A FUNCTIONAL-DRIVEN DESIGN APPROACH FOR ADVANCED FLIGHT CONTROL SYSTEMS OF COMMERCIAL TRANSPORT AIRCRAFT

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Abstract
The functional enhancement of the Flight Control System (FCS) by using new technologies and concepts show potential benefit for commercial transport aircraft. Thus, to conceive the entire design space in early phases of aircraft design, the transition from a knowledge-based to a functional-driven design approach is recommended. The objective of this contribution is to enable such a functional-driven design approach for Advanced Flight Control Systems (AFCS), including multifunctional flight control devices. After a short background section on the design of FCS, various enabling technologies and concepts are presented. The functional-driven design approach represents the first part of an overall AFCS design method. A Functional Multiple Domain Matrix (FMDM) is the core of the design approach and accompanies the entire development process and supports in handling the system complexity. Based on a functional cluster analysis, various AFCS concepts can be derived. This functional-driven approach can be applied for new aircraft configurations in the early stages of the transport aircraft design process or for retrofit studies, with respect to the FCS design.

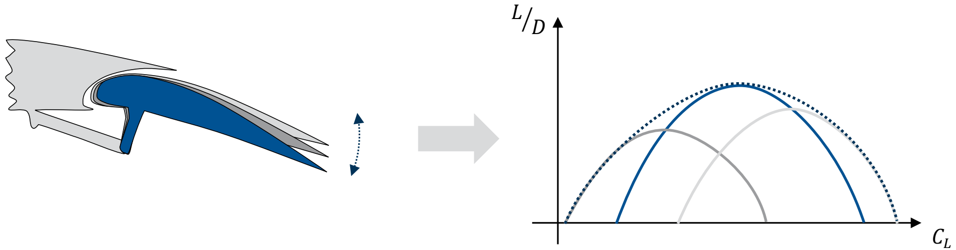
1 INTRODCUTION

Flight Control Systems (FCS) play a major role on sizing, efficiency, and safety of commercial transport aircraft. The design of FCS is a multidisciplinary design problem with many requirements, specifications and constraints. Furthermore, it is a safety critical system and has to tolerate hardware and software design faults.

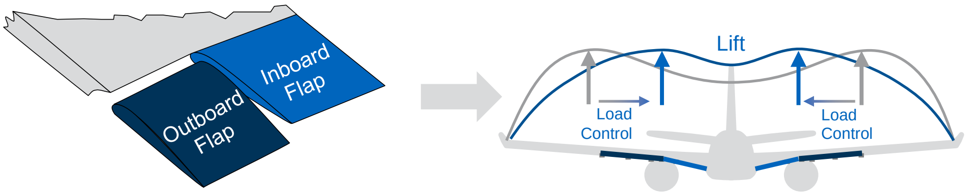
Today's FCS consist of highly optimized flight control devices, which are conventionally classified as primary or secondary – depending on their function and criticality. This knowledge-based design with classical and mainly mono-functional allocation, is often limited to small and local improvements under high effort [1–3].

Various research studies show the potential of new technologies and concepts to increase aircraft efficiency or performance by functional enhancement of the flight control system [1, 4–9]. Descriptive examples are Cruise Variable Camber (CVC) for aerodynamic improvements [1], or Differential Flap Setting (DFS) for wing load control – leading among others to overall structure weight savings [2] (see Figure 1). Also active flow control concepts are able to enhance the performance of local areas at the wing, airframe or different flight control devices [9–11].

Moreover, the trend towards more-electric aircraft and all-electric aircraft lead to considerable changes on system level and consequently have an impact on the FCS architecture design [3, 12].



Cruise Variable Camber (CVC)



Differential Flap Setting (DFS)

Figure 1 – Multifunctional use of trailing edge flaps for Cruise Variable Camber (CVC) or Differential Flap Setting (DFS) (Source: Airbus)

However, only few studies show how functional enhancement or new technologies for flight control systems can be considered and integrated in early phases of the aircraft design process.

