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Generation of Potential System Architectures by Applying a Stochastic Clustering Algorithm in the High-Lift Actuation Preliminary Design Process

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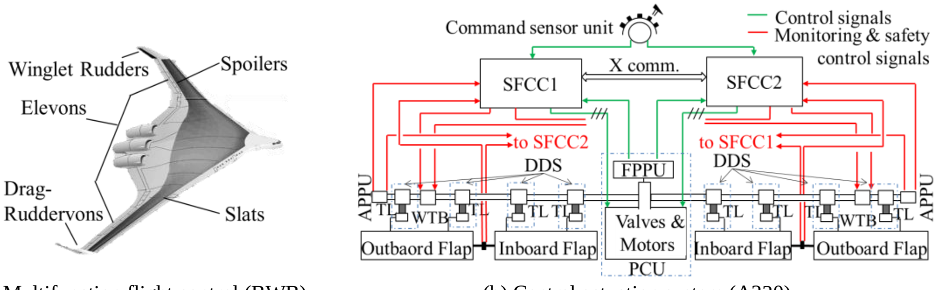
Abstract: High-lift systems are highly complex subsystems of aircraft, composed of hundreds of components working together in synergy. Designing new concepts for new aircraft configurations and requirements (e.g. multi-functional flight control systems) for more efficient flight is a complex and demanding task, thus designers are prone to using existing system solutions with slight modifications. Hence, new flight control system architectures are based on solutions mainly optimized for different (old) aircraft. This inhibits the complete capture of the benefits that come with systems optimized for present aircraft configurations and requirements. As a first step towards generating innovative architectures driven by the new requirements, this paper applies a stochastic design structure matrix clustering algorithm within the pre-design process, to generate alternative system architectures. With this approach, near-optimal system architectures for novel aircraft configurations and requirements can be analyzed and alternatives can be evaluated for system level impact.

Keywords: Aircraft, High-Lift, Actuation Systems, Design Structure Matrix, Architecture, Clustering, Preliminary Design

1 Introduction

Flight control systems are moving from single function to multifunction systems, because of the potential benefits such as improved roll maneuver, load alleviation etc. (Reckzeh, 2014) (Cook & de Castro, 2004) (Reckzeh, et al., 2012). Thus, multifunction movables where systems support multiple functions are seen as the future of new aircraft configurations. Figure 1(a) shows a blended wing body aircraft (an example of an aircraft concept with new configuration and requirements) with control surfaces (movables) that may be used as elevators, ailerons, or simultaneously as combined elevators and ailerons (elevons) (Cook & de Castro, 2004). In general these systems are very complex, made up of many subsystems with interconnections, working together in synergy. These new configurations and their accompanying design requirements impose new constraints on the design space. Considering that the optimization capabilities of today‘s highly optimized high lift system architectures has reached a plateau and are limited to small local improvements (Recksiek, 2009), meaningful design changes to capture new design requirements and benefits become very challenging. Moreover the classical economic and technical targets and constraints are still in place, thus, the only way to comply with the new requirements without overly penalizing the aircraft is to account for them as early as possible in the design process (i.e. considering them during the preliminary design phase) (Werner-Westphal, et al., 2008). A typical single function flap actuation concept used in many aircraft of today is shown in Figure 1(b) (A320) (Udo, 2003). This actuation system is composed mainly of a central PCU connected to torque shafts running through each wing as shown in Figure 1(b).



(a) Multifunction flight control (BWB) (b) Central actuation system (A320)

Figure 1. Multifunction flight control (a) vs Central actuation system of today (b)

Where:	SFCC	: Slat/Flap Control Computer	FPPU	: Feedback Position Pickup Unit
	WTB	: Wing Tip Brake	APPU	: Asymmetry Position Pickup Unit
	TL	: Torque Limiter	PCU	: Power Control Unit
	DDS	: Down Drive Station		

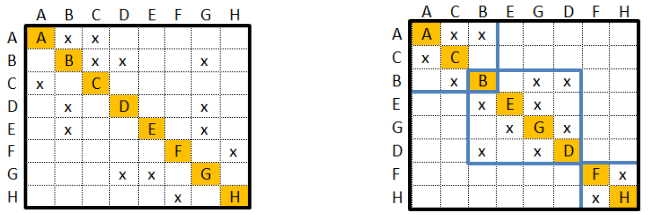
These shafts are connected to four down drive stations which move the flaps. The first two stations drive the inner flap and the other two drive the outer flap. The complete system is controlled and monitored by two computers (SFCCs) and other safety components such as the APPU, TL and WTB. This system has the basic functionality of deploying the flap control surfaces synchronously, but does not allow for their asynchronous deflection. Such functionality (asynchronous deflection of the outboard flap) may enable the use of the outboard flap to not only provide lift but also to assist in the roll maneuver of an aircraft (multi-functionality). This and other potential benefits could be exploited in the conceptual development of aircraft systems through the development and analysis of different system architectures using these new requirements.

