A MODEL-BASED SYSTEM ENGINEERING APPROACH TOWARDS AIRCRAFT DIGITAL CERTIFICATION

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Abstract

This article is part of the framework of the DIGACE research project, **DIG**ital Innovative **A**ircraft **CE**rtification, funded by the Italian University Research Ministry through the PRIN 2022 financing strategy. The DIGACE Project has the objective to provide a new, fully - digital approach towards General Aviation (GA) aircraft certification. A Model - Based System Engineering (MBSE) will be extensively used to develop a Digital Certification Pipeline (DCP), capable of supporting both conventional and innovative, unconventional aircraft configurations to be certified under the European Union Aviation Safety Agency (EASA) Certification Specification CS - 23, including electric/hybrid propulsion systems (EHPS) and distributed propulsion (DP) configuration. Essentially, the DCP produce all the EASA - required certification artifacts, switching from the past Document - Based paradigm to a more effective, less error - prone, digital certification process; all certification artifacts will be centrally managed, with only minor correction before the final submission to the Certification Agency. The DCP will represent an easy - to - use, effective tool to reduce certification time and costs significantly, enabling aircraft manufacturers to introduce new aircraft models with high safety standards and technologically adequate for the future of the GA market.

Keywords: EASA, MBSE, Digital Certification, General Aviation

1. General Introduction

Modern General Aviation Aircraft are complex flying machines incorporating complex systems and sub - systems [1, 2]. To legally operate, these machines must undergo a certification process under certification authorities' supervision, with the issuance of a Type Certificate (TC) as the end product. Aircraft certification is still a cumbersome procedure, with frequent exchange of data and documents between the certification applicant and the certification authority [3]. The classical Document - based approach is not efficient in managing increasingly intricate certification tasks.

Certification tasks are currently tracked through intricated Excel files, using the handwork of specifically designed experts [4]. These are tricky, convoluted tasks requiring a continuous review process for manufacturers and certification authorities.

This article proposes to adopt SysML formal language to collect technical requirements inside a compact and easy - to - use framework based on MATLAB object - oriented code. The scope of the automatic certification framework is the automatic production of certification artefacts, like certification technical reports. Technologies like the one described in this article will be crucial to successfully deploy new aviation, innovative products [5] on the market with acceptable costs and time [6].

Medium and small - size aeronautical manufacturers could benefit from a Model - based System Engineering (MBSE) systematic approach, exploiting formal modelling of Certification rules to efficiently and automatically track technical requirements and certification data, matching results with the required specifications in an automatic verification and validation framework. Any reduction of

certification time and costs for these subjects is critical, especially considering the future development of innovative architecture, and the introduction of new means of propulsion and more complex avionics technologies.
General Aviation aircraft certification regulations will change significantly to encompass technological novelties and innovative configurations. It will be difficult to model these changes in an automatic framework because of the different implemented nomenclature. EASA [7] is working on the complete switch to ASTM certification requirements, with the actual CS - 23 Amendment 4 still valid and accepted only in Europe. The ASTM documents are also cumbersome to include in a SysML model. Future works will identify the benefits of the Digital Certification Framework, including test - case scenarios and KPIs.

1.1 Structure of this article

The structure of this article is the following:

1. A section that provides a general introduction to present the state - of - the - art and currently adopted certification strategies, explaining the scope of this work.
2. A section to explain the MBSE proposed approach to construct and exploit a SysML model encompassing all the EASA requirements and acceptable means of compliance [8].
3. A section to evaluate the benefits and advantages deriving from the Digital Certification Framework and to enumerate problems, disadvantages and challenges [9].

2. Framework Implementation

The MBSE framework proposed in this article is composed of three main phases:

1. The first phase collects and formalizes applicable certification rules [10].
2. The second phase combines user-defined test cases with the developed model to establish a Verification and Validation framework.
3. The third phase condenses all the certification-related information to produce certification artefacts, like certification reports.

Figure 1 shows a graphical representation of the proposed Digital Certification Framework.

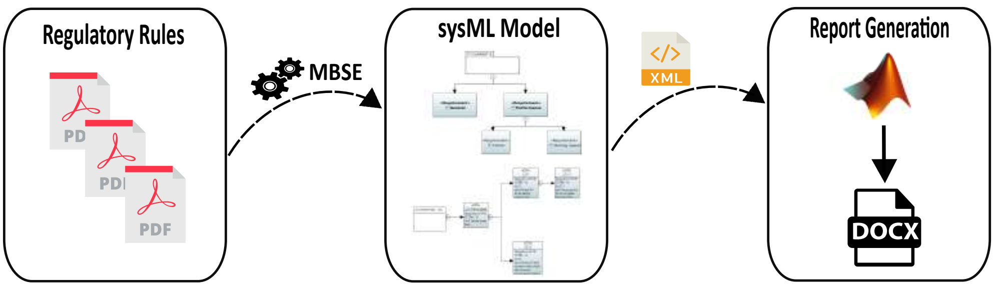

Figure 1 – Model - based certification process

Figure 2 shows a more detailed digital framework structure. Table 1 illustrates the differences between the Document - based and the Model - based approach.
Before starting to describe the SysML model, the subsequent sub - section provides a brief description of the selected software and tools [11, 12].

2.1 Selected Software

The requirements for the SysML modelling tool were the following:

- Open-source and free of fee.
- Capable of supporting graphical and textual modelling.

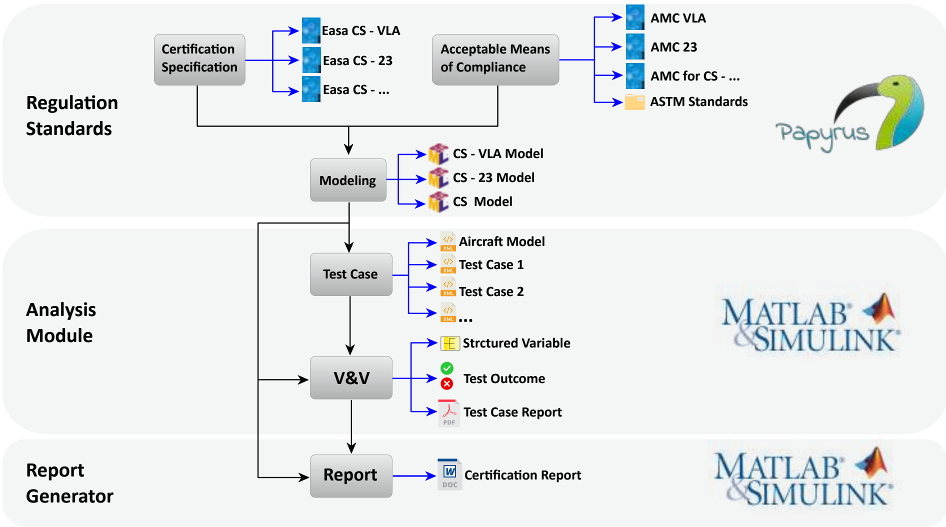

Figure 2 – Workflow implementation

	Document - Based	Model- -Based
Basic Elements	Documents	Models
Update	New documents	Model element update
Traceability	Manual, Cumbersome	Automatic
Transparency	Weak	Strong
Verification	Standalone	Easy to implement
Compliance Checklist	Cumbersome	Automatic
Report Generation	Manual	Automatic

Table 1 – Document - Based and Model - Based Comparison

- High level of portability.
- Relatively easy to use and stable.

