Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 29 (2018) 146–156

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th CEAS AIR & SPACE CONFERENCE AEROSPACE EUROPE 2017, CEAS 2017, 16-20 October 2017, Bucharest, Romania

A modelling framework to support power architecture trade-off studies for More-Electric Aircraft

Ana García Garriga[a]*, Parithi Govindaraju[a], Sangeeth Saagar Ponnusamy[a], Nicola Cimmino[b], Laura Mainini[a]

[a]*United Technologies Research Centre Ireland, Penrose Wharf Business Centre, Cork, T23XN53, Ireland*
[b]*Università degli Studi di Napoli "Federico II", Corso Umberto I, Napoli, 80138, Italy*

Abstract

This work presents a modelling framework to enable comparison and trade-off study of different aircraft system architectures. The framework integrates a computational module to select feasible architectures with a modelling platform that simulates the power generation, distribution and fuel consumption of the aircraft as well as system-level models for the system being evaluated. Its capabilities are demonstrated for the case of the electrification of the primary flight control system (PFCS) using different electric technologies (EHA, EMA) and different levels of electrification ranging from the conventional hydraulic to the all-electric. The performances of different architectures are analysed with respect to the change in the mechanical power extracted from the engine, the weight and the fuel burn of the aircraft. The framework demonstrates the capability of evaluating multiple, different, system architectures in a way that is scalable for different systems or different aircraft. It supports a designer evaluating the aircraft-level impact of their design choice at system-level, and it can aid in assessing technology options early in the design process.

Peer-review under responsibility of the scientific committee of the 6th CEAS Air & Space Conference Aerospace Europe 2017.

Keywords: *More-Electric Aircraft; Architecture Evaluation; Trade-off Analysis; Modelling and Simulation*

* Corresponding author. Tel.: +353 21-455-1772.
E-mail address: garciaga@utrc.utc.com

2352-1465 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 6th CEAS Air & Space Conference Aerospace Europe 2017.
10.1016/j.trpro.2018.02.013

1. Introduction

The number of passengers transported by commercial aircraft is expected to double by 2035 [IATA (2016)] and as the aviation industry rises to meet those market needs, some considerations need to be taken. The increase in passenger numbers means an increase in the environmental impacts of aircraft, and an increase in the number of aircraft being designed and built in a short period of time. To outline clear goals that take these and other factors into account, the Advisory Council for Aeronautics Research in Europe (ACARE) set clear goals for the aviation industry to reach by the year 2050 [ACARE (2017)]: A reduction in perceived noise to one half of current average levels, a 50% cut in carbon dioxide (CO2) emissions per passenger kilometre and an 80% cut in nitrogen oxide (NOx) emissions. In addition to the environmental goals, ACARE proposes to establish ways in which different companies are able to work together more effectively. This enhanced collaboration in conjunction with advanced tools, methods and processes would allow the time to market of new products to be reduced.

In this context, the European Commission launched the Clean Sky 2 Joint Technology Initiative [European Commission (2014)], a public-private partnership which provides funding for research and development of the processes, tools and technologies that will enable the aviation industry to reach the goals set out by ACARE. The studies presented in this paper are conducted within the ModellIng and Simulation tools for Systems IntegratiON on Aircraft (MISSION) project [Valdivia – Guerrero *et al.* (2016)] which is funded by Clean Sky 2. The MISSION project aims to develop an integrated framework capable of supporting aircraft design, development, and validation processes. The development of such a framework presents many challenges [Cimmino *et al.* (2017), Burgio *et al.* (2017)]. Specifically, this paper focuses on the trade-off comparison of different aircraft power architectures. To enable this comparison, several modules are integrated: a modelling platform to simulate power generation, transformation and distribution at aircraft-level; a computational module to filter sets of feasible architectures; and system-level models. The framework is demonstrated for the case study of the electrification of the aircraft's flight control system using different technologies and different levels of electrification ranging from the conventional hydraulic to the completely electric.

The challenge is that the conceptual phase of the design process of aircraft involves the largest amount of design freedom, and while this allows the designer the opportunity to explore numerous solutions, the effective exploration of the vastness of the potential overall trade space is difficult. The overall trade space comprises of a set of feasible architectures that can provide the necessary functions and the design space for the individual systems and components of each architecture. Effective exploration and evaluation of the overall trade space is becoming increasingly important in the aerospace domain due to the emergence of several technologies that can be used as drivers of systems within the aircraft. This allows for the possibility of unearthing innovative architecture and design solutions that may not conform to conventional architectures and designs of the past generations of aircraft via a systematic exploration of this design space. Because of the combinatorial explosion of the number of candidate architectures, an automated architecture exploration and filtering process is essential to narrow down the design space to a list of feasible candidate solutions.

This work follows on the steps taken within previous European Union (EU) research frameworks. Several other projects have undertaken efforts to improve aircraft design, development, validation and verification processes. For example, within the sixth framework program (FP6), Vivace (2011) developed a collaborative enterprise to support the aeronautic product engineering life cycle, Moet (2011) developed a framework for the integrated design of validated electrical technologies for More-Electric Aircraft (MEA); in the seventh framework programme (FP7), Toica (2017) created an integrated platform for the aircraft thermal system, Across (2017) created an integrated framework for cockpit design and Crescendo (2012) laid the foundations for the Behavioural Digital Aircraft up to MISSION in the current Horizon 2020 Clean Sky 2 Initiative.

