33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4–9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

Systems architecting: a practical example of design space modeling and safety-based filtering within the AGILE 4.0 project

Andrew. K. Jeyaraj[1], Jasper H. Bussemaker[2], Susan Liscouët-Hanke [3] & Luca Boggero[4]

[1 & 3] Concordia University, Department of Mechanical, Industrial and Aerospace Engineering, Montreal, Canada
[2 & 4]DLR, Institute of System Architectures in Aeronautics, Hamburg, Germany

Abstract

The aerospace industry strives towards innovative aircraft concepts that feature increasing electrification to meet environmental and business targets. Advanced Multi-Disciplinary Analysis and Optimization (MDAO) frameworks have been developed to help evaluate these aircraft and their systems. However, the system architecting process still relies on a system architecture baseline from past aircraft programs or historical data, thereby precluding the exploration of a larger design space and identifying optimal solutions for further development. Furthermore, the evolution of system safety is a critical factor in establishing the feasibility of a system architecture solution. Therefore, there is a need to explore a large design space of system architectures for safety, certification, and performance requirements in an efficient manner. This paper presents a rule-based safety assessment approach within a systems architecting framework that demonstrates the ability to generate and filter a large design space based on safety heuristics. This approach is demonstrated using a case study for an aircraft landing gear braking system.

Keywords: system architecture, design space exploration, design space modeling, safety assessment, conceptual design.

1. Introduction

Exploring multiple aircraft concepts at the conceptual design stage in the aircraft development process is critical to identifying the best fit for a given set of requirements. This process is called design space exploration and is typically carried out at the aircraft level, reflecting choices in engine placement, wing configuration and placement. However, typically only a few aircraft system architectures[1] are explored as they add significant complexity to the design problem and require detailed knowledge about many subsystems. This is not ideal as a large design space of system architecture options is excluded and a potentially inefficient fit must be made between the baseline architecture and the aircraft level configurational choices. To mitigate this, one needs to move towards systematic design space exploration methods coupled with a physics-based evaluation of architecture candidates.

Recent advances in system architecting have focused on using physics-based methods for evaluating system architecture options. Liscouët-Hanke in [1] & [2] demonstrates a power-based framework for system architecture evaluation. Similarly, Chakraborty [3] and Lammering [4] also introduce system architecture and sizing and performance evaluation frameworks. Although these techniques are generic in formulation, they are demonstrated on more electric systems architectures that are based on an underlying conventional baseline. Furthermore, a large number of architecture variants are not explored, and unconventional architectures are typically not considered.

Efforts have also been made to develop Multidisciplinary Analysis and Optimization (MDAO) capabilities that also integrate system-level analyses. In the AGILE project[2], system-level analyses

[1] Sometimes also called “onboard system”; here, the authors address system architecting as the definition, documentation and evaluation of aircraft system architectures such as flight control system, electrical or hydraulic power systems.

[2] AGILE: Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts: https://www.agile-project.eu/

that consider increasing levels of system electrification are included in an MDAO workflow [5]. These are based on the system architecture evaluation methods developed by Boggero et al. [6]. The follow-up project called AGILE 4.0[3] focuses on integrating system architecting by adopting a Model-Based Systems Engineering (MBSE) approach - from stakeholder definition and requirements modeling to architecture design space modeling capabilities to support the design process [7]. The architecture modeling capabilities are implemented in the ADORE (Architecture Design and Optimization Reasoning Environment) tool, developed by the German Aerospace Research Center DLR [8] .

The system architecture design space exploration process has benefitted from improved architecture generation and evaluation methods. However, searching through a design space based on performance evaluation alone can be intractable due to a large number of available combinations and potentially significant time needed to evaluate one candidate design. Judt et al. [9], [10] have presented the use of genetic algorithms in the evaluation of large combinatorial spaces. Although these techniques have demonstrated utility, it is important to note that aspects of safety and certifiability, which are important in establishing feasibility, are not explicitly considered.

Certification considerations have recently been addressed through a performance evaluation-based approach in the AGILE4.0 project. However, methods to filter the design space to ensure that a remaining set of system architectures are implicitly safe are yet to be developed. Initial work on architecture definition based on heuristics by Chakraborty and Mavris [11] is promising, and the development of a generic set of safety heuristics would be beneficial to filter through a large design space. This has been developed in the “Aircraft Systems Safety assESSment” (ASSESS) tool, which implements a set of generic safety heuristics on a system-by-system basis. Furthermore, it provides a simplified means of representing a system architecture in such a way that the safety rules can be quickly evaluated and enable the filtering of a large design space.

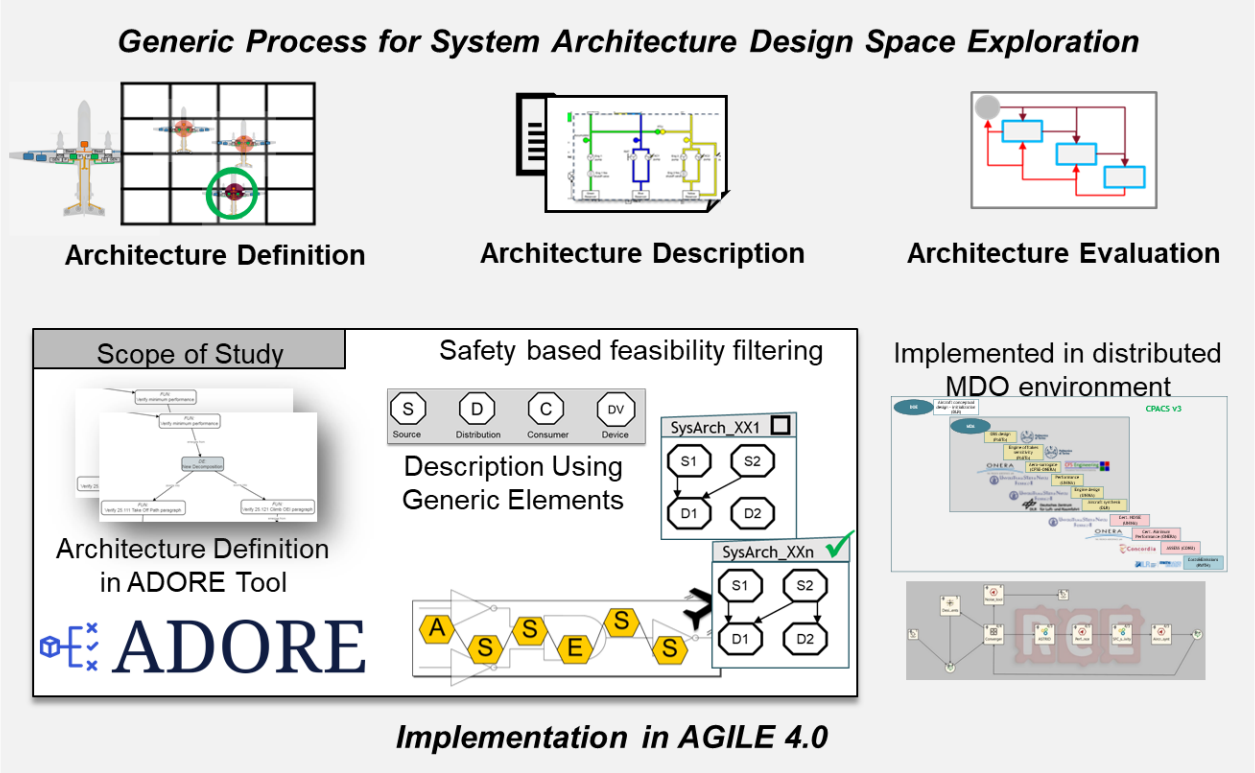


Figure 1: Design space exploration activities and corresponding means of implementation in this study