From a brief analysis which compared different software solutions, Eclipse Papyrus was the final choice. Papyrus has an intuitive graphical interface and supports textual requirements modelling; it also allows the extension of Unified Modelling Language (UML) metaclasses to create model elements with user-defined properties, enabling the possibility to convey a much larger set of information in a structured SysML model.
The Eclipse framework also allows the installation of multiple plugins, such as Acceleo, an Eclipse implementation of the *Object Management Group* (OMG) MOF2Text Transformation Language (MTL). Acceleo creates large structured files from a generic *Eclipse Modelling Framework* (EMF) model. In the present work, Acceleo creates an XML file from the UML model's file.
The selected programming language to build the digital certification framework is MATLAB. MATLAB is extensively used in industry contexts and provides an integrated set of tools useful for this particular application. It partially supports *Object Oriented Programming* (OOP), with features that increase the maintainability of the code. Even though MATLAB is not open-source, it is nowadays widely adopted. Finally, it includes *Simulink* modelling environment, which supports and integrates a fully functional Verification and Validation framework within the code framework to speed up the automatic report generation tool and collect results in structured variables or files.

2.2 EASA Certification Specifications Modelling

EASA subdivides aircraft certification requirements in a specific, peculiar manner inside Certification Specifications (CS) documents. The SysML formal language provides standard stereotypes to model requirements; unfortunately, their features are not enough for the scope of this work. In the

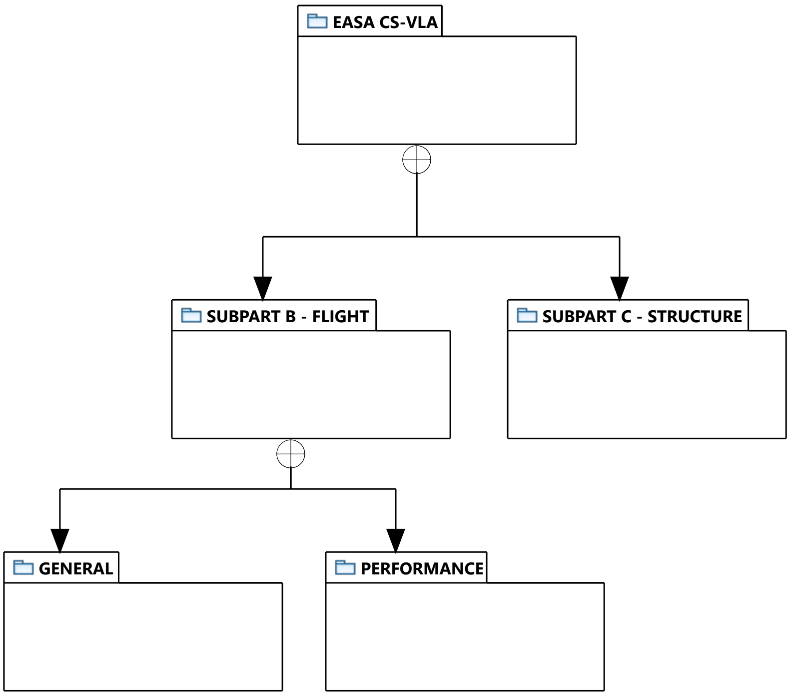

Figure 3 – EASA CS - VLA package structure – partial

proposed digital certification framework, the SysML Requirement model element is extended to account for specific regulation rule attributes, creating at the same time a reusable tool. When applied to aircraft certification regulations, Classes and Packages create a hierarchical structure, exploiting linking relationships among its elements (such as the *Trace* or *Refine* relationships); the resulting SysML model encapsulates information in a hierarchical and formal structure (with a single UML file as output). Figure 3 illustrates this hierarchy using the Papyrus environment's graphical representation. The extension process uses the UML Profile extension application integrated into the Eclipse Papyrus perspective; Figure 4 shows the graphical representation of this user - defined element. The definition of the CS Stereotype is an extension of the standard Requirement model element; in this way, the user - defined CS element inherits all the attributes from the SysML standard, adding multiple additional attributes. Table 2 collects the added attributes and their type's definitions. These attributes apply in the context of Very Light Airplane (VLA) [13] or EASA CS - 23 general aviation aircraft [14]:

Amendment It is an integer number, providing information about the last regulation rules issue.

Category This attribute applies to EASA CS - 23 general aviation aircraft and provides information about the aircraft category to which the specific requirement applies.

TestValue and TestValue2 These two attributes provide information about the performance that the aircraft must have. These attributes are string types to account for atomic and non - atomic performance - based requirements.

A real number defines atomic performance. For instance, according to EASA CS - VLA 65, the steady rate of climb must be at least $2\,\mathrm{m\,s^{-1}}$; this means, in the *International System of Units*,

$$\text{TestValue} = 2$$

Attribute	Type
Amendment	Integer
Category	Enumeration
TestValue	String
TestValue2	String

Table 2 – *CS* stereotype attributes

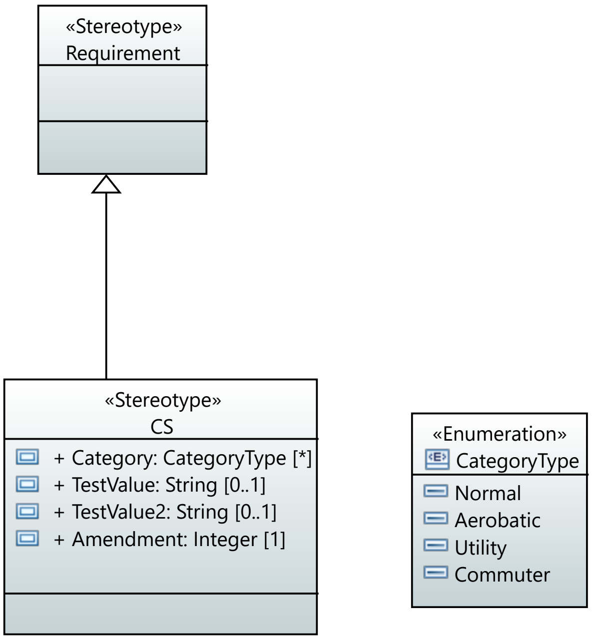

Figure 4 – EASA certification specification profile

	EASA CS - VLA	EASA CS - 23 Amdt. 4
Level 0	CS - VLA 25	CS 23.25
Level 1	CS - VLA 25.(a)	CS 23.25.(a)
Level 2	CS - VLA 25.(a).(1)	CS 23.25.(a).(1)
Level 3	CS - VLA 25.(a).(1).(i)	CS 23.25.(a).(1).(i)

Table 3 – Certification specifications hierarchical levels

Analogously, according to EASA CS 23.51.(a).(2) aircraft rotation speed, V_R, for single - engined land aeroplanes must not be less than V_{S1}; this means

$$\text{TestValue} = V_{S1}$$

Atomic requirements are characteristics of the EASA CS - VLA rules, while CS - 23 Amendment 4 uses non-atomic requirements, i.e. a combination of more performance - related requirements. For example, according to EASA CS - 23.51.(a).(1), for twin-engined land aeroplanes, the rotation speed, V_R, must not be less than the greater of

- $1.05 \cdot V_{MC}$
- $1.10 \cdot V_{S1}$

In this case,

$$TestValue = 1.05 \cdot V_{MC}$$
$$TestValue2 = 1.10 \cdot V_{S1}$$

The CS stereotype represents the fundamental model element for the hierarchical description of regulation rules. For both sets of artefacts, a four - level subdivision represents children - model elements that contain requirements; they are necessary to select a proper numbering strategy and the collection of formal SysML relationships to link them. Table 3 provides a complete representation of the levels subdivision and an example of the CS model element numbering strategy for EASA CS - VLA and EASA CS - 23 Amendment 4. The proposed digital certification framework uses three different types of SysML relationships, representing dependencies among model elements:

Containment Link This relationship conveys the information that CS requirement is nested into another one. It provides a graphical representation of the numbering strategy adopted in this work.

