AIRCRAFT SYSTEM ARCHITECTURES SELECTION FOR AIRCRAFT DESIGN OPTIMIZATION IN AN AUTOMATED PROCESS

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Abstract

The on-board systems have having even more importance in aircraft design since the need to design a competitive, more optimized and less costly aircraft. A second driver is the introduction of new technologies related to the More Electric Aircraft and All Electric Aircraft concepts that give to the designer the possibility of choosing different architectures. The present paper would enhance the selection of the best on-board systems architecture introducing a new workflow, which is able to define the solution, which yield a lower procurement and operating cost. The workflow is implemented in Optimus framework within a collaborative and multidisciplinary environment. The workflow presented is open to be enhanced and to catch the effect of the on-board systems selection on the overall aircraft design and vice versa and is enough flexible to be used with different aircraft typology.

1. Introduction

At present, the competitiveness and the environmental constraints in the field of aeronautical products have boosted the need for a design even more optimized with a low operating cost. Aerospace engineers and researchers are focusing their attention towards a more integrated design between the different disciplines: aerodynamics, structure design, propulsion and on-board systems. In the past, during conceptual design phase, the on-board systems have been considered merely for their weight [1]. Only in preliminary design phase the on-board systems architectures, the power required and their volumes are taken in consideration. In order to obtain a more integrated and optimized design, all parameters, usually considered in preliminary design phase, are now evaluated in conceptual design. In this way, a real multidisciplinary design optimization

(MDO) can be carried out from the very beginning of the project considering, in more details, a large part of the aircraft empty mass, acquisition and operating cost represented by on-board systems (see Fig. 1).

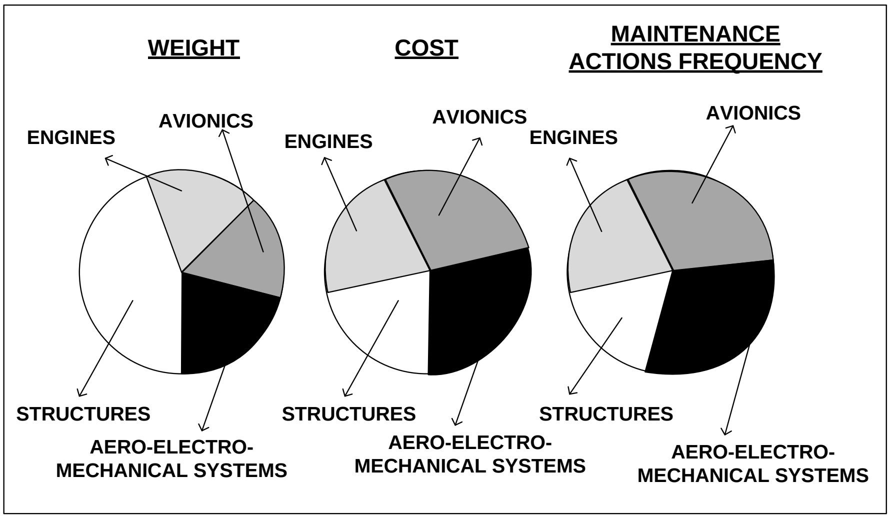

Fig. 1. Importance of on-board systems in aircraft empty weight, cost and maintenance actions.

Furthermore, on-board systems have other significant effects on aircraft overall design, the most important are: the additional fuel weight, the volume required for installation, aircraft reliability and safety. The on-board systems require electric, hydraulic and pneumatic power to operate. This power is produced by engine as non-propulsive power, hence the engine will require additional fuel just to supply energy to the sub-systems. Other quantity of fuel is required because of the additional induced drag as consequence of systems weight and additional friction drag due to the relating air intakes and fairings. The systems architectures have also an effect on global aircraft reliability and safety. The increment of the number of redundancy lines and equipment increases the aircraft safety level but, conversely, it reduces its logistic reliability. Since, when more equipment are installed, more equipment could have a failure.

Moreover, from the last decades, the on-board systems can exist in different types of architecture, from standard technology to more or all electric. As shown in Fig. 2 (a), for state-of-the-art (SOTA) architecture, the utilities systems use hydraulic, electric and pneumatic power. Thus, electric and hydraulic power are derived transforming the mechanical power gathered from the engine by accessory drive gearbox. The pneumatic power is generated bleeding compressed air from engine compressor stages. The innovative architecture presented in Fig. 2 (b) is similar to the Boeing 787 one, however it represents only one example of the several more electric architectures that can be designed. In this example, electric, hydraulic and pneumatic users are still present. However, the mechanical power taken from the engine is exclusively transformed in electric power. Hydraulic and pneumatic users are powered by electric power generation and distribution system (EPGDS). Engine cycle efficiency could be increase and power generation could be optimized removing the engine air bleed off-takes and engine driven hydraulic pump. Other kind of innovative architectures could include electric flight control system actuators, removing part or the entire hydraulic system. Moreover, other different system architectures are derived from a combination of the two described ones.

Seeing the importance of on-board systems and their architectures already in conceptual design, it is essential to define the optimal one for the designed aircraft. The present paper is focused on a novel methodology to automatically select the optimal (i.e. minimized cost and weight) sub-system architecture considering the impact on the overall aircraft design. In particular, the proposed procedure takes into account the effect of fuel required by on-board systems, their cost and weight. For the sake of simplicity, in the implemented model, the “snow ball” effect of fuel and systems weight obtained with the further design iteration is not accounted. This should not be a limit of the present study since the first outcome proposed is an algorithm for the automatic definition and selection of the best subsystems configuration instead of the evaluation of the final and more refined weight of the aircraft. Other researchers have focused their attention in the selection of more suitable system architecture [1], however, in the present work, the model proposed and its implementation is compatible with a collaborative design, using Noesis Optimus, and a little more comprehensive due to the consideration of the cost discipline within the design process.