In the same vein as the Moet project mentioned above, one of the key design evolutions the MISSION project will support is the progressive electrification of aircraft towards MEA and All-Electric Aircraft (AEA). There are numerous efforts reported in current literature [Cao *et al.* (2012) to Sarlioglu *et al.* (2015)] that give an overview of the key technology enablers for MEA. One such enabler is the electrification of the actuation system of the aircraft and subsequent removal of the hydraulic power system, which motivates the choice of this case study to demonstrate the MISSION framework. Previous work in this topic is extensive and a selection of the most relevant efforts in the context of this paper is presented below. In Jackson (2013), the author compares a conventional hydraulic actuation and a hybrid architecture featuring both Electro-Hydrostatic Actuators (EHAs) and hydraulic actuators this approach didn't address Electro-Mechanical Actuators (EMA). To be able to study a complete electric architecture, a deeper study of the power architecture of the aircraft had to be undertaken. Liscouet-Hanke (2008) and Lammering (2014) analysed different power architectures but focused on a small number of options for each system. De Tenorio (2010) and Armstrong (2008) proposed approaches to manage a larger number of alternatives through the use of Model Based System Engineering (MBSE) techniques, but the number of options for individual systems was still limited. Chakraborty (2015) proposed a methodology to enable the analysis of changes at the system-level, but uses heuristics to reduce the size of the design space to a small subset of architectures.

The increase in electrification causes the electric loads to become larger and operational requirements to increase. These were studied further by Armstrong (2011), Seresinhe and Lawson (2014) and Xia (2011). The loads required by the actuators have to be calculated through performance models: Servo-Hydraulic Actuators (SHA) and EHA are more mature technologies that have been implemented in commercial aircraft such as the A380 or the B787, therefore there is more information available; for the study of EMAs, and the EU-funded project Actuation 2015 (2017) provided a number of resources.

Once all the available technology options are clear, the different options for a system can be considered and the design space for that system explored in greater detail. Bauer *et al.* (2007) and Haitao *et al.* (2011) proposed methods and constraints to explore the optimization of the different primary flight control actuation architectures. The approach taken to the architecture exploration of the Primary Flight Control System (PFCS) in this paper follows the method introduced by Becz *et al.* (2010) and Zeidner *et al.* (2010) to explore the design space, and then couples it with a model of the power platform of the aircraft and models of the different types of the actuator to enable the trade-off comparison among architectures.

The paper is structured as follows: Section 2 describes the case study chosen. In Section 3 a description of the overall process is presented, as well as the method followed in each of the modules. Section 4 shows the results of the evaluation of several architectures and their comparison. Finally, Section 5 summarises the conclusions and discusses further improvements and future work.

2. Case Study

The electrification of the primary flight control actuation system is an ongoing effort in the aviation industry; therefore it was chosen as a representative case study to demonstrate the MISSION framework. An architecture evaluation tool was adopted to down select a representative subset of feasible architectures with varying degrees of electrification. The architectures chosen determined the technology type and number of each type of actuator for each control surface.

The case study was a single-aisle commercial aircraft with a conventional configuration, such as the Airbus A320, performing a typical mission. The configuration of the PFCS for an A320 was taken as the starting point [0]: Each of the flight control surfaces has to be moved by 2 to 3 actuators, each characterised by their geometry, attachment characteristics, kinematics, components, aerodynamic loads, stroke, speed, etc.

The scope of this study was limited to PFC actuators. The main actuators studied were:

- Aileron actuators (2 surfaces and 2 actuators per surface on A320)
- Elevator actuators (2 surfaces and 2 actuators per surface on A320)
- Rudder actuators (1 surface and 3 actuators on A320)

A large number of possible architectures were generated due to various possible technologies (namely SHA, EMA and EHA) and the different locations where they can be placed. The control surface configuration of the A320 and the redundancy rules imposed by regulation were respected. During an initial run it was found that, despite the number of constraints imposed, the size of the design space remained large and many of the possible architectures had a similar impact on the aircraft performance. This motivated the choice to discuss architectures that are feasible and significantly differ from each other in order to demonstrate the framework.

3. Method

The framework discussed in this paper includes several modules that are integrated to enable architecture trade-offs, namely, a computational architecture exploration tool that filters sets of feasible architectures, a power platform to simulate the power distribution of the aircraft, and system-level models. The first step in the proposed process involved the identification of requirements. The next step was to identify the geometry for a conventional (tube-and-wing) aircraft. These specifications then served as inputs to the aircraft architecture exploration tool, and the other modules. The tool searched for architecture solutions based on different technology solutions for different systems, functional requirements (e.g., consistency in generation and distribution technology types) and safety constraints (e.g., reliability requirements). After feasible architectures are identified they were fed into the power platform. The power platform provided estimates for several aircraft-level metrics such as mass and fuel burn, which were then used to analyse the performance of the architectures.

The aircraft size, geometry, mission requirements and regulation translated into system-level requirements and determined the primary flight control actuators size and behaviour. The distribution model calculated the amount and type of power it needed to deliver to the primary flight control model, taking into account power losses, space constraints and redundancy requirements. Based on the amount of power that needs to be distributed, the power platform calculated the performance and size of the power extraction and conversion systems (i.e. electric generators, hydraulic pumps, etc.) subject to space, mass and reliability constraints. Knowing the power required by the power conversion systems enabled the sizing of the power sources (engine and auxiliary power unit) and the change in their performance. Finally, all of the aircraft-level impacts (weight, drag, fuel efficiency) from all the systems were compounded to calculate the aircraft performance. The process was repeated for several architectures and the performance results were compared.