Bertram et al. [13] presents a case study with a “function-driven design process” for a blended wing body FCS for attitude and trajectory control [13]. A simulation-driven methodology with focus on requirements verification and safety assessment of innovative FCS architectures is shown by Kreitz [3]. But both studies don’t consider the implementation of additional functions for performance or efficiency increase. Lammering et al. [5] see future improvements by blending primary and secondary control functions with distributed control surface architectures for trailing edge flaps [5]. Reckzeh [1] presents a first idea of a functional-driven design approach. The intent of this approach is the transition from a knowledge-based design to a functional-driven design, to increase the solution space and enabling multifunctional concepts [1].

The purpose of this contribution is to enable a functional-driven design of Advanced Flight Control Systems (AFCS) consisting of highly integrated and multifunctional flight control devices (see Figure 2). In this study, the term “multifunctional” implies that flight control devices have (by design) or fulfill (by use) multiple flight control functions. Flight control devices include all movables, surfaces and technologies which are providing or supporting flight control functions.

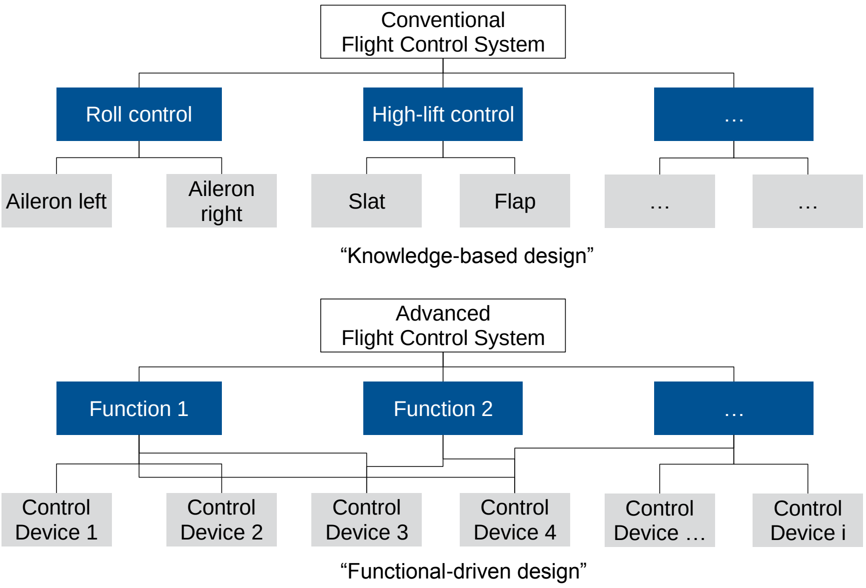


Figure 2 – Functional breakdown of conventional flight control systems (top) and advanced flight control systems (bottom) (based on [1, p. 5])

2 BACKGROUND

Conventional FCS of commercial transport aircraft are full fly-by-wire systems with automatic control features, envelope protections, and control laws for safety enhancement. The FCS have very stringent dependability requirements in terms of safety and availability and are designed to tolerate hardware and software design faults. Dedicating standards and regulations are defined by the CS-25 of the European Aviation Safety Agency (EASA) and the FAR 25 of the Federal Aviation Administration (FAA).

2.1 Flight Control System Design

To meet the requirements in terms of preliminary aircraft design, the FCS definition in this study – in contrast to the ATA27 definition – includes the flight control devices. Based on this definition the FCS can be divided into a configurational system and an architectural system (see Figure 3).

The configuration describes the type, allocation and positions of flight control devices as well as the kinematics and support, fairings, and airframe integration aspects. In general, primary flight control devices (e.g. aileron, elevator, and rudder) are flight-critical and continuously activated to maintain safe attitude and trajectory control of the aircraft. Secondary flight control devices are high-lift control devices at the leading and trailing edge of the wing, and spoilers. They are classified as less critical, but in general they are not less essential for the sizing and efficiency of transport aircraft. The architecture defines the number of the flight control computers and their clear assignment to dedicated flight control devices for redundancy and reconfiguration in the case of an error. Also linkage, actuation and redundant distribution of the power supply is attributed to the architecture.