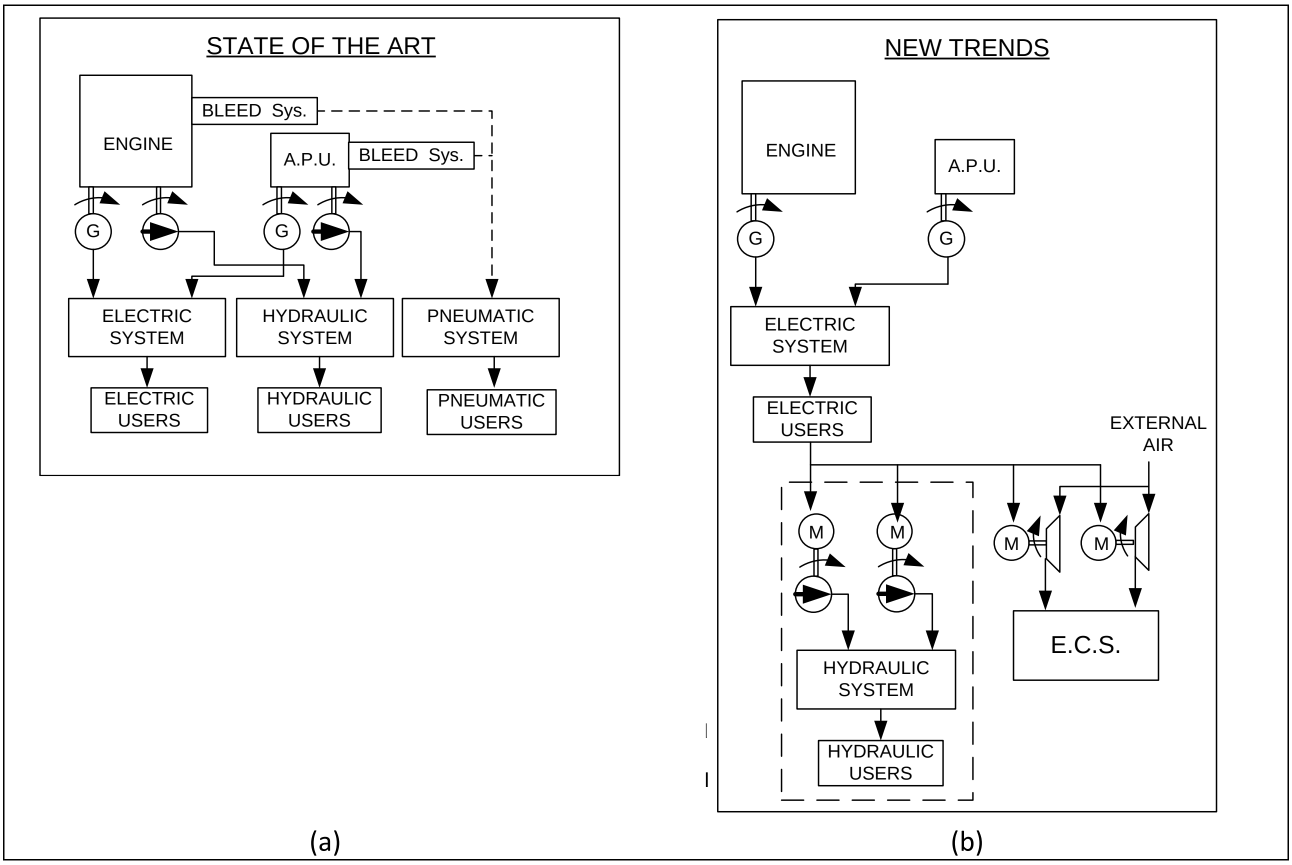

Fig. 2. Example of state-of-the-art and more electric systems architectures.

In the second section, the proposed methodology is described considering its implementation in Optimus framework. The third section describes the aircraft selected as case study and the results obtained using the proposed model. Finally the fourth is devoted to a possible enhancement of the present model using a surrogate model of the on-board systems design tool.

2. Automated model for subsystem architecture selection

The workflow for the on-board systems design is implemented in Optimus, a process integration and design optimization system environment provided by Noesis [2]. The framework allows the users to automatically visualize and explore the design space and gain the critical insights into the dynamics of a given (multidisciplinary) virtual design problem. The Optimus software environment provides the means to:

- integrate different processes within a unique simulation workflow
- automate the tasks required to execute these processes
- explore the design space

- perform the design optimization

The Integration of different processes in a unique framework requires defining from a conceptual point of view how a set of input (or design) variables is linked to a set of output variables. In Optimus, a Graphical User Interface (GUI) provides the tools required to define input / output variables, files, analyses and all the intermediate activities (e.g., rules defining the mapping / extraction of variables to / from files, batch commands, etc) involved during the simulation of a design process. All these entities are then linked together to form an oriented graph (i.e., the simulation workflow) that allows defining in a logical and quantitative way how the data is transferred from the input to the output variables.

A simulation workflow is typically linked with one or more analysis methods: numerical algorithms that are embedded in the Optimus engine. They can be used to:

- investigate the design space (i.e. design of experiment) in order to explore the model behavior, extract the most significant model features and build surrogate models (i.e. response surfaces);

- investigate how the uncertainty associated with the input variables is propagated to the outputs and how the uncertainty in the outputs can be apportioned to different sources of uncertainty in the associated inputs (i.e. sensitivity analysis);

- perform the design optimization in order to find the values of the (usually bounded) input parameters that minimize or maximize the target output variable(s) of interest under a set constraints.