3.1. Architecture selection

This paper exploited the Architecture Evaluation and Enumeration (AEE) method [Becz *et al.* (2010) and Zeidner *et al.* (2010)] developed at United Technologies Research Center to demonstrate the use case of exploring primary flight control architectures. The AEE method is a novel solution strategy that provides a systematic, rigorous and exhaustive exploration of the technology and architecture design space for new application domains. This method follows a multi-level filtering process, wherein the design trade space is adaptively reduced in successive refinement levels. Typically, this method employs two levels of successive filtering, though this method can be extended to several more levels. In the first level of this two-level filtering process, AEE used an abstraction of the architecture design space to rapidly explore the design space and identify feasible solutions. This set of feasible solutions was further screened using higher fidelity analysis in the second level. **Error! Reference source not found.** illustrates the AEE technology screening process. Zeidner *et al.* (2010) explains in more detail the AEE method and the application case study of investigating alternative aircraft power systems.

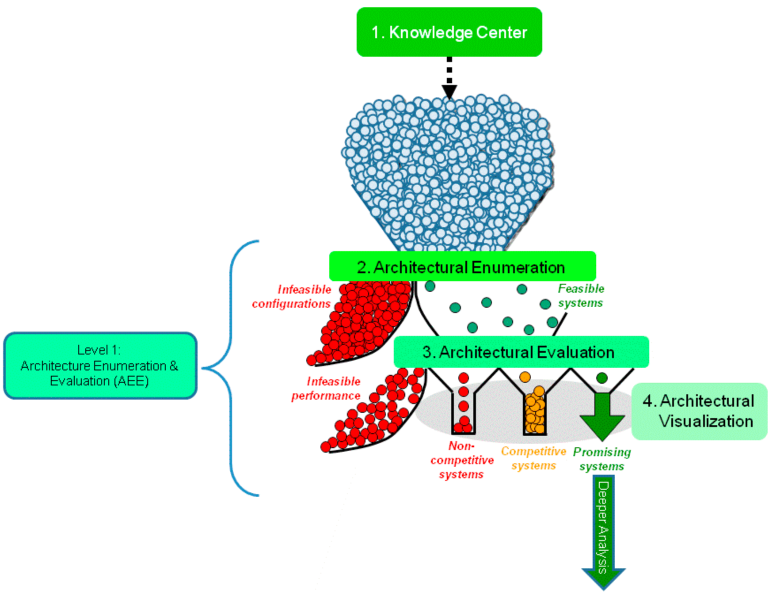

Figure 1.Illustration of the AEE method [Zeidner *et al.* (2010)]

The goal of the flight control architecture problem implemented using the AEE method was to identify a feasible collection of control surfaces, Flight Control Computers (FCCs), power sources and actuators forming feasible architectures. This design problem of identifying promising flight control system architectures was based on the problem formulation and technological constraints proposed by Bauer *et al.* (2007). Some of the technological constraints imposed are:

- Each actuator must be connected to the appropriate power source type. For instance, a SHA must be connected to a hydraulic power source; an EMA must be connected to an electric power source.
- Depending on the actuators in the architecture, an appropriate power source (hydraulic and/or electric) must be generated
- Each actuator must be connected to at least one FCC and to a maximum of two FCCs
- Each actuator must be connected to only one control surface
- Each primary flight control surfaces must be connected to at least two actuators
- The actuators for each primary flight control surface must be of different types

These technological constraints served as the first refinement level in the AEE method and reduced the architecture design space to a manageable list of feasible architectures. To demonstrate the solution approach for the trade-off comparison between different primary flight control architectures, the list of feasible architectures identified at the first level was down selected to a set of significantly different architectures which were then evaluated using the power platform.

3.2. Power Platform

The power platform is composed of models for different aircraft systems. It requires that a representative subset of the systems involved in aircraft functions is modelled so as to capture the full effects of the technology change in the interaction between essential aircraft systems. An example of the system models involved is depicted in Figure 2. These models can be realised at different levels of detail depending on fidelity needs and computational budget.

The scope of the power platform includes, amongst others, models of the mass, electrical performance, mechanical performance. Developing such aircraft-wide models requires associated models in the system as well as a certain level of detail in the geometry of the aircraft. For example, the mass calculation of the primary flight control system required models of the actuators attached to the wing and tail control surfaces, and the associated hydraulic (pipes, reservoir etc.) or electric lines (power electronics, cables etc.). It also required knowledge of the size and position of the flight control surfaces and the flight control requirements of the aircraft. This level of detail drives the need for key inputs or design characteristics from an aircraft sizing model such as aircraft loads, structure, configuration, and from the system architecture evaluation tool such as number of components, technology type etc.

