ASSESSMENT OF ELECTROMECHANICAL FLIGHT CONTROL ACTUATORS WITH REGARD TO DIRECT OPERATING COSTS

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ABSTRACT

A major objective of civil aviation is the progressive electrification of aircraft systems in order to enhance reliability while reducing operating costs at the same time. An aircraft's flight control system is considered as one of the identified key technologies to reach this goal. In this paper an approach for a novel flight control system architecture aiming towards a more electric aircraft is introduced and analyzed. The implemented concept consists of one hydraulic and two electrical systems (2E1H architecture) as power supply for the flight control system of a civil transport aircraft, which targets to represent a feasible medium term approach. The focus is put on the assessment of the impact on direct operating costs (DOC) compared to a traditional flight control architecture with exclusively hydraulically powered flight controls. In addition to the monetary analysis, a preliminary system safety assessment with emphasis on roll control is carried out to ensure the fulfillment of required safety standards. The Airbus A320 aircraft, which is currently equipped with three hydraulic power supply circuits (3H architecture) for flight controls, serves as the reference case for the analyses. The presented concept was developed in a cooperation project between the Institute of Aerospace Systems (ILR) of RWTH Aachen University and Liebherr-Aerospace Lindenberg GmbH.

NOMENCLATURE

(HV)DC	*(High Voltage) Direct Current*
AC	*Alternate Current*
AFDX	*Avionics Full Duplex Switched Ethernet*
CeRAS	*Central Reference Aircraft data System*
CS-25	*Certification Specifications for Large Aeroplanes*
CSR	*CeRAS Short Range*
DOC	*Direct Operating Costs*
EHA	*Electro-Hydrostatic Actuator*
ELAC	*Elevator Aileron Computer*
EMA	*Electro-Mechanical Actuator*
FAR-25	*Federal Aviation Regulations Part 25 - Airworthiness standards: Transport category airplanes*
JASC	*Joint Aircraft System/Component Code*
MCE	*Motor Control Electronics*
MICADO	*Multidisciplinary Integrated Conceptual Aircraft Design and Optimization*
PCU	*Power Control Unit*
ROM	*Rough Order Magnitude*
SEC	*Spoiler Elevator Computer*
SFCC	*Slat Flap Control Computer*

1. INTRODUCTION

A major objective of civil aviation is the full electrification of all aircraft systems in order to enhance reliability while reducing operating costs at the same time. An aircraft's direct operating costs (DOC) are significantly important for an airline in the course of the buyer decision process. The potential cost savings during operations that might result from applying new technologies often justify higher aircraft purchase prices. One of the key systems for electrification is the flight control system, which is traditionally powered hydraulically due to the required actuation forces and speeds. Civil transport aircraft are therefore usually equipped with various redundant hydraulic systems to meet safety requirements. Major disadvantages in comparison to electric systems are higher weights, energy losses during operation due to internal leakage as well as higher maintenance expenses.

Over the past decades increasing effort was put into research and development of electrical actuation concepts for civil transport aircraft, like electro-hydrostatic actuators (EHAs) or electro-mechanical actuators (EMAs). However, at present there is no CS/FAR-25 certified aircraft in service that use a fully electrically powered flight control system. Recently on aircraft such as Boeing 787 and Airbus A350 EMAs have been integrated on some control surfaces. Nevertheless, the aforementioned main advantage of eliminating heavy and energy consuming hydraulic circuits does not come into effect on these aircraft, because hydraulic energy is still used as main power supply for most control surfaces in front-line operation.

A concept for electrifying large amounts of an aircraft's flight control system has been developed in this cooperation project study between the Institute of Aerospace Systems (ILR) of RWTH Aachen University and Liebherr-Aerospace Lindenberg GmbH. The approach is feasible in the medium term and enables the predicted cost benefits of an electrically powered flight control system while simultaneously the required safety standards are taken into account. The novel flight control architecture concept therefore will be introduced and analyzed based on the Airbus A320 aircraft concerning the given safety requirements. A cost assessment will be carried out afterwards, comparing the newly developed approach with the traditional A320 flight control architecture. The affected DOC – taking into account the system weight and energy demand with regard to fuel consumption as well as maintenance expenses – will be analyzed.

2. AIRBUS A320 SYSTEM ARCHITECTURE

The focus of this paper is on the assessment of an aircraft's flight control system and its main interfacing systems, the electric and hydraulic supply systems, based on the Airbus A320. Therefore, as a first step, an introduction to relevant aircraft systems, their functions and basic structure with special regard to the A320 is given.

2.1. Flight Control System

In the presented work, for the definition of all system boundaries, the joint aircraft system/component (JASC) code table is used [1]. In the JASC standard the flight control system is included in chapter 27. Sidesticks or yokes, flight control computers, actuators and the signaling elements (cables, wires and mechanical transmission) are part of the flight control system according to the definition. The autopilot as well as the kinematics between the actuators and the control surfaces are explicitly excluded from chapter 27 [1], [2].

Different flight control actuator concepts are currently in place. The traditional and still most common one is the hydraulic servo control actuator, which is powered by the aircraft's hydraulic system. Hydraulic actuators have been used on civil aircraft for a long time. They are very reliable and able to provide high actuation forces and speeds.

On the Airbus A320, which is the observed reference aircraft in the present paper, servo control actuators are used for the entire flight control system. The general setup of the A320 flight control system logic is presented in Fig. 1 and Fig. 2.

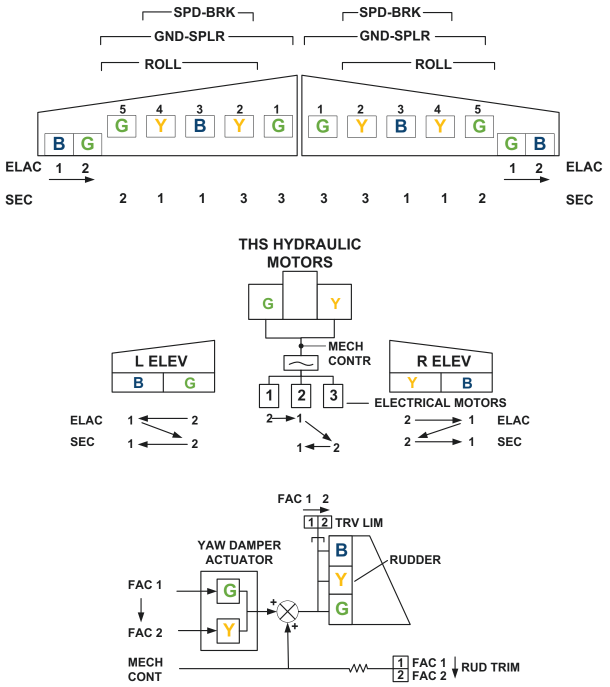

Fig. 1: A320 primary flight control system [3]

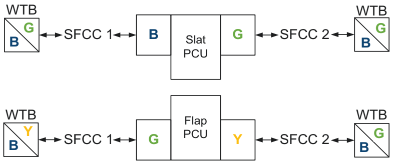

Fig. 2: A320 high-lift system [3]

Three redundant hydraulic circuits, blue (B), green (G), and yellow (Y) serve as power supply for the hydraulic actuators. The actuators are distributed so that the aircraft can be controlled about all three axes by each of the circuits independently. That way, in case of a failure of one or two particular hydraulic circuits, the aircraft still can be operated safely.