2 Generation of system architectures

System architecture can be defined as the scheme by which the functional elements of the system are arranged into physical chunks and by which the chunks interact. These chunks can be thought of as modules of the system (Ulrich, et al., 2003). Modularity, using structurally independent modules to form product architectures, is a widely accepted approach to save development and manufacturing costs, and bring flexibility to a design (Holtta & Salonen, 2003). Modularity methods that have been accepted and used in industry in generating system architectures include the function structure heuristic method (Pahl, et al., 2007), clustering a design structure matrix (Eppinger & Browning, 2012) and modular function deployment (Gunner, et al., 2007). The function structure heuristics method can be applied to single products and a couple of product families of similar products. The modular function deployment method is designed to modularize a single product. The design structure matrix method is designed especially for complex product architectures and thus, will be the approach applied in this paper because of the high complexity of the actuation systems.

2.1. Creation of Design Structure Matrix

The previously mentioned (including DSM) modularity methods all require a good functional model in order to generate meaningful system architectures (Holtta & Salonen, 2003). The DSM, also referred to as dependency structure matrix is a tool for network modeling. It is used to represent a system's architecture (or design structure) by mapping the interactions among the elements that make up a system (Figure 2 (a)). The DSM is represented as a square $n \times n$ matrix, with relations (or interactions) among the set n of system elements. One can think of a DSM as a collection of cells (A to H in Figure 2(a)) along the diagonal of the matrix as representing the system elements-analogous to the nodes in the digraph model (Eppinger & Browning, 2012). The diagonal cell has inputs entering from its left and right sides and outputs leaving from above and below as shown on Figure 2(a). The corresponding marks in the off- diagonal cells indicate the sources and destinations of the inputs and outputs, analogous to the directional arcs in a digraph. The inputs to an element in a row (which are outputs of other elements) are indicated by marks in that row. The outputs to an element in a column (which are inputs to other elements) are indicated by marks in that column.



(a) (b)

Figure 2. (a) A DSM representation of a system's original architecture; (b) A DSM representation of the same system's alternative architecture after clustering

Depending on the system being modeled, DSM can represent various types of architectures (Eppinger & Browning, 2012). For this application, a function-based DSM is used. Here the elements are the sub-functions of the high- lift actuation system and the interactions are the interfaces between the functions.

2.2. Clustering algorithm

While Figure 2(a) shows the DSM representation of a system's original architecture generated from a functional model, Figure 2(b) shows an example of an alternative (new) DSM representation derived by clustering the elements of the original DSM (Figure 2(a)). This new DSM represents an alternative architecture of the same system whose elements are the clusters (in blue boxes), derived by clustering the elements (A to H). Similarly the original DSM of Figure 2(b) is clustered to form the new DSM as shown in Figure 6(a). To capture the randomness and unpredictable nature in designing real systems, which is an intrinsic and unavoidable element of any complex design process (Huberman & M, 14 Jnauray 2006) this work uses a stochastic method and algorithm by (Carlos Inaki, 1998) (Thebeau, 2001) to cluster system elements. The algorithm uses an objective function which favors intra-cluster interactions while disfavoring extra-cluster interactions, whose calculated value is called the Coordination Cost (or Total Cost). The algorithm begins by placing each element in its own cluster and calculating the Coordination Cost of the cluster matrix. Then an element (E) is chosen randomly and the bid from all clusters calculated. By default, E becomes a member of the cluster with the highest bid. To prevent getting stuck in local optima, in one of rand_bid (see Table 2) cases the cluster with the second highest bid is chosen instead. The change is applied if the new Coordination Cost is lower than the old Coordination Cost. If this is not the case, the change is still applied randomly in one out of rand_accept (see Table 2) cases, to fully explore the solution space. This process is repeated until all elements belong to a cluster. The bid on an element from each cluster j, is given by equation (1). The Coordination Cost was calculated as the sum of the cluster costs (equations 2, 3 and 4).

