Point 3	78630	0.0017	349
Pareto Point 4	77815	0.0228	1444

V. Conclusions

On-board systems are important enablers for future aircraft and their assessment is key to understand the feasibility of new innovative concepts. Performance is the first discipline to evaluate in order to decide how impactful a new concept can be. However, considering more disciplines from other life cycle stages of the aircraft (such as maintenance or manufacturing) is key to fully understand the impact of a new technology. This manuscript aims at adding certification and maintenance to the analysis, leaving other life-cycle stages for further studies. One specific problem that appears during on-board system architectures design is the high amount of possible solutions that can fulfill a specific function. This creates a huge design space that cannot be fully explored. Filtering the architectures and using optimization algorithms becomes a need to narrow down such design space to the most feasible solutions. This paper focuses on providing a methodology to assess performance, certification and maintenance aspects of on-board system architectures during preliminary design. Performance aspects are key to assess the potential of a new architecture. Maintenance adds an important layer to the analysis, providing estimations on the maintainability of new innovative concepts not assessed before. Certification can be used to discard the architectures that are not compliant with the certification specifications, this can be used as a filter that saves computational time and lets the evaluation framework to just assess architectures that are potentially certifiable. Automation is needed in order to properly explore the design space and connect such analyses to optimization algorithms that can narrow down the interesting solution and show interesting trade-offs. This methodology aims at helping and supporting the decision making process during multi-disciplinary and multi-objective design of OBS architectures.

An application case is provided in order to better understand the capabilities of the proposed methodology. The application focuses on the roll control of the Airbus A320neo. The design space is built following a system architecting process. The total number of architectures surpasses the order of billions, which highlights the need for automation and filtering. The design space is connected to a framework that automatically filters the architectures that are not compliant with the certification specifications. The architectures are then evaluated in terms of performance passing through different tools. First, a dedicated tool for flight control system sizing estimates the mass and power of the architecture. Then, the rest of the on-board systems are sized and installed inside an aircraft baseline. Lastly, maintenance aspects are evaluated in terms of MMH reduction with respect to a the conventional A320neo. Results are given to optimization algorithms which explore the interesting areas of the design space, providing the most interesting architectures without needing to evaluate all of them.

Results show interesting trade-offs. As a general result, all-electric architectures have strong potential in terms of performance and maintenance, but they need the addition of extra redundancies in order to be certified when compared to the baseline aircraft. Most of the AEA do not pass the certification filter. However, the ones that pass it show great potential and improvement. MEA architectures have some slight benefits with respect to the conventional one. They represent a realistic middle point between conventional and AEA, but it is noticeable how changing to full all-electric concepts highly benefits the results. It is also remarkable how the certification filter discards the majority of the architectures, leaving only some interesting ones. This greatly supports the decision making process, narrowing down the feasible solutions and providing interesting conclusions and trade-offs to the designer.

References

[1] Fioriti, M., Cabaleiro De La Hoz, C., Lefebvre, T., Della Vecchia, P., Mandorino, M., Liscouet-Hanke, S., Jeyaraj, A. K., Donelli, G., and Jungo, A., "Multidisciplinary design of a more electric regional aircraft including certification constraints," *AIAA AVIATION 2022 Forum*, 2022, p. 3932.

[2] Viola, N., Fusaro, R., Saracoglu, B., Schram, C., Grewe, V., Martinez, J., Marini, M., Hernandez, S., Lammers, K., Vincent, A., et al., "Main challenges and goals of the H2020 STRATOFLY project," *Aerotecnica Missili & Spazio*, Vol. 100, No. 2, 2021, pp. 95–110.

[3] Moir, I., and Seabridge, A., *Aircraft Systems: Mechanical, electrical, and avionics subsystems integration*, Vol. 52, John Wiley & Sons, 2011.

[4] Haskins, C., Forsberg, K., Krueger, M., Walden, D., and Hamelin, D., *Systems engineering handbook*, INCOSE, 2006.

[5] Pardessus, T., "Concurrent engineering development and practices for aircraft design at Airbus," *the 24rd congress of the international council of the aeronautical sciences. ICAS*, 2004.

[6] Donelli, G., Ciampa, P. D., Nagel, B., Lemos, G., Mello, J., Cuco, A. P. C., and van der Laan, T., "A Model-Based Approach to Trade-Space Evaluation Coupling Design-Manufacturing–Supply Chain in the Early Stages of Aircraft Development," *AIAA AVIATION 2021 FORUM*, 2021, p. 3057.

[7] Crawley, E., Cameron, B., and Selva, D., *System architecture: strategy and product development for complex systems*, Prentice Hall Press, 2015.

[8] Sobieszczanski-Sobieski, J., Morris, A., and Van Tooren, M., *Multidisciplinary design optimization supported by knowledge based engineering*, John Wiley & Sons, 2015.

[9] Bussemaker, J. H., Ciampa, P. D., and Nagel, B., "System architecture design space exploration: An approach to modeling and optimization," *AIAA Aviation 2020 Forum*, 2020, p. 3172.

[10] Chakraborty, I., Mavris, D. N., Emeneth, M., and Schneegans, A., "A methodology for vehicle and mission level comparison of More Electric Aircraft subsystem solutions: Application to the flight control actuation system," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 229, No. 6, 2015, pp. 1088–1102.

[11] Liscouet-Hanke, S., "A model-based methodology for integrated preliminary sizing and analysis of aircraft power system architectures," Ph.D. thesis, Institut National des Sciences Appliquées de Toulouse, 2008.