Another actuation concept is the electro-hydrostatic actuator (EHA) that uses its internal hydraulic circuit, which is powered by an electric pump. The third fundamental concept is the electro-mechanical actuator (EMA). It is powered directly with the help of an electromotor. Furthermore, there is hybrid forms of the above-described concepts, like electrical back-up hydraulic actuators that are implemented on the Airbus A380 [4]. Recent developments in civil aviation aim towards more electrical actuation concepts like EHAs and EMAs and thus realizing the elimination of hydraulics on the aircraft where possible. Hydraulic circuits are comparatively heavy and compared to electric cables the rigid piping is more difficult to install. Their power efficiency is relatively low, because of internal/external leakage and pressure losses. Additionally, they are very maintenance-intensive and the aggressive hydraulic fluid is hazardous for maintenance personnel and other aircraft systems.

This study focusses on the integration of EMAs for the flight control system of an A320 aircraft. EMAs are still an area of great interest in aerospace research. A variety of challenges and problems have not been fully solved yet, like jamming and the overall actuator reliability [5]. Fig. 3 shows a linear EMA with ball screw. The rotational motion of the electric motor is converted to a linear movement with the help of a gearbox and a ball screw. The motor control electronics provide the required electric power to the motor depending on the input signal from the flight control computers.

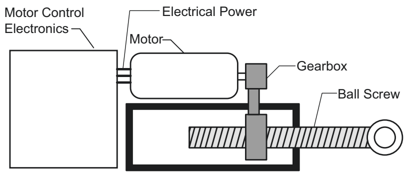

Fig. 3: Linear EMA with ball screw [6]

2.2. Hydraulic Supply System

Hydraulic power is mainly used for systems that require high operating loads, for instance landing gear extension and retraction. Traditionally, flight control actuators are also driven hydraulically due to the required actuation forces and speeds. The hydraulic power is provided by a hydraulic supply system (JASC chapter 29). Due to the high safety requirements in aerospace that could not be met with a single hydraulic circuit, most aircraft have several redundant hydraulic circuits. The layout of the three hydraulic circuits of the A320 aircraft is briefly presented in Fig. 4. The green and yellow systems are each powered by an engine driven pump during normal operations. The electromotor pump in the yellow circuit is mainly for maintenance but can also be used as backup. The blue system has an electromotor pump and a ram air turbine pump as backup for emergency situations.

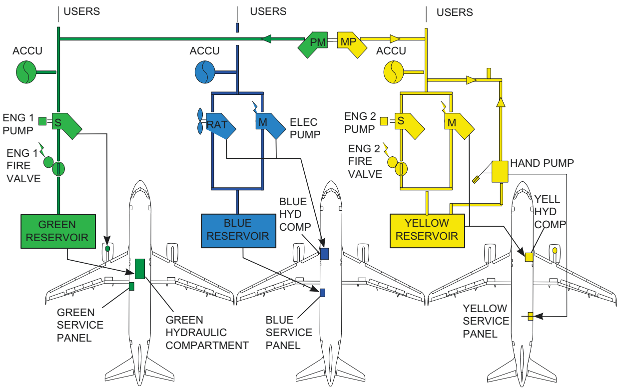

Fig. 4: A320 hydraulic system layout [7]

2.3. Electric Supply System

Electrically powered systems have gained in importance over the last years and have been under continuous development. The amount and complexity of electrical systems, for example for the evaluation of flight data, system monitoring and automatic flight control have constantly increased. Most of today's civil transport aircraft have both an alternate (AC) and a direct current (DC) network as parts of the electric supply system (JASC chapter 24). Direct current is mainly used for systems with low energy demand, like avionics and cockpit displays. Alternate current is used for systems with high energy demands, such as galleys, environmental control system and cabin lighting.

In most traditional aircraft the alternate current network is a three phase AC grid with 115/200 V at a constant frequency of 400 Hz. The general arrangement of the A320 electric system is shown in Fig. 5.

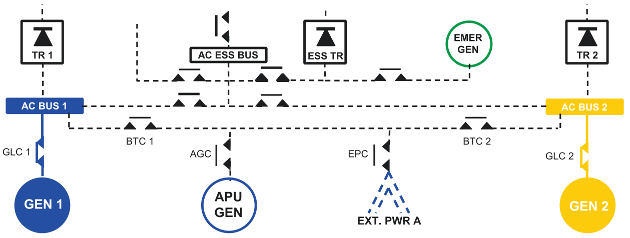

Fig. 5: A320 Electrical System [8]

The electrical power is generated by two integrated driven generators (GEN 1 & 2) – each consists of a generator and a constant speed drive, a transmission gear that keeps the generator input speed at 400 Hz – that are mounted on the accessory gearbox of the engines. An auxiliary power unit generator (APU GEN) serves as a backup. A constant speed motor/generator (EMER GEN) can be used in emergency situations to power the most essential systems. It is powered by the blue hydraulic circuit and can also be utilized when the ram air turbine is operating.

Modern aircraft like the Airbus A380 and the Boeing 787 make use of a variable frequency network operating between 380 Hz and 800 Hz. This allows for eliminating heavy and maintenance-intensive constant speed drives, which are normally responsible for transmission of the variable engine speeds to a constant frequency for the generators. In addition to variable frequency, on some aircraft the operating voltage has been raised from 115/200 V to 230/400 V due to constantly increasing electrical power demands [6].

Current investigations in aerospace aim at implementing distributed direct current grids with a voltage of +/- 270 V for various applications. The increase in voltage enables smaller electrical currents, which has several positive impacts. A smaller electric current leads to a decrease of energy losses. Also, weight savings due to reduced cable diameters can be realized. Furthermore, direct current can be easily stored in compensators or batteries, which enhances availability and efficiency [9].