Jeyaraj and Liscouët-Hanke [12] present a unified safety-focused system architecting framework that addresses each stage of the systems architecture design space exploration process, namely:

[3] AGILE 4.0 is a follow up to the AGILE project to develop cyber-physical methods for aircraft development: https://www.agile4.eu/

architecture definition, architecture description and architecture evaluation, as shown in Figure 1. In their approach, the system architecture definition phase is characterized by the population of a large design space of system architecture options which are then selectively filtered based on a set of safety heuristics. The architecture description phase involves the development of system architecture specification models in an MBSE environment, which are then evaluated in an MDAO workflow during the evaluation phase.

This paper presents a practical example of architecture design space exploration that covers the system architecture definition and description phases using the design space modelling capabilities of the ADORE tool and the rule-based safety filtering approach implemented in the ASSESS tool. A landing gear braking system is used to demonstrate the process of generating a design space of landing gear braking system architecture options. These options vary in the nature of actuation technology that is used on the braking device. The architectural options are then filtered based on conformity to a predefined set of safety heuristics. This manner of filtering the architectural options ensures that only feasible architectures are then evaluated using physics-based approaches which makes the architecting process more efficient.

2. Workflow Description

This section outlines the workflow used within the AGILE 4.0 project to develop and filter the design space of system architectures which are then evaluated using system analysis tools. The key tools for design space modeling, ADORE and ASSESS are described below.

2.1 ADORE (Architecture Design and Optimization Reasoning Environment)

The implemented architecture design space modeling methodology is based on the Architecture Design Space Graph (ADSG) [13]: a directed graph with nodes representing architecture elements like functions and components, and edges representing derivation relationships (e.g. a function derives the existence of a component). This graph can be used to identify architectural decisions and generate architecture instances by making these decisions. By mapping decisions to design variables and performance metrics to objectives and constraints, numerical optimization problems can be formulated.

ADORE implements the ADSG in a Python environment coupled with a web-based graphical user interface for editing and inspecting the design space model [8]. Figure 2 shows a jet engine architecture design space model. In this model, the top-level function “Provide propulsive power” drives the derivation of architectures shown by directed edges. Blue-dashed edges represent architectural decisions with mutually exclusive options, for example, whether to use the fan or nozzle component to fulfill the “Accelerate air” function. Incompatible elements are linked by bi-directional red lines.

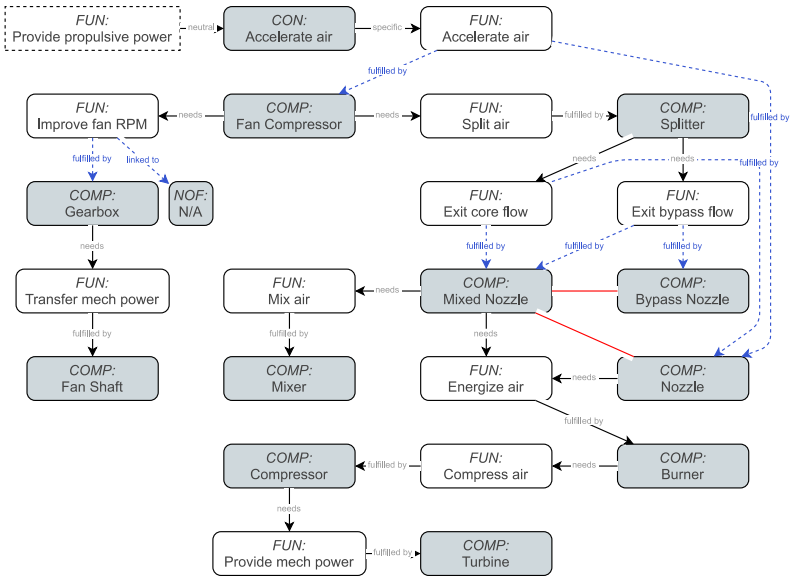


Figure 2: Example jet engine architecture model created using ADORE.

Additionally, ADORE offers interfaces to various Python-based optimization frameworks, which enables using existing optimization algorithms to suggest new design vectors to evaluate. These design vectors can then be converted to architecture instances for evaluation, taking design variable hierarchy (see [13] for more details) into account. No architecture evaluation capabilities are implemented in ADORE. Rather, it is up to the user to implement architecture evaluation by connecting an evaluation tool or workflow to the architecture generation process, and providing feedback to the optimizer in terms of objectives and constraints.

2.2 ASSESS (Aircraft Systems Safety assESSment)

The conventional aircraft safety assessment follows the SAE ARP4761 [14],which consists of several steps at the aircraft and system levels and is a key activity in the certification of an aircraft. This process is typically done manually over various stages in the aircraft development process. The ASSESS tool implements these safety assessment processes in a manner that is conducive to system architecting at the conceptual design stage. The ASSESS tool consists of two modules L0 and L1. The L0 module introduces a rule-based safety assessment using safety heuristics derived from the following sources: 1) analysis of existing system architectures, 2) pertinent certification regulations corresponding to required redundancies in power generating, power distribution, and power-consuming system architecture elements 3) established literature and best practices (e.g., by Chakraborty and Mavris [11]) and 4) industry derived best practices in specifying system architectures. This study will focus on filtering a design space of landing gear braking systems architectures using safety-heuristics derived for Part-25[4] aircraft.

The authors (1&3) extensively analyzed more than 30 different aircraft systems architectures. The cohort of aircraft was divided based on certification basis into the Part 23[5] and Part 25 based categories. System schematics from training, flight, and maintenance manuals were used as sources in addition to academic literature and supplier documentation. Initially, the authors considered the schematics and sources on a system-by-system basis. Electrical, Hydraulic, Flight Control and Landing Gear Braking systems- to name a few- were analyzed in isolation to determine typical redundancies in power distribution and generation systems and allocation of these distribution sources to power-consuming systems.

In addition to the allocation of power distribution sources to power consumption sources, the authors identified that in the case of electrified aircraft systems, there is a component of electrical control involved that requires power supply- the absence of which can have an equivalent impact on a system function as the loss of primary sources of power or a distribution system. Therefore, it is essential to consider the incorporation of electrical controllers as analog to conduits of power, especially in the signaling of electrical actuation functions.