$$ClusterBid_j = \frac{(inout)^{powdep}}{(ClusterSize_j)^{powbid}} \quad (1)$$

Where: j = cluster number
$ClusterBid_j$ = bid from cluster j for the chosen element
inout = sum of DSM interactions of the chosen element with each of the elements in cluster j
powdep = exponential to emphasize interactions
powbid = exponential to penalize size of the cluster

Intra-cluster cost for an interaction between element j & k occurring within a cluster

$$IntraClusterCost = (DSM(j,k) + DSM(k,j)) \times ClusterSize(y)^{powcc} \quad (2)$$

Extra-cluster cost for an interaction between element j & k occurring outside of a cluster

$$ExtraClusterCost = (DSM(j,k) + DSM(k,j)) \times DSMSize^{powcc} \quad (3)$$

$$TotalCost = \sum IntraClusterCost + \sum ExtraClusterCost \quad (4)$$

Where: TotalCost = Coordination Cost
IntraClusterCost = Cost of interaction occurring within a cluster
ExtraClusterCost = Cost of interaction occurring outside of any clusters
DSM(j,k), DSM(k,j) = DSM interaction between element j & k
ClusterSize(y) = Number of elements in the cluster y
DSMSize = Number of elements in the DSM
powcc = Penalizes the size of clusters

These equations served as the basis and starting point for the analysis and clustering of the high-lift system DSM.

3 Current design process of high-lift systems in aircrafts

The system (Figure 1(b)) is optimized for reliability, safety, weight and synchronous deflection of inboard and outboard flaps etc. The typical design process of the different actuation system types (mechanical, electromechanical or hydraulic) on aircrafts today is shown in Figure 3 below (Thielecke, 2013) (Mare & Budinger, 2012):

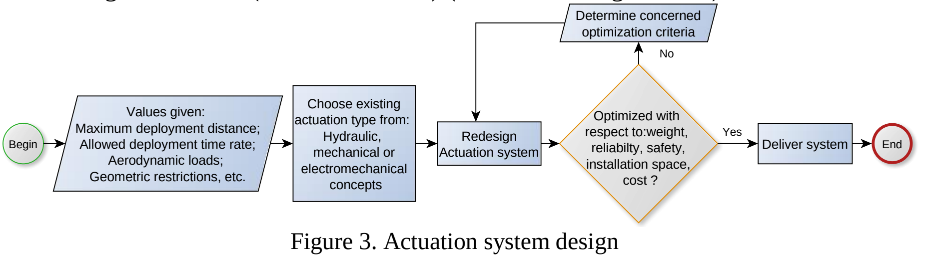


Figure 3. Actuation system design

Pre-defined values such as the maximum deployment distance, allowed deployment time, aerodynamic loads etc. are used as inputs to the design process. The actuation type is then chosen and optimized with respect to the weight, reliability and other design constraints. This procedure principally focuses on optimizing a chosen actuation type (or slight variations thereof) to meet target specifications. A generalized step preceding the process (Figure 3), which is primarily the generation of alternative system concepts independent of technology, is missing. Thus, as a first step towards defining a better and more effective design process where the benefits of the new design configuration and requirements can be maximized, this paper presents a pre-design process that uses the design structure of a system to generate alternative architecture concepts before the detail design phase (Figure 3). Using the DSM to generate architectures is well known in industry with applications ranging from space exploration, to car systems etc. (Eppinger & Browning, 2012). In this work, the algorithm described in section 2.2 (Carlos Inaki, 1998) (Thebeau, 2001) is applied to the actuation architecture of Figure 1(b) using with the requirement of section 4.1 to generate a new innovative actuation architecture. For simplicity only one wing is used in this study.

4 Application of the DSM clustering approach in generating an alternative High-lift Actuation system architecture

The process which is an iterative process starts with the identification of stakeholder requirements and the establishment of target specification and ends with an architecture evaluated based on stakeholder needs. A summary of the complete process is presented below (Figure 4). This process was executed on an A320 actuation system to obtain the new multifunctional architecture shown in the Figure 7 below.