3. DEVELOPMENT OF A MORE ELECTRIC FLIGHT CONTROL SYSTEM ARCHITECTURE

The approach introduced in this paper is a so-called 2E1H architecture, which is a hybrid concept, composed of both hydraulic and electric energy supply. One remaining hydraulic system serves as back-up and emergency system for two electric systems, which act in front-line operation for the flight control power supply. From a certification point of view the solution is considered as more realistic in the medium term than directly switching to an all-electric flight control system [5]. Especially, when considering that the hydraulic system also supplies other systems with high short-time power demand like the landing gear – on which EMA technologies are not yet mature – this intermediate step appears reasonable. However, this paper is confined solely on the flight control system and its interfacing systems. The reference aircraft, an Airbus A320 is equipped with a fly-by-wire flight control system that is powered by three independent hydraulic systems (3H architecture). In the following the reference aircraft A320 with traditional architecture is referred to as A320-3H. The modified version with the newly developed electrical flight control is referred to as A320-2E1H.

3.1. A320-2E1H Flight Control System

For the novel electrified flight control system architecture the authors chose a configuration that has a similar setup as the traditional 3H architecture of the A320. The reference architecture is only modified where necessary without fundamentally changing the layout of redundancy and especially the fly-by-wire concept.

3.1.1. Energy Supply of the A320-2E1H Flight Control System

The introduced system architecture consists of two electrical systems and one hydraulic system (hereinafter referred to as E1 and E2 for the electrical systems and H for the hydraulic system). Compared to the traditional A320-3H, two hydraulic systems were eliminated. Thus, the energy supply layout of the flight control system has to be redesigned.

In Fig. 6 - Fig. 8 the 2E1H primary flight control system is shown. Most primary flight control surfaces are operated with an electrical energy supply. As stated before, the hydraulic system is designed to serve as a highly reliable backup system that has to be capable of independently supplying the control surfaces about all three axes. Thus, the power supply for the flight control actuators is distributed accordingly.

As can be seen in Fig. 6, for the roll controls the front line actuators of the ailerons controlled by ELAC 1 are supplied by the electrical system E2, whereas the backup actuators controlled by ELAC 2 are still powered hydraulically. The roll spoilers are mostly electrified as well. Only the outboard spoilers 5 controlled by SEC 2 remain hydraulic in order to ensure maximum maneuverability in an emergency situation.

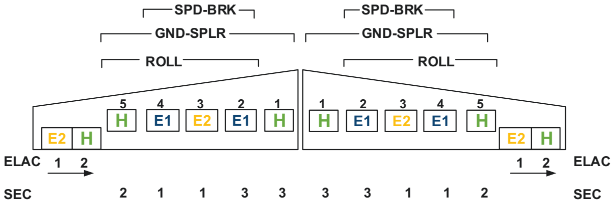

Fig. 6: A320-2E1H roll control system

The pitch control supply is distributed similarly (see Fig. 7). The hydraulically powered actuators on both sides of the elevator are in standby mode during normal operations and guarantee for the required safety. For the trimmable horizontal stabilizer (THS) both motors are driven completely by the electrical systems and are synchronized by a gearbox [3]. A hydraulic backup was considered unnecessary in this case because a non-operational THS is assumed to be not safety-critical for the operation of the aircraft.

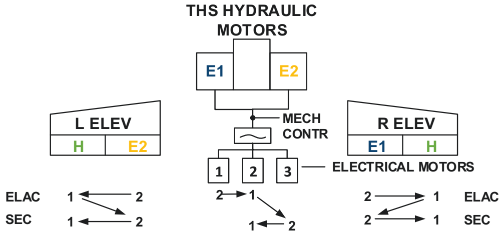

Fig. 7: A320-2E1H pitch control system

The three rudder actuators, which are operated in parallel mode during normal operation, are each supplied by one of the energy systems (see Fig. 8). The yaw damper actuators remain fully hydraulic because there are not enough reliable experiences with electronically powered yaw dampers yet.

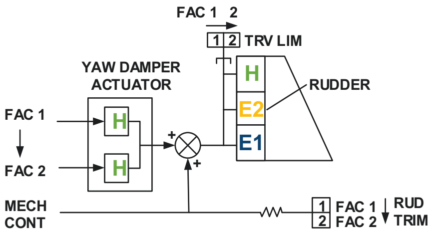

Fig. 8: A320-2E1H yaw control system

Fig. 9 shows the A320-2E1H high-lift system. It was chosen to apply a hybrid power control unit (PCU) for flap and slat actuation, as well as hybrid wing tip brakes. That way, the high-lift system can be operated solely by the hydraulic backup system in emergency situations.

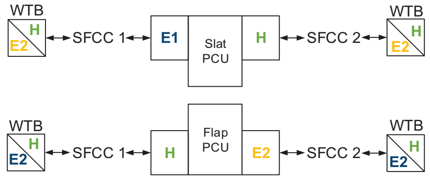

Fig. 9: A320-2E1H high-lift system

3.2. Description of the Applied Actuator Concept for the A320-2E1H

Different concepts for the application of EMAs have been observed in various research projects at Liebherr-Aerospace over the last years. The insights from these projects were consulted for the implementation of the general EMA concept in this study (see Fig. 10).

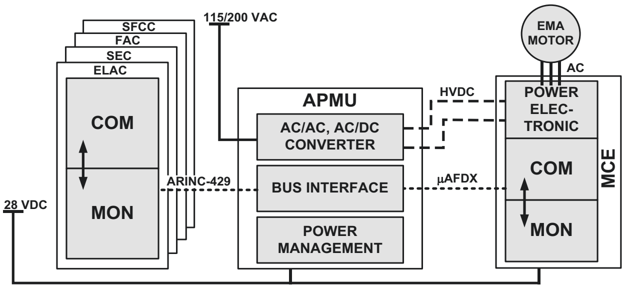

Fig. 10: EMA concept for the A320-2E1H

The electric power supply for the flight control system is realized by a separate high voltage direct current (HVDC) grid at +/- 270 V (540 V). The power supply for the flight control system is centrally regulated by two so-called actuator power management units (APMUs), which are connected to the 115/200 VAC network of the aircraft. The concept of installing an isolated HVDC grid with a central APMU was adapted from Airbus S.A.S [10]. It leads to a significant benefit for the actuators. The aerodynamic forces on the actuators result in reverse electric currents from the actuators to the electric network. However, feeding electric energy back to the aircraft's central power network is not permitted due to safety reasons. Therefore, the excess energy needs to be dissipated into heat. The HVDC network concept enables the possibility to return recuperated energy, because it is isolated from the rest of the aircraft's electric grid. This increases the efficiency of the actuator.