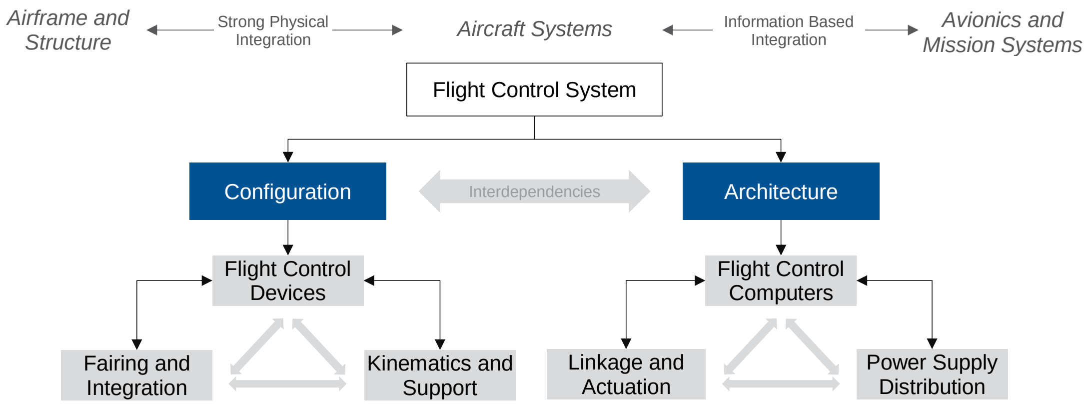


Figure 3 – Breakdown of a flight control system into configuration and architecture

The FCS is one of few essential aircraft systems with strong physical integration into airframe and structure, and significant information based integration into avionics and mission systems (see Figure 3).

2.2 New Technologies and Concepts

Figure 4 gives an overview of the main disciplines and technologies which enable a functional enhancement or efficiency improvement, or have a major influence on the FCS design. On this basis, functions, requirements and constraints can be derived on aircraft, system and device level. Table 1 shows the major effects of certain technologies and concepts on the FCS design.

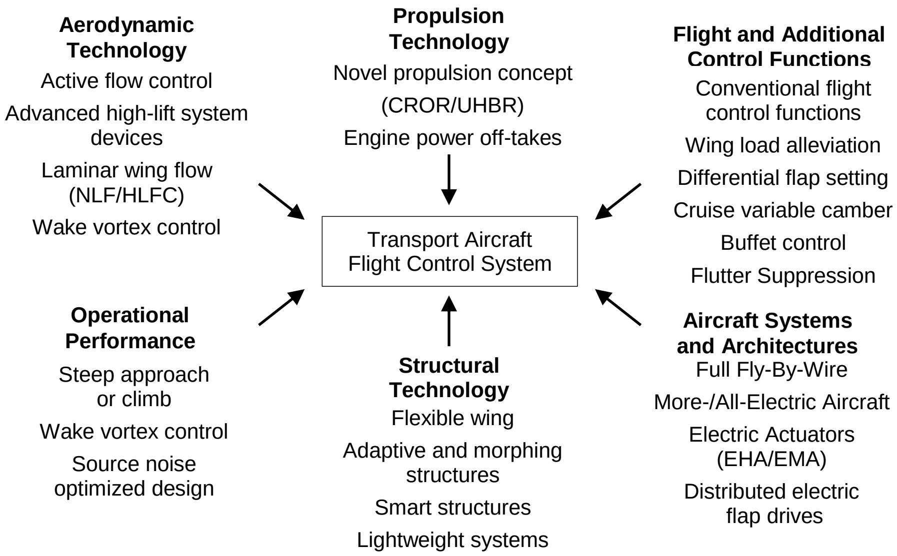


Figure 4 – Overview of enabling technologies/concepts and functions regarding flight control systems (based on [14, p. 23])

Table 1 – Technologies and concepts with major effects on the flight control system design