The safety heuristics that are evaluated on each architecture are based on literature and a survey of existing system architecture implementations. The allocation of power systems to actuation elements is also studied to determine a pattern in the nature of allocations and the minimum so required. Additionally, certification rules are used to determine the minimum number of power systems that supply a given brake actuation element. In addition to power allocation, control allocation was also investigated. This is important in the case of electrically signaled braking architectures where both power and control influence the braking function and require redundancies.

In ASSESS L0, the authors (1&3) introduce a set of generic elements that are used to represent a system architecture. These elements are used to describe the architecture and simplify the process of rule evaluation. The generic elements are shown in Figure 3 and each architecture is comprised of connections between these elements.

[4] In this paper, the abbreviation “Part 25” is used, referring to the Part 25 of the airworthiness standards for transport category airplanes (e.g. in Canada: 14 CFR Part 25)
[5] In this paper, the abbreviation “Part 23” is used, referring to the Part 23 of the airworthiness standards for normal category airplanes (e.g. in Canada: 14 CFR Part 23)

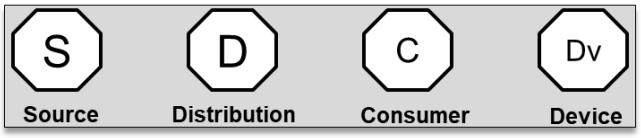


Figure 3: Generic elements used to represent system architectures

These elements are classified based on their interaction with the flow of power in a system architecture. As such, they may be related to existing classifications in literature, as shown in Table 1 **Error! Reference source not found.**. The source element deals with the provision of power and is representative of power generation elements of which a prime mover is a possible physical implementation. An important feature of these generic elements is that they may be used at different levels of granularity. For instance, the source element could be used at the system or component level, representing either a complete power generation system or a specific power generation element.

Table 1: Nomenclature of generic elements used to represent architectures in the ASSESS tool

Generic Element	Referenced Nomenclature	Physical Components	Associated Elements
Source	Power Generation Systems[1] Prime Movers [11]	Engine, Battery	Fuel
Distribution	(PDS)[1],(MPGDS,HPGDS,EPGDS) [11]	Hydraulic, Electrical Distribution System	EDP[6], EMP[7], IDG[8]
Consumer	Power Consuming Systems[1], Subsystem (FCS, ECS,LDG)[11]	Flight Control System, Flight Control Actuators, Landing Gear Braking Devices	EHA[9], EMA[10], EHSA[11]
Device	-	Wheels, Control Surfaces	-

The distribution element represents a routing of power from the source element and can be used to model power distribution systems and elements. Consumer elements are used to represent power-consuming systems and individual components. One can use the Device elements to represent passive or structural components such as wheels and control surfaces. Connections between elements are made hierarchically, starting from the source elements and proceeding to distribution, consumer, and device elements. Connections between elements of the same type are permitted and a single element on the lower rung of the hierarchy can be connected to multiple elements at higher levels. However, a direct connection between any two elements without passing through the intermediate elements is not permitted. Elements of control that fall within the power path such as controllers are also accommodated as Consumer elements within this nomenclature. Additionally, intermediate elements may also be specified but a description of these are beyond the scope of this paper.

2.3 ADORE-ASSESS Link

The ADORE tool generates a large number of architecture instances from the design space model. This design space will be filtered for safety by the ASSESS tool. ADORE and ASSESS represent architectures in different formats according to their respective modeling purposes, and so a translation step is needed [15]. The passing of information between ADORE and ASSESS can be accomplished using two methods: direct transfer and through a common data language shown in Figure 4. The usage of a common data language, as would be appropriate in large-scale collaborative MDAO processes, is described in [8]. In this study, the direct transfer using class factories is applied [16]. Class factories offer a convenient way to extract relevant information from generated ADORE system architectures: class factories represent rules for instantiating custom Python objects for every linked ADORE element encountered in a specific architecture instance. For example, a class factory might

[6] Engine Driven Pump
[7] Electric Motor Pump
[8] Integrated Drive Generator
[9] Electro-Hydrostatic Actuator
[10] Electro-Mechanical Actuator
[11] Electro-Hydraulic Servo Actuator

define the rule: instantiate the `Propeller` class for every “Propeller” component instance, and set the `diameter` property to the value of the “Diameter” attribute of the component instance.

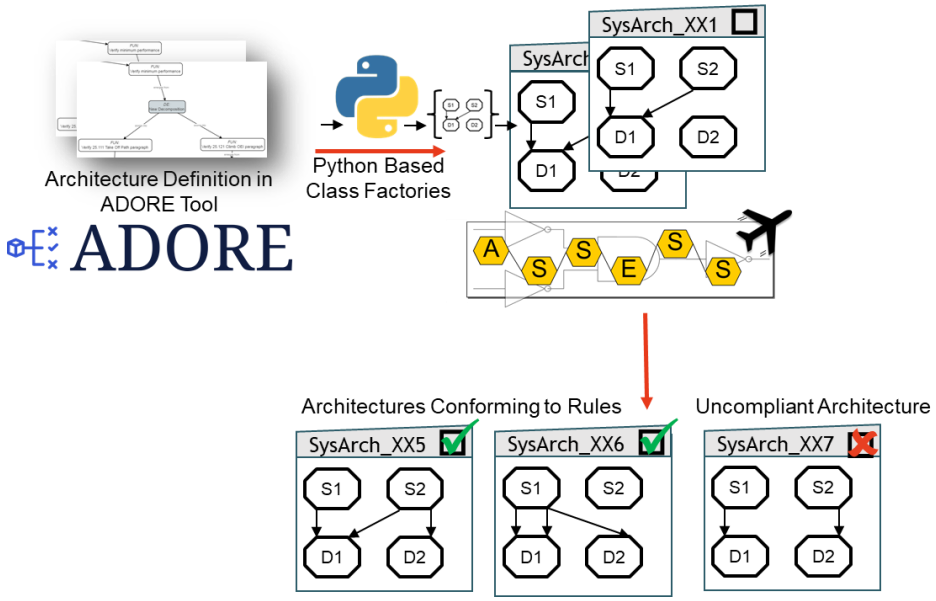


Figure 4: ADORE- ASSESS interaction

3. Case Study: Landing Gear Braking System Architecture

3.1 Case Study Description

The case study is focused on generating a large design space for aircraft landing gear braking system architectures using the ADORE tool and then filtering the resulting architectures for feasibility based on safety heuristics. This will determine whether an architecture in the design space conforms to a set of heuristics that represent implicit system safety. In this case study no feedback will be provided to ADORE for guiding the design space exploration, something that could be realized in other workflows by evaluating design objectives.