The APMU mainly consists of three different units (see Fig. 10). Firstly, the actual power management that controls the power supply for each of the connected actuators. Moreover, a bus interface is used for communication between flight control computers, APMU and the local motor control electronics. Finally, for conversion from alternate to direct current, an AC/DC converter is the interface between the aircraft's AC network and the HVDC network. The APMU has 9 power output connections with 222 W of steady state power per consumer. The maximum peak power output of 10 kW can be provided for about 1 sec. In the A320-2E1H the APMU is placed in the pressurized forward avionics compartment.

As depicted in Fig. 10, a motor control electronic (MCE) unit that communicates with the APMU via the digital data transfer (COM/MON function) is located directly on each EMA. The internal electronics of the MCE are powered by the aircraft's 28 VDC network. An AC/DC converter is necessary to convert HVDC back to AC for the EMA motor.

The data transfer between APMU and actuators is based on the µAFDX (avionics full duplex switched Ethernet) bus standard that has a data rate of up to 1 GBit per second [11]. The communication between the APMU and the flight control computers (ELAC, SEC, etc.) is realized via an ARINC-429 interface that is also used in the traditional A320-3H system architecture. This approach was chosen to fully maintain the logic of the flight control computers from the reference aircraft.

3.3. A320-2E1H Hydraulic Supply System

In the course of the modification from A320-3H to A320-2E1H most of the flight control actuators have been electrified. Thus, it was possible to eliminate two entire hydraulic circuits from the aircraft. The remaining hydraulic system, which is shown in Fig. 11, is a combination of the most important parts of the three hydraulic systems from the A320-3H.

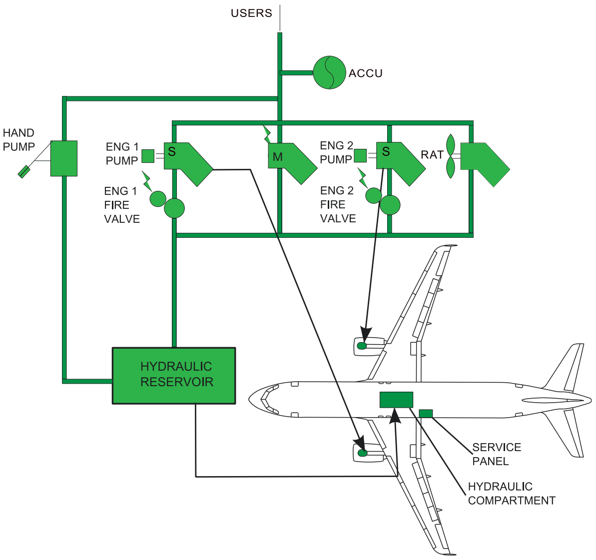

Fig. 11: Hydraulic System of the A320-2E1H

The Hydraulic power is generated by two engine driven pumps that are equivalent to the ones from the reference aircraft. The maximum hydraulic flow of 140 l/min [12] – designed for the case of one engine inoperative at takeoff – is considered to be sufficient for the supply of the entire flight control system. The electric motor pump is mainly for maintenance operations but can also be used as a backup. It has a maximum flow of 32 l/min [13]. Due to the fact that the hydraulic system is required to serve as a highly reliable back up for emergency, the ram air turbine is also adopted from the A320-3H. Hence, in an emergency situation the hydraulic system will be able to power the entire flight control system with the ram air turbine hydraulic pump.

The hand pump has been taken over from the reference's yellow hydraulic system to operate the cargo doors from the ground. The other components, like reservoir, accumulator and engine fire valves have also been taken over from the reference aircraft's green hydraulic system.

3.4. A320-2E1H Electric Supply System

The general arrangement of the A320-2E1H electrical system is mostly adopted from the reference aircraft (see Fig. 5). The modification is in the two APMUs that are now each directly connected to one of the main bus bars (AC BUS 1 & 2).

3.5. Preliminary System Safety Assessment

In order to ensure the general safety of the newly implemented flight control system architecture, some basic aspects of a preliminary system safety assessment were executed using the example of the roll control system. Pitch and law control functions were neglected due to simplification. Also the jamming of the rudder EMAs was assumed to be uncritical.

The preliminary system safety analysis was carried out by selecting feasible failure modes for the ailerons and spoilers from an already existing functional hazard assessment of an A320 aircraft. The FHA had been performed by Liebherr-Aerospace in the course of the national research project SYSTAVIO. Two relatively simple failure modes were investigated, one for the ailerons and one for the spoilers. For both control surface types the total loss of control was considered, but without uncontrolled floating of the control surfaces (actuators in damping mode). The FHA indicated the hazard level HAZ (hazardous) for both cases. The failure therefore has to be excluded with a probability of 1E-07 per flight hour. The subsequent failure analysis was realized by conducting a fault tree analysis for both failure modes. The fault tree analysis was carried out on the modified A320-2E1H as well as on the reference aircraft A320-3H. Thereby, a direct comparison between the two architecture concepts was realized.

The absolute numbers of the fault tree analysis are not displayed here and have to be handled with caution. This is because the underlying failure rates for already existing components were collected from in-service data, whereas the failure rates of the A320-2E1H components (for instance not yet existing EMAs) were mainly estimated by the authors. Hence, they do not have the same level of accuracy. Nevertheless, the qualitative assessment indicates that the failure probabilities of the 2E1H architecture are roughly in the same dimension as for the reference aircraft. It can therefore be concluded that the amodified architecture should conform to the required safety standards. However, as mentioned earlier, this has only been analyzed for the roll function and needs to be studied in detail for pitch and yaw as well.

4. SYSTEM PARAMETER ASSESSMENT

In order to enable the evaluation the DOC of the newly developed 2E1H flight control architecture compared to the traditional architecture, the relevant system parameters have to be identified. All system characteristics that have an impact on DOC have to be compared for the two architecture types. Tab. 1 indicates the most significant system parameters and their associated DOC subchapter.

The DOC chapters for this study indicated in Tab. 1 contain fuel costs and planned maintenance. For a full assessment of the DOC, also costs for unplanned maintenance and repair, depreciation, interest and insurance costs have to be investigated.