The workflow provides the systems design in terms of weights, required fuel and costs of several system architectures. A system architecture is characterized by different combinations of technology levels. As instance, a conventional architecture is constituted by the transformation of three types of non-propulsive (or *secondary*) power, namely electric, hydraulic and pneumatic power. The first two kinds of power are result of a transformation from mechanical power extracted from the engines through a gearbox generally mounted on the high pressure shaft. The pneumatic power is obtained by bleeding from the jet engines part of high temperature and pressure airflow. In a More Electric Aircraft (MEA), either the hydraulic system or the pneumatic system is removed, entailing a conversion from hydraulic and pneumatic users to electric ones. Otherwise, in an All Electric Aircraft, both systems are removed in favor of a more powerful, heavy but also more fuel-efficient electric system. Three design modules are integrated within the workflow. The main integrated module is represented by the tool ASTRID [3], an in-house software conceived and realized by Politecnico di Torino, aimed at the preliminary design of the aircraft sub-systems. The results of the model are represented by system masses and engine shaft power off-takes and bleed off takes required to supply energy to on board systems. The two last outcomes are used by a second integrated module aimed at the preliminary quantification of fuel required for the non-propulsive power, meant as the power extracted from the engines and provided to the systems. The last module is the cost model, which, given the results of systems weight and fuel quantity for secondary power, estimates the acquisition and operating costs of each system architecture.

The flow chart of the entire workflow is depicted in Fig. 3. The aircraft general inputs, such as Top Level Aircraft Requirements (TLARs), airplane dimensions and geometries (e.g. fuselage length, wing area), design weights like Maximum Take Off Weight (MTOW), Operating Empty Weight (OEW) and other generic considerations (e.g. type and position of engines), are given to the on-board systems design module, ASTRID. The software receives other specific inputs of sub-systems. These groups of data contain specialized information of each on-board system, as instance the number of wheels of the landing gear, the pressure of the hydraulic system and the number of redundant equipment. Each group of specific inputs characterize the different system architectures. ASTRID estimates the masses and the mechanical shaft power off-takes and bleed of takes of the following systems: avionics, Flight Control System, landing gear (i.e. retraction, steering and braking sub-systems), Ice Protection System (IPS), Environmental Control System (ECS), Fuel system, Auxiliary Power Unit (APU) System, furnishing, Pneumatic System, Hydraulic System and Electric System. Different methodologies are implemented to evaluate masses and secondary power requests of both

conventional and innovative systems, such as MEAs and AEAs. Other details about ASTRID and the implemented design modules are reported in [3].
Systems weight results, together with aircraft generic information, such as mission profile and engine deck (performances, thrust levels, fuel consumption), are inputs of the Engine Module. This simplified model estimates the fuel required by on-board systems during the mission according to the methodology proposed in [4]. This methodology evaluates the reduction of engine core efficiency due to non-propulsive power (η_{co}^*/η_{co}). This decrease affects the engine Specific Fuel Consumption (SFC). Furthermore, the methodology discerns between mechanical power off-takes (eq. 1) and air bleeds (eq. 2), showing the impacts on the engine of the two types of power extraction.

$$\frac{\eta_{co}^*}{\eta_{co}} = 1 - \frac{2 \cdot P_{po} \cdot (BPR + 1)}{T \cdot [BPR/(\eta_f \eta_{lpt}) + 1] \cdot (2V_0 + ST)} \qquad \text{(eq. 1)}$$

$$\frac{\eta_{co}^*}{\eta_{co}} = 1 - \frac{2 \cdot W_b \Delta h_b \cdot (BPR + 1)}{(1 - \beta) \cdot T \cdot [BPR/(\eta_f \eta_{lpt}) + 1] \cdot (2V_0 + ST)} \qquad \text{(eq. 2)}$$

where the relative bleed air mass flow β is expressed as

$$\beta = \frac{W_b \cdot ST \cdot (BPR + 1)}{T} \qquad \text{(eq. 3)}$$

The terms P_{po} [kW] in (eq. 1) and W_b[kg/s] (eq. 2) represent respectively the mechanical power off-takes and the bleed airflow. They are both results of the on-board systems design module. From the aircraft generic input block are derived the other parameters, namely the engine By-Pass Ratio (BPR), the engine net thrust (T [kN]), the fan (η_f) and low-pressure-turbine (η_{lpt}) isentropic efficiencies, the aircraft flight velocity (V_0 [m/s]), the engine specific thrust (ST [m/s]) and the bleed air enthalpy increment through the core (Δh_b [kJ/kg]).

The fuel weight resulting from the Engine Module and the systems masses obtained through ASTRID become an input for the Costs Estimation Module. This model [5] is based on the costs estimation methodology proposed by Beltramo [6] modified to consider the inflation, the variation of the cost of traditional technologies and the cost of novel technologies (i.e. MEA and AEA systems). It allows the estimation of the procurement cost of each subsystem in a preliminary phase of the aircraft design process. This represent the systems purchasing costs and they depend on the technology level of the sub-system, their "quantity per aircraft" (generally expressed in terms of mass), and the number of production units (meant as number of aircraft to be produced with each type of system architecture). Concerning the operating cost, the implemented module evaluates only the fuel cost overlooking the other items of the direct operating cost (DOC) in this preliminary design phase.

The workflow ends with the achievement of preliminary results of on-board systems design, as masses, costs, and impacts on fuel quantity. All these outcomes can be used by the designer in the selection of the best system architecture, meant as the lightest (taking into account both systems weight and fuel quantity) or the cheapest one.

The workflow so far described is implemented in Noesis Optimus, as represented in Fig. 4. The three integrated modules are marked with a green circle. They are all implemented in Matlab code, and they are integrated within the framework through User Customizable Interfaces (UCI); a UCI is a wrapper that allow for pervasive customization and integration of third-party simulation file syntax in a unique framework.