Several application cases have been explored in the AGILE 4.0 project that focus on evaluating safety, certification, and maintenance constraints in an MDAO workflow. A regional aircraft is used for these studies which includes the evaluation of aircraft electrification and also retrofitting a hybrid electric powertrain. The top-level aircraft level aircraft requirements for these aircraft are at the border between Part 23 and Part 25 certification regulations and provide a favorable testbed for observing the impact of certification regulations on the overall aircraft design. Within this subset of top-level aircraft requirements, this study focuses on the landing gear braking system, as it represents a system that is characterized by a choice in actuation technology that further results in the need for a power system which requires redundancies in selection and allocation. Furthermore, landing gear braking system requirements also vary depending on the set of applicable certification rules (Part 25 or 23). The elements of this study are illustrated in Figure 5.

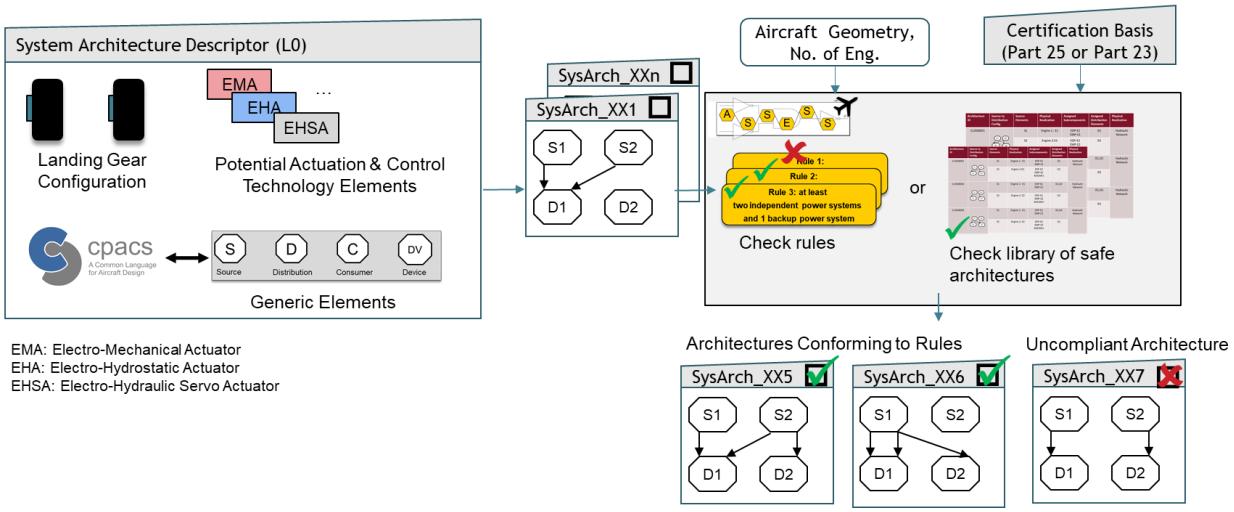


Figure 5: Case Study Description: Landing gear braking system with brake actuation technology choices evaluated for safety rules in the ASSESS tool

The landing gear configuration is fixed to that of the tricycle type, which consists of one nose gear and two wing mounted main gears. Each main gear consists of two wheels, and each wheel is considered to have a single braking device. Each braking unit can comprise of an electro-hydraulic servo actuator (EHSA), electromechanical actuator (EMA), and local hydraulic generation-based actuator. Therefore, each gear can also feature combinations of braking units which use different actuation technologies. Exceptionally, in the case of fully electric actuation, each braking unit is assumed to be comprised of four individual EMA.

3.2 Design Space Definition in ADORE

This study covers two important aspects systems architecting: (1) design space definition and architecture generation (using ADORE) and (2) design space evaluation/filtering (using ASSESS). The first step involves creating a design space of landing gear braking system architectures in ADORE which will be described in this section. These candidate system architectures are then filtered using the generic safety heuristics in ASSESS which will be described in section 3.4.The design space generation process in adore requires an initial system architecture model to be defined. This requires the identification of functions, components to fulfill those functions and also to provide multiple options for function fulfillment. The implemented architecture design space model starts from the boundary function “provide wheel braking”, which is specialized to the “provide wheel braking actuation” function. This function is implemented by either hydraulic or electric brake actuators as shown in section 3 of Figure 6. Both actuator types induce the function “provide deceleration”, fulfilled by the wheels, and functions for providing their respective power types (i.e. hydraulic or electric). Providing power is fulfilled by the hydraulic and electric system shown in section 2 of Figure 6. Power is generated by the engine or emergency power system shown in section 1 of the same figure. One actuator is installed per wheel, leading to 4 actuators in total. The distribution system components have been configured to present three instances and the engine has two instances (representing two engines).

