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A SysML-based framework towards EASA CS-23 digitalization: An MBSE approach

Pierluigi Della Vecchia [a], Claudio Mirabella [a],*, Michele Tuccillo [a], Carlo Emanuele Riboldi [b], Marco Fioriti [c], Fixherald Shahini [c], Francesca Roncolini [b]

[a] *University of Naples Federico II, Department of Industrial Engineering, Via Claudio, 21, Naples, 80125, Italy*
[b] *Politecnico di Milano, Department of Aerospace Engineering, Via La Masa, 34, Milan, 20156, Italy*
[c] *Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Corso Duca degli Abruzzi, 24, Turin, 10129, Italy*

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ABSTRACT

The general aviation sector is undergoing rapid transformation, driven by technological innovation and increasing market demand. However, certification frameworks remain predominantly document-based, resulting in inefficiencies and elevated costs. This study presents a digital certification framework grounded in Model-Based Systems Engineering (MBSE), utilizing the Systems Modeling Language (SysML) to encode the European Union Aviation Safety Agency (EASA) Certification Specifications (CS-23) and Acceptable Means of Compliance (AMC) into a structured, machine-readable model. The proposed methodology enables automated verification and validation, report generation, and traceability across regulatory artifacts.

Beyond its technical contributions, the framework addresses interdisciplinary challenges in the present regulatory landscape, systems engineering, and organizational communication. It highlights the complexity of certification processes, emphasizing the need for coherent information exchange among stakeholders with varying levels of technical proficiency. The study contributes to ongoing discussions in the social sciences regarding institutional adaptation, digital transformation, and collaborative governance in high-reliability sectors. The framework's scalability to commercial aviation and its potential to support emerging aircraft architectures underscore its relevance to both industry and regulatory bodies.

1. Introduction

1.1. Certification landscape

Introducing a new aircraft requires aeronautical manufacturers and firms to apply for a Type Certificate (TC) issued by the Regulatory Authorities. This process, commonly referred to as *aircraft certification*, involves a complex and structured sequence of activities. From the earliest stages of design, manufacturers must demonstrate that the product is inherently safe and capable of meeting a defined set of performance-based, functional, and operational requirements (Torenbeek, 2013b,a). The practices and established procedures of aviation stakeholders often do not account for the integration of new technologies (see Puranik et al., 2020). Current industrial practice predominantly follows a *Document-Based* approach. In this framework, a complex body of documentation is progressively developed and managed, typically through a collection of Excel files. These documents include the results of ground and flight tests, certification data, certification-related calculations, and other information relevant to the certification process. Information about people directly involved in the completion and verification of each certification task is also relevant, establishing the correct channel through which the firm can exchange information with EASA (or FAA) personnel (see Bleu-Laine et al., 2019; Bendarkar et al., 2020). Indeed, the applicant and the Regulatory Agency agree on assigning tasks to various panels, providing expert consultancies timed according to the task risk index. The so-called *Level of Involvement* (LoI) measures the frequency with which the Regulatory Agency personnel review the certification material, assigning specific standards to comply with a particular certification task. A high LoI typically indicates that manufacturers must repeat the task multiple times to achieve compliance with applicable regulations and EASA standards. This results in increased costs and labor hours, justified by the stringent safety and quality requirements necessary for a product to be deemed flyable—or more precisely, airworthy. Since the release of EASA CS-23, Amendment 5, the agency has recognized the *American Society for Testing and Materials* (ASTM) International Standards documents as an AMC. This decision aligns with the broader effort to enhance interoperability

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* Corresponding author.
E-mail address: claudio.mirabella@unina.it (C. Mirabella).

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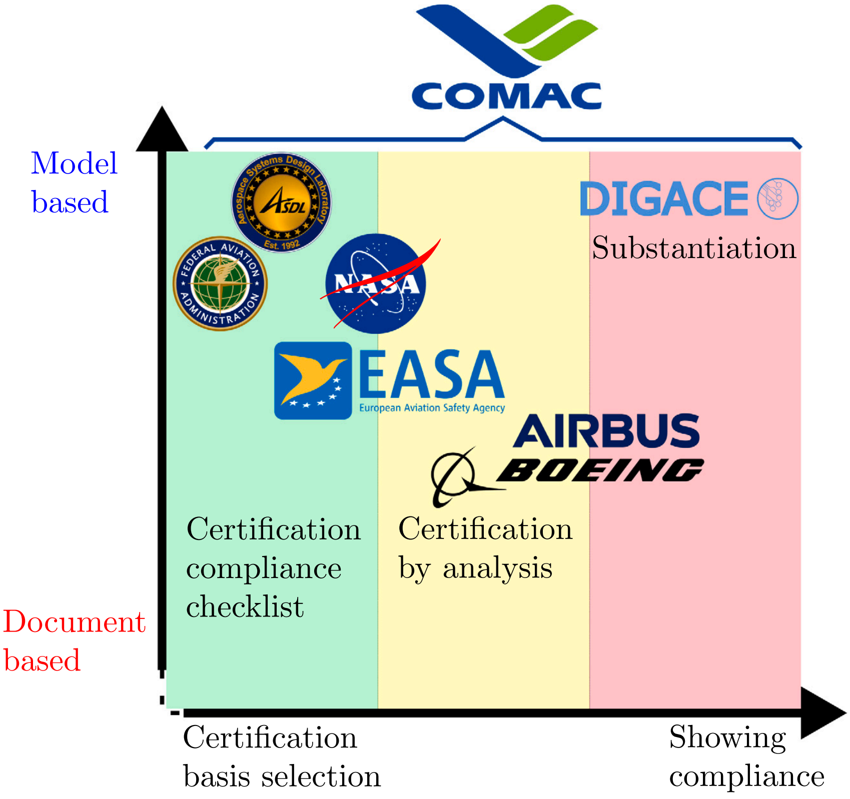