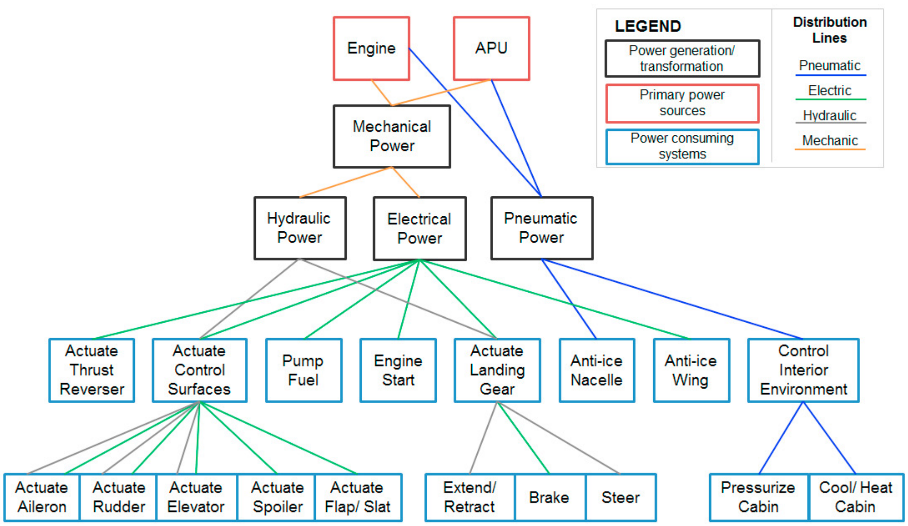

Figure 2. Simplified view of the systems involved in the power platform

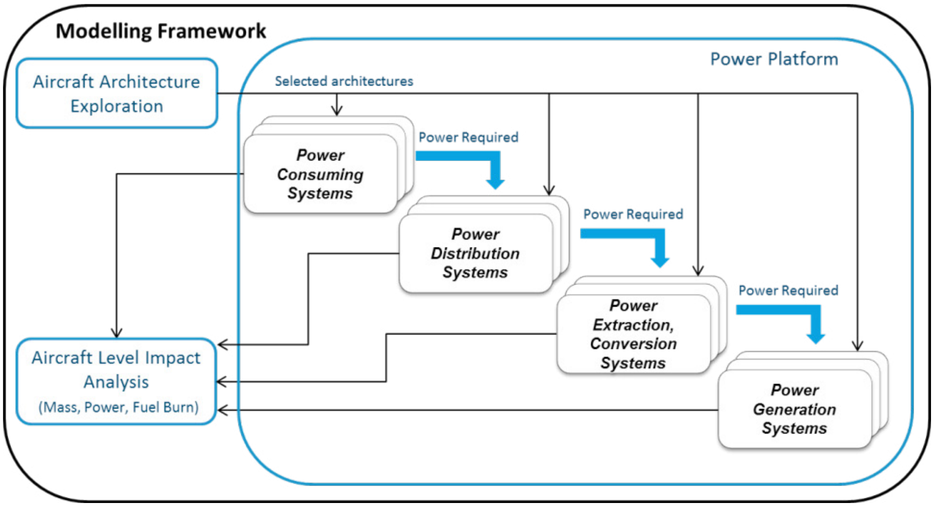

Figure 3. Schematic of the power platform data flow

The power generation and distribution systems depend strongly on the amount of power required by the power sinks. The schematic flow of data for the power platform is given in Figure 3. Each of the blocks is a system model that is implemented in the power platform to capture the overall flow of different kinds of power and their impact on aircraft performance. For the present case study, all the architectures were compared to a baseline aircraft configuration including a pneumatic power system and an all-hydraulic actuation configuration unless otherwise specified.

3.3. System models

For the purpose of this paper, three different types of actuators were considered: SHA, EMA and EHA. In addition to the actuator themselves, the change from a hydraulically-powered actuator to an electrically powered actuator means that the power distribution lines and the power generating systems also need to be modelled.

Modelling of systems involves sizing the system for the worst case scenario and estimating its mission performance. The worst cases are derived from regulation and occur at points during the flight envelope where performing certain manoeuvres imposes the greatest hinge moments on the control surfaces which, in turn, defines the maximum power required by the actuators. These manoeuvres are outlined in certification specification documents from the Federal Aviation Administration and the European Aviation Safety Agency for large commercial airplanes [Part 25, FAA (2017) and Part 25, EASA (2017)]. The requirements for the ailerons are given in FAR/CS 25.349, for the elevators in FAR/CS 25.255 and for the rudder they occur in cases where one engine fails as outlined in FAR/CS 25.147.

Since the actuator performance under worst case conditions drives the sizing of the actuator system's components involved in the use case, a model that captures the dynamics of the actuator is needed. However, dynamic models are too computationally expensive when many architectures are being considered, therefore, the dynamic models are run offline for the different cases and the results integrated in lookup tables. The power platform can then choose the correct set of data for the different mission cases. The choice spans three dimensions: the type of actuator (SHA, EMA, EHA), the control surface involved (aileron, elevator, rudder) and the mission conditions.

The first cases run were the worst case scenarios for the maximum hinge moment and maximum deflection of the surface. The geometry of the control surfaces, their wing attachment points and hinge structure is fixed for a given aircraft. The size and geometry of the actuator varies depending on the max power required for a given manoeuvre. The maximum power required is also used when calculating the power budget for the whole aircraft in the emergency conditions of rejected take-off and one-engine landing, since those cases will be the limiting cases for the power consumption and availability of the aircraft as a whole [Seresinhe and Lawson (2014) and Xia (2011)].

However, during normal operation, the control surfaces do not experience limiting loads and their angle of deflection is small as manoeuvres are performed during larger time intervals. During regular operation, the actuator has to keep the control surface steady under aerodynamic conditions and deflect the surface according to the command given. An example manoeuvre is the command to deflect the control surface 5 degrees one direction, hold for some time, then deflect it in the other direction and then back to the zero deflection position, all of these subject to wind gusts of varying intensity modelled as simple disturbances. The power required for this type of manoeuvre is much smaller than the sizing condition and, therefore, the models were also run for normal operational conditions to reflect the power required at different mission points in a normal operation mission profile. Worst case conditions are used to size the capacity of the distribution lines for different power systems, their length is fixed by the geometry of the aircraft. The generators or pumps were also sized for the worst case scenario but their number is fixed according to general design rules. The power losses in the transformation and distribution of the power are computed using normal operation conditions for the given mission profile and worst case conditions for the emergency cases.