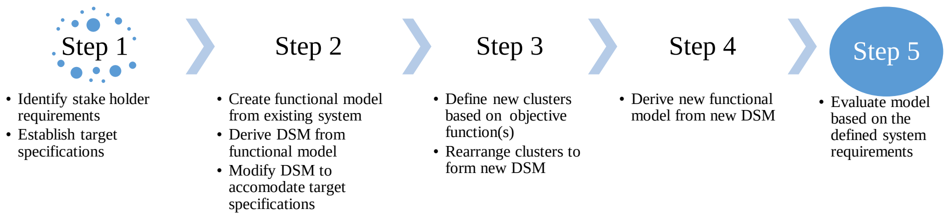


Figure 4. Simplified Architecture generation process

4.1 Identify stakeholder requirements and establishment of target specifications (Step 1)

The roll assist configuration of the outboard flap is used as a new requirement for the design of the flight control system. Hence, the outboard flap is now required to perform two functions i.e. provide high lift as well as assist in roll (roll is typically provided by the Ailerons). The implication of this requirement is the independent deflection of the outboard flap. Though not accounted for in the A320 concept of Figure 1, it will be exploited in its design structure. To keep it simple, the speed of deflection, and other requirements that may arise are not considered.

4.2. Creation of functional model, original DSM and modified DSM (Step 2)

4.2.1 Functional model

A functional model of a system is an abstraction that identifies the system's functions and their interactions. It represents the transformation of energy, material or signal information flows as they pass through the system elements (Stone, et al., 2000) (Hutcheson, et al., 2007) (Chakrabarti, et al., 2011) (Pahl, et al., 2007). It defines how the functions will operate together to perform the system mission. Generally, more than one functional model can satisfy the system requirements. Because of complexity, a less detailed version of that used in this work (Figure 1(b)) is shown in Figure 5 below. The simplified model shows the interconnections between high level system elements together with the flow of energy, signal and material.

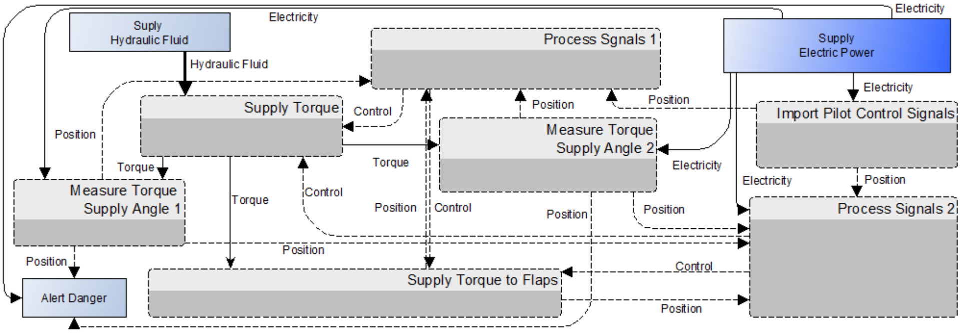


Figure 5. Simplified section of aDSMctuation system functional architecture

From the detailed functional model, a DSM was generated and modified according to the new system requirement (section 4.1) to serve as the input into the algorithm (method).

4.2.2 Design Structure Matrix (DSM)

In the detailed DSM of the system, 81 elements were labelled with interconnections, making it very difficult to manage the complexity. For clarity, Table 1 shows a less detailed DSM, corresponding to the functional model in Figure 5. To keep the matrix diagram compact, the full names of the elements are listed on the first column as shown in Table 1below. Based on analysis of the original DSM where all connections were assumed equal (having a value of 1), a modified DSM was derived. New connections were created to accommodate the roll assist requirement of the outboard flap, some edges were broken as well as some element-element interaction strengths were changed. Here the connection between the second and third down drive stations was broken, dividing the complete actuation system into two halves, with the first still attached to the power control and signal processing elements.

Table 1. A section of the DSM of the A320 central actuation system

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Supply Electric Power	**1**	1									
Supply Hydraulic Fluid	**2**		2								
Import Pilot Control Signals	**3**	x		3							
Process Signals 1	**4**			x	4			x	x		x
Process Signals 2	**5**	x		x		5		x	x		x
Supply Torque	**6**		x		x	x	6				
Measure Torque Supply Angle 1	**7**	x					x	7			
Measure Torque Supply Angle 1	**8**	x					x		8		
Alert Danger	**9**	x						x	x	9	
Supply Torque to Flaps	**10**				x	x	x				10

An interaction was then created between the second half and the power control and signal processing units. The functions concerned with safety were equally linked to both halves of the decoupled system. Interactions strengths of safety, signal processing and power control elements were increased because of their necessity, due to the very high failure-free system targets in aerospace applications.