Fig. 1. Qualitative representation of MBSE techniques implemented in the context of aeronautical certification. Notably, COMAC has applied these techniques to the entire certification process for its latest family of commercial aircraft.

between global airworthiness and certification frameworks, particularly those of the FAA and EASA. Interoperability enables aviation market stakeholders to enhance the marketability of aeronautical products by promoting broader acceptance of their certification frameworks. However, the ASTM document system is often difficult to interpret and manage for aircraft manufacturers accustomed to the previous EASA CS-23 arrangements.

1.2. State of the art

Fig. 1 qualitatively illustrates how various industry and research entities are currently experimenting with the application of *Model-Based Systems Engineering* (MBSE) techniques to address the challenges of aeronautical certification. Most industry-oriented implementations focus on the selection of an appropriate certification basis at the outset of a certification program. *Certification by Analysis* (CbA) has been adopted using MBSE-derived approaches by major aeronautical companies such as Airbus and Boeing, employing complex simulation frameworks whose capabilities and methods are negotiated and accepted by regulatory agencies for certification purposes. Notably, COMAC applied MBSE approaches, tools, and methodologies across all phases of the certification process for its newly introduced family of commercial aircraft. The authors of this study specifically address the challenge of demonstrating compliance with the high-level requirements of EASA CS-23. This study does not address specific analytical methods within the broader framework of CbA (Mauery et al., 2021; Padfield et al., 2025). Instead, to satisfy EASA CS-23 structural and flight quality requirements, simulation and calculation tools were implemented in MATLAB/Simulink using established methods. The novelty lies in integrating input data from both the aircraft and a *System Modeling Language* (SysML) model exported as a UML file, which encapsulates relevant airworthiness regulations. This model-driven approach enhances the effectiveness and traceability of the applied analytical methods. This use of the SysML/UML formalism represents an interdisciplinary and innovative application of this technology in a domain rarely considered when introducing MBSE techniques in industrial settings. It also addresses institutional challenges in certification, such as inconsistent standards and regulatory gaps that hinder the adoption of new technologies. By potentially reducing regulatory inertia and overregulation in complex industrial sectors, MBSE methodologies may reshape how aeronautical companies and regulatory agencies interact, influencing both the interpretation and application of airworthiness rules and the broader concept of aircraft certification. EASA, in partnership with various industry stakeholders — such as COMAC and Airbus — is actively pursuing a path toward digitalization, aiming for a fundamental transformation in both the philosophical and practical approach to certification (European Union Aviation Safety Agency, 2024), addressing the challenges above mentioned. As already observed previously, COMAC has claimed to have fully implemented a digital certification process for its latest family of commercial aircraft—a significant milestone that, despite its associated advantages and disadvantages, marks a pivotal step in the digitalization of aircraft design and certification.

This work expands on a previous publication by the authors (Mirabella et al., 2024), providing a more detailed application of the MBSE approach to the certification of a *General Aviation* (GA) aircraft and investigating a systematic solution to traceability and consistency issues in EASA CS-23 airworthiness rules, thereby improving regulatory compliance of the final product. The MBSE framework includes a digital model of certification specifications built using SysML (Fazal et al., 2022; Lemazurier et al., 2017). SysML has primarily been applied in production, manufacturing, and aerospace contexts (Wolny et al., 2020; Hill et al., 2024; Kaslow et al., 2017, 2015), including regulatory domains such as cybersecurity (Hechelmann and Mannchen, 2025; Estefan et al., 2007). Its development over the past thirteen years by international research networks has improved its capacity to model complex systems (Schamai et al., 2009; Denil et al., 2017). Usually, the requirements must be modeled in a coherent framework enabling the users to exploit them, applying the MBSE logic to each use case scenario (Mažeika and Butleris, 2020; Ryan et al., 2013) with a high level of reusability. Applications that have historically benefited from MBSE adoption show improved collaboration and communication among stakeholders, with greater coherence of design data across organizational departments. At the same time, these sources report a noticeable increase in the complexity of internal practices and design processes, along with a significant shift in the knowledge and competencies required to perform design tasks. A notable example is the substantial effort by the United States Department of Defense to transition its systems entirely from analog to digital (Department of Defense, 2022; U.S. Department of Defense, 2023, 2024a).