4. Results

As explained in Section 3.3 above, certain command manoeuvres are given for different operation conditions. The maximum force on the control surface hinge associated with the manoeuvre for emergency conditions (with an added safety factor) represents the stall load the actuator is rated for, and therefore, its sizing point. The comparison between two electric actuators and the baseline performance obtained from running the models for each control surface under the same stall load conditions is presented in Figure 4. The power consumed by the electric actuators was compared to the SHA performance by calculating the hydraulic power needed from the mass flow rate and pressure of the system.

Figure 4 shows that both EMA and EHA are significantly heavier than the conventional hydraulic solution: the EHA doubles and the EMA almost triples the weight of the conventional solution. The benefit from using EMAs and EHAs in terms of power consumption is also illustrated. From the analysis of the single actuators, the option with the best performance for a given mission can't be established since the lower power consumption of the EMA might balance out its larger mass. Therefore, the need to analyse the effects this change in technology at aircraft-level becomes apparent early in design process.

As explained in section 3.1, there are many feasible architectures possible, all were compared to a baseline of an all-hydraulic architecture as present in the previous generation of single-aisle aircraft. While the results presented in this section are limited to one design of the actuators, and it is likely that their performance could be improved when more details are known later in the design process, the comparison between the different architectures still serves to showcase the examples of trade-offs that exist when choosing different technologies to perform the same function. It might also be used to build new derivative designs using legacy models.

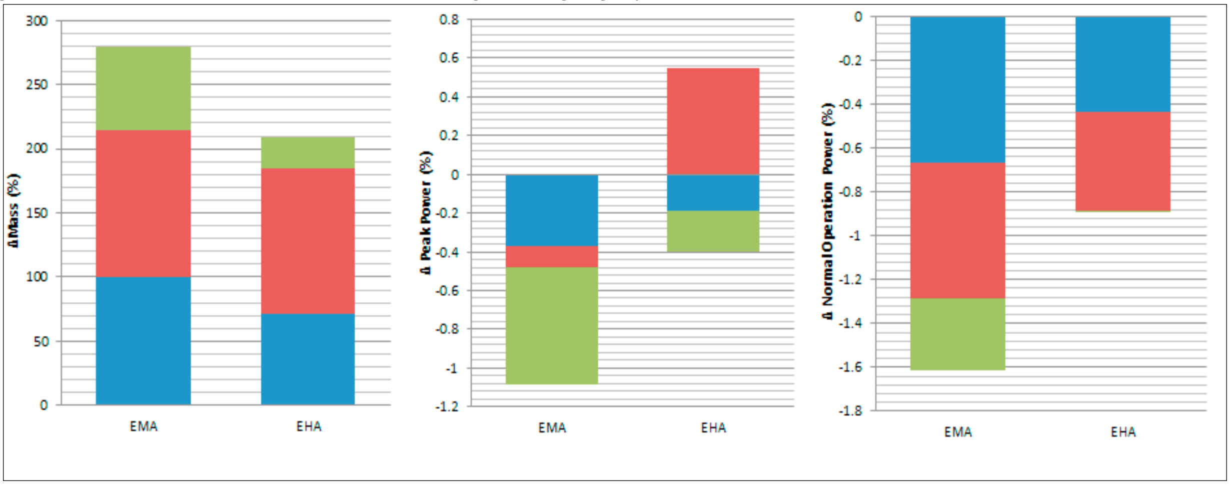

Figure 4. Comparison of EHA and EMA Actuator to Baseline

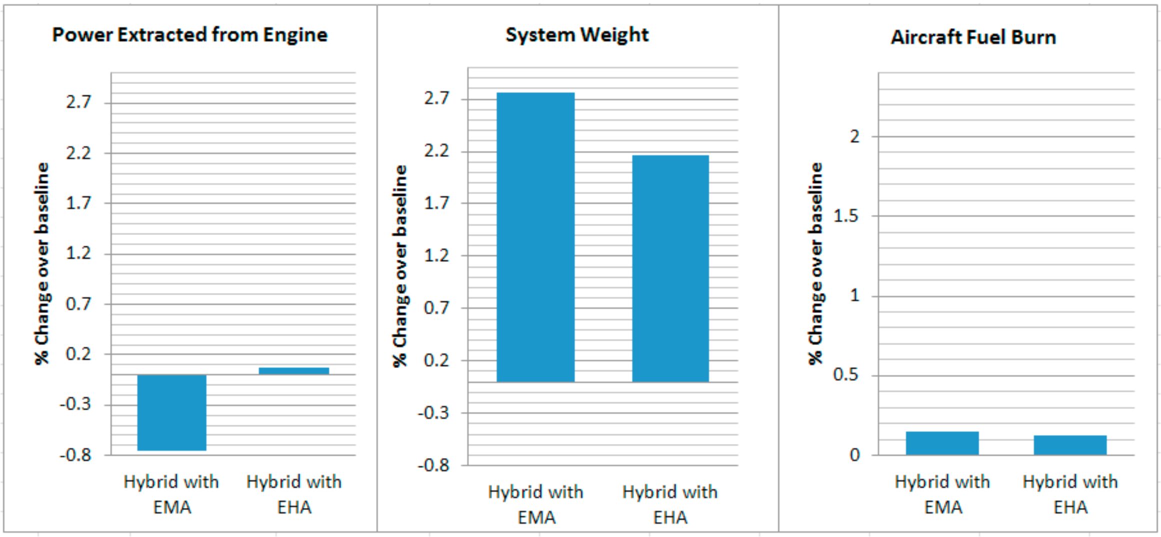

Figure 5. Comparison of hybrid architectures with distributed hydraulic and electric power

The first set of architectures that were analysed was composed of hybrid architectures where each control surface is powered by both hydraulic and electric actuators. Current aircraft such as the A380, A350 and B787 have some EHAs as part of the primary flight control configuration even if in a backup role. EMAs have not yet flown commercially due to reliability issues such as jamming but they are expected to once these issues are addressed [Sarlioglu *et al.* (2015)] so the case of architectures including both hydraulics and EMAs was also studied .