Refine relationship This relationship implies that a particular model element, such as a *Block* or another CS requirement, at the *client* (the element at the arrow bottom) end is more concrete (i.e. less abstract) than the *supplier* end element (the element at the arrowhead).

Trace relationship This relationship is a kind of UML dependency. It represents a weak relationship, conveying nothing more than a light dependency. If the supplier element changes, the client element may as well change.

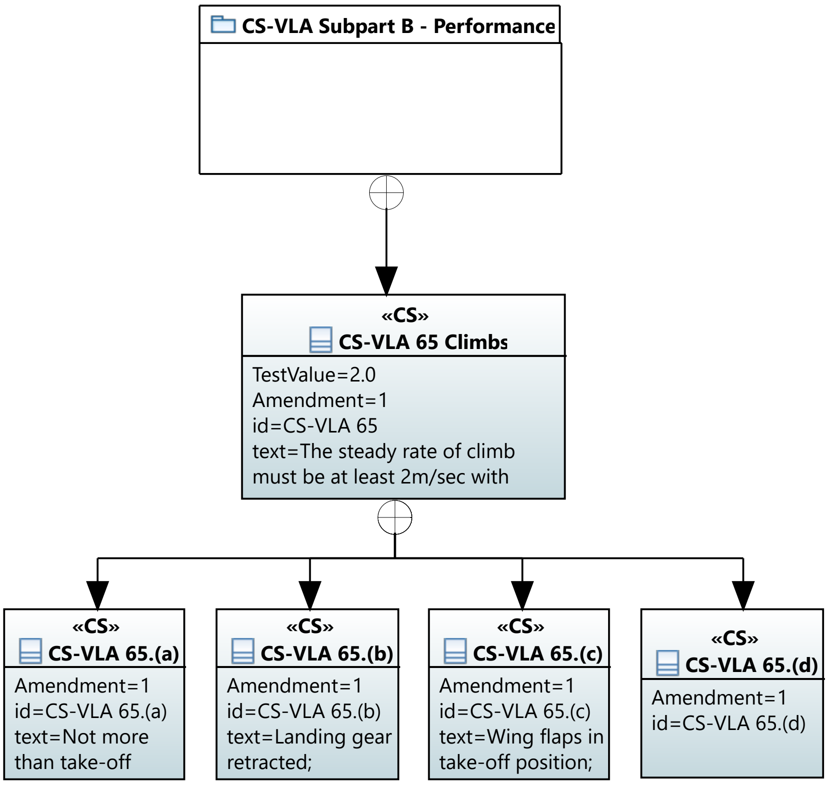

Figure 5 – EASA CS - VLA subpart B hierarchical view - partial

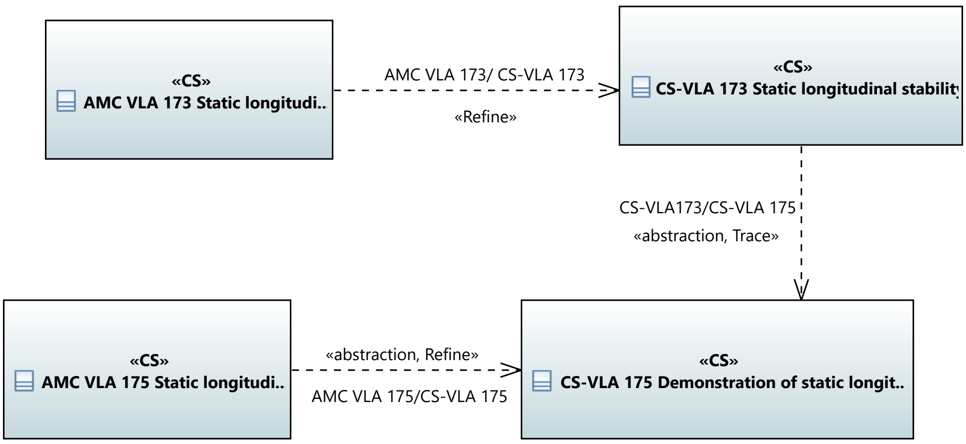

Figure 6 – EASA CS - VLA, subpart B, dependency mapping – partial

Figure 5 shows a graphical representation of the Containment Link applied to climb flight test requirements for Very Light Aeroplanes. Figure 6 illustrates the modelling of the CS - VLA 173; the

applicant must demonstrate Longitudinal stability characteristics in all flight conditions and configurations specified in CS - VLA 175. Figure 6 shows that the AMC VLA 173 is less abstract than CS - VLA 173; it also illustrates that any modification in the CS - VLA 175 may lead to a new validation activity for the CS - VLA 173, for which the applicant performs tests in flight conditions depicted in the CS - VLA 175 [15].
The application of formal relationships provides two main advantages:

- It increases the model traceability, allowing the determination of dependencies among regulatory rules.
- Allows to build a compliance checklist for any certification artefact under consideration.

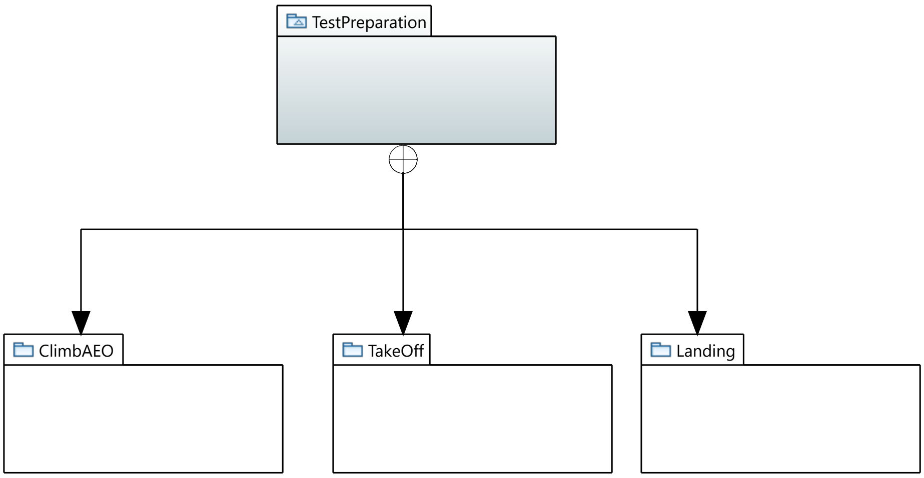

Figure 7 – Test methods hierarchical view – partial

The tree - model representation collects possible methods of compliance that applicants may use in test activities to prove the aircraft is satisfactory. Figure 7 shows the hierarchical representation of the *Package* model elements used as *Namespace* for each `TestMethod` stereotyped model element, obtained extending the standard UML *Class* model element; it provides information about the test ID, i.e. the name, the textual description of the test and relevant comments.