Parameter	Description	DOC subchapter
m_{sys}	System mass	DOC_{fuel}
P_{sys}	System power offtakes	
$t_{\Delta maint}$	Time between two maint. intervals	$DOC_{maint,planned}$
t_{maint}	Time for maint. checks [PH]	

Tab. 1: Identified system parameters for DOC assessment

However, since no reliable data regarding acquisition and repair prices were available for the 2E1H architecture, these cost parts have not been considered. This assumption was considered to be reasonable, since the main differences are expected to occur for fuel costs when moving to a more electric flight control architecture [5].

In the following sections the two considered flight control system architectures (traditional 3H and novel 2E1H) are compared with respect to the identified system parameters from Tab. 1. On the basis of this comparison, the final cost assessment is then carried out in chapter 5.

4.1. Observation of System Weight

The comparison of system weight of the reference aircraft A320-3H and the modified A320-2E1H is split up according to the three relevant systems, flight control system (JASC 27), electric system (JASC 24) and hydraulic system (JASC 29).

4.1.1. Weight Comparison of the Hydraulic Supply Systems

The weights of these components (pumps, reservoirs, filters, manifolds, accumulators, etc.) could be obtained from several sources in the course of this study (manufacturer data sheets, Liebherr in-house data, and maintenance facility planning documents). Thus, on component level, the weight savings for the A320-2E1H can be calculated relatively straightforward.

On the other hand, the estimation of weight differences for hydraulic piping and fluid cannot be done as easily. However, it can be gathered from literature that these two contribute the major proportion of the total hydraulic system weight [2]. For the reference aircraft the total hydraulic system weight as well as the total fluid amount have been obtained from previous research at ILR [14]. With the additional knowledge of the component weights, the only missing weight proportion was the hydraulic piping and its installations. By manually drawing the connections between pumps, hydraulic compartment and individual consumers in an original drawing of the A320 aircraft with the help of a 2D CAD software, the geometrical length of the piping for each hydraulic system (G, B, Y) could be identified (see Fig. 12) [15].

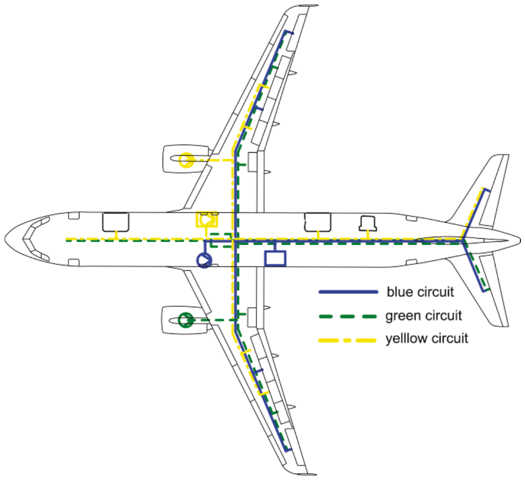

Fig. 12: A320-3H hydraulic piping routes

In a second step, a length-to-weight ratio for the piping as well as for the fluid was determined with the previously calculated weight proportions. The piping length for the A320-2E1H was obtained accordingly. Subsequently, the length-to-weight ratios were applied to the A320-2E1H. Hereby, the weight of piping and fluid for the 2E1H hydraulic system could finally be calculated. In total, about 500 kg of hydraulic system weight are saved for the A320-2E1H.

4.1.2. Weight Comparison of the Flight Control Systems

When observing the weight differences between the flight control systems of A320-3H and A320-2E1H, only modified parts have to be taken into account for the analysis. The sidesticks and flight control computers as well as the signaling between the two have been kept, as already stated in section 3.1. On the contrary, the entire signaling between flight control computers and actuators has been modified. On the A320-3H the computers are directly connected to the actuators. On the A320-2E1H, however, the APMUs are interconnected via a digital AFDX connection to the EMAs and an ARINC-429 interface to the computers. Hence, the entire flight control wiring has to be investigated for the weight analysis. The cable weights were obtained from various data sheets from cable manufacturers for the different types of cables. To give an example, the cable length-to-weight ratio for the µAFDX digital Ethernet connections were taken from a datasheet of the supplier Emteq Inc. [16].
Similar to the approach presented in section 4.1.1, the wiring was laid with the help of a CAD drawing of the A320 aircraft [15]. Therefore, the cable weights could be calculated using the determined lengths and the length-to-weight ratio for the different cable types. The weights of the hydraulic actuators were obtained from the A320 maintenance facility planning document and Liebherr in-house data [17]. The EMA weights for the A320-2E1H were estimated by the authors with experience from previous research at Liebherr-Aerospace.
In total, an additional weight of 107 kg for the A320-2E1H flight control system was identified. This is mainly due to the relatively heavy EMAs – for instance, the aileron EMA weighs about twice as much as the hydraulic actuator – and the new HVDC network (including APMUs and power cables) that has been implemented for electric power distribution for the flight control system. When regarding only the weights of signaling cables, however, the A320-2E1H saves a significant amount of weight due to the fact of decreasing amount of cables for digital data transfer.
Taking into account the weight of the hydraulic system together with the flight control system, the total weight savings of the A320-2E1H result in approximately 390 kg compared to the reference aircraft. Note that the modifications to the electric system (connection between aircraft's power network and APMUs) were neglected for the weight analyses.

4.2. Observation of System Power Offtakes

The energy for the flight control system is extracted from the engines as secondary shaft power. Variations of surface deflections at different phases of the flight mission (taxi, takeoff, cruise, etc.) lead to variable power demands. Determining the exact energy amount of the flight control system would thus require actual flight data, which has not been available within the scope of this study. Another possibility would be the use of a mission simulation with a three-dimensional mission trajectory and the actual control surface deflections of the aircraft in order to calculate the actual energy demand of each actuator. Since there was no such simulation model available, the authors decided to apply a simplified approach, which is described in the following section.
From a previous project at Liebherr-Aerospace the average power provided by the blue hydraulic system of the A320-3H was obtained for flight as well as for taxiing. Generally, total hydraulic flow is calculated from the hydraulic flow that is required for the consumers, plus the internal leakage flows. Multiplied with the hydraulic pressure, the total hydraulic power could be calculated. The information on how the total hydraulic flow is distributed among the consumers as well as the fraction between internal leakage and effectively required flow of each consumer were also given for the blue system. The data indicated that most of the required hydraulic energy is caused by internal leakage (almost 70%). This underlines the previously stated inefficiency of hydraulic power for flight control actuation, especially when actuators are currently not deflected or constantly in standby mode. Together with the pump efficiencies from a manufacturer data sheet, the effective power demand of the hydraulic system could be obtained. Fig. 13 shows the average total hydraulic power demand for the blue hydraulic system and the resulting pump efficiency of the Eaton electromotor pump that is installed in the blue hydraulic system. It can be seen that the average operating point of the hydraulic pump clearly deviates from an optimum operating condition, which, as the study has shown, is true for the hydraulic pumps in the other circuits as well.