Figure 5 shows that the hybrid architecture with both hydraulic actuators and EMAs is both more efficient in terms of power required, and heavier than the baseline and the EHA hybrid architecture, as expected from the results in Figure 4. However, it also shows that while the architecture with EHAs still consumes more fuel overall than the baseline, its lighter weight results in slightly better fuel efficiency than the architecture with EMAs. Both hybrid architectures are, nevertheless, less fuel efficient and heavier than the conventional, largely due to the greater mass of the actuator themselves, increase their overall impact on the systems weight.

One of the significant theoretical advantages of converting to electric actuation systems is the reduction in the hydraulic distribution system which is both heavy and causes problems due to leakage of fluid [Wheeler and Bozhko (2014)] and other maintenance issues. In the architectures presented above, each surface now needs to be provided with both electric and hydraulic distribution lines and the associated the weight penalty that represents. In the next set of hybrid architectures studied, all the actuators in either wing or empennage will be either hydraulic or electric, with the electrically powered control surfaces including both types of electric actuators for the sake of redundancy. In order to assess the impact the reduction in the distribution lines may have other surfaces such as the spoilers in the wing and the horizontal stabilizer in the tail, they are also electrified with respect to the baseline.

For the case of electrifying the empennage, the weight reduction in the hydraulic system offsets a large amount of the weight gain due to the heavier actuator as seen in Figure 6. This fact, coupled with the reduction in power extracted from the engine, causes the architecture with the electrified tail to burn only 0.1% more fuel than the baseline, well within the margin of error in the conceptual design. In the case of electrifying the wing, the benefits are not so immediately evident due to the fact that a lot of the remaining hydraulic architecture remains in the wings due to the position of the main landing gear and the engines; therefore the reduction in weight is significantly less.

Once the benefits of having only one type of distribution lines to the surface was demonstrated, the next step was to investigate a fully electric primary flight control system, such as in the case of an All-Electric-Aircraft. The first electric architecture studied features both EMAs and EHAs on all surfaces, but the cases of the all-EHA and all-EMA architecture were also studied to observe the full impact of each technology. For all cases, the hydraulic systems in the aircraft were replaced with their electric counterparts so the weight of the hydraulic system is eliminated.

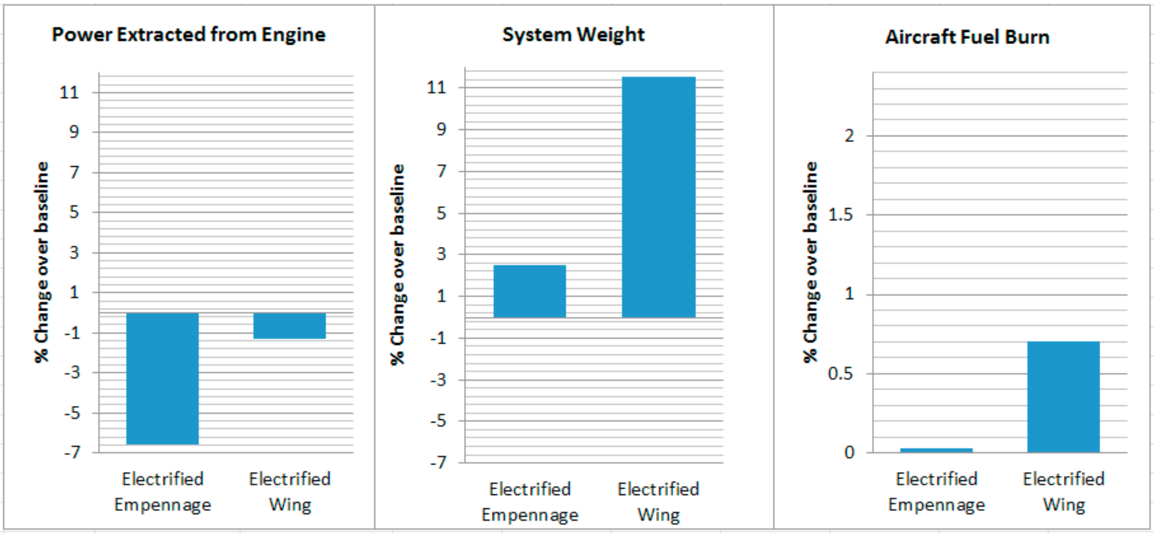

Figure 6. Comparison of hybrid architectures with completely electric surfaces

Figure 7 shows that the all-electric actuation architectures all require less power from the engine but they are also all significantly heavier (more than 15% increase). This weight increase is due to the individual actuator weight as well as the increase in the electric system weight caused by the higher loads required. Although, overall these electric actuation architectures consume from 1 to 2 % more fuel than the baseline, the huge impact of weight on the fuel burn performance of the aircraft shown here indicates that if the power density of the system models improves, the fuel efficiency could be reduced to baseline levels or even further.