By means of the interface, the first design module, ASTRID, receives both the aircraft generic inputs, which are listed inside a CPACS-format xml file (red circle), and the on-board systems inputs. The latter are parameters whose influence has been investigated and are passed through the three block encompassed in the yellow bubble.

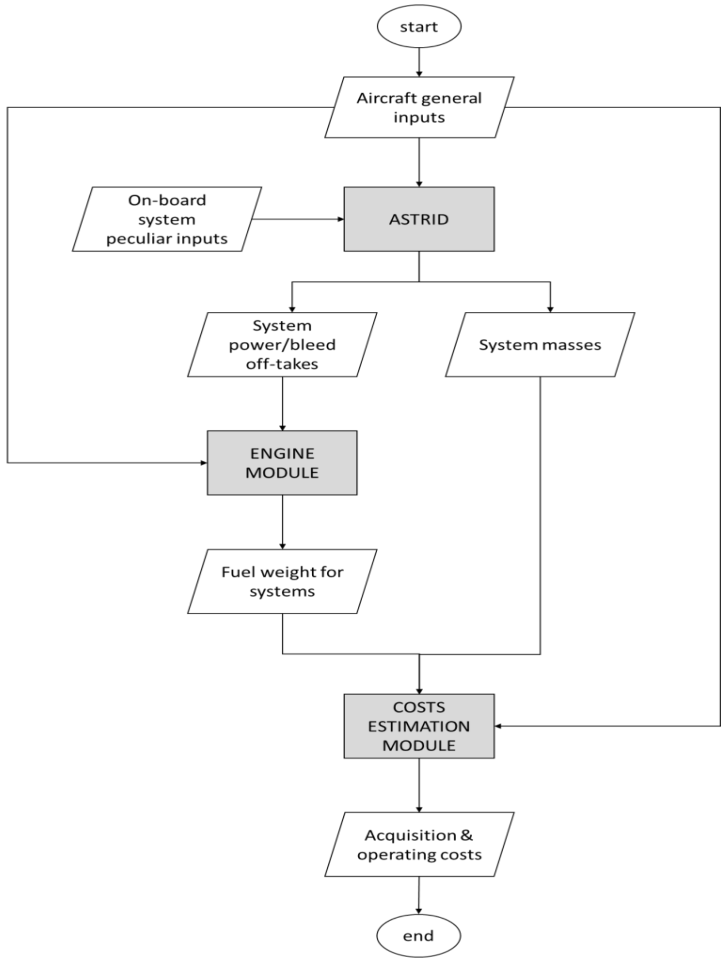

Fig. 3 Flowchart of the workflow including systems sizing, engine and cost estimating modules.

Input Variable Name	Value - Meaning
FCS_Power_Supply	0 – the Flight Control System is supplied by electric power 1 – the Flight Control System is supplied by hydraulic power
LND_GEAR_RETRACTION_Power_Supply	0 – the retraction of the landing gear is supplied by electric power 1 – the retraction of the landing gear is supplied by hydraulic power
LND_GEAR_STEERING_Power_Supply	0 – the steering of the nose landing gear is supplied by electric power 1 – the steering of the nose landing gear is supplied by hydraulic power
LND_GEAR_BRAKING_Power_Supply	0 – the braking of the main landing gear is supplied by electric power 1 – the braking of the main landing gear is supplied by hydraulic power
Brake_Hydraulic_pressure	207 – Hydraulic pressure [bar] of the landing gear braking system 344 – Hydraulic pressure [bar] of the landing gear braking system
Hydr_Pressure	207 – Pressure [bar] of the hydraulic system 344 – Pressure [bar] of the hydraulic system
Primary_Electric_voltage	2 – Primary generated electric voltage: 115 V AC (400 Hz) 5 – Primary generated electric voltage: 235 V AC wf
Primary_Electric_Machine	1 – Type of electric generator: Integrated Drive Generator 4 – Type of electric generator: Permanent Magnets Alternator + AC/DC
Bleedless_architecture	0 – Conventional pneumatic architecture (with air bleed) 1 – Innovative pneumatic architecture (bleedless)

Table 1: Workflow Input variables.

In this workflow, inputs (listed in the variable array represented by the cyan icon) are discrete variables that describe the configuration of the on-board systems; they are resumed in Table 1. They are either controlled directly by the user to investigate specific system architectures or by the DOE/optimization method to explore the design space and search for a quantifiably “better” solution. The input variables are written on file by the “infile” block (light green icon) to be fed to ASTRID.

The results of the systems design module are saved in a copy of the input xml file (blue circle), and the power off-takes and bleed air results are transferred to the Engine Module, which receives also the input xml file (red circle) in which some engine parameters – those contained in (eq. 1) and (eq. 2) – are listed. The new result of fuel consumed by systems is used together with system masses and other inputs by the Cost Estimation Model. At the end of analysis, the outputs marked by the purple round are obtained. All the other Optimus elements, such as the “Dependancies” and the “Actions” (represented by the yellow bolt inside the orange square), are necessary for the correct running of the workflow, performing services as loading additional (constant) files and copying inputs and outputs to and from execution folders.