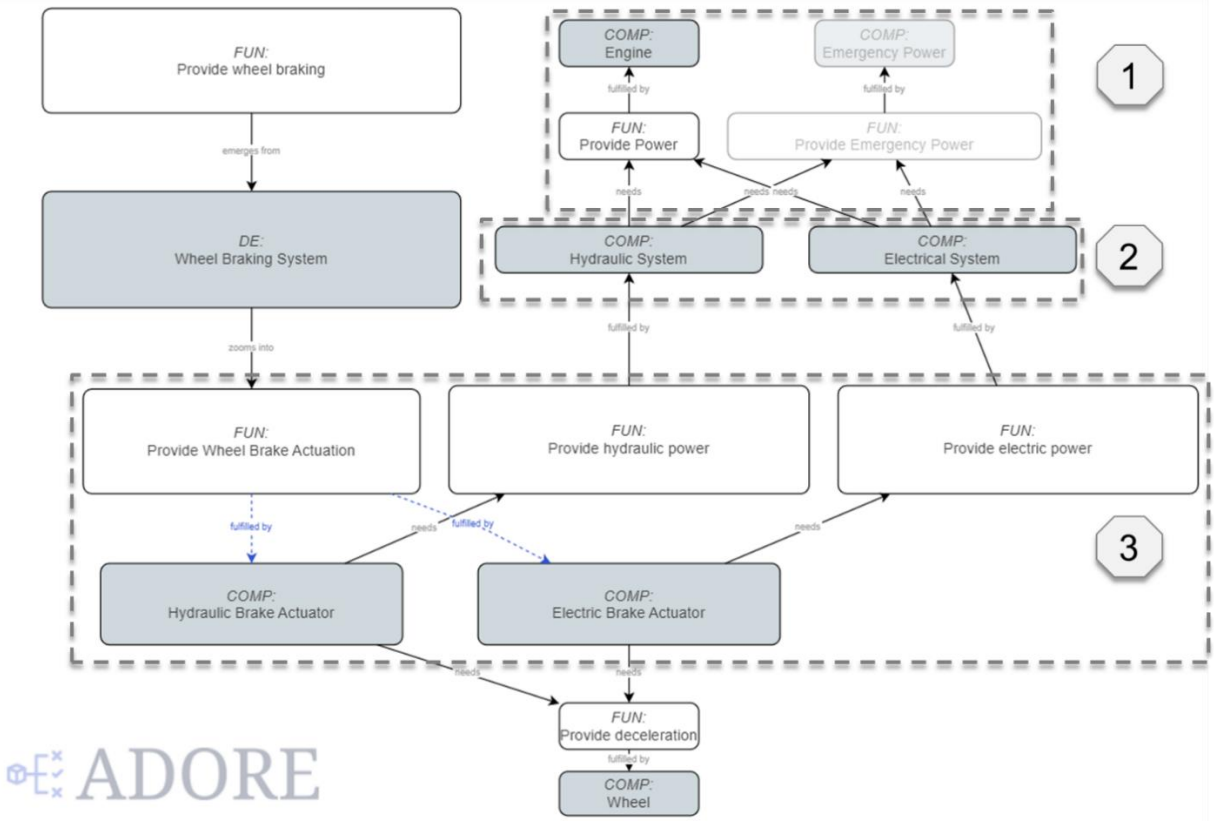


Figure 6: System architecture definition in ADORE

Next to the choice on the type of actuation to use, the most relevant choices are about how to connect the engines (power generation source) to the hydraulic or electrical system (power distribution) and then on to the actuators (consumers). These choices are implemented using ports. Ports represent connection decisions from one or more outputs to one or more inputs. For example, from engines to hydraulic system, the port represents a connection from 2 outputs (for 2 engines) to 3 inputs (for 3 hydraulic systems). Additionally, limits can be placed on the number of connections that each output or input port can establish or accept, respectively. In this case, each engine can be connected to none or any of the systems: each engine can establish between 0 and 3 connections as shown in Figure 7. Each hydraulic system needs to be connected to at least one source: their input ports accept between 0 and 2 connections from the engines, as one input can also come from an emergency power generation system. In total, connections from engines to hydraulic system can be established in 49 different patterns

3.3 Translation from ADORE to ASSESS Architectures

The ADORE design space model is used to automatically generate different architectures. A generated architecture instance represents a combination of the choice between electric or hydraulic actuation and a specific connection pattern from sources, through distributions, to consumers (as required by ASSESS). To evaluate whether the architecture complies with safety regulations, it needs to be translated to a representation that ASSESS can interpret.

In ASSESS, a system architecture is defined using a directed graph containing the node types discussed in previous sections. Translation from the ADORE to the ASSESS format is implemented using class factories[16]. Five class factories are defined: one for connection ports and four for each type of ASSESS node. The port class factory is needed to extract connection information from the architecture model. The four node class factories represent each ASSESS node type (source, distribution, consumer, device), and are linked to the respective components in the ADORE model. These factories instantiate a `GraphNode` class, with following properties:

- Prefix: a string representing the ASSESS node type;
- Connection targets: a list of `GraphNode` objects that this node is connected to.

.

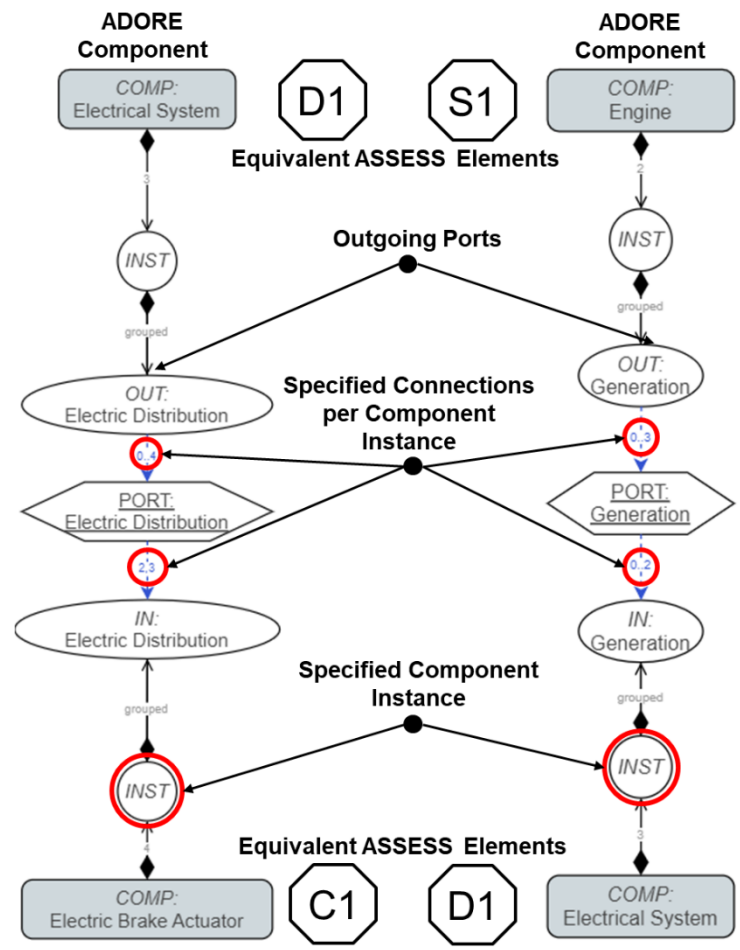


Figure 7: Port connections definition in ADORE and mapping to ASSESS elements

This way, a component representing an engine that is connected to a hydraulic system, would result in the instantiation of a `GraphNode` that contains each of the `GraphNode` objects representing the hydraulic systems as its connection targets. Finally, the directed graph needed for ASSESS is then created by adding a node and relevant edges to a directed graph for each instantiated `GraphNode` object.

3.4 Safety-heuristics based Filtering

The certification basis in the Aviation Regulations Part 23 and Part 25 was analyzed to extract safety heuristics that are applied to power generation and distribution systems. Comparing these regulations with existing system architecture implementations allows ambiguities to be resolved and a generic heuristic developed. For instance, in the case of landing gear systems, it was identified that Part 25 basis results in two primary sources of power for conventional (hydraulic) braking systems. These are also supplied with a third backup source that fulfills a secondary braking function such as parking. However, upon making a similar comparison for Part 23 certification basis, the authors noted that only a single primary source of hydraulic power was required, along with a backup source. Here, the authors distinguish between *main*, *alternate* and *backup* as being supplied by primary power generation sources (main and alternate) and secondary power sources (backup), respectively. These secondary sources can range from manual hydraulic actuation such as an accumulator augmented handpump to an independent source of backup power such as an APU driven pump or generator etc.

Below, a sample of three rules is presented for the wheel braking actuation system:

- **Rule 1: Number of independent power supply sources**. This ensures that each hydraulic braking consumer is supplied by at least two main hydraulic systems. The backup system could also derive from an independent power source or could also be supplied locally (using an accumulator, or human powered supply).
    - For Part 25 based aircraft, each braking consumer device must be supplied with at least two independent hydraulic sources and one backup source. In case of electrical braking systems – at least 3 independent electrical power distribution systems must be

provisioned for each electrical braking consumer. This rule may also be satisfied by using an independent backup source connected to at least one of the electrical distribution systems along with connections from other sources elements. In this case two independent electrical systems will suffice.