SysML has been used to link technical and safety requirements (Nejati et al., 2012; Bruggeman and La Rocca, 2023), and to enhance communication across organizations with varied interpretations of technical contexts (Biggs et al., 2016). In aircraft certification, few studies address compliance with high-level requirements, focusing instead on building a certification basis for small and medium-sized companies (Lemoussu et al., 2025). The encoding procedure remains essential for implementing a fully digital certification process. This requires complex, user-defined stereotypes to represent all features of the EASA CS, including numerical data. Similar modeling approaches have been used in aviation for operational performance evaluation and aircraft performance data collection (Gopalakrishnan et al., 2021; Sun et al., 2019).

The modeling process proposed in this work integrates CS-23 paragraphs and ASTM Standards to digitally represent certification requirements. While SysML is not yet widely used in aircraft certification, this study demonstrates its potential by encoding requirements into a structured UML file. Numerical data and mathematical expressions are embedded in the SysML model via user-defined stereotypes, supporting MATLAB-based calculation routines—forming the core of the modeling phase.

This work builds on creating a digital model of the current Consensus Standard documentation. ASTM documents are more complex than CS-23, Amendment 4, and the traditional *Document-Based* approach often proves inadequate. This motivates an automated framework to manage certification in an integrated manner. Structured data can be used to generate reports and identify issues. Potential errors, inconsistencies, or omissions can be promptly identified, and the user can easily revise the certification artifacts as needed. This is the key advantage of the MBSE approach proposed here and justifies its use in industry-oriented applications, such as obtaining a new TC. To fully realize this potential, MBSE methodologies require a fundamental shift in organizational culture, training, and interpretation of the aeronautical product. This includes adopting new mechanisms for sharing information, data, and procedures—ideally minimizing reliance on traditional documents and certification artifacts (U.S. Department of Defense, 2024b).

A digitally managed certification process, based on MBSE, links CS-23 requirements with suitable AMCs, selected according to aircraft-specific factors. This tailored approach supports compliance and efficient artifact generation aligned with EASA standards. Structured around a SysML-based model and grounded in airworthiness regulations, the proposed framework meets modern development needs. Automation enhances traceability and may reduce costs in engineering, flight testing, and emergency procedure validation, as discussed below.

1.3. MBSE advantages and disadvantages

Regulations significantly influence overall program costs. The methodologies presented in this study may offer a more accurate means of evaluating these expenses (Delgado et al., 2021). The proposed MBSE approach has the potential to reduce both labor and time required for certification, although its cost-saving impact remains difficult to quantify. Previous studies (Subarna et al., 2020; Madni and Purohit, 2019; Henderson and Salado, 2021) indicate that MBSE is particularly effective in complex applications, with possible reductions in cost and time of up to twenty percent—especially during later stages of the product lifecycle. However, these benefits must be weighed against increased expenses related to tool acquisition, licensing, and training.

Despite these challenges, MBSE techniques using SysML support efficient verification and validation of requirements (Hecht and Chen, 2021). Improved efficiency may enable manufacturers to introduce next-generation aircraft featuring hybrid or electric powerplants and distributed propulsion systems (van Oosterom and Mitici, 2023). These innovations, though unfamiliar to most users (Guo et al., 2014), can be implemented without compromising safety or airworthiness standards. Ultimately, MBSE could facilitate the adoption of technologies that reduce operational costs and enhance aviation sector efficiency (Molesworth and Koo, 2016). Several firms are already advancing these technologies, such as Safran's recently certified fully electric powerplants in Europe (FAA, 2010; EASA, 2025).

To meet future market demands, researchers are also examining favorable aircraft characteristics, including environmental impacts (Gao et al., 2022) and safety insights derived from past incidents (Kuhn, 2018). The certification process itself involves continuous interaction among organizations exchanging specialized data and reports. MBSE may reduce labor costs by improving data and documentation management. Enhanced traceability can also lower costs associated with updates to the TC. Additionally, regulatory agencies may need to strengthen digital systems to manage consensus materials, airworthiness requirements, and certification documentation submitted by applicants within a model-based framework (Gough and Phojanamongkolkij, 2018). However, it is unlikely that aviation stakeholders will fully abandon document-based practices in the near future. A blended approach — combining document-based and model-based techniques — is the most probable scenario (Cook, 2025).