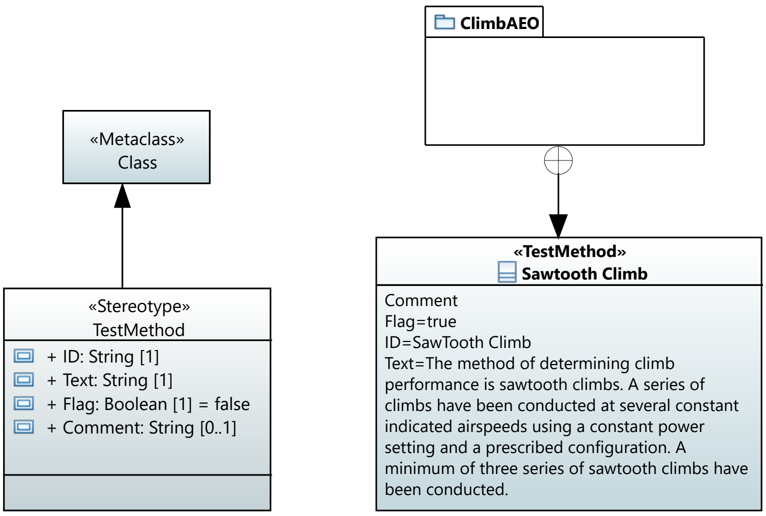

Figure 8 – Climb test methods class diagram – partial

The stereotype has a *Boolean* property *Flag*; it is equal to false by default and switches to true by the user if the applicant selects the specific test method to prove aircraft compliance. A custom - defined Acceleo code for a Model - To - Text (M2T) transformation accepts the model as an input and converts the SysML model into an XML file. The tool creates certification reports using information encapsulated in this file, providing a relevant description of the tests. Figure 8 shows an example relative to the climb test method suggested by Kimberlin [15, 16], the so - called *Sawtooth Climb*.

2.3 Validation and Verification Module

One of the engineering tools that this work aims to construct is an automatic digital Validation and verification module. The selected developing environment is MATLAB and Simulink, as already described in this article. The Validation and verification procedure checks that the aircraft meets its intended functions considering the selected certification basis and the associated *Means of Compliance* (MOCs). Using MATLAB and Simulink, it is possible to focus on test cases that might come from flight dynamic simulations, flight test campaigns or methodologies developed in the context of aircraft *Certification by Analysis* (CBA), including techniques of *Virtual Certification*. In any case, the scope of this procedure is to check that the aircraft meets performance - based requirements and certification constraints.

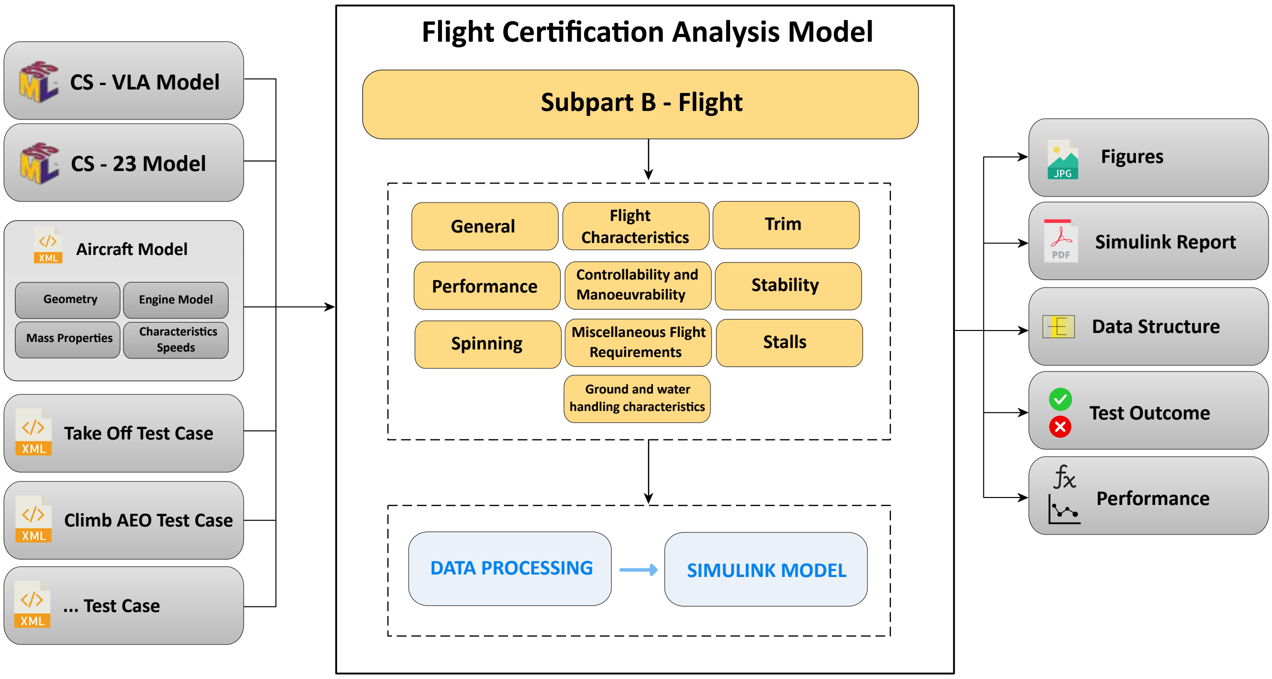

Figure 9 – Analysis module

Figure 9 shows the analysis module applied to Subpart B of the EASA Certification Specifications. This model has two main parts:

1. A data processing unit.
2. A Simulink validation model.

The framework accepts the SysML model of applicable regulation rules, the aircraft model, and the performed test case models. The outputs of the analysis module are the following:

1. Time histories of flight parameters.
2. The test case data structure, with all the required data.
3. Simulink reports resulting from each single validation task.

The model first extracts relevant information from Subpart B, Flight. Subsequently, the data processing block reads the aircraft properties from the corresponding data structure; next, the code extracts the tests' flight conditions and configurations from another data structure and performs aircraft performance analysis through data reduction methods proposed by the Airworthiness Authority. Finally, the code saves results in a data structure suitable for the Simulink model to verify the aircraft's compliance with previous certification artefacts. Figure 10 illustrates the *Test Case Analysis* module; this

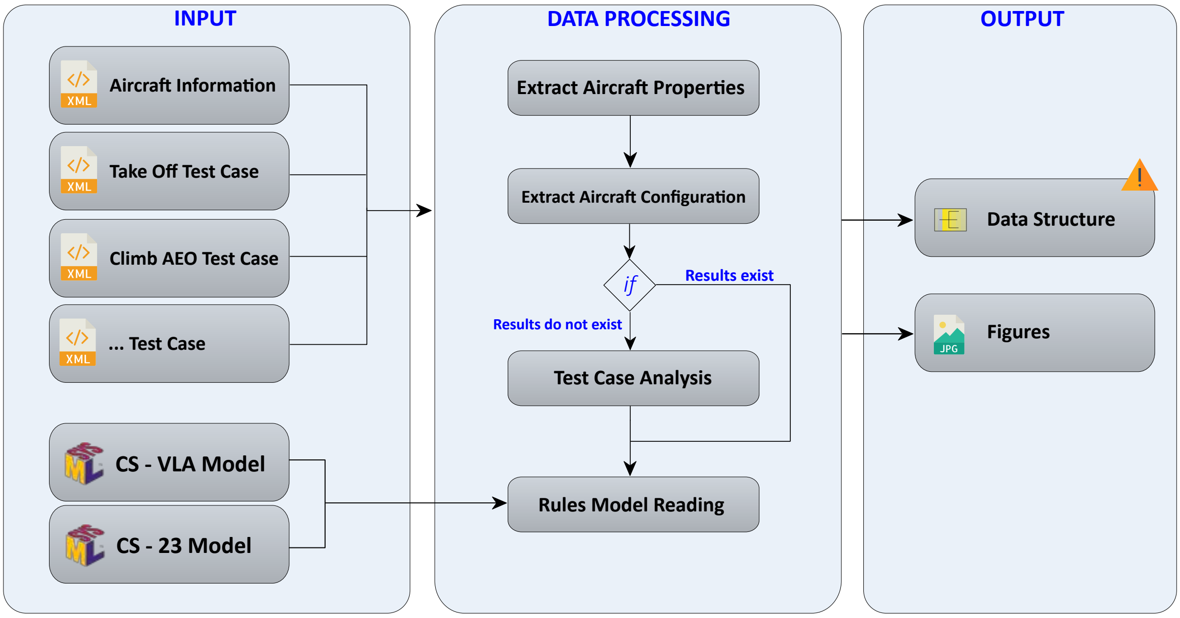

Figure 10 – MATLAB code processing

module processes flight test data; for each test case (i.e. for each sawtooth climb test or each takeoff test performed with the strip camera acquisition method), the Test Case Analysis module accepts as input time histories of acquired data for the processing and the extraction of the aircraft performance [17]. This module skips the data processing if such results already exist in the XML model of the relevant test case. Finally, it proceeds with the writing of the output data structure.