[12] Sarlioglu, B., and Morris, C. T., "More electric aircraft: Review, challenges, and opportunities for commercial transport aircraft," *IEEE transactions on Transportation Electrification*, Vol. 1, No. 1, 2015, pp. 54–64.

[13] Fioriti, M., Della Vecchia, P., and Donelli, G., "Effect of Progressive Integration of On-Board Systems Design Discipline in an MDA Framework for Aircraft Design with Different Level of Systems Electrification," *Aerospace*, Vol. 9, No. 3, 2022, p. 161.

[14] Qiao, G., Liu, G., Shi, Z., Wang, Y., Ma, S., and Lim, T. C., "A review of electromechanical actuators for More/All Electric aircraft systems," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 232, No. 22, 2018, pp. 4128–4151.

[15] Cabaleiro de la Hoz, C., Bussemaker, J. H., Fioriti, M., Boggero, L., Ciampa, P. D., and Nagel, B., "Environmental and Flight Control System Architecture Optimization from a Family Concept Design Perspective," *AIAA Aviation 2020 Forum*, 2020, p. 3113.

[16] Mazzoleni, M., Di Rito, G., Previdi, F., et al., *Electro-Mechanical Actuators for the More Electric Aircraft*, Vol. 2021, Springer, 2021.

[17] Chiesa, S., Di Meo, G. A., Fioriti, M., Medici, G., and Viola, N., "ASTRID–aircraft on board systems sizing and trade-off analysis in initial design," *Research and Education in Aircraft Design–READ 2012*, 2012.

[18] Cabaleiro de la Hoz, C., and Fioriti, M., "New methodology for flight control system sizing and hinge moment estimation," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 236, No. 12, 2022, pp. 2375–2390.

[19] Brusa, E., "Digital Twin: Towards the Integration Between System Design and RAMS Assessment Through the Model-Based Systems Engineering," *IEEE Systems Journal*, 2020.

[20] Cabaleiro, C., Fioriti, M., and Boggero, L., "Methodology for the Automated Preliminary Certification of On-Board Systems Architectures through Requirements Analysis," *Proceedings of the 33rd Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden*, 2022, pp. 4–9.

[21] Jeyaraj, A. K., Bussemaker, J. H., Liscouët-Hanke, S., and Boggero, L., "Systems architecting: a practical example of design space modeling and safety-based filtering within the AGILE 4.0 project," *the 33rd congress of the international council of the aeronautical sciences. ICAS*, 2022.

[22] Dell'Anna, S., *Concept Development for Maintenance Cost Estimation of More-electric Aircraft On-board System Architectures*, MSc thesis. Politecnico di Torino, Turin, Italy, 2023.

[23] Fioriti, M., Vercella, V., and Viola, N., "Cost-estimating model for aircraft maintenance," *Journal of Aircraft*, Vol. 55, No. 4, 2018, pp. 1564–1575.

[24] Cabaleiro, C., Fioriti, M., Boggero, L., Corpino, S., Ciampa, P., Nagel, B., et al., "Assessment of New technologies in a Multi-Disciplinary Design Analysis and Optimization Environment including RAMS and Cost Discliplines," *32nd Congress of the International Council of the Aeronautical Sciences, ICAS 2021*, International Council of the Aeronautical Sciences, 2021.

[25] Bussemaker, J., Boggero, L., and Ciampa, P. D., "From system architecting to system design and optimization: A link between mbse and mdao," *INCOSE International Symposium*, Vol. 32, Wiley Online Library, 2022, pp. 343–359.

[26] IEC, "Analysis techniques for dependability–reliability block diagram and boolean methods," , 2006.

[27] Cabaleiro, C., Fioriti, M., and Boggero, L., "Automated generation of aircraft on-board system architectures and filtering through certification specification requirements," *Proceedings of the 13rd EASN Conference, Salerno, Italy*, 2023.

[28] Woehler, S., Atanasov, G., Silberhorn, D., Fröhler, B., and Zill, T., "Preliminary aircraft design within a multidisciplinary and multifidelity design environment," *Aerospace Europe Conference 2020*, 2020.

[29] Cabaleiro de la Hoz, C., Fioriti, M., and Boggero, L., "Performance and Reliability Evaluation of Innovative High-Lift Devices for Aircraft Using Electromechanical Actuators," *Aerospace*, Vol. 11, No. 6, 2024, p. 468.

[30] Ninotta, N., *Development of a Maintenance Man Hours Estimating Relationship during preliminary design of More and All Electric Aircraft*, MSc thesis. Politecnico di Torino, Turin, Italy, 2024.

[31] Scarcelli, F., *RAMS-and mass-based optimization of aircraft on-board system architectures during preliminary aircraft design*, MSc thesis. Politecnico di Torino, Turin, Italy, 2023.

[32] Page Risueño, A., Bussemaker, J., Ciampa, P. D., and Nagel, B., "MDAx: Agile generation of collaborative MDAO workflows for complex systems," *AIAA Aviation 2020 Forum*, 2020, p. 3133.

[33] S.A.S, A., "Airbus Training - A320 Flight Crew Operating Manual." , 1990.

[34] Bussemaker, J. H., Boggero, L., and Nagel, B., "System Architecture Design Space Exploration: Integration with Computational Environments and Efficient Optimization," *AIAA Aviation 2024 Forum*, 2024.

[35] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE transactions on evolutionary computation*, Vol. 6, No. 2, 2002, pp. 182–197.