- For Part 23 based aircraft, each braking unit must be supplied by at least a main hydraulic distribution and a backup distribution.

- **Rule 2: Power supply must be allocated symmetrically**, to prevent asymmetric braking in case of power loss). Rule 2 focuses on preventing asymmetrical braking due to loss of specific power systems- this is a case that is typically identified during the Aircraft Level Functional Hazard Assessment (AFHA).
- **Rule 3: At least one power-consuming braking device is allocated to each wheel.** This rule filters-out unfeasible allocations between the braking device and the wheels for conventional landing gear braking systems. The rule checking algorithm analyzes the generic element based architecture descriptor and evaluates each rule individually.

Table 2: Relation of proposed heuristics to aircraft certification basis

Certification Rule	Category	Includes	Allocated Heuristic
14 CFR Part 25			
Subpart F 25.1309	Equipment, systems, and installations	25.1309 (subparts a,b)	Rules 1, 2 and 3
Subpart F 25.1310	Power source capacity and distribution	25.1310 (subparts 1-4)	Rule 1
Subpart F 25.1351	Electrical Systems and Equipment (General)	25.1351 (subpart a, b(1-2))	Rule 1
Subpart F 25.1355	Electrical Systems and Equipment (Distribution System)	25.1355 (subparts a-c)	Rule 1a
Subpart D 25.735	Brakes and Braking Systems	25.735 (subpart b,h,k)	Rule 1,2 and 3
14 CFR Part 23			
23.2510	Equipemt Systems, and Installations	23.2510 (a,b,c)	Rule 1b,2 and 3
23.2525	System Power Generation,Storage and Distribution	23.2525 (a,b,c)	Rule 1
23.2305	Landing Gear Systems	23.2305(a -2)	Rule 1b,2,3

Table 2 shows how the proposed heuristcs are related to certain certification refulations. CFR 25.1309 and 23.2510 prescribe safety requirments for the proper functioning of installed onboard systems under any forseeable operating condition. These further impose safety requirements that ensure that any failures leading to an unsafe condition of the aircraft are extremely improbably. Under the assumption that the ARP 4761 process is used to demonstrate complinnace to these regulations, and that the probabilistic approach of safety assessment techniques tends to prescribe increasing system redundancy [17]- it is possible to consider that heuristics extracted from an analysis of certifed aircraft (rules 1,2 and 3) are able to satisfy these regulations. Similarily, Rule 1 also finds basis in 25.1310 which stipulates the need for alternate power sources for essential loads. A similar finding is also apparent in 23.2525. 25.1351 and 25.1355 deal with electrical distribution systems and are relevant to Rule 1a in the prescription of three independent electrical systems for electric landing gear braking. Furthermore, 25.1351 references back to 25.1309 and thus provides a similar basis for Rule 1a as that for Rule 1 with 25.1310.

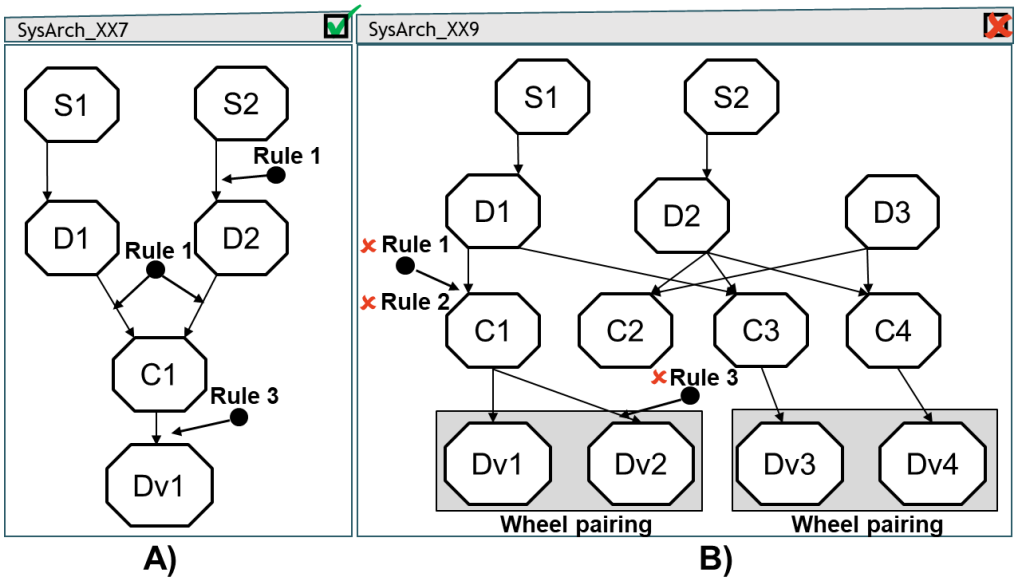


Figure 8: Example of rule evaluation on sample landing gear braking (conventional) system architecture

Figure 8 shows illustrates examples of rule evaluation within ASSESS. In Figure 8A), the connections between sources (S1 & S2) and distribution (D1 & D2) are such that the consumer (C1) is always supplied with two independent system – since S1 and S2 are independent primary sources. The consumer C1 is allocated to a unique device Dv1 and thus satisfies rule 3. On the other hand, Figure 8 B) shows a case which fails checks for compliance to Rule 1 2 and 3. Here the consumer C1 is only supplied by one independent primary distribution, D1 and this further violates rule 2 as C1 is supplied asymmetrically to other braking elements (C2-C4). Finally, C1 is allocated to both Dv1 and Dv2 which is an unphysical case and hence a violation of rule 3.

4. Results

This section presents the results of the study and is structured as follows: First an overview of the Design of Experiments (DOE) used to populate the design space using the ADORE model is presented. Second, the results of filtering the design space for hydraulic landing gear braking architectures is described followed by those for the electric landing gear braking. Finally, a specific case of building a design space using the safety-heuristics is shown.

4.1 Design of Experiments

The python library ‘pymoo’ [18] used within ADORE is used to generate a DOE of different sample sizes using the Latin hypercube sampling algorithm. Here, the ADORE model is provided as an input and a design space is populated based on the points generated by the algorithm. Three discrete design variables are varied during the DOE: one determining the engine to distribution system connection, one for the emergency generation system to the distribution system, and one for the distribution system to the actuators. These design variables represent 49, 8, and 256 different connection patterns, respectively. Combining these numbers shows that a little over a 100 000 different architectures can be generated. There is no design variable dependency, so this represents the complete combinatorial size of the design space.The results are included in the “DOE Size” column of Table 3 and Table 4.