The use of emerging, currently unregulated airspaces will require significant certification efforts from aeronautical manufacturers. These efforts include Urban Air Mobility (UAM) operations in city centers and short, point-to-point flights using small aircraft with unconventional designs and novel propulsion systems. Key challenges include collision avoidance and airspace deconfliction (Wang et al., 2019; Garrow et al., 2021). Compliance with strict noise standards is critical, as non-compliance may render aircraft non-airworthy (Gao et al., 2024). This highlights the need for new certification approaches to support the entry of innovative vehicles and services into emerging airspaces.

1.4. Objectives and scope of this work

This study aims to present advanced MBSE applications in certifying general aviation aircraft. As the market for normal category aircraft grows, evolving demands and emerging airspaces call for cutting-edge technologies. This approach aligns with FAA and EASA positions on airworthiness and certification management.

The work is developed in the framework of the **Digital Innovative Aircraft Certification** (DIGACE) project,[1] led by the University of Naples (UNINA) in collaboration with POLIMI and POLITO. UNINA focused on CS-23 Subpart C, POLIMI on Subpart B and simulation, and POLITO on Subpart F, evaluating MBSE's impact on certification processes for both conventional and novel designs. This research has limited applicability due to its low Technology Readiness Level and potential tool unavailability, which may challenge industrial adoption. Ensuring process stability and repeatability is essential for practical implementation. In light of these considerations, the long-term objective is to provide manufacturers with a self-contained, integrated suite of tools, ideally within a unified digital environment.

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[1] https://www.digace.it/.

1.5. Structure of this work

The structure of this article is as follows:

- Section 1 (Introduction) provides a general overview of the context and includes references to existing research addressing the digitalization of aircraft certification processes.
- Section 2 (Tools and Methodologies) presents the tools and methodologies used to develop the digital certification framework. It explains the rationale for adopting programming environments such as Eclipse Papyrus and MATLAB/Simulink. This section also offers a detailed description of the stereotypes and their application to standard *Class* SysML elements.
- Section 3 (Results) demonstrates the execution of the framework, describes the data storage mechanism, and provides an example of the final output generated by the digital certification procedure. It includes verification and validation test cases implemented using MATLAB/Simulink routines. Finally, it presents a Flight Loads report addressing CS-23 Subpart C (Structure), automatically generated by the digital certification framework.
- Section 4 (Conclusions and future works) discusses the practical implications of applying MBSE methodologies and outlines future applications and prospects.

2. Tools and methodologies

This section presents the rationale behind the selection of modeling tools used to develop the SysML model. It also describes the MATLAB/Simulink infrastructure, which supports certification-related calculations and enables the automatic *Verification and Validation* (V&V) framework and report generation. In the context of this work, the application of MBSE methodologies to the EASA CS-23 certification landscape implies establishing a link between the high-level requirements and the AMCs applicable to them. MBSE methodologies require an interdisciplinary approach, allowing engineers to consider systems and processes comprehensively and to address all relevant phases and components. As a result, the selected development tools must support the full range of activities, including stakeholder requirement modeling, use-case scenario simulation and execution, system architecture design, verification and validation, production, delivery, maintenance, and project management. However, no single tool currently encompasses all these tasks. An effective MBSE framework must therefore integrate multiple tools to cover the entire system lifecycle. To enhance overall effectiveness, organizations typically adopt a combination of modeling tools tailored to their specific needs. The approach followed in this study can be summarized as follows:

- A comprehensive investigation was conducted to identify the most suitable modeling environment. Section 2.1 provides a detailed description of this phase.
- Upon selecting the modeling environment, EASA CS-23, Amendment 6, along with the relevant ASTM International consensus standard documents, was encoded into a SysML model. This was accomplished using a carefully designed modeling strategy based on regulation-specific stereotypes. Section 2.2 presents the stereotypes and modeling strategy, outlining the underlying modeling logic.
- Section 2.3 briefly illustrates the applicability of the proposed MBSE framework. It is important to emphasize that the primary focus lies in the application of SysML and user-defined stereotypes to encode and operationalize all certification and substantiation requirements necessary for compliance with EASA CS-23 provisions and prescriptions.
- The SysML model was then exported in a machine-readable format (UML/XML). The output of the decoding phase is a structured variable, defined within the MATLAB programming environment, containing all relevant certification data. This step is discussed in Section 2.4.
- Certification calculations and test case outputs were encoded into a MATLAB structured variable, following the defined execution sequence. Section 2.5 explains how the proposed MBSE approach accomplishes this step.
- Finally, the execution of the code ends with the generation of certification reports, including tables, figures, and all associated certification artifacts. This critical phase is described in Section 2.6.

Table 1
SysML, INCOSE-compliant modeling software. The table illustrates whether the software is or is not available under open source licensing.