These results demonstrate the capability of the MISSION framework to support trade-off analysis, both in terms of the type of design choices and the aircraft-level impacts. The results are, nonetheless, dependent on the system models chosen and the optimization of these would lead to changes at the aircraft-level and likely better performance. In addition, when the aircraft manufacturer is making a design decision there are many other factors to consider such as safety concerns, ease of maintenance, modularity of the design etc. which are not yet captured in the framework.

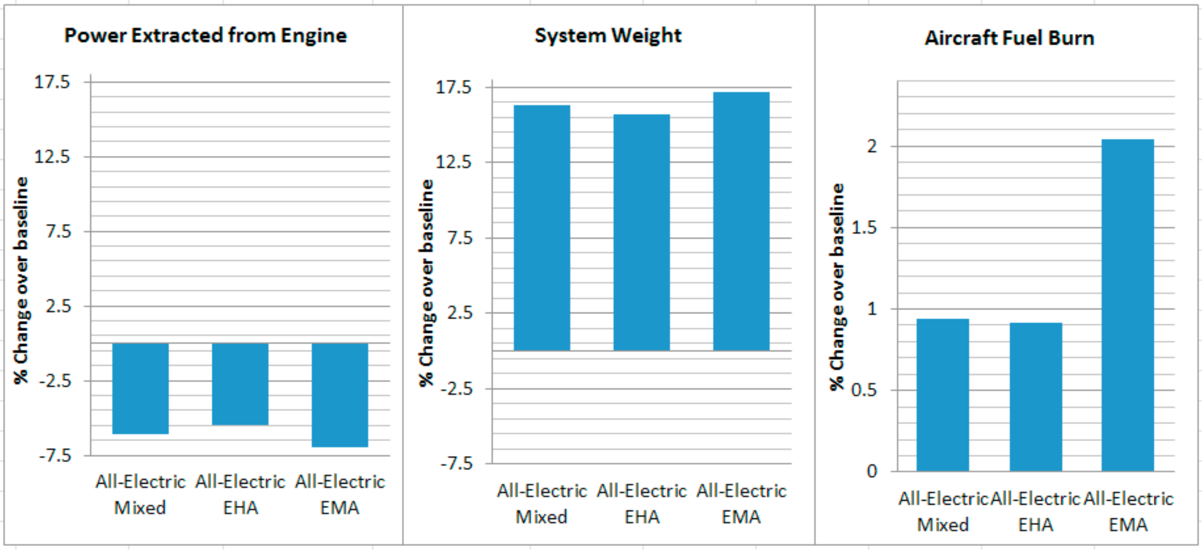

Figure 7. Comparison of all electric actuation architectures

5. Conclusion

This paper proposed and discussed a methodological framework for the trade-off analysis of early design decisions for the use case of electrifying the Primary Flight Control System of a short range, single aisle aircraft. The type of performance data that can be assessed as well as the range of architectures that can be evaluated was illustrated. Future developments include the optimization of the system model accounting for its aircraft-level impact, and expanding the results shown to take into account metrics such as emissions, maintenance and cost. The results discussed in this paper demonstrated that the framework can assist large-scale evaluation of many similar architectures; it can be expanded to aircraft of different size and different configurations at system-level. The final goal is allowing an aircraft manufacturer or supplier to assess the impact of a system change at aircraft-level for a range of design options early in design process.

Acknowledgements

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No CS2-SYS-GAM-2014-2015-01. The authors wish to acknowledge C. Lentz, L. Zeidner and the team at UTRC-East Hartford and D. Mehta at UTRC-Ireland for their valuable inputs and suggestions.

References

International Air Transport Association, 2016, "Air passenger forecast: Global Report", Montreal, Canada

Advisory Council for Aeronautics Research in Europe, 2017, "Strategic Research & Innovation Agenda", Executive Summary, http://www.acare4europe.org/

European Commission, 2014, "Clean Sky 2: developing new generations of greener aircraft", HORIZON 2020 The EU Framework Programme for Research and Innovation, http://www.cleansky.eu/

V. Valdivia – Guerrero, R. Foley, S. Riverso, P. Govindaraju, A. Elseikh, L. Mangeruca, G. Burgio, A. Ferrari, M. Gottschall, T. Blochwitz, S. Bloch, D. Taylor, D. Hayes-McCoy and A. Himmler, 2016, "Modelling and Simulation Tools for Systems Integration on Aircraft", SAE Technical Paper, No. 2016-01-2052

N. Cimmino, S.S. Ponnusamy, P. Govindaraju, A. Garcia Garriga, V. Valdivia Guerrero, L. Albiol Tendillo, L. Mainini, (2017), "A Modelling and Simulation Framework for the Integrated Design of Aircraft Systems", To appear in proceedings of *7TH European Conference For Aeronautics And Aerospace Sciences (EUCASS)*, Milan, Italy, July 3 -6

G. Burgio, L. Mangeruca, A. Ferrari, M. Carloni, L. Albiol Tendillo, P. Govindaraju, V. Valdivia Guerrero, S. Reglitz, J. Stavesand, A. Himmler, O. Oelsner, M. Gottschall and L. Yapi, (2017), "Framework for modelling and simulation of multi-physics aircraft systems with distributed electronic controllers", To appear in proceedings of *SAE AeroTech Congress & Exhibition 2017*, Fort Worth, TX, USA, September 26-28

VIVACE, 2011, "Value Improvement through a Virtual Aeronautical Collaborative Enterprise. Final Report Summary", Final Report Summary, Project: FP6-Aerospace-502917, http://cordis.europa.eu/result/rcn/47814_en.html