At the end of data processing activities, the identification of performance to be verified uses the SysML model of applicable certification rules as input. The module reads the SysML model, collecting information about the `TestValue` and `TestValue2` attributes defined during the Certification Specifications modelling phase. It determines if a particular required performance is atomic or non - atomic. The final output is a MATLAB data structure.

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Finally, the module initializes each test case a `Status` variable on the `Unchecked` value at the end of its processing task. The compliance analysis takes place in Simulink, exploiting the Simulink Test toolbox; in this phase, the code accepts the aircraft data structures with performance - based certification requirements and aircraft computed performance during test case data processing. The model performs two main activities:

1. A comparison between requirements and evaluated aircraft performance.
2. Automatic generation of Simulink reports with a summary of test outcomes.

Figure 12 graphically depicts the compliance analysis, emphasizing the outputs of this phase. The Simulink model comprises two sets of model elements to store performance from certification rules and the analysis of test cases. The outputs of such model elements are Simulink signals that represent inputs for logical assessments created through the Simulink Test toolbox. Each assessment procedure has as output a Simulink object that updates the data structure according to the test outcome.

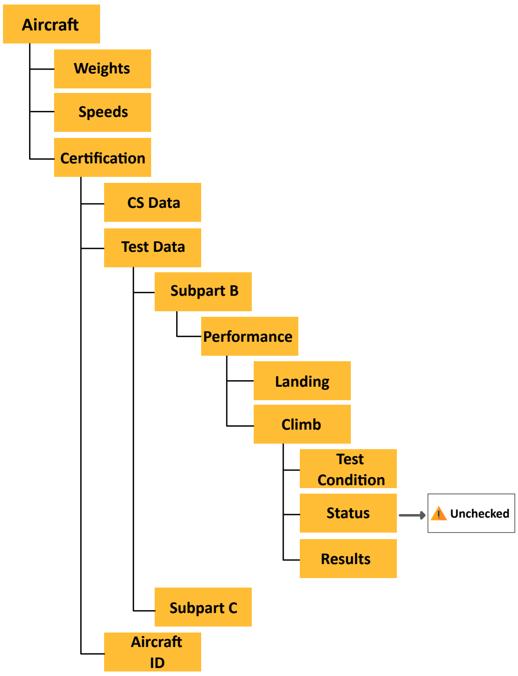


Figure 11 – Data structure - partial

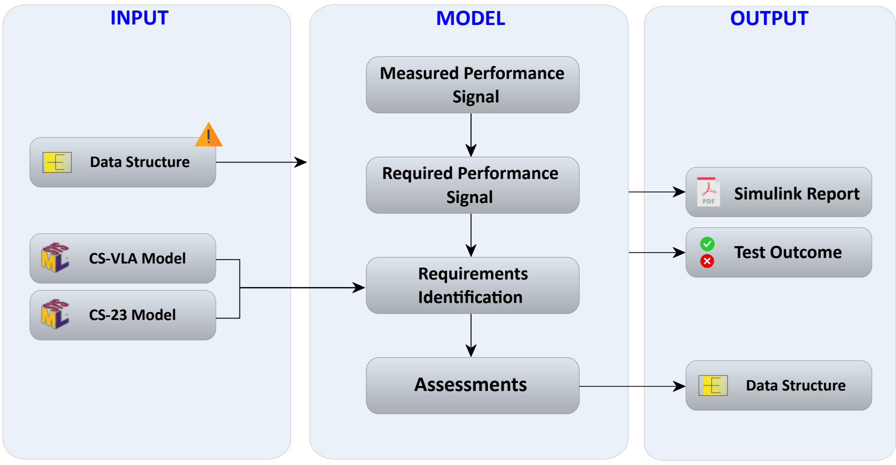


Figure 12 – Validation model

Figures 13 and 14 show the climb test case and a Simulink report in PDF format. The Simulink report provides information about the executed test, the outcome, and relevant requirements; it represents a first means for understanding if the aircraft complies with the selected certification basis.
The proposed Simulink model applies to aircraft regulated under CS - VLA and CS - 23; however, the increased complexity of the CS - 23, accounting for more aircraft properties in the selection process of applicable rules, like the maximum weight, the number of engines and their type, forces the adoption of a different model element to store performance coming from regulatory models.

2.4 Report Generation Module

The typical aircraft certification process requires continuous reporting of certification data and activities. The applicant submits these descriptive, technical reports to Airworthiness Authorities to show compliance with the applicable certification basis. Therefore, the digital certification framework has a Report Generation Module that writes EASA - compliant technical reports automatically, increasing the automation level of report - making activity. As for the Verification and Validation phase, the inputs are the updated data structure, the SysML model of applicable certification artefacts and the path to directories storing produced results and time histories. Figure 15 shows the automatic report - making process. A `main` function defines the report title, authors, and the aircraft for which the *Type*

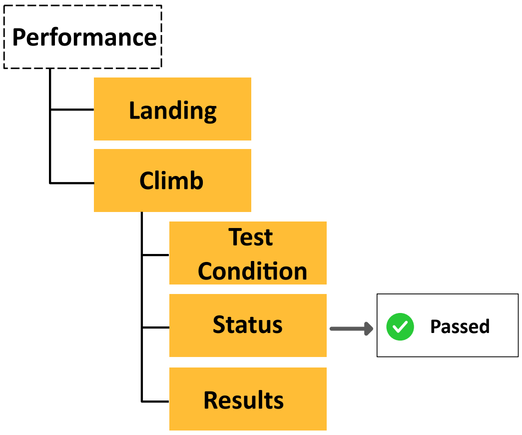
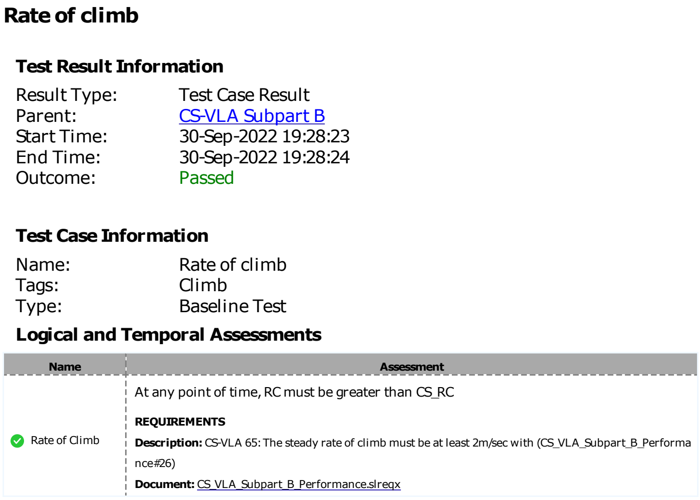