Tool	Owner	License
MagicDraw	Dassault Systemes	Proprietary
Capella	Eclipse	Open - Source
Modelio	Modelio Soft	Open - Source
Papyrus	Eclipse	Open - Source
PTC Windchill Modeler	PTC	Proprietary
IBM Rhapsody	IBM	Proprietary
Enterprise Architect	Sparx Systems	Proprietary

2.1. Modeling environment and certification rules encoding

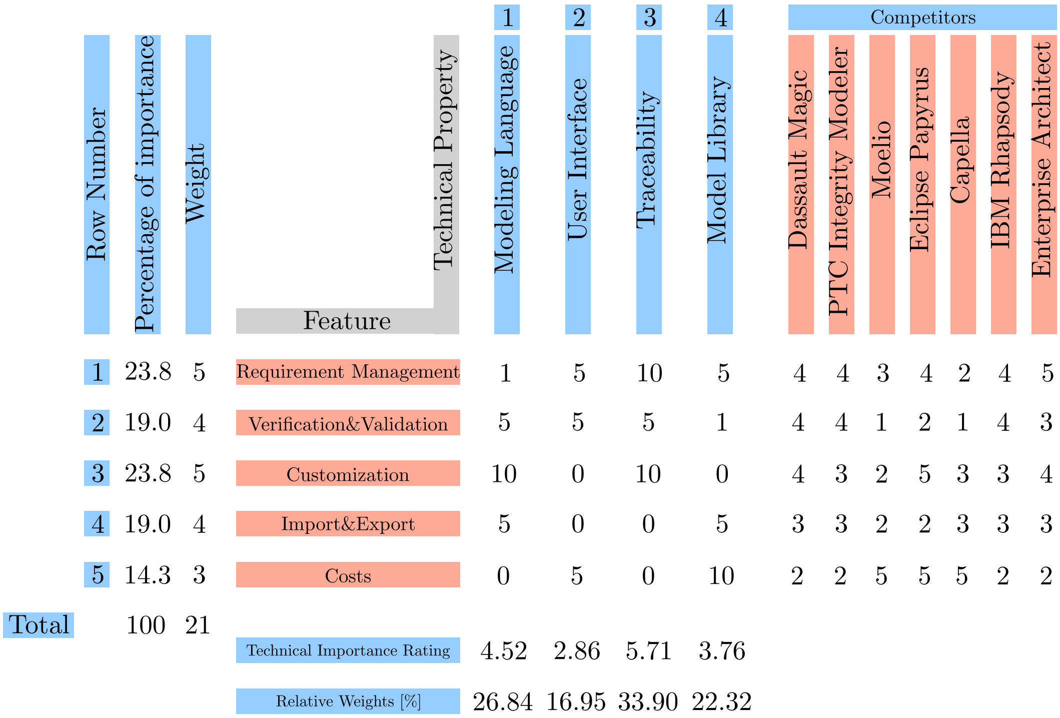
The modeling environment, including formal languages, was selected from a range of both open-source and proprietary software tools. The most relevant tools considered in this study are *Dassault Cameo MagicDraw*, *Capella*, *Modelio*, *Eclipse Papyrus*, *PTC Windchill Modeler*, *IBM Rhapsody*, and *Enterprise Architect*, as summarized in Table 1, which also indicates whether each tool is available under an open-source license (Khandoker et al., 2022). The selection process took into account various factors, including user experience and practical differences among the tools. The evaluation focused primarily on the ability to organize stakeholder requirements and ensure traceability, the capacity to implement a simulation toolbox for the V&V framework, licensing costs, support for customization and stereotype definition, and import/export capabilities.

Technological criteria considered during the selection included characteristics of the software environment, such as the modeling language, user interface, traceability features, and model library support.

Software performance evaluation is conducted using a *Quality Function Deployment* (QFD) matrix, shown in Fig. 2, which takes into account both the explicit and implicit needs of users. Each need is assigned a weight, guiding the final selection toward the software that best fulfills these requirements. Fig. 3 shows the final Decision matrix, illustrating how Papyrus has been evaluated as the best choice for this research study.