4.3 Defining new element clusters from the modified high-lift DSM (Step 3)

Before running the clustering algorithm, electric power supply, flight control computers, flight warning computer elements were left out of the clustering. This is because these subsystems were deemed too delicate for major redesigning at this stage. Also algorithm parameters values (Table 2) were changed until a suitable set of parameters producing meaningful clusters was obtained.

4.3.1 Parameter application

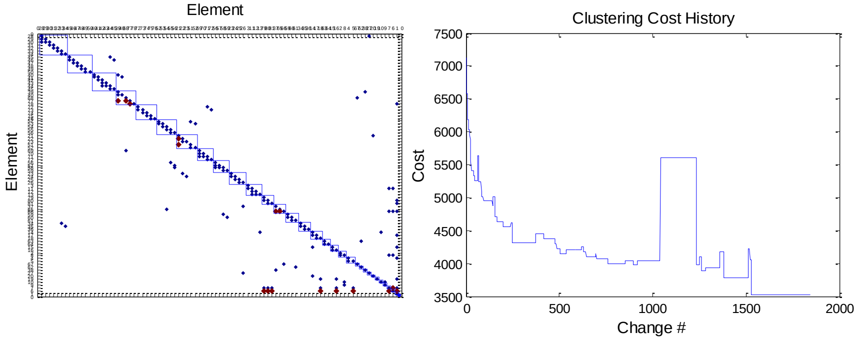
The clustering algorithm was applied to the modified High-lift system DSM with different interactions values. The initial run had the parameters set at their default values (Thebeau, 2001) and then they were adjusted to get an appropriate level of clustering. The process of getting suitable parameters was done on a trial and error basis. The parameters' default values and final values together with their descriptions are listed on the Table 2 below.

Table 2. Clustering parameter settings

Description	Parameter	Default	Final
Penalize the size of the cluster in the cost calculation	pow_cc	1	1
Penalizes cluster size	pow_bid	1	0
Emphasize high interactions during bidding process	pow_dep	4	8
Specifies the maximum cluster size	max_cluster_size	61	81
Specifies how often to proceed with changes, even if there is no improvement in coordination cost	rand_accept	122	122
Specifies how often to accept the bid from the second highest bidder instead of the highest bidder	rand_bid	122	122
Specifies number of times algorithm will pick a new element before checking for stability	times	2	2
Specifies number of times algorithm must loop through without making a change before it finishes	stable_limit	2	2

4.3.2 Executing the clustering algorithm

Just as the clusters of Figure 2(b) were derived from Figure 2(a), Figure 6 (a) shows the derived clusters generated by the algorithm from the original DSM of Figure 1 (a).



(a) (b)

Figure 6. (a) New DSM of the actuation system; (b) Clustering cost history

After running the algorithm, many DSMs depicting different clustering arrangements were generated. The DSMs were analyzed and based on experience and, meaningful architecture was chosen for further analysis. Figure 6 (a) above shows the new chosen DSM depicting 31 clusters (31 modules out of the 81 elements in the original DSM) after executing the algorithm. The cost history for clustering is shown in Figure 6(b). The lowest cost is the last solution which implies that the generated clustering is the best for this run. To keep it simple the generated architecture is analyzed based on its feasibility in achieving the multi-function requirement. Safety, reliability and other requirements are left out deliberately and are beyond the scope of this work.

4.4 Derivation of new functional model from new DSM clusters (Step 4)

The clusters generated through the optimization routine greatly reduced the complexity of the system to a manageable level. These clusters were then analyzed and manually regrouped to form the final architecture in Figure 7 (single wing). This architecture is different from the original A320 architecture in the sense that the arrangement of functions is different as well as some relationships between the element and clusters.