MOET, 2011, "More Open Electrical Technologies", Final Report Summary, Project: FP6-Aerospace-30861, http://cordis.europa.eu/project/rcn/81472_en.html

TOICA, 2017, "Thermal Overall Integrated Conception of Aircraft", Final Report Summary, Project: FP7-Transport-604981, http://cordis.europa.eu/result/rcn/197012_en.html

ACROSS, 2017, "Advanced Cockpit for Reduction Of Stress and Workload", Final Report Summary, Project: FP7-Transport-314501, http://cordis.europa.eu/result/rcn/193446_en.html

CRESCENDO, 2012, "Collaborative & Robust Engineering using Simulation Capability Enabling Next Design Optimisation", Final Report Summary, Project: FP7-Transport-234344, http://cordis.europa.eu/project/rcn/93958_en.html

W. Cao, B. C. Mecrow, G. J. Atkinson, J. W. Bennett and D. J. Atkinson, 2012, "Overview of Electric Motor Technologies Used for More Electric Aircraft (MEA)", *IEEE Transactions on Industrial Electronics*, 59.9, pp. 3523-3531

R. T. Naayagi, 2013, “A review of more electric aircraft technology”, *International Conference on Energy Efficient Technologies for Sustainability*, Nagercoil, India, pp. 750-753.

P. Wheeler and S. Bozhko, 2014, “The More Electric Aircraft: Technology and challenges,” *IEEE Electrification Magazine*, 2.4, pp. 6-12

B. Sarlioglu and C. T. Morris, 2015, “More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft*", IEEE Transactions on Transportation Electrification*, 1.1, pp. 54-64

D. Jackson, 2013, “Robust Aircraft Subsystem Conceptual Architecting”, *Ph.D. thesis*, Georgia Institute of Technology, Atlanta, GA, USA

S. Liscouet-Hanke, 2008, “A Model-Based Methodology for Integrated Preliminary Sizing and Analysis of Aircraft Power System Architectures”, *Ph.D. thesis*, Université de Toulouse, Toulouse, France

T. Lammering, 2014, “Integration of Aircraft Systems into Conceptual Design Synthesis”, *Ph.D. thesis*, Institute of Aeronautics and Astronautics (ILR), RWTH Aachen University, Aachen, Germany

C. de Tenorio, 2010, “Method for Collaborative Conceptual Design of Aircraft Power Architectures”, *Ph.D. thesis*, Georgia Institute of Technology, Atlanta, GA, USA

M. Armstrong, 2008, “A Process for Function Based Architecture Definition and Modeling”, *Master’s thesis*, Georgia Institute of Technology, Atlanta, GA, USA

I. Chakraborty, 2015, “Subsystem Architecture Sizing and Analysis for Aircraft Conceptual Design”, *Ph.D. thesis*, Georgia Institute of Technology, Atlanta, GA, USA

M. Armstrong, 2011, “Identification of Emergent Off-Nominal Operational Requirements During Conceptual Architecting of the More Electric Aircraft”, *Ph.D. thesis,* Georgia Institute of Technology, Atlanta, GA, USA

R. Seresinhe and C. Lawson, 2014, “Electrical load-sizing methodology to aid conceptual and preliminary design of large commercial aircraft”, Proceedings of the Institution of Mechanical Engineers Part G, *Journal of Aerospace Engineering*, pp. 1–22

X. Xia, 2011, “Dynamic Power Distribution management for All Electric Aircraft”, *Master’s thesis*, Cranfield University, Cranfield, England

Actuation 2015, 2017, “Modular Electro Mechanical Actuators for ACARE 2020 Aircraft and Helicopters”, Final Report Summary, Project: FP7-Transport-284915, http://cordis.europa.eu/result/ rcn/193428_en.html

C. Bauer, K. Lagadec, C. Bès, and M. Mongeau, 2007, "Flight Control System Architecture Optimization for Fly-By-Wire Airliners", *Journal of Guidance, Control, and Dynamics*, 30.4, pp. 1023-1029

Q.I. Haitao , F.U. Yongling, Q.I. Xiaoye, and L.A.N.G. Yan, 2011, “Architecture optimization of more electric aircraft actuation system”, *Chinese Journal of Aeronautics*, 24.4, pp. 506-513

S. Becz, A. Pinto, L.E. Zeidner, K. Ritesh, A. Banaszuk and H.M. Reeve, 2010, “Design system for managing complexity in aerospace systems.”, *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference,* Fort Worth, TX,USA, 13-15 September, Paper No. AIAA-2010-9223

L.E. Zeidner, B.E. St. Rock, N.A. Desai, H.M. Reeve and M.P. Strauss, 2010, “Application of a technology screening methodology for rotorcraft alternative power systems.”, *48th AIAA Aerospace sciences meeting*, Orlando, FL, USA, 4-7 January, Paper No. AIAA 2010-1505

D. Briere, C. Favre and P. Traverse, 2001, “Electrical Flight Controls, From Airbus A320/330/340 to Future Military Transport Aircraft: A Family of Fault-Tolerant Systems”, Editor C.R. Spitzer, *The Avionics Handbook*, Second edition, **12**, CRC Press LLC, Boca Raton, FL, USA

Part 25, 2017, “Airworthiness Standards: Transport Category Airplanes”, *Federal Aviation Regulation*, FAA, www.ecfr.gov

Part 25, 2017, “Acceptable Means of Compliance for Large Aeroplanes CS-25”, *Certification Specification*, amendment 19, EASA, https://www.easa.europa.eu/document-library/certification-specifications