Figure 13 – Data structure update - partial



Rate of climb

Test Result Information

Result Type:	Test Case Result
Parent:	CS-VLA Subpart B
Start Time:	30-Sep-2022 19:28:23
End Time:	30-Sep-2022 19:28:24
Outcome:	Passed

Test Case Information

Name:	Rate of climb
Tags:	Climb
Type:	Baseline Test

Logical and Temporal Assessments

Name	Assessment
Rate of Climb	At any point of time, RC must be greater than CS_RC **REQUIREMENTS** **Description:** CS-VLA 65: The steady rate of climb must be at least 2m/sec with (CS_VLA_Subpart_B_Performance#26) **Document:** CS_VLA_Subpart_B_Performance.slreqx

Figure 14 – SIMULINK report - partial

Certificate (TC) has to be requested; subsequently, the code creates multiple chapters describing all aspects of the performed test case; for each test case, the code evaluates its `Status` field in the data structure and then proceeds with the chapter writing if such a field is equal to `Passed` value; otherwise, the code skips entirely the Chapter. If even one test case result is unsuccessful, the aircraft does not comply with some regulation sections, making it not certifiable.
The final output of Verification and Validation activities is a structured variable that stores specific information from the certification basis, from the test case models, and other relevant data. This structured variable is acceptable by several MATLAB functions, implementing the automatic report generation module. Each function generates a different report's chapter, extracting information from the structured variable. The chapter generation tasks are the following:

Chapter introduction It introduces the topic discussed by the chapter, providing additional information about the performed flight test (where, when, duration and so forth).

Reference Identification A list of accepted references to interpret the chapter's material. References can be textbooks, accepted analysis and testing methodologies, Compliance Checklists (CCs), and others.

Test Configuration It describes the flight test configuration and conditions encountered during flight operations. According to the reference CC, testing conditions are explained and enumerated.

Test preparation Data collection and reduction methodologies are detailed here, explaining how and with what equipment. It provides information about the flight crew, engineering crew and Airworthiness Authority officer who witnessed the flight test.

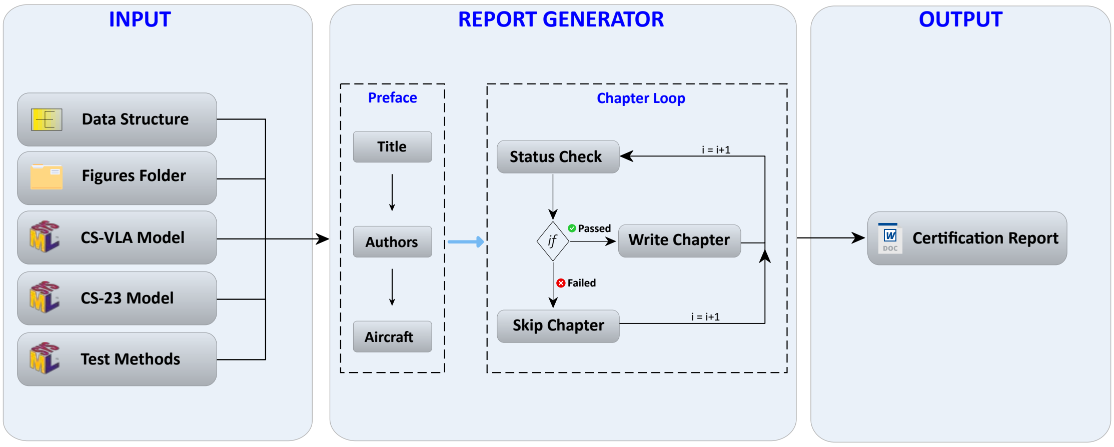


Figure 15 – Report generation structure

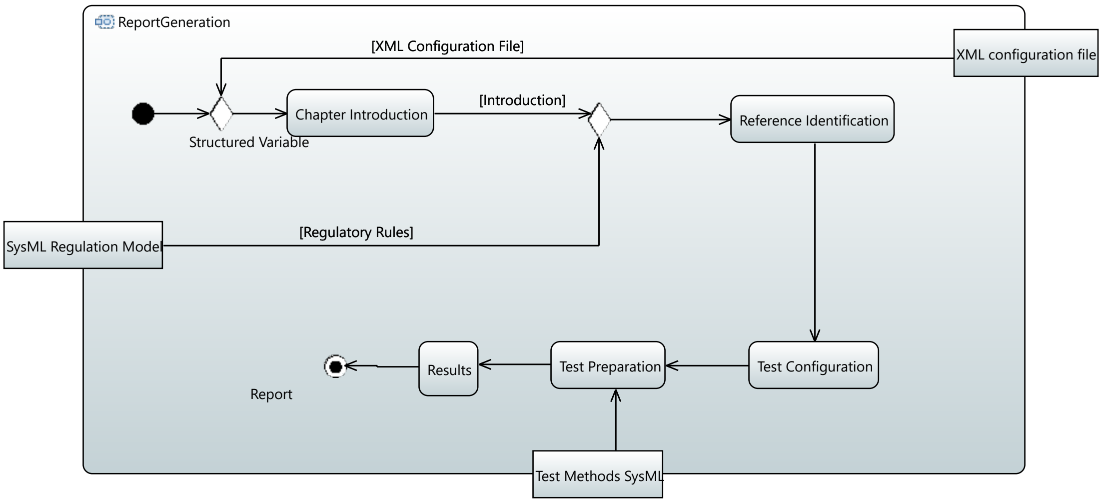


Figure 16 – Chapter Generation Activity Diagram

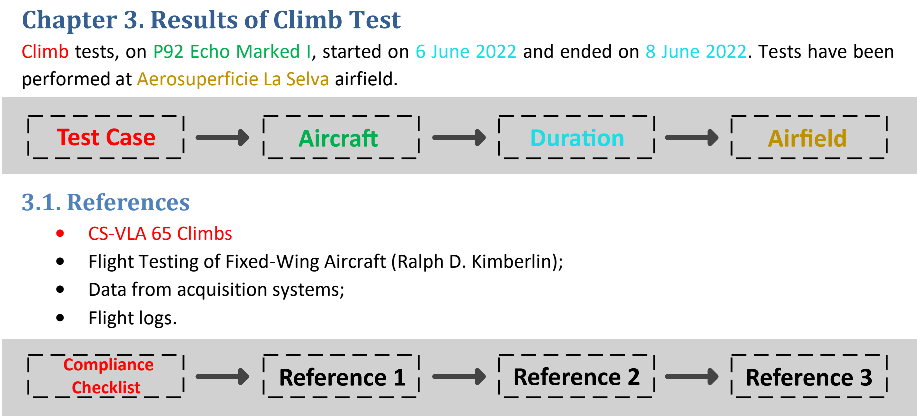
Results It presents Flight Test data, data processing and validation and adds a graphical representation of data if present or necessary. The code creates tables with raw observed and corrected data, demonstrating that the aircraft complies with the applicable certification rules.

Figure 16 shows graphically the Chapter Generation Activity (valid for each report chapter). The code writes every chapter after the Status field check, ensuring that the code writes a chapter only when the aircraft passes the minimum certification criteria. The final step in the chapter - making procedure reports results from validation activities; the code collects results in tables, including flight - test time histories. Figures 17 and 18 provide an example applied to climb tests of a Tecnam P92 and illustrate how elements extracted from the data structure and from SysML models coupled to build each chapter's section.