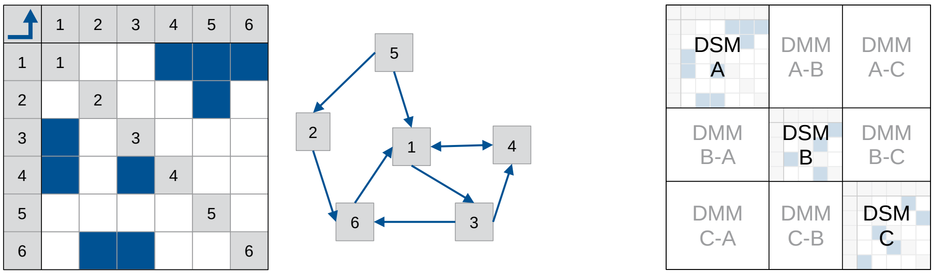
	FCS Configuration			*FCS Architecture*		
	Flight Control Devices	Fairing and Integration	Kinematic and Support	Flight Control Computers[1]	Linkage and Actuation	Power Supply Distribution
Active flow control	x	x		x	x	x
Natural/Hybrid laminar flow	x	x	x			x
Wake vortex control	x					
New propulsions (UHBR)	x		x			
Wing load alleviation	x		x	x		
Differential flap setting	x		x	x		
Cruise variable camber	x		x	x	x	
Buffet control	x		x	x		
Flutter suppression	x		x			
More-/All-electric aircraft					x	x
Electric actuators					x	x
Distributed electric flap drives			x	x	x	x
Flexible wing	x	x	x			
Adaptive/morphing structures	x	x	x			
Smart structures	x	x	x			
Lightweight systems	x	x	x			
Steep approach capability	x		x	x	x	
Wake vortex control	x		x			
Source noise optimized design	x	x	x			

[1] Also additional sensors or control requirements are considered

2.3 Design Structure Matrix and Multiple Domain Matrix

The core of the presented functional-driven approach is a Multiple Domain Matrix (MDM). A MDM is based on the theory of the Design Structure Matrix (DSM), which was first developed by Steward in 1981 [15] and advanced by Eppinger and Browning [16] at the Massachusetts Institute of Technology.

The DSM enables the modelling and analyzing of complex systems or processes. In general, the DSM is defined as a NxN matrix, where relations and interactions between the N elements of the system of the same domain are depicted, as illustrated in Figure 5.



Design Structure Matrix (DSM)

Directed graphs

Multiple Domain Matrix (MDM)

Figure 5 – Schematic of a Design Structure Matrix (DSM) (left) with derived directed graphs (middle) and a Multiple Domain Matrix (MDM) with different domains (right)

An extension of the basic DSM is the Multiple Domain Matrix (MDM). The MDM includes several DSMs and corresponding Domain Mapping Matrices (DMM), which represent relations between elements of different domains (see Figure 5).

3 OVERALL DESIGN METHOD

The overall objective is to enable a functional-driven design and analysis of Advanced Flight Control Systems (AFCS) with multifunctional flight control devices. Figure 6 shows the schematic of the overall design method with the three main stages. This design method is dedicated for the conceptual and preliminary design of subsonic commercial transport aircraft.

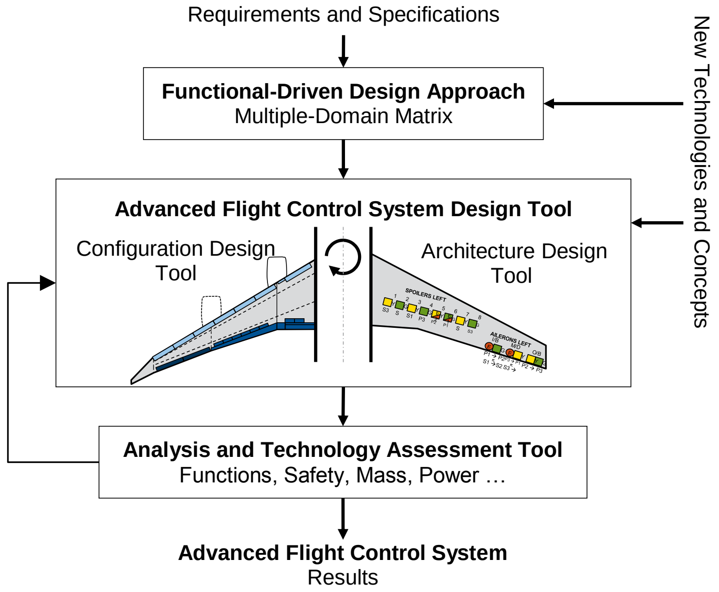


Figure 6 – Schematic of the overall design method (simplified)