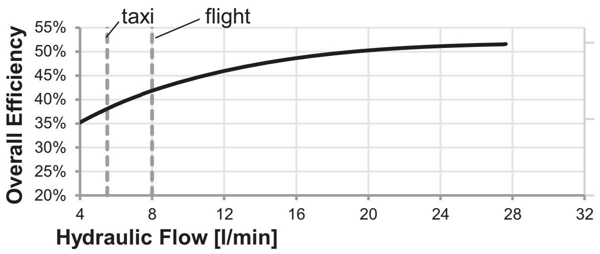

Fig. 13: Power characteristics of the Eaton electromotor pump [18]

In case of the blue electromotor pump the hydraulic power demand has to be reduced by the generator efficiency in order to calculate the effective engine shaft power offtake. This does of course not occur for the engine driven pumps in the green, yellow or A320-2E1H hydraulic systems.

In order to determine the shaft power offtakes for the other hydraulic systems, the energy demand among the consumers was distributed for the green, yellow and the A320-2E1H hydraulic systems in the same manner as for the blue hydraulic system.

The average energy demand of the electrically driven actuators on the A320-2E1H was estimated under some simplifications. It was assumed that the APMU provides a steady state power of 2 kW as an average value for the flight mission. The power was equally distributed among the nine EMAs for each APMU (222 W per actuator). It was also assumed that the EMAs do not require energy in standby mode, which applies during taxiing, or on actuators that are not active in front line operation.

After observing the energy demands of all hydraulic and electric actuators on both A320-3H and A320-2E1H, the total energy difference could be determined. The results were that for the 2E1H architecture, savings of almost 12 kW for flight and about 10 kW for taxiing are achieved. This is mainly due to the inefficiency of using hydraulic power for the flight control actuation. A large amount of energy is required to compensate the leakage flows. Additionally, in average the hydraulic pumps operate in off-design conditions where the pump efficiency is relatively low.

When regarding the power consumption of each supply system on the two aircraft, the lower efficiency of the hydraulic circuits compared to the electric HVDC network is illustrated (see Fig. 14).

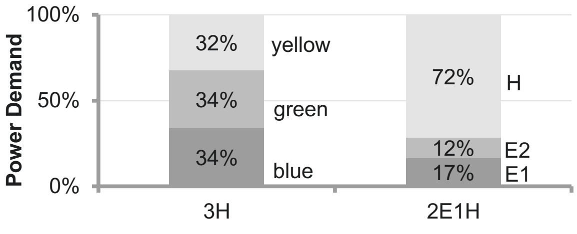

Fig. 14: Distribution of the total power demand among the power supply systems (normalized)

Note that in the figure above, the power demand for each of the two architectures has been normalized separately. The figure shows that for the 3H architecture, all three hydraulic circuits have nearly the same share in power consumption. On the A320-2E1H, however, the remaining hydraulic circuit holds more than 70 % of the total power demand. This makes clear that moving to a fully electrified architecture would even enhance the power savings for the flight control system. As stated before, the intermediate step of the 2E1H architecture was done intentionally with regard to the current developments in EMA technologies.

4.3. Observation of Planned Maintenance

The planned maintenance expenses were obtained with assumptions based on current technology standards and with the authors with experience from previous research at Liebherr-Aerospace.

The findings from the maintenance analysis were that some maintenance actions could be cancelled on the A320-2E1H. This is due to the fact, that large parts of the maintenance expensive A320-3H hydraulic system were eliminated. In order to conclude actual maintenance costs from maintenance actions, it is essential to be aware of the underlying mission scenario of the aircraft. Since maintenance intervals are mostly dependent on flight hours or flight cycles, a more frequently operated aircraft requires more shop visits. The selected reference mission for the assessment will be described in detail in section 5.1.

5. DOC ASSESSMENT

After analyzing all the relevant changes in system parameters from A320-3H to A320-2E1H, the final DOC assessment could be performed. The fuel consumption was analyzed in detail with the ILR in-house conceptual design software MICADO (Multidisciplinary Integrated Conceptual Aircraft Design and Optimization). The detailed fuel analysis was chosen, because it was assumed that the changes in system architecture will have a great impact on the fuel consumption, and thus, fuel costs.

In this study, a delta DOC analysis was carried out by building the difference between the DOC of A320-3H and A320-2E1H (see Eq. (1)).

$$\Delta DOC_n = DOC_{3H,n} - DOC_{2E1H,n} \tag{1}$$

In order to analyze the DOC, first the total DOC are subdivided into the different DOC parts n. In the scope of this paper the two relevant DOC parts are fuel costs and planned maintenance costs. Each cost part first have been separately analyzed and finally the two were merged to a total ΔDOC.

5.1. Reference Scenario

Fuel and maintenance costs are highly dependent on the scenario in which the aircraft is used. An aircraft is operated on various types of routes and it is not always utilized in the same manner. This is why for this paper an average A320 mission scenario was identified from statistical data [19]. The resulting reference mission has a range of 800 NM, a payload of 13608 kg (150 PAX, each at 90,72 kg) and a total taxi time of 15 min. The mission is carried out 1661 times per year.

It can be seen that the 800 NM range of the reference mission is significantly lower than the A320 design range of 2500 NM. In order to analyze the effect of the newly developed 2E1H architecture on the DOC over a wider spectrum of operating points, the studies were performed with varying mission ranges. The mission range was altered between 400 NM and 2400 NM in steps of 200 NM. This of course leads to different scenarios. The daily utilization of the reference mission was calculated to about 10 h, neglecting the turn-around time on the ground as well as potential maintenance actions. The same utilization was assumed for all other mission ranges. Since the flight and block time increase with the range, the missions per year decrease accordingly. For example, the 400 NM mission has a block time (including 15 min taxiing) of 1.3 h, leading to a utilization of 2784 missions per year whereas the reference mission of 800 NM has a block time of 2.2 h. This, of course, has an effect on the DOC of the aircraft, as will be shown in the next sections. Nevertheless, the focus of the final statement of the assessment should be on the reference mission of 800 NM, since it is the statistical average mission of the real A320 aircraft.