3. Benefits and Challenges

The proposed Digital Certification Framework can provide profound benefits to aviation industry stakeholders:

- General Aviation aircraft manufacturers will benefit from a tool capable of generating certification artefacts that help throughout the aircraft certification process, including constructing an acceptable Compliance Checklist. The increased level of automation streamlines the certification process and reduces the final certification report delivery time, compared with a classical document - based approach.
- Airworthiness Authorities will rely on a Model - Based (using formal language like SysML) representation of certification rules; it will provide consistency to the certification consensus standard,



Chapter 3. Results of Climb Test

Climb tests, on P92 Echo Marked I, started on 6 June 2022 and ended on 8 June 2022. Tests have been performed at Aerosuperficie La Selva airfield.

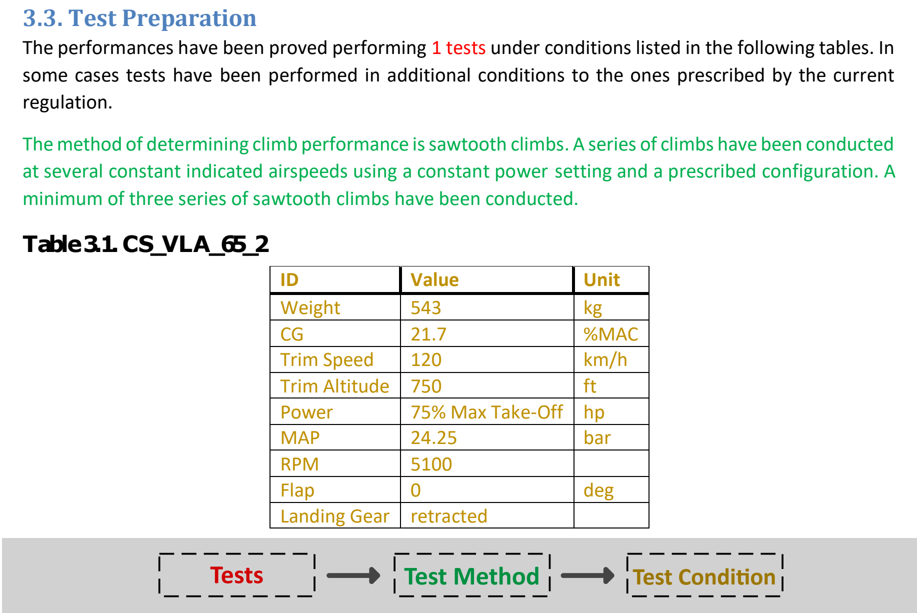
Test Case → Aircraft → Duration → Airfield

3.1. References

- CS-VLA 65 Climbs
- Flight Testing of Fixed-Wing Aircraft (Ralph D. Kimberlin);
- Data from acquisition systems;
- Flight logs.

Compliance Checklist → Reference 1 → Reference 2 → Reference 3

Figure 17 – Chapter introduction and references



3.3. Test Preparation

The performances have been proved performing 1 tests under conditions listed in the following tables. In some cases tests have been performed in additional conditions to the ones prescribed by the current regulation.

The method of determining climb performance is sawtooth climbs. A series of climbs have been conducted at several constant indicated airspeeds using a constant power setting and a prescribed configuration. A minimum of three series of sawtooth climbs have been conducted.

Table3.1. CS_VLA_65_2

ID	Value	Unit
Weight	543	kg
CG	21.7	%MAC
Trim Speed	120	km/h
Trim Altitude	750	ft
Power	75% Max Take-Off	hp
MAP	24.25	bar
RPM	5100	
Flap	0	deg
Landing Gear	retracted	

Tests → Test Method → Test Condition

Figure 18 – Test preparation section

enhancing quality control on new Type Certificates with innovative technologies and configurations; with this approach, tracing dependencies and certification artefacts will be extremely easy. Further, if performance - based requirements or Acceptable Means of Compliance change, the Airworthiness Authority can update the corresponding part of the requirements digital model, transmitting it to the aviation community almost immediately.

One major disadvantage of the MBSE approach depends on the adopted modelling language or modelling tools. Switching from a document - based approach to a model - based approach is always an expensive initial investment, with a cost too high for aviation firms. Further, novelties and innovative technologies in avionics, propulsion and other critical certification areas are hard to model due to the lack of specific rules in the current certification framework [18, 19]. As stated in this article, the standard verification and validation capabilities of SysML - based tools are unsuitable to perform Aviation Verification and Validation activities. MATLAB and Simulink aided in overcoming this difficulty, but this required the construction of a hard - programmed infrastructure. The developed tools enabled to discriminate between requirements to focus on aircraft certification performances, deciding when a certification criteria was or was not satisfied. Building such an infrastructure is, obviously enough, a task for experienced personnel, and the risk of errors is high. Finally, the commercial transport aircraft certification framework is too complex to imagine an automated digital certification infrastructure. The FAR 25 and CS - 25 regulations involve a decision - making process and a complex total quality control system. Often the applicant confronts him or herself with nested requirements, which are difficult to encapsulate inside a SysML model.

4. Conclusive Remarks

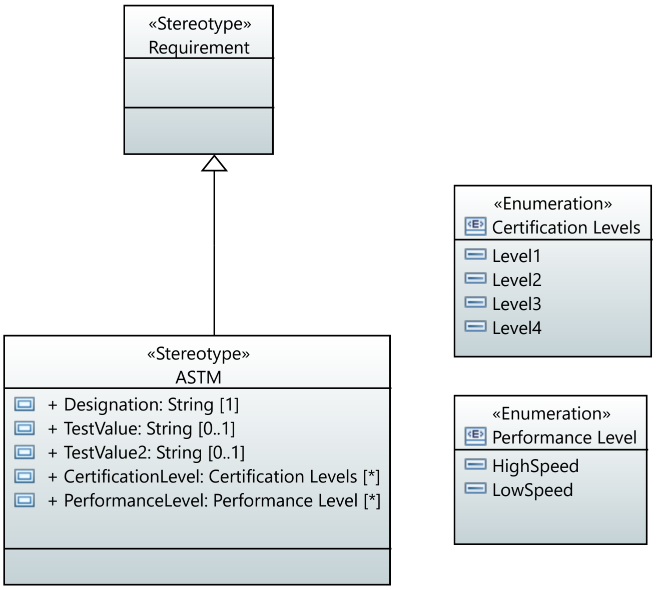


Figure 19 – ASTM Profile for EASA CS - 23, Amendment 5

The digital certification framework presented in this work is not fully automated and requires manual input to create models of the regulatory requirements, Means of Compliance and models of test cases. Once this phase is complete, the user has a flexible, easy to update and adaptable tool. Any change to the model automatically propagates through all related parts of the framework. To apply the model to EASA CS - 23 Amendment 5 or superior, it has to include the ASTM International Standards. Indeed, the applicable certification criteria will change significantly: Amendment 4 specifies the aircraft category (Normal, Utility, Aerobatic and Commuter) to determine the applicable certification rules. Amendment 5 and superior introduce the concept of Certification Levels and Performance Levels to determine the certification basis. ASTM International Standards certification documents follow a different formal subdivision in section and subsection, enumerated differently. For these reasons, a new UML profile will model the ASTM single requirement. Figure 19 shows this newly defined profile. The introduction of the ASTM certification documents is the first step toward certification gap identification and risk mitigation concerning new propulsive technologies, like *Distributed Electric Propulsion* (DEP) and hybrid-electric propulsion devices, developing a new definition of concepts like *Critical Loss of Thrust* (CLT) [20, 21]; however, the necessity to handle many scattered documents causes these requirements to be often not well interpreted or neglected in the preliminary design phase of innovative configurations [22, 23], resulting in non - certifiable architectures [24]. The digital certification framework proposed in this article provides methods and tools that mitigate the risks associated with new general aviation aircraft embodying new technologies with extended or augmented mission envelope [25, 26], which will be an enabling factor in the future profitability of the aviation industry, involving regulators and manufacturers to commit in a more transparent and modular certification approach.