4.2 Hydraulic (Conventional) Landing Gear Braking

Table 3: Rule-based design space filtering results for hydraulic (conventional) landing gear braking system architecture

DOE Size	Sample Size	Certification Basis	No of filtered architectures	No of feasible architectures	% of Design Space Deemed Feasible
100	100	Part 25	84	16	16.00
	100	Part 23	50	50	50.00
5000	4873	Part 25	4106	767	15.73
	4882	Part 23	2387	2495	51.10
10000	9473	Part 25	7966	1507	15.90
	9496	Part 23	4640	4856	51.13

Table 3 presents the results of this study for the conventional landing gear braking case. Here, the DOE size is capped at 100, 5000 and 10000 architectures respectively for cases that include both Part 23 and Part 25 derived rules. The rule-based filtering eliminated 84% of the design space as unfeasible for the Part 25 case. For Part 23 based rules, the stipulation of one main and one backup system per consumer results in a larger space of architectures that are feasible with the rules filtering out 50% of the design space as unfeasible. Evaluating rule 1 and rule 2 on the connection between distribution and consumer elements eliminates a third of the design space with the remainder being filtered out by checking if the connections between source and distribution comply to rule 1.

4.3 Electrical Landing Gear Braking Case

Table 4: Rule-based design space filtering results for electric landing gear braking system architecture

DOE Size	Sample Size	Certification Basis	No of filtered architectures	No of feasible architectures	% of Design Space Feasible
100	100	Part 25	86	14	14.00
	100	Part 23	60	40	40.00
5000	4873	Part 25	4250	623	12.78
	4889	Part 23	2950	1939	39.66
10000	9513	Part 25	8288	1225	12.87
	9489	Part 23	5678	3811	40.16

Table 4 presents the results of this study for the electric landing gear braking case. The same DOE sizes are used as in the previous section for the Part 23 and Part 25 derived safety rule application. The rules filter out a maximum of 86% of the design space which is more than the hydraulic case as the requirements for three main systems allocated per consumer element is more stringent. Furthermore, ensuring independence of electrical systems also requires an independent backup to be supplied to at least one distribution element.

4.4 Constrained Design Space Analysis

The constrained design space analysis presents a bottom up approach to safety-heuristc application. In this example two source and hydraulic distribution elements are considered and four hydraulic landing gear braking devices are used. Rule 1 is used to constrain the connections between distribution and consumer elements to reduce the combinatorial problem to one in which only connections between source and distribution elements need to be enumerated. Rule 1 ensures that each consumer element receives a connection from both distribution system. To further simplify this scenario an independent backup is assumed to be supplied to each consumer element as well.

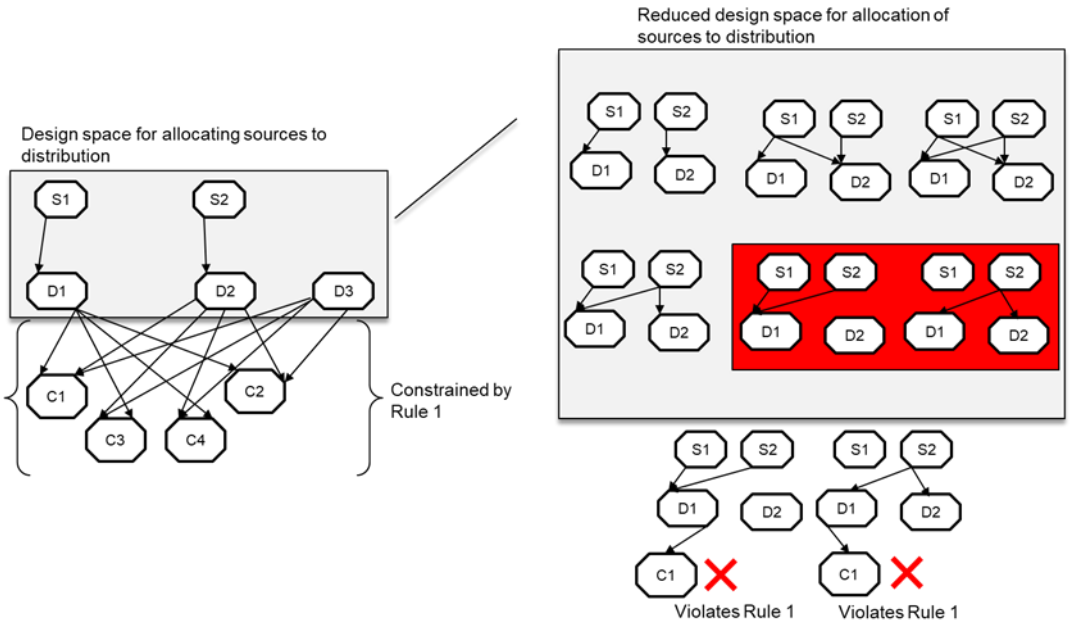


Figure 9: Generation of a constrained design space

Finally, the connections between source and distribution are enumerated and shown in Figure 9 for the hydraulic case. Once all possible connections are enumerated, Rule 1 is once again applied to test if each source element is connected to an independent distribution element. This further reduces the design space to the four options shown in Table 5 for the hydraulic based braking system case. A similar case is observed for the electric landing gear braking case as well. Here rule 1 is applied under the provisions of the special condition of having two distribution elements along with an independent bakup source element (SE) that is connected to at least one of the main distribution elements. Table 6 shows the reduced list of architectures conforming to the rules.

Table 5: Architectures generated based on safety rules for conventional hydraulic brake actuation

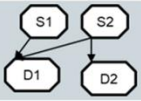
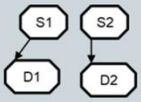
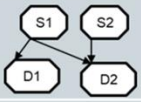
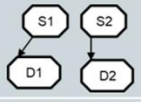
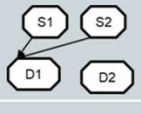
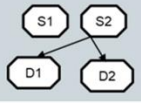
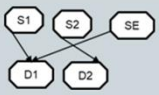
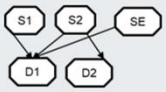
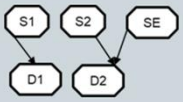
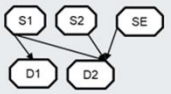
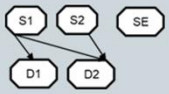
Architecture ID	Source to Distribution Config.	Source Elements	Physical Realization	Assigned Subcomponents	Assigned Distribution Elements	Physical Realization
CLDGB001 ✓		S1	Engine 1: E1	EDP-E1, EMP-E1	D1	Hydraulic Network
		S2	Engine 2: E2	EDP-E2, EMP-E2, RAT/APU	D2	
CLDGB002 ✓		S1	Engine 1: E1	EDP-E1, EMP-E1	D1,D2	Hydraulic Network
		S2	Engine 2: E2	EDP-E2, EMP-E2, RAT/APU	D2	
CLDGB003 ✓		S1	Engine 1: E1	EDP-E1, EMP-E1	D1,D2	Hydraulic Network
		S2	Engine 2: E2	EDP-E2, EMP-E2, RAT/APU	D1	
CLDGB004 ✓		S1	Engine 1: E1	EDP-E1, EMP-E1	D1	Hydraulic Network
		S2	Engine 2:E2	EDP-E2, EMP-E2 RAT/APU	D2	
CLDGB005 ✗		S1	Engine 1: E1	EDP-E1, EMP-E1	D1,D2	Hydraulic Network
		S2	Engine 2:E2	EDP-E2, EMP-E2, RAT/APU	D2	
CLDGB006 ✗		S1	Engine 1: E1	EDP-E1, EMP-E1	-	Hydraulic Network
		S2	Engine 2: E2	EDP-E2, EMP-E2, RAT/APU	D1,D2	