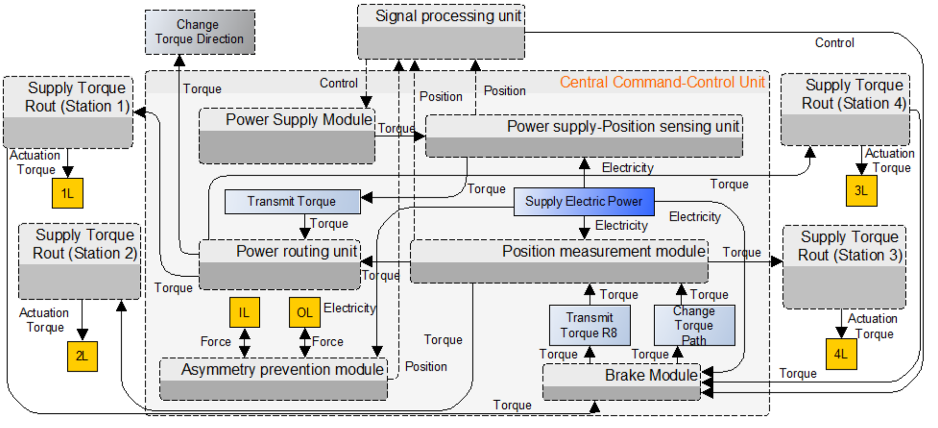


Figure 7. New functional architecture derived from the new DSM

4.5 Evaluation of functional model based on defined system requirement (Step 5)

A much simpler representation for the complete aircraft (both wings) architecture is shown in the Figure 8 below.

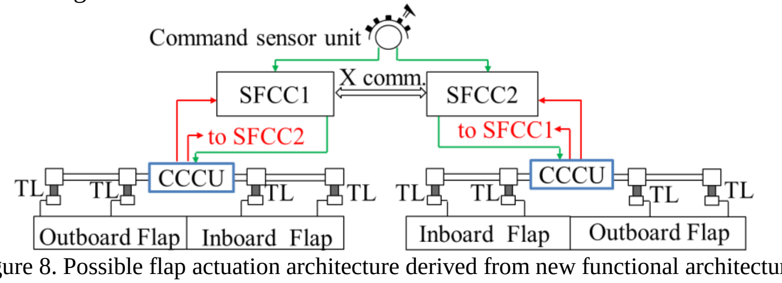


Figure 8. Possible flap actuation architecture derived from new functional architecture

Where: SFCC: Slat/Flap Control computer; CCCU: Central Command-Control Unit; TL: Torque Limiter.

Of particular note is the Central-Command-Control Unit (CCCU) that is placed between the inboard and the outboard flap and can be considered as the main module driving the design of this derived actuation concept. This is in contrast to the original solution architecture which has one central power control unit. This unit is made up of 6 modules composed of the following main clusters:

Table 3. Modules of the Central Control-Command Unit (CCCU)

Module	Function
Power Supply Module	Supplies the power for moving the flaps
Power Supply-Position Sensing Unit	supplies torque from power source, receive position signal from flap sensors and also measure the commanded position of the power supply module
Power Routing unit	Routes the supply torque within the Central-Command-Control unit for a better torque supply to the flaps if needed and allows for differential deflection of both inboard and outboard flaps
Position measurement module	Measures deflection position of inboard and outboard flap
Brake module	Brakes the inboard an outboard flaps when commanded
Asymmetry prevention module	Prevents unwanted asymmetry between inboard and outboard flap

In addition the CCCU is connected to the flight control computer that performs the necessary computations and gives the required command signals. A module such as the CCCU makes the architecture to achieve the multifunctional requirement of independent inboard and outboard flap deflections. Contrary to the concept in (Reckzeh, 2014) which also provides asymmetric deflection between the inboard and outboard flap, the architecture arrived at in this work has additional modules such as Asymmetry prevention module, a brake module and position measurement module as described on Table 3 above. The architecture obtained in this work could then be taken into the next step of the classical design process where safety analysis, value and impact analysis as well as sizing could be carried out.

5 Conclusion and further recommendations

For more efficient flight, it was required that the outboard flap should not only provide high lift but to also assist the Aileron to perform the roll maneuver of the aircraft. This new multifunctional requirement was imposed on an existing system architecture (A320). Applying the DSM approach within the preliminary design process, a new system architecture Figure 8 was obtained. Even though the design requirement of the architecture was the roll maneuver, other possible benefits of the derived architecture could include: variable camber functionality to increase aircraft efficiency; span-wise lift variation to reduce wing loads under gust conditions and high operation of outer flaps under emergency conditions. This in turn maximizes the benefits that come with the new design requirement, thus demonstrating the possibility and potential benefits of using the DSM approach in generating multi-functional flight system architectures. However, some improvement which could be done to enhance the applicability of the process in the aerospace sector includes evaluation of system safety and introduction of redundancies as well as to relax the tight coupling between individual experience and subjective thinking in creating the modified DSM. Furthermore, a clear framework between the complete multi-functional flight control requirements and the DSM of the system is still missing. Nevertheless, the feasibility of using the DSM to generate new system (in this case functional) architectures using a new requirement has been successfully demonstrated. Finally, other potential avenues to continue this research would be to investigate how the “stochastic” nature of key components drives the resulting architecture and also to connect the approach in this work into a broader architecture design initiative.

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