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6. Copyright Statement

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References

[1] Tianlong, LIN and Pecora, ROSARIO and Ciliberti, DANILO and Wei, XIA and Shuling, HU, *Aerodynamic optimization of an adaptive flap for next-generation green aircraft*, Chinese Journal of Aeronautics, Vol. 37, number 2, 100 - 122, 2024, Elsevier, doi: https://doi.org/10.1016/j.cja.2023.10.010

[2] L. Li, N. L. Soskin, A. Jbara, M. Karpel and D. Dori, *Model-Based Systems Engineering for Aircraft Design With Dynamic Landing Constraints Using Object-Process Methodology*, in IEEE Access, vol. 7, pp. 61494-61511, 2019, doi: 10.1109/ACCESS.2019.2915917.

[3] Luca Boggero, Pier Davide Ciampa and Björn Nagel. *An MBSE Architectural Framework for the Agile Definition of System Stakeholders, Needs and Requirements*, AIAA 2021-3076. AIAA AVIATION 2021 FORUM. August 2021. https://doi.org/10.2514/6.2021-3076

[4] Mayank V. Bendarkar, Jiacheng Xie, Simon Briceno, Evan Harrison, Dimitri N. Mavris, *A Model - Based Aircraft Certification Framework for Normal Category Airplanes*, AIAA Aviation 2020 Forum (AIAA 2020-3096). https://doi.org/10.2514/6.2020-3096

[5] Marciello, Valerio and Cusati, Vincenzo and Nicolosi, Fabrizio and Saavedra-Rubio, Karen and Pierrat, Eleonore and Thonemann, Nils and Laurent, Alexis, *Evaluating the economic landscape of hybrid-electric regional aircraft: A cost analysis across three time horizons*, Energy Conversion and Management, vol. 312, pages: 118517, year: 2024, publisher: Elsevier. https://doi.org/10.1016/j.enconman.2024.118517

[6] Marc-Henri Bleu-Laine, Mayank V. Bendarkar, Jiacheng Xie, Simon Briceno, Dimitri N. Mavris, *A Model - Based System Engineering Approach to Normal Category Airplane Airworthiness Certification*, AIAA Aviation 2019 Forum (AIAA 2019-3344). https://doi.org/10.2514/6.2019-3344

[7] EASA, *Easy Access Rules for Normal, Utility, Aerobatic and Commuter Category Aeroplanes (CS-23)*, (Amendment 4), June 2018.

[8] INCOSE, *Systems Engineering Vision 2020*, INCOSE-TP-2004-004-02, September 2007.

[9] Enrique Krajmalnik, *Model-Based Systems Engineering: Past, Present and Future*, PowerPoint Presentation, NMWS2018.

[10] Salado, Alejandro and Wach, Paul. (2019). *Constructing True Model-Based Requirements in SysML*. Systems. 7. 10.3390/systems7020019.

[11] Friedenthal, S., Moore, A., and Steiner, R., *A Practical Guide to SysML: The Systems Modeling Language*, 2nd ed., Morgan Kaufmann Publishers Inc., 2011.

[12] Delligatti, L., *SysML distilled: A brief guide to the systems modeling language*, Addison-Wesley, 2013.

[13] EASA, *Easy Access Rules for Very Light Aeroplanes (CS-VLA)*, (Amendment 1), November 2018.

[14] EASA, European Union Aviation Safety Agency Certification Specification. https://www.easa.europa.eu/en/document-library/certification-specifications

[15] Kimberlin, R.D. (2003). *Flight Testing of Fixed Wing Aircraft* (AIAA Education Series). American Institute of Aeronautics & Astronautics.

[16] Corcione, Salvatore and Bonavolontà, Giordana and De Marco, Agostino and Nicolosi, Fabrizio, *Downwash modelling for three - lifting - surface aircraft configuration design*, Chinese Journal of Aeronautics, vol. 36, number 6, pages 161 - 173, year: 2023, publisher: Elsevier https://doi.org/10.1016/j.cja.2023.03.035

[17] Timothy Mauery, Juan Alonso, Andrew Cary, Vincent Lee, Robert Malecki, Dimitri Mavriplis, Gorazd Medic, John Schaefer and Jeffrey Slotnick, *A Guide for Aircraft Certification by Analysis*, NASA Langley Research Center Hampton, VA 23681-2199, NASA/CR-20210015404.

[18] Danilo Ciliberti, Pierluigi Della Vecchia, Vittorio Memmolo, Fabrizio Nicolosi, Guido Wortmann and Fabrizio Ricci,*The Enabling Technologies for a Quasi-Zero Emissions Commuter Aircraft*, MDPI Aerospace Journal, 12 June 2022, https://doi.org/10.3390/aerospace9060319

[19] Thonemann, Nils and Saavedra-Rubio, Karen and Pierrat, Eleonore and Dudka, Katarzyna and Bangoura, Mathilde and Baumann, Nils and Bentheimer, Christian and Caliandro, Priscilla and De Breuker, Roeland and De Ruiter, Cor and others,*Prospective life cycle inventory datasets for conventional and hybrid - electric aircraft technologies*, Journal of Cleaner Production, vol. 434, 140314, 2024, Elsevier, doi: https://doi.org/10.1016/j.jclepro.2023.140314

[20] Shireen Datta, Rukmini Roy, Mayank V. Bendarkar, Evan Harrison and Dimitri N. Mavris, *MBSE-Enabled Risk Reduction for Certification of Novel Aircraft Configurations*, AIAA SciTech 2022 Forum, AIAA 2022-1189. https://doi.org/10.2514/6.2022-1189

[21] De Marco, Agostino and D'Onza, Paolo Maria and Manfredi, Sabato, *A deep reinforcement learning control approach for high-performance aircraft*, Nonlinear Dynamics, vol. 111, number 18, pages 17037 - 17077, 2023, publisher: Springer, https://doi.org/10.1007/s11071-023-08725-y

[22] Corcione, Salvatore and Cusati, Vincenzo and Memmolo, Vittorio and Nicolosi, Fabrizio and Sandin, Raul Llamas, *Impact at aircraft level of elastic efficiency of a forward-swept tailplane*, Aerospace Science and Technology, vol. 140, pages: 108461, year: 2023, publisher: Elsevier, https://doi.org/10.1016/j.ast.2023.108461

[23] Corcione, Salvatore and Mandorino, Massimo and Cusati, Vincenzo, *Beyond Conventional: An Integrated Aerostructural Optimization Approach for Innovative Tailplane Configurations*, Aerospace Science and Technology, pages: 109242, year: 2024, publisher: Elsevier. https://doi.org/10.1016/j.ast.2024.109242

[24] EASA, *Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25)*, (Amendment 27), November 2021.

[25] Di Mauro, Gennaro and Corcione, Salvatore and Cusati, Vincenzo and Marciello, Valerio and Guida, Michele and Nicolosi, Fabrizio, *The Potential of Structural Batteries for Commuter Aircraft Hybridization*, Journal of Materials Engineering and Performance, vol . 32, number 9, pages: 3871 - 3880, year: 2023, publisher: Springer, https://doi.org/10.1007/s11665-023-07856-y

[26] Cusati, Vincenzo and Corcione, Salvatore and Memmolo, Vittorio, *Impact of structural health monitoring on aircraft operating costs by multidisciplinary analysis*, journal: Sensors, vol. 21, number: 20, pages: 6938, year: 2021, publisher: MDPI. https://doi.org/10.3390/s21206938