Functional-driven design approach (see Chapter 4)
The objective of the functional-driven design approach is to explore the potential design space to derive several solutions of AFCS concepts. These solutions are then used as the starting point for sizing and further investigations.

Advanced flight control system design tool
Analogue to the breakdown illustrated in Figure 3, the tool is divided into a configuration and an architecture tool. The configuration tool calculates the aerodynamics of an aircraft model, considering fuselage, wing planform and flight control devices. The architecture tools determines redundant flight control system architectures of a given configuration. The method behind is realized by defining technological assumptions and implementing rules for redundancy, power supply distribution and reconfiguration. If a valid configuration and architecture is found, the mass of the flight control system is calculated.

Analysis and technology assessment tool
The functional analysis and technology assessment tool enables the assessment and comparison of the found solutions. To have a basis, reference aircraft with modelled aircraft systems and mission profiles are defined.

4 FUNCTIONAL-DRIVEN DESIGN APPROACH

The functional-driven design approach, as illustrated in Figure 7, represents the first step of the aforementioned overall design method. The approach starts with requirements engineering. On the basis of a stakeholder analysis, a clear definition of requirements and objectives is essential for a successful design process. In general, the main objective is to design a safe, reliable, efficient and simple (low complex) system.

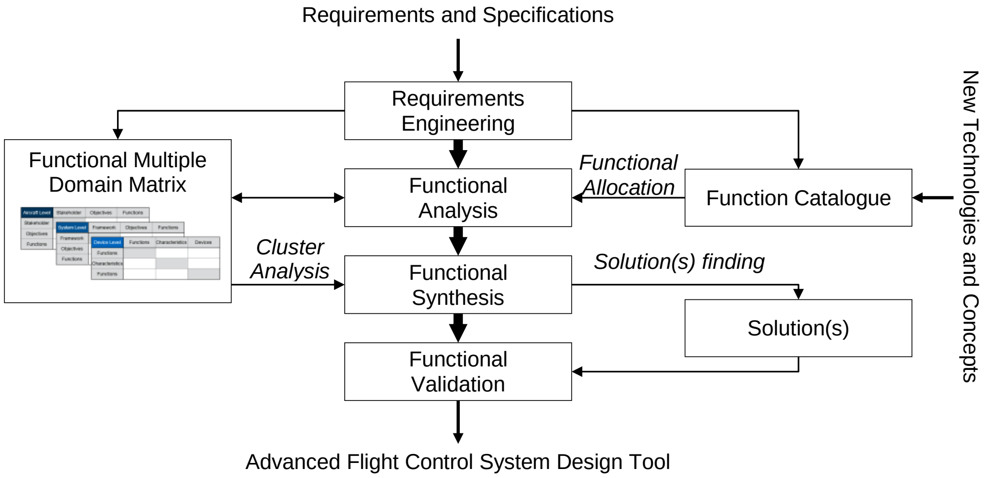


Figure 7 – Schematic of the functional-driven design approach

4.1 Functional Multiple Domain Matrix

The Functional Multiple Domain Matrix (FMDM) represents the core of the design approach and accompanies the entire development process. It is divided in MDMs on aircraft level, system level and device level. This hierarchical segmentation allows a differentiated view on various design aspects of each level. Besides the usage for analyses, the FMDM also serve as a database, where coherences are modelled and information is stored.