Table 6: Architectures generated based on safety rules for electrical brake actuation

Architecture ID	Source to Distribution Config.	Source Elements	Physical Realization	Assigned Subcomponents	Assigned Distribution Elements	Physical Realization
eLDGB001 ✓		S1	Engine 1: E1	IDG1	D1	Electrical Bus
		S2	Engine 2: E2	IDG2	D2	
		SE	Emergency	RAT	D1	
eLDGB002 ✓		S1	Engine 1: E1	IDG1	D1	Electrical Bus
		S2	Engine 2: E2	IDG2	D1,D2	
		SE	Emergency	RAT	D1	
eLDGB003 ✓		S1	Engine 1: E1	EDP-E1, EMP-E1	D1	Electrical Bus
		S2	Engine 2: E2	EDP-E2, EMP-E2 RAT/APU	D1,D2	
		SE	Emergency	RAT	D2	
eLDGB004 ✓		S1	Engine 1 : E1	IDG1	D1,D2	Electrical Bus
		S2	Engine 2:E2	IDG2	D2	
		SE	Emergency	RAT	D2	
eLDGB005 ✗		S1	Engine 1: E1	IDG1	D1,D2	Electrical Bus
		S2	Engine 2:E2	IDG2	D2	
		SE	Emergency	RAT	-	

This reduced set of architectures can then be expanded by assigning physical components to each of the generic elements involved. This is done according to the prescriptions of Chakraborty and Mavris [11] as shown in Table 5 and Table 6. Source elements are allocated individual engines, which are further allocated engine-driven pumps and distribution elements are identified as electrical or hydraulic networks.

Some advantages of this approach include the ability to quickly generate a reduced set of system architectures using the generic element representation. These can then be allocated physical components and evaluated within a MDAO workflow. Additionally, when a large number of systems are considered in conjunction, then the overall complexity of the design space can be reduced by choosing to focus on specific systems for complete enumeration of their respective design spaces and using the constrained design space approach for the remainder..

5. Conclusion and future work

This paper presents a practical approach to modelling and filtering large design spaces of candidate system architectures using safety heuristics. The link between the ADORE and ASSESS tools enables such a filtering process to take place.

Future work will involve testing the safety heuristics on novel system architectures and also applying the generic heuristics to multiple systems concurrently.

6. Contact Author Email Address

mailto: andrew.jeyaraj@mail.concordia.ca

7. Acknowledgements

We acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), Grant Number CRDPJ 538897-19 and RGPIN/5515-2019, and the Consortium de recherche et d'innovation en aérospatiale au Québec (CRIAQ). The presented work also benefited from the authors' collaboration within the AGILE4.0 project, which receives funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 815122.

The authors (1&3) would like to acknowledge the contributions of Alvaro Tamayo from Bombardier Aerospace for his expert insight through discussions, reviews, and suggestions.

8. Copyright Statement

References

[1] S. Liscouët-Hanke, “A Model Based Methodology for Integrated Preliminary Sizing and Analysis of Aircraft Power System Architectures,” Université Toulouse III - Paul Sabatier, 2008.

[2] S. Liscouët-Hanke, J. C. Maré, and S. Pufe, “Simulation framework for aircraft power system architecting,” *J. Aircr.*, vol. 46, no. 4, pp. 1375–1380, Jul. 2009.

[3] I. Chakraborty and D. N. Mavris, “Integrated Assessment of Aircraft and Novel Subsystems Architectures in Early Design,” *J. Aircr.*, vol. 54, no. 4, pp. 1268–1282, 2017.

[4] T. Lammering, “Integration of aircraft systems into conceptual design synthesis,” RTWH Aachen, Aachen, 2014.

[5] M. Fioriti, L. Boggero, F. Tomasella, A. Mirzoyan, A. Isyanov, and P. S. Prakasha, “Propulsion and on-board system integration for regional, medium and long range jet with different level of systems electrification in the agile project,” in *2018 Joint Propulsion Conference*, 2018.

[6] L. Boggero, M. Fioriti, S. Corpino, and P. D. Ciampa, “On-board systems preliminary sizing in an overall aircraft design environment,” in *17th AIAA Aviation Technology, Integration, and Operations Conference, 2017*, 2017.

[7] L. Boggero, P. D. Ciampa, and B. Nagel, “An MBSE Architectural Framework for the Agile Definition of Complex System Architectures,” in *AIAA AVIATION FORUM*, 2022.

[8] J. H. Bussemaker, L. Boggero, and P. D. Ciampa, “From System Architecting to System Design and Optimization: A Link Between MBSE and MDAO,” in *INCOSE International Symposium*, 2022.

[9] D. Judt and C. P. Lawson, “Methodology for automated aircraft systems architecture enumeration and analysis,” in *AIAA ATIO*, 2012.

[10] D. M. Judt and C. Lawson, “Development of an automated aircraft subsystem architecture generation and analysis tool,” *Eng. Comput.*, vol. 33, no. 5, pp. 1327–1352, Jul. 2016.

[11] I. Chakraborty and D. N. Mavris, “Heuristic definition, evaluation, and impact decomposition of aircraft subsystem architectures,” in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016.

[12] A. K. Jeyaraj, N. Tabesh, and S. Liscouet-Hanke, “Connecting Model-based Systems Engineering and Multidisciplinary Design Analysis and Optimization for Aircraft Systems Architecting,” in *AIAA AVIATION 2021 FORUM*, 2021.

[13] J. H. Bussemaker, P. D. Ciampa, and B. Nagel, “System architecture design space exploration: An approach to modeling and optimization,” in *AIAA Aviation 2020 Forum*, 2020, vol. 1 PartF, pp. 1–22.

[14] SAE International, “ARP4761:Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment.,” 1996.

[15] J. H. Bussemaker, P. D. Ciampa, and B. Nagel, “System Architecture Design Space Modeling and Optimization Elements,” in *32nd Congress of the International Council of the Aeronautical Sciences*, 2021.

[16] J. H. Bussemaker and L. Boggero, “Technologies for Enabling System Architecture Optimization,” in *ODAS Symposium*, 2022.

[17] N. Leveson, C. Wilkinson, H. C. Fleming, J. Thomas, and I. Tracy, “A Comparison of STPA and the ARP 4761 Safety Assessment Process 1,” 2014.

[18] J. Blank and K. Deb, “Pymoo: Multi-Objective Optimization in Python,” *IEEE Access*, vol. 8, pp. 89497–89509, 2020.