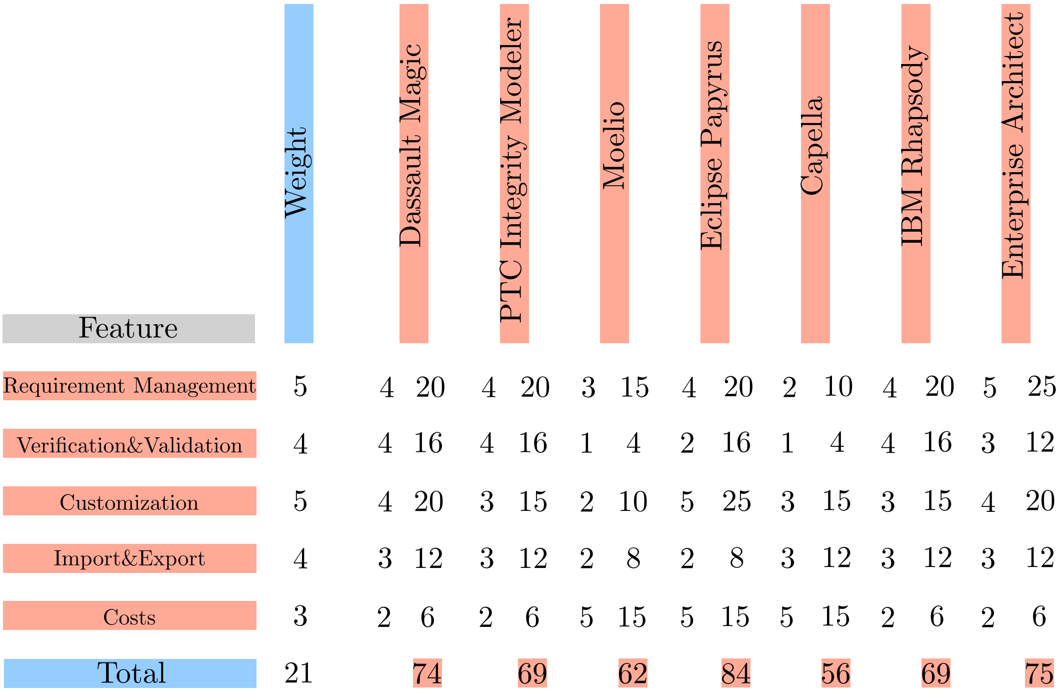
Eclipse Papyrus is an open-source SysML modeling environment compliant with the standards of the *International Council on Systems Engineering* (INCOSE). This research is based on version 1.6 of the SysML standard developed by INCOSE. At the time of writing, INCOSE is preparing to release a stable version of SysML 2.0, which introduces new features and an improved syntax. While the adoption of updated modeling standards is of considerable interest from a research perspective, such developments are not yet suitable for deployment in industry-proven technologies. The forthcoming INCOSE standard will be evaluated to determine whether the trade-offs associated with its adoption align with the objectives of this research. However, the industrial and practical implementation of new standards is inherently more complex and will require time to establish consistent practices, procedures, and a stable operational framework suitable for certification applications.

The SysML 1.6 standard has been deemed suitable for the application described in this study. SysML is a general-purpose modeling language designed for MBSE applications and is widely recognized as a standard in systems engineering. According to this standard, users can



				1	2	3	4	Competitors						
Row Number	Percentage of importance	Weight	Feature / Technical Property	Modeling Language	User Interface	Traceability	Model Library	Dassault Magic	PTC Integrity Modeler	Moelio	Eclipse Papyrus	Capella	IBM Rhapsody	Enterprise Architect
1	23.8	5	Requirement Management	1	5	10	5	4	4	3	4	2	4	5
2	19.0	4	Verification&Validation	5	5	5	1	4	4	1	2	1	4	3
3	23.8	5	Customization	10	0	10	0	4	3	2	5	3	3	4
4	19.0	4	Import&Export	5	0	0	5	3	3	2	2	3	3	3
5	14.3	3	Costs	0	5	0	10	2	2	5	5	5	2	2
Total	100	21												
			Technical Importance Rating	4.52	2.86	5.71	3.76							
			Relative Weights [%]	26.84	16.95	33.90	22.32							

Fig. 2. The Quality Function Deployment to assess software performance. For the application described in this article, the authors have agreed upon Eclipse Papyrus.



Feature	Weight	Dassault Magic		PTC Integrity Modeler		Moelio		Eclipse Papyrus		Capella		IBM Rhapsody		Enterprise Architect	
Requirement Management	5	4	20	4	20	3	15	4	20	2	10	4	20	5	25
Verification&Validation	4	4	16	4	16	1	4	2	16	1	4	4	16	3	12
Customization	5	4	20	3	15	2	10	5	25	3	15	3	15	4	20
Import&Export	4	3	12	3	12	2	8	2	8	3	12	3	12	3	12
Costs	3	2	6	2	6	5	15	5	15	5	15	2	6	2	6
Total	21		74		69		62		84		56		69		75

Fig. 3. The Decision Matrix to determine software final adoption. For the application described in this article, the authors have agreed upon Eclipse Papyrus.

model complex real-world systems and their requirements. However, additional constraints or practical limitations may affect the effectiveness of SysML in specific contexts. The language also enables users to construct graphical representations of models, thereby enhancing their readability and overall comprehensibility. Eclipse Papyrus, like many other open-source modeling tools, does not offer advanced features available in proprietary software such as *Dassault Systèmes Cameo MagicDraw*. These features include automation capabilities and behavioral diagrams that support the development of a V&V framework directly within the modeling environment. Nevertheless, Eclipse Papyrus is sufficiently supported and user-friendly for modeling the EASA CS-23, Amendment 6 regulations. It effectively displays dependencies among model elements through tables and diagrams.