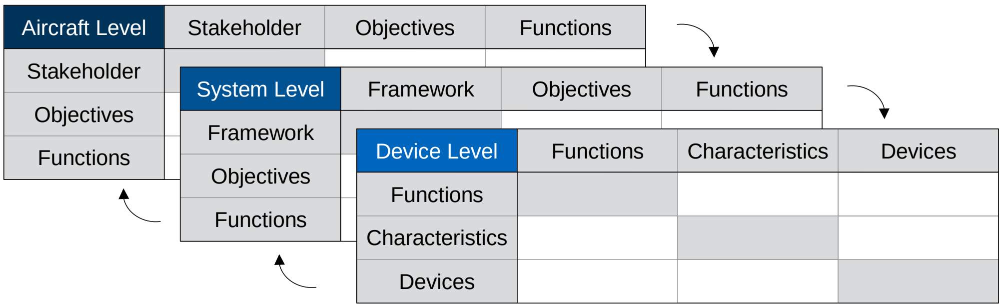


Figure 8 – Setup of the Functional Multiple Domain Matrix (FMDM)

4.2 Functional Analysis

The functional analysis is the link between the requirements engineering and functional synthesis for finding several solutions. The objective is not to find the best configuration, but to exploit the basic design space. Figure 9 illustrates the main steps of the functional analysis.

In a first step, the control functions are determined. To support the determination and analysis of the characteristics of different flight control functions, a function catalogue is set up. The function catalogue describes all potential functions with their characteristics, requirements and constraints for the design process. The function catalogue works as a data basis and supports a differentiated view on each level. The flight mechanical aspects are defined on aircraft level. System integration aspects as well as the coordination of flight control devices and redundancy are described on system level. On device level, the characteristics of potential flight control devices (deflection up/down, translation, positions, modes…) are described

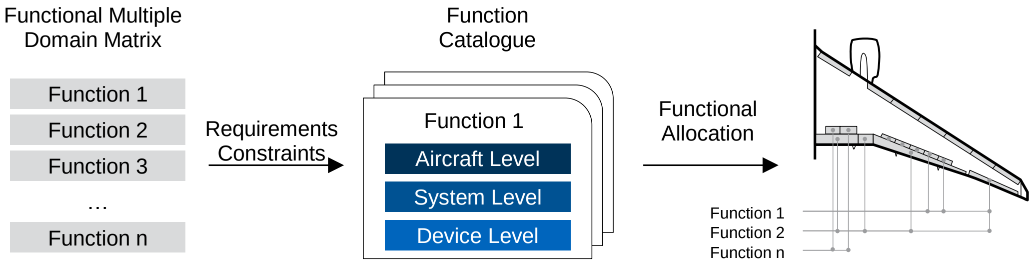
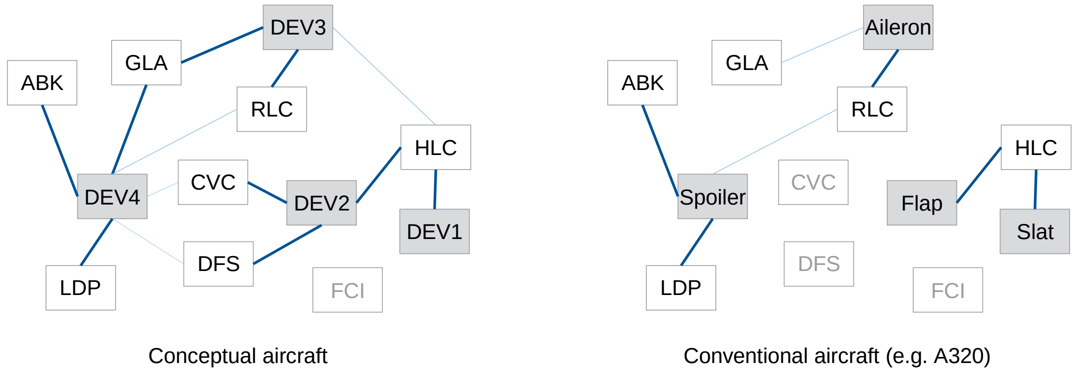


Figure 9 – Major steps of the functional analysis using the function catalogue

Finally, the basic design space for further investigations is generated by allocating functions to flight control devices. Figure 10 exemplary shows the simplified results of the functional allocation of a conceptual aircraft configuration and a conventional aircraft (e.g. A320).