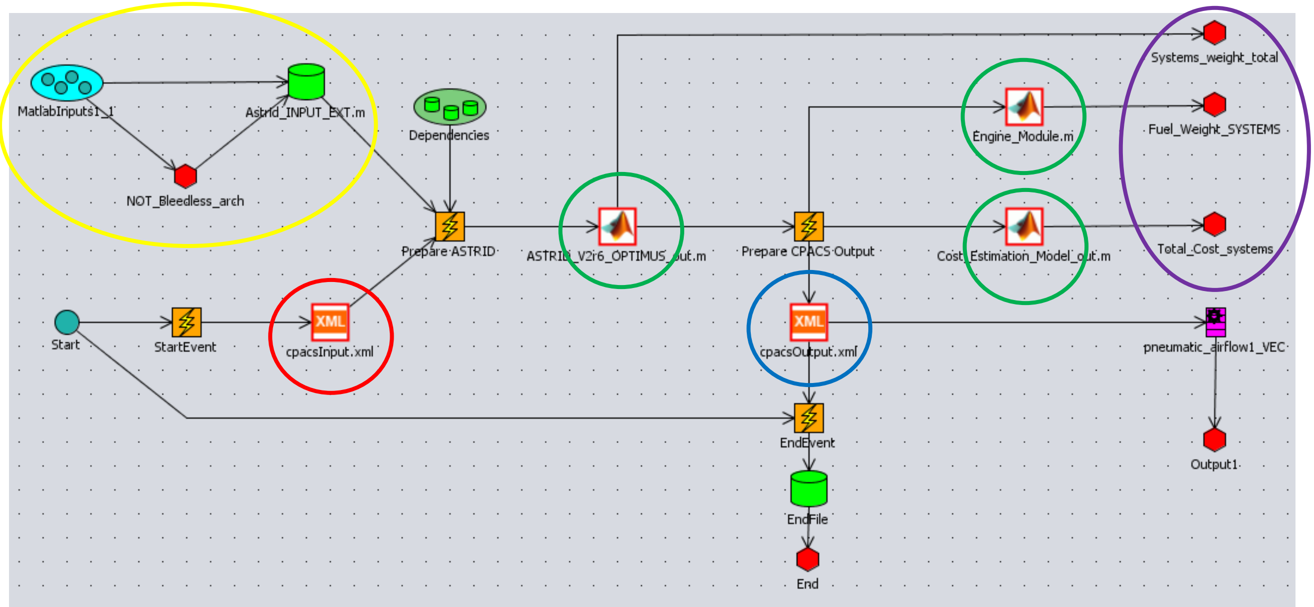

Fig. 4 Workflow integrated within Noesis Optimus showing the building blocks (i.e., inputs, files, analyses, outputs) required to link the design variables to the system responses and the connection between these items.

3. Case Study and results: AGILE regional aircraft

The workflow previously presented is under development within a European funded Research Project named AGILE – H2020 [7]. This project involves several worldwide aerospace partners from academia, research centers and industries. Its aim is the enhancement of the aircraft design phase by realizing an innovative MDO collaborative environment joining various discipline experts of, as instance, aerodynamics, structures, flight mechanics, propulsion. Politecnico di Torino is involved due to its expertise about on-board systems preliminary design, while Noesis provides its software Optimus and it supports the integration of the different design disciplines and the design and optimization processes.

A conventional reference regional jet is selected within the AGILE Consortium as case study to set-up and operate the AGILE state-of-the-art Design System. The Top TLAR and the main airplane specifications obtained from the preliminary design are listed in Table 2. In this work, several subsystem architectures are identified and designed as case study of the workflow.

Range [km]	3500
Design payload [kg]	9180
Max. payload [kg]	11500
Num of passengers	90
Cruise Mach	0.78
TOFL @ ISA, SL [m]	1500
Wing Area [m2]	84,3
Wing Span [m]	28,4
MTOM [kg]	45046
OEM [kg]	27421

Table 2: AGILE state-of-the-art reference aircraft: TLAR and main specifications.

As introduced in the previous section, several on-board system architectures could be identified, varying as instance:

- the power supply of the different systems users as the FCS and the landing gear, selecting between electric and hydraulic power;
- the hydraulic pressure, selecting between 207 bar and 344 bar;
- the pneumatic system architecture, selecting between the presence of bleed air off-take and the bleedless configuration.

The authors in [1] have proposed several other possiblities, some of them with at an higher level of detail, as the typology of actuators (linear vs. rotary, hydraulic vs electric). In total, over 13 millions of combinations have been counted, but not everyone is realizable or possible from a logical or engineering point of view. As instance, the system architecture characterized by the absence of the centralized hydraulic system, but the presence of hydraulic actuators, is infeasible.

From the Design of Experiments, 512 possible combinations have been identified combining the inputs listed in Table 1. It is worth to notice that not all these architectures are feasible from a logical point of view. As instance, in an all-electric architecture nothing changes if the variable “Hydr_Pressure” assumes the values 207 bar or 344 bar, as no hydraulic pressurized fluid is present inside this configuration. At the moment, unfeasible solutions have been discarded by hand, with the future goal to automate this process.

In Table 3 is reported an extract of the list of system architectures, ordered from the most affordable to the most expensive ones. As the reader can notice, the solutions with a lower cost are those characterized by the bleedless configuration. The acquisition costs of these architectures is higher respect to conventional solutions because of the innovative technology and higher complexity. On the other hand, the fuel required to power the bleedless systems is lower, attaining an important reduction of the operating costs. This fact is also noticeable from the correlation matrix of Fig. 5, which shows the linear dependence between each input and output of the workflow, estimated by means of the Pearson coefficients. From the matrix results that moving from a conventional architecture (variable “Bleedless_architecture” equal to 0) to an innovative one (variable “Bleedless_architecture” equal to 1) entails more benefits in terms of costs reduction compared to other solutions, as increment the hydraulic pressure from 207 bar to 344 bar. According to the Table 3, another design choice that could be adopted in order to limit costs is the typology of power needed to move the actuators of the FCS. In fact, as represented by the correlation value of the matrix, innovative electric actuation of control surfaces causes an increment of the acquisition costs, without entailing a fuel savings sufficient to reduce the operating costs.