Eclipse Papyrus features can be expanded via Eclipse IDE plugins. Model-to-Text (M2T) transformations, using tools such as Acceleo (Sindico et al., 2011; Di Rocco et al., 2014) or Epsilon (Kolovos et al., 2008, 2006), extract information from SysML models. These transformations require an *Eclipse Modeling Framework* (EMF) metamodel and a conforming model, producing an XML output that can be parsed for further use. While SysML relationships can improve model readability, each transformation must be tailored to the specific model, limiting generalizability. For the requirements V&V process within the context of this work, other simulation environments — such as MATLAB/Simulink — will be employed.

One of the most powerful features of the SysML language for modeling complex requirements is its ability to enhance or extend existing Unified Modeling Language (UML) classes or metaclasses. This capability allows information to be conveyed in a structured, hierarchical format by defining user-specific stereotypes and extending standard SysML profiles, such as the *Requirements* model element. By adding properties and methods to the standard *Requirements* element, the extended profile captures both the structure and content of the EASA CS-23 regulation, including relevant data and its relationships with neighboring requirements.

2.2. Regulation stereotypes

A SysML stereotype extends or enhances an existing element of the SysML language. For example, using the features of SysML, it is possible to define a new element that inherits all the properties and behaviors of an existing one. This capability enables the creation of a rich, extensible set of modeling tools suitable for encoding complex document systems, such as EASA CS-23, Amendment 6, along with all current AMCs. The design of the stereotypes within the model must reflect the structural characteristics of the source documents, particularly their paragraph and sub-paragraph hierarchy, thereby establishing a tree-like, hierarchical representation. In this work, two distinct stereotypes are introduced:

1. The **CS stereotype**, which is used to accurately encode the paragraphs contained in CS-23, Amendment 6.
2. The **ASTM stereotype**, which encodes information from the ASTM Consensus Standard Documents. These documents are accepted as *Means of Compliance* and serve to substantiate high-level certification requirements.

The model is organized hierarchically, a structure that enhances information retrieval and provides a clearer understanding of where relevant content is located and how it can be accessed. Moreover, the modeling phase benefits from the extensive set of relational constructs offered by SysML, which supports the representation of complex dependencies and interactions within the certification framework. The model can be enriched by establishing formal relationships between its elements, thereby enhancing traceability and connectivity throughout the regulatory framework. When properly defined, such a system of relationships enables the automatic generation of a *Certification Checklist* (CC). EASA requires applicants to submit a well-structured CC that links *Certification Demonstration Items* (CDIs) — including Certification Activities, Artifacts, Metadata, and Data — to the corresponding regulatory requirements.

The Eclipse Papyrus modeling environment allows the extension of the standard SysML *Requirement* model element within the context of the SysML Profile extension to account for specific needs. In this instance, the CS stereotype would have all the attributes of the former, with additional ones, since the default *Requirement* model element is not sufficiently rich to encode aircraft certification specifications.

Table 2 summarizes the additional attributes used for modeling CS-23 requirements, originally aligned with Amendment 4 but applicable to Amendment 5 and later. The `Amendment` attribute is an integer that specifies the version of the regulatory framework that is being considered. The `Amendment` property can be useful in handling different versions of the same documents. Revisions and amendments can change the textual content of paragraphs and subparagraphs over time. Handling amendments separately can help applicants discriminate between different versions of the same requirement, according to the certification basis selected when the TC application was started. The MATLAB decoding routine described in this work does not currently read the model for different amendments, as the model includes only documents referenced in EASA CS-23, Amendment 6. However, the routine can be modified to account for this property. The `Category` attribute applies to EASA CS-23 aircraft and indicates the class of the vehicle, thereby identifying the specific set of applicable requirements. The `TestValue1` and `TestValue2` attributes provide information related to performance-based requirements that the aircraft must satisfy. These are modeled as string attributes to accommodate both atomic and non-atomic performance-based requirements. Fig. 4 illustrates the CS stereotype, including these additional attributes. Fig. 5 illustrates the corresponding stereotype for ASTM requirements. The parsing strategy for the resulting UML file can be streamlined by defining an appropriate set of properties at this stage of the modeling phase. These properties, once established, facilitate the application of the user-defined ASTM stereotype to all model elements that correspond to sections, paragraphs, and subparagraphs of the ASTM documents included in the UML model root. From the perspective of airworthiness regulations, the DIGACE UML model is sufficiently detailed and accessible to support comprehensive certification analysis. It enables the automatic integration of information for use in simulations and calculations through a set of MATLAB routines.