5.2. Implementation into Conceptual Design Software for Fuel Analysis

In recent years, the ILR of RWTH Aachen developed the conceptual aircraft design and analysis tool MICADO. Besides the ability of designing an aircraft from scratch with only a minimum user input required, it is also capable of analyzing preexisting aircraft with a detailed mission simulation [20]. The mission is discretized into incremental mission steps. For each step the equations of motion are solved with the help of the underlying aerodynamic performance (lift and drag) so that the required thrust can be calculated. A thermodynamic engine deck is then used to calculate the required fuel flow at the current engine operating point (flight level, Mach number, airspeed, engine rating). System shaft power and bleed air offtakes are also considered as additional energy consumption for the engine.

The above described MICADO mission analysis approach enables the consideration of how system masses and power offtakes effect the fuel consumption for a specific flight mission. Within the scope of this paper, the two aircraft architectures were both implemented into MICADO with the system masses and average power offtakes calculated in chapter 4. The mission analysis was performed for each range in order to additionally analyze the effects of mission range on fuel burn. The simulation model called CSR-01, on which the analyses were performed, is a short range reference aircraft very similar to the real A320. It was created at ILR within the scope of the project CeRAS (central reference aircraft data system) in close cooperation and consultation with Airbus in order to provide a common reference aircraft to research community [14]. For the transfer from mission fuel amount to fuel costs a fuel price of 1 US-$ /kg was assumed.

5.3. Results

As already mentioned, the DOC analysis is subdivided into two parts. First, the effect on fuel costs will be observed. The focus will be then on maintenance costs, and finally, the two will be merged to a total DOC analysis.

5.3.1. Fuel Cost Assessment

The input parameters for the fuel cost analysis are the difference in mass ($\Delta m_{sys} = 390$ kg) and power offtakes ($\Delta P_{taxi} = 10$ kW; $\Delta P_{flight} = 12$ kW) calculated in section 4. The results for the fuel cost assessment are summarized in Fig. 15. The results are shown in the format $\Delta DOC_{fuel} = DOC_{3H,fuel} - DOC_{2E1H,fuel}$.

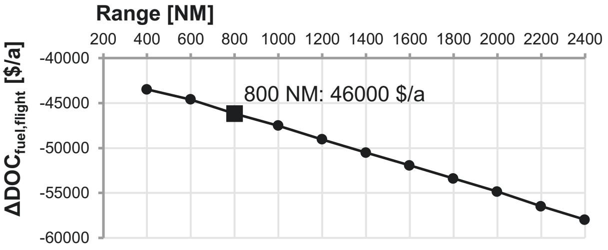

Fig. 15: Development of fuel costs over range

The yearly savings for the 2E1H architecture are about 46000 US-$ on the reference mission. It can also be depicted from the figure that for an increasing flight range, the benefits of the 2E1H architecture increase almost linearly. This is obvious, if we consider that for a larger range, the same amount of system weight and system power offtakes have to be transported over a longer period of time.

The total fuel costs can be further divided into taxi and flight fuel costs. Fig. 16 shows the development of the share between the two over varying mission ranges.

The fuel costs caused by taxiing are almost negligible compared to flight. However, for a decreasing range, the share of the taxi fuel costs becomes more important. This is due to the fact that for decreasing flight times, more missions can be realized, and thus, more taxiing segments are carried out.

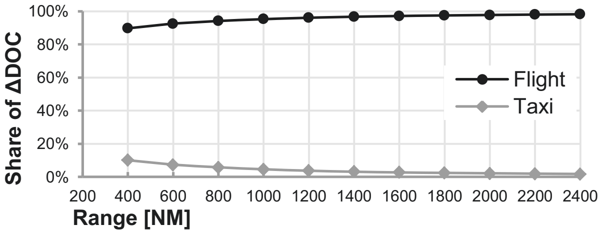

Fig. 16: Share of DOC between taxiing and flight

5.3.2. Planned Maintenance Cost Assessment

The planned maintenance costs for one year were calculated by multiplying the person hours of planned maintenance actions for the time period (taking into account the maintenance intervals) with the specific labor costs. The labor costs were assumed at 100 US-$ per person hour. Fig. 17 shows the delta in DOC for planned maintenance over range.

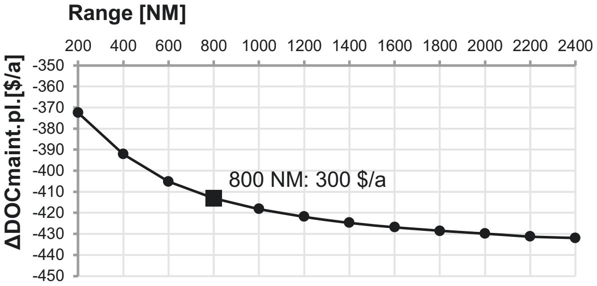

Fig. 17: Development of maintenance costs over range

It is noticeable that compared to the differences in fuel costs, the savings are almost insignificantly small. Only about 300 US-$ per year can be saved for the A320-2E1H. Analogous to the fuel cost observations, an increase in mission range obviously leads to higher savings in maintenance costs.

5.3.3. Total Cost Assessment

Considering fuel and maintenance costs for the DOC assessment, a total amount of 46,300 US-$ can be saved for the A320-2E1H compared to the A320-3H on the reference mission (800 NM, 1661 flights per year). Fig. 18 highlights the impact of each system parameter on the DOC identified in section 4 for the reference mission.

It appears that most of the savings in operating costs are based on the decrease in weight due to the elimination of two hydraulic circuits. About 20 % of the savings occur due to the higher efficiency of the EMAs. As already illustrated before, the difference in planned maintenance expenses can almost be neglected.

Since no real purchase prices for EMA components could be obtained in the course of this study, it is difficult to make a statement on whether the change from 3H to 2E1H architecture is actually beneficial from an airliner's perspective.