The most cost effective system architecture is characterized by high pressure (i.e. 344 bar) hydraulic actuators for FCS and for the retraction and steering subsystems of the landing gear. Instead, the braking system should be supplied by the electric system. Concerning the pneumatic systems, the most affordable architecture is characterized by a bleedless configuration, entailing the electrification of the Ice Protection System (IPS) and the installation of dedicated electrically-driven compressors for the ECS. This particular solution has also resulted from the surface response describes in the following section. It is worth to notice that this particular on-board systems architecture has been adopted in the Boeing 787 program [8].

Apart from the most cost effective architecture, also the lightest solution has been identified, meant as the design characterized by the lower result of system and fuel weight. This solution matches with the All Electric Aircraft (AEA), which is characterized by the elimination of the hydraulic and pneumatic systems, which are replaced by a enhanced electric system. The advantage of this solution is firstly due to the fuel reduction caused by the bleedless architecture, which is more efficient compared to the conventional one. Then, the correlation matrix in Fig. 5 shows that another aspect causes the weight reduction: the higher hydraulic pressure that entails smaller and lighter hydraulic lines and equipment.

Num exp.	FCS power (hydr/elec)	lnd gear retracion power (hydr/elec)	lnd gear steering power (hydr/elec)	lnd gear braking power (hydr/elec)	Hydraulic pressure [bar]	Primary electric voltage	Bleedless architecture (y/n)	Systems weight [kg]	Systems fuel Weight [kg]	Sys+fuel weight [kg]	Total Cost
239	hydr	hydr	hydr	elec	344	235 VAC wf	y	8175,592371	53,21153481	8228,80391	$ 10.788.312
247	hydr	hydr	hydr	hydr	344	235 VAC wf	y	8175,592371	53,21195922	8228,80433	$ 10.788.325
227	hydr	hydr	hydr	elec	207	235 VAC wf	y	8295,529605	53,21153481	8348,74114	$ 10.803.731
251	hydr	hydr	hydr	hydr	207	235 VAC wf	y	8295,529605	53,21195922	8348,74156	$ 10.803.743
199	hydr	hydr	elec	elec	344	235 VAC wf	y	8175,592371	53,20773164	8228,8001	$ 10.842.884
223	hydr	hydr	elec	hydr	344	235 VAC wf	y	8175,592371	53,20815606	8228,80053	$ 10.842.896
229	hydr	hydr	hydr	elec	344	115 VAC (400 Hz)	y	8279,327797	53,21153481	8332,53933	$ 10.858.188
253	hydr	hydr	hydr	hydr	344	115 VAC (400 Hz)	y	8279,327797	53,21195922	8332,53976	$ 10.858.201
203	hydr	hydr	elec	elec	207	235 VAC wf	y	8295,529605	53,20773164	8348,73734	$ 10.858.302
211	hydr	hydr	elec	hydr	207	235 VAC wf	y	8295,529605	53,20815606	8348,73776	$ 10.858.315
…	…	…	…	…	…	…	…	…	…	…	…
7	elec	elec	elec	elec	-	235 VAC wf	y	8119,365281	52,32393801	8171,68922	$ 11.203.602
11	elec	elec	elec	elec	-	235 VAC wf	y	8119,365281	52,32393801	8171,68922	$ 11.203.602
103	elec	hydr	hydr	elec	344	235 VAC wf	y	8382,692797	52,32778751	8435,02058	$ 11.262.613
127	elec	hydr	hydr	hydr	344	235 VAC wf	y	8382,692797	52,32821167	8435,02101	$ 11.262.625
107	elec	hydr	hydr	elec	207	235 VAC wf	y	8502,630031	52,32778751	8554,95782	$ 11.278.031
115	elec	hydr	hydr	hydr	207	235 VAC wf	y	8502,630031	52,32821167	8554,95824	$ 11.278.044
1	elec	elec	elec	elec	-	115 VAC (400 Hz)	y	8237,753309	52,32393801	8290,07725	$ 11.283.348
13	elec	elec	elec	elec	-	115 VAC (400 Hz)	y	8237,753309	52,32393801	8290,07725	$ 11.283.348
79	elec	hydr	elec	elec	344	235 VAC wf	y	8382,692797	52,3239862	8435,01678	$ 11.317.184
87	elec	hydr	elec	hydr	344	235 VAC wf	y	8382,692797	52,32441036	8435,01721	$ 11.317.197
67	elec	hydr	elec	elec	207	235 VAC wf	y	8502,630031	52,3239862	8554,95402	$ 11.332.603
…	…	…	…	…	…	…	…	…	…	…	…
255	hydr	hydr	hydr	hydr	344	235 VAC wf	n	8070,876508	120,4415145	8191,31802	$ 12.619.333
245	hydr	hydr	hydr	hydr	344	115 VAC (400 Hz)	n	8081,281718	120,4415145	8201,72323	$ 12.626.342
231	hydr	hydr	hydr	elec	344	235 VAC wf	n	8092,599806	120,4410893	8213,0409	$ 12.633.954
243	hydr	hydr	hydr	hydr	207	235 VAC wf	n	8190,813741	120,4415145	8311,25526	$ 12.634.752
249	hydr	hydr	hydr	hydr	207	115 VAC (400 Hz)	n	8201,218951	120,4415145	8321,66047	$ 12.641.761
237	hydr	hydr	hydr	elec	344	115 VAC (400 Hz)	n	8112,741728	120,4410893	8233,18282	$ 12.647.521
235	hydr	hydr	hydr	elec	207	235 VAC wf	n	8212,537039	120,4410893	8332,97813	$ 12.649.372
225	hydr	hydr	hydr	elec	207	115 VAC (400 Hz)	n	8232,678962	120,4410893	8353,12005	$ 12.662.939
215	hydr	hydr	elec	hydr	344	235 VAC wf	n	8074,306701	120,4377046	8194,74441	$ 12.676.215
221	hydr	hydr	elec	hydr	344	115 VAC (400 Hz)	n	8086,739436	120,4377046	8207,17714	$ 12.684.590
207	hydr	hydr	elec	elec	344	235 VAC wf	n	8092,599806	120,4372795	8213,03709	$ 12.688.525
…	…	…	…	…	…	…	…	…	…	…	…