—	Standard	HLC	High-Lift Control	RLC	Roll Control
—	Option	ABK	Airbrake	GLA	Gust Load Alleviation
DEV	Flight Control Device	LDP	Lift Dump	DFS	Differential Flap Setting
☐	Function	FCI	Function i (general)	CVC	Cruise Variable Camber

Figure 10 – Simplified comparison of the functional allocation for the flight control system of a conceptual aircraft (left) and of a conventional aircraft (right)

4.3 Functional Synthesis

The objective of the functional synthesis is find several solutions within the basic design space. This is done in close cooperation with the FMDM. Based on the aforementioned functional allocation, a cluster analysis is conducted. A cluster defines a group of elements with a lot of internal coherences and few or none external coherences. The coherences can be dependencies, synergies or conflicts.

Figure 10 shows an exemplary cluster analysis on device level. Further cluster analysis on aircraft or system level leads to another perspectives. For example the emphasis of effects of certain functions on aircraft level (e.g. flight mechanics) or on system level (e.g. system integration aspects). To support the analysis, a cluster algorithm for optimizing assignment is recommended to provide a structured approach. A good example of a cluster algorithm tool is presented by Thebeau [17].

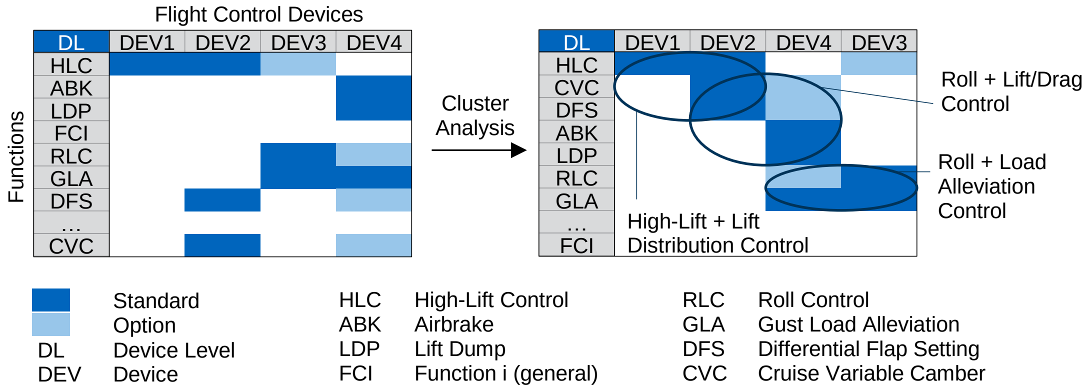


Figure 11 – Exemplary cluster analysis on device level for a conceptual aircraft (simplified)

4.4 Functional Validation

In the last step, the solutions are validated (safety analysis) and evaluated (metric) on aircraft and system level. This can be done for each defined cluster or for the overall AFCS design solutions. On the basis of a general Functional Hazardous Assessment (FHA), a preliminary system safety analysis (PSSA) is conducted. Therefore, a Fault Tree Analysis (FTA) for each considered function is created. For the evaluation the definition of a reasonable metric for the assessment of the solutions is required.

5 CONCLUSION

This study contributes to a functional-driven design approach for Advanced Flight Control Systems (AFCS) of commercial transport aircraft. This approach can be applied for new aircraft configurations in the early stages of the aircraft design or for aircraft retrofit studies. The approach presented is based on a Functional Multiple Domain Matrix (FMDM) which enables a transparent design process, while considering different aspects on aircraft, system and device level. A set up function catalogue supports the determination and analysis for the functional allocation to find the basic design space. On this basis, a cluster analysis reduces the complexity of the design process and allows to derive solution alternatives for each. Finally, the found solutions are validated and evaluated. The best solutions serve as input data for the AFCS design tool for sizing and further investigations.

For the future, a partly implementation of the functional-driven design approach, including the framework of the FMDM and the function catalogue, in MATLAB is planned. Especially an implemented cluster algorithm enables structured analyses.

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