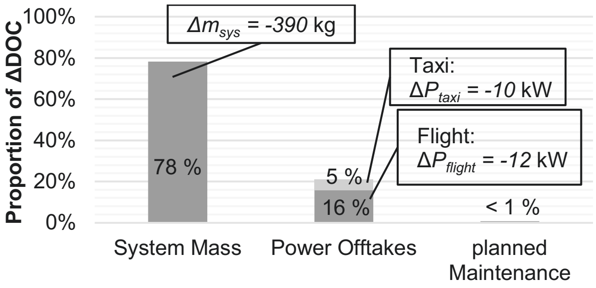

Fig. 18: Effects of system parameters on ΔDOC

In order to get a better overview, a potential airliner scenario was selected and observed. The aircraft's service life was assumed at 25 years and the airline was expected to request a break-even point at 1/3 of the service life (8.33 years) when choosing an aircraft equipped with the novel system architecture. Based on these operator requirements, the maximum rough order magnitude (ROM) aircraft purchase price difference for the A320-2E1H was calculated (see Fig. 19). The figure indicates that an aircraft equipped with the 2E1H flight control system could cost about 400,000 US-$ more than the traditional A320-3H. However, in the course of this paper, it could not be investigated if these costs can actually enable the implementation of the 2E1H system.

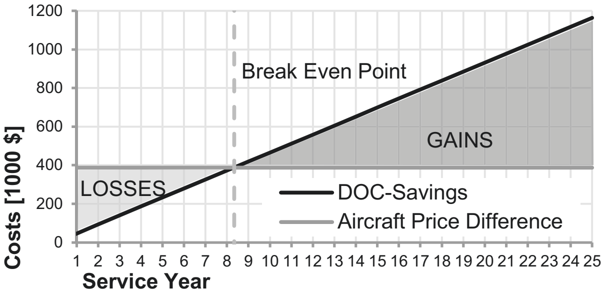

Fig. 19: Break-even point of the A320-2E1H

6. CONCLUSION AND OUTLOOK

In the course of this paper a traditional Airbus A320 was modified by electrifying large amounts of the flight control actuators. The entire system architecture was therefore moved from 3H to 2E1H. A preliminary system safety analysis with emphasis on roll function indicated that the chosen architecture meets the current required safety standards.

The delta DOC analysis of the 2E1H flight control architecture on aircraft level demonstrated that significant operational cost benefits arise due to the elimination of large amounts of the hydraulic supply system. These benefits have shown to be twofold. On the one hand, the total aircraft mass can be decreased, because heavy hydraulic piping and fluids are replaced with lighter electric cables. On the other hand, the higher power efficiency of the EMAs in comparison to hydraulically powered actuators reduces fuel burn. The additional lower maintenance expenses can almost be neglected as a side effect. However, maintenance costs might have a bigger impact on an all-electric aircraft, when hydraulic power is fully replaced.

It could also be shown that an increase in mission range considerably enhances the cost benefits. Therefore, an implementation of the 2E1H architecture on long range aircraft could be even more beneficial than on short/medium range aircraft like the A320. Additionally, since long range aircraft are usually larger, the mass savings might increase.

Besides the obvious economical profits, the lower fuel burn during flight can also lower exhaust emissions leading to positive ecological effects.

Future developments at ILR are aiming towards automatically building up more-electric architectures for the flight control system.

REFERENCES

[1] Federal Aviation Administration (FAA), "Joint Aircraft System/Component Code Table and Definitions," Federal Aviation Administration (FAA), 2002.

[2] Koeppen, C., Carl, U. B., and Horst, P., *Methodik zur modellbasierten Prognose von Flugzeugsystemparametern im Vorentwurf von Verkehrsflugzeugen*, Shaker, Aachen, 2006.

[3] Airbus S.A.S, "Airbus Training - A320 Flight Crew Operating Manual: Flight Controls," http://www.smartcockpit.com/plane/AIRBUS/A320.html, [retrieved 1 September 2016].

[4] van den Bossche, D., "The A380 Flight Control Electrohydrostatic Actuators, Achievements and Lessons Learnt," *25th International Congress of Aeronautical Sciences,* Optimage Ltd, Edinburgh, 2006, pp. 1–8.

[5] Fervel, M., Todeschi, M., Recksiek, M., and Roizes, J., "More Electrical Aircraft Control," Airbus S.A.S, 2010.

[6] Moir, I., and Seabridge, A. G., *Aircraft Systems. Mechanical, Electrical, and Avionics Subsystems Integration,* 3rd edn., Wiley, Chichester, Hoboken, NJ, 2008.

[7] Lufthansa, "Training Manual A319/320/321: ATA 29 Hydraulic Power: General Familiarization," Lufthansa Technical Training, 2004.

[8] Gombert, P., "A320 Family - Electrical Generation and Distribution System," Airbus S.A.S, 2007.

[9] Römelt, Stefan, Pecher, Wolfgang, "More Electric Aircraft – Elektrische Grundsysteme," Cassidian, 17 Sep. 2010.

[10] Todeschi, M., and Salas, F., "Power Electronics for the Flight Control Actuators," *7th International Conference on Recent Advances in Aerospace Actuation Systems and Components*, 2016.

[11] AIM GmbH, "AFDX Workshop: Avionics Databus Solutions," 2010.

[12] Eaton Aerospace, "Product Improvement - P/N 3031863-001 (PV3-240-10D) Engine-Driven Pump," Eaton Aerospace, 2013.

[13] Eaton Aerospace, "Aerospace Capabilities - Airbus A318, A319, A320, A321," Eaton Aerospace, 2003.

[14] Risse, K., Schäfer, K., Schültke, F., and Stumpf, E., "Central Reference Aircraft data System (CeRAS) for research community," *CEAS Aeronautical Journal*; Vol. 7, No. 1, 2016, pp. 121–133. doi: 10.1007/s13272-015-0177-9.

[15] Airbus, "AutoCAD 6-view aircraft drawings: A320 with Sharklet," http://www.airbus.com/support/maintenance-engineering/technical-data/autocad-6-view-aircraft-drawings/, [retrieved 15 July 2016].

[16] Emtec Inc., "D10004-664 10/100 Base-T Ethernet Cable: Data Sheet," Emtec Inc., 2010, http://www.emteq.com/cmsdocuments/EMTEQ_D10004-664.pdf, [retrieved 15 July 2016].

[17] Airbus, "A320 Facility Planning Manual: Maintenance Facility Planning (MFP)," Airbus S.A.S, 2002.

[18] Eaton Aerospace, "Eaton MPEV3-032-15 Air Cooled Motorpump," Eaton Aerospace, 2013.

[19] Airbus, "Airbus In-Service Data: Fleet Brief Single Aisle," Airbus S.A.S, April 2014.

[20] Risse, K., Anton, E., Lammering, T., Franz, K., and Hoernschemeyer, R., "An Integrated Environment for Preliminary Aircraft Design and Optimization," *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference,* AIAA, 2012.