Table 3 – Synthesis of the 512 system architectures (inputs and results)

Pearson (Spearman)	FCS_Power_Supply_1	LND_GEAR_RETRACTION_Power_Supply	LND_GEAR_STEERING_Power_Supply_	LND_GEAR_BRAKING_Power_Supply_	Hydr_Pressure_1	Primary_electric_voltage_1	Bleedless_architecture	Systems_weight_total	Fuel_Weight_SYSTEMS	Total_Cost_systems
FCS_Power_Supply_1	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	-0.602 (-0.617)	0.013 (0.433)	-0.256 (-0.433)
LND_GEAR_RETRACTION_Power_Supply_1	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.014 (0.019)	0.000 (0.054)	-0.016 (-0.049)
LND_GEAR_STEERING_Power_Supply_1	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.140 (0.141)	0.000 (0.217)	-0.005 (-0.004)
LND_GEAR_BRAKING_Power_Supply_1	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.102 (0.099)	0.000 (0.108)	0.004 (0.004)
Hydr_Pressure_1	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	-0.349 (-0.339)	0.000 (0.000)	-0.008 (-0.023)
Primary_electric_voltage_1	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	-0.312 (-0.289)	0.000 (0.000)	-0.042 (-0.079)
Bleedless_architecture	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	0.346 (0.335)	-1.000 (-0.866)	-0.958 (-0.866)
Systems_weight_total	-0.602 (-0.617)	0.014 (0.019)	0.140 (0.141)	0.102 (0.099)	-0.349 (-0.339)	-0.312 (-0.289)	0.346 (0.335)	1.000 (1.000)	-0.354 (-0.515)	-0.131 (0.060)
Fuel_Weight_SYSTEMS	0.013 (0.433)	0.000 (0.054)	0.000 (0.217)	0.000 (0.108)	0.000 (0.000)	0.000 (0.000)	-1.000 (-0.866)	-0.354 (-0.515)	1.000 (1.000)	0.955 (0.560)
Total_Cost_systems	-0.256 (-0.433)	-0.016 (-0.049)	-0.005 (-0.004)	0.004 (0.004)	-0.008 (-0.023)	-0.042 (-0.079)	-0.958 (-0.866)	-0.131 (0.060)	0.955 (0.560)	1.000 (1.000)

Fig. 5 Correlation matrix (Pearson coefficients)

The histogram in Fig. 6 shows the comparisons in terms of masses and costs of four different architectures: a conventional, two More Electric Aircraft (MEA) and an AEA ones. Their features are listed in Table 4. The lightest one is the AEA architecture, but this solution is not the most affordable. In fact, the most cost effective is the second MEA architecture (MEA 2), which is similar to the one used in Boeing 787 airliner.

	Conventional	**MEA 1**	**MEA 2**	**AEA**
Actuators (FCS & landing gear)	Hydraulic actuators	High voltage electric actuators (EHA e EMA)	High pressure hydraulic actuators (5000 psi)	High voltage electric actuators (EHA e EMA)
Wing Ice Protection System & Environmental Control System	By airflow bled from the engines	By airflow bled from the engines	Electric systems (bleedless architectures)	Electric systems (bleedless architectures)
Hydraulic system	Present, 3000 psi	Absent	Present, 5000 psi	Absent
Electric system	Generated: 115 VAC (400 Hz); converted: 28 VDC	Generated: 235 VAC wf; converted: 28 VDC, 115 VAC e 270 VDC	Generated: 235 VAC wf; converted: 28 VDC, 115 VAC e 270 VDC	Generated: 235 VAC wf; converted: 28 VDC, 115 VAC e 270 VDC

Table 4 – Feature of four on-board system architectures

Fig. 6 Weight and Cost comparisons of four on-board systems architectures

4. Possible enhancement: use of a response surface

The generated workflow has 9 discrete Inputs (each able to assume only 2 values) and 3 continuous Outputs. In order to avoid the exploit of a discrete optimization method, we preferred to construct a response surface to correlate inputs and outputs. The choice of this approach has been lead not only by the mathematical issues that affect discrete optimization, but also to create an approximated model for future reference. The first step has been the definition of a reference set of experiments (DOE). In this case a full factorial DOE would have required 2^9 = 512 experiments. Due to the reduced computational time requested by ASTRID (30 seconds per run on average) we choose to perform the full exploration of the design space, thus providing us the highest possible number of points to be used for the construction of the response surface. The second step has been the definition of the response surface itself. Due to the discrete nature of the inputs, we expected inputs/outputs correlations in the form of twisted planes Fig. 7; among the possible interpolating surfaces available in Optimus we used the linear radial basis functions (RBF) as higher order approaches would have been unable to improve the accuracy of the surface in spite of an additional computational effort. The obtained approximation model has been validated over the experiments set leading (predictably) to coefficient of determination R^2 equal to 1 and a sum of squared error (SSE) value that is only introduced by the machine epsilon.

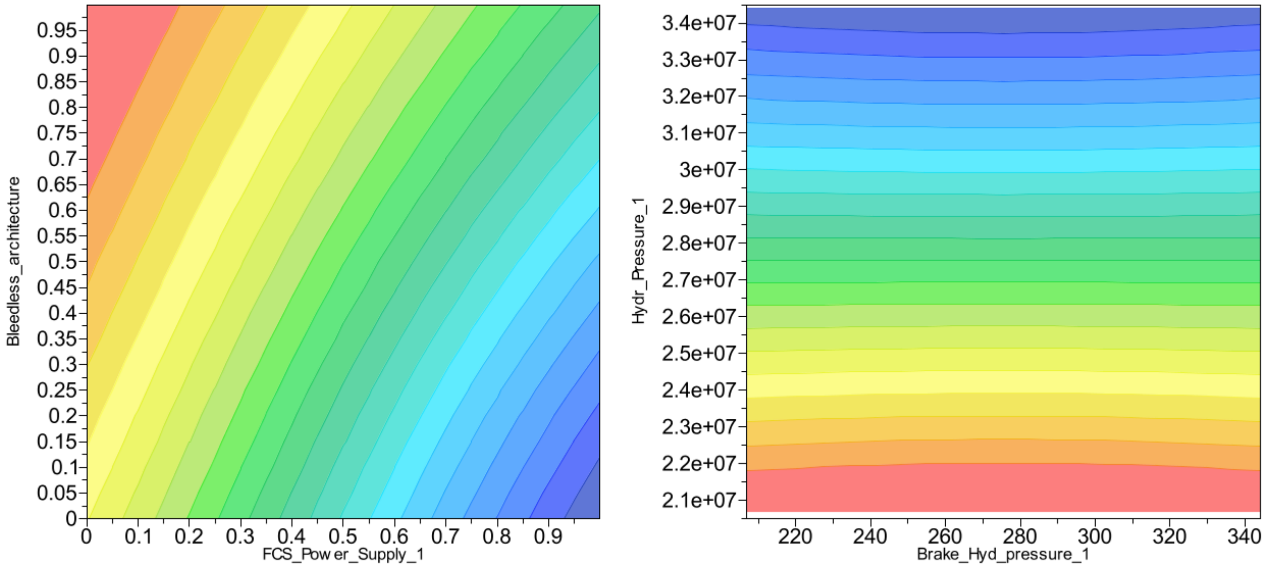

Fig. 7 RSMs showing systems total weight dependencies on FCS power supply and chosen bleedless architecture (left) and systems total cost function of brake and hydraulic system pressure (right)

Finally the RSM has been used to identify the systems configuration parameters associated to minimum total cost and minimum total system and fuel mass. We used a global optimization algorithm to ensure the widest coverage of the design space; the input variables were constrained as in Table 1.

In the first case, Table 5, the Differential Evolution algorithm needed only 20 iterations to find the best solution but performed additional runs because of the poor convergence given by the discrete nature of the problem. The result has been confirmed both by running the optimization with different starting point (resulting in different number of iterations to reach the optimum, ranging from 18 to 80) and by finding the desired result among the DOE experiment.

Inputs	**Start**	**End**	**Low**	**High**
FCS_Power_Supply	0	1	0	1
LND_GEAR_RETRACTION_Power_Supply	0	1	0	1
LND_GEAR_STEERING_Power_Supply	0	1	0	1
LND_GEAR_BRAKING_Power_Supply	0	0	0	1
Brake_Hyd_pressure	206.8	344	206.8	344
Hydr_Pressure	2.068e7	3.44e7	2.068e7	3.44e7
Primary_electric_voltage	2	5	2	5
Primary_Electric_Machine	1	1	1	4
Bleedless_architecture	0	1	0	1
Outputs				
Systems_weight_total	8248.025	8175.592371		
Fuel_Weight_SYSTEMS	119.1605	53.21153481		
Total_Cost_systems	1.31E+07	1.08E+07		

Table 5: Optimization result for minimum systems total cost.

A similar approach has been used to explore the solutions characterized by the minimum value for sum of systems and additional fuel mass, Table 6.

Inputs	Start	End	Low	High
FCS_Power_Supply	0	1	0	1
LND_GEAR_RETRACTION_Power_Supply	0	1	0	1
LND_GEAR_STEERING_Power_Supply	0	1	0	1
LND_GEAR_BRAKING_Power_Supply	0	0	0	1
Brake_Hyd_pressure	206.8	344	206.8	344
Hydr_Pressure	2.068e7	3.44e7	2.068e7	3.44e7
Primary_electric_voltage	2	5	2	5
Primary_Electric_Machine	1	1	1	4
Bleedless_architecture	0	1	0	1
Outputs				
Systems_weight_total	8248.025	8175.592371		
Fuel_Weight_SYSTEMS	119.1605	53.21153481		
Total_Cost_systems	1.31E+07	1.08E+07		

Table 6: Optimization result for minimum sum of systems and fuel mass.

5. Conclusions

In this paper, a workflow for the automated on-board system architecture selection during the preliminary design of the aircraft has been presented. The work has been carried out within a collaboration between Politecnico di Torino and Noesis Solutions. A 90 passengers regional jet has been selected as case study. Optimus software has automatically derived 512 possible system architectures, which have been designed by Politecnico's tool named Astrid. In particular, results of system masses, system fuel consumptions and costs have been obtained, identifying the two solutions characterized by the lower weight (system and fuel) and lower costs (acquisition and operating costs).

This work has been performed in the contest of AGILE project. The described workflow has been developed in order to be integrated within the entire MDO environment being realized in AGILE project. This work have been the aim of demonstrating the potentialities of the automatic selection of the system architecture, noticing the effects of the configurations in terms of masses, fuel consumption and, most important, costs.

Simplified models for fuel and cost estimation have been coded and integrated within the workflow. More affordable results could be obtained employing other higher fidelity tools, as those that could be provided by other partners of the project consortium. In this way, the maintenance cost could be included togheter with the „snow ball” effect giving by the other design disciplines.

Acknowledgment

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