Table 2
Additional attributes for the CS stereotype, a Profile extension of the SysML standard *Requirement* element.

Attribute	Type
Amendment	Integer
Category	Enumeration
Test1	String
Test2	String

To illustrate the utility of these fields, consider the EASA CS-23.2120 paragraph on *Climb requirements*, which specifies the minimum climb performance criteria for various aircraft certification levels. For instance, CS 23.2120.(a).(1) outlines the requirements applicable to Level 1 and Level 2 low-speed aircraft. For landplanes, the required climb gradient is 8.30%, which corresponds to a `TestValue1` value of 8.3. Similarly, for seaplanes, the climb gradient is 6.70%, also represented by the `TestValue1` property. The CS 23.2120 requirement is typically modeled using the hierarchical tree structure of elements within the model. Accordingly, any class elements extended with user-defined stereotypes are modeled in a similar hierarchical manner. A non-atomic requirement is defined as a combination of multiple performance-based requirements. An example is EASA CS 23.51.(a).(1), which applies to twin-engine landplanes. This regulation states that the rotation speed, V_R, must not be less than the greater of $1.05 \cdot V_{MC}$ and $1.10 \cdot V_{S1}$. In this case, `TestValue1` is set to `1.05*VMC`, and `TestValue2` to `1.10*VS1`, meaning that V_R is expressed as a function of two distinct characteristic speeds. From a research-oriented perspective, these examples clearly illustrate the scope and applicability of this study, which focuses on developing a strategy to encode the high-level certification requirements of EASA CS-23, along with the AMCs derived from consensus standard material, into a coherent SysML model. This model includes relationships and digital linking mechanisms designed to assist the applicant in identifying and applying the minimum set of substantiation methods necessary to demonstrate compliance.

SysML provides a comprehensive set of relationships that enable users to describe the interrelationships between model elements. To illustrate this capability, consider paragraph CS 23.2150, *Stall Characteristics, Stall Warning, and Spins*, which defines the expected behavior

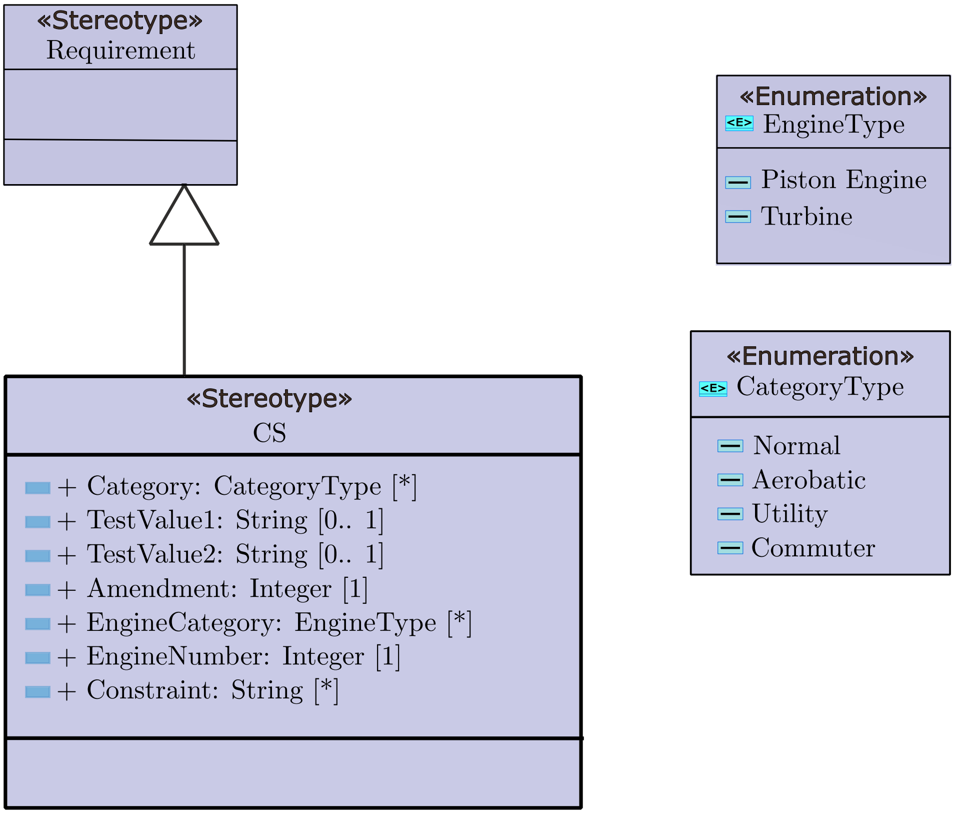


Fig. 4. The SysML graphical representation of the user-defined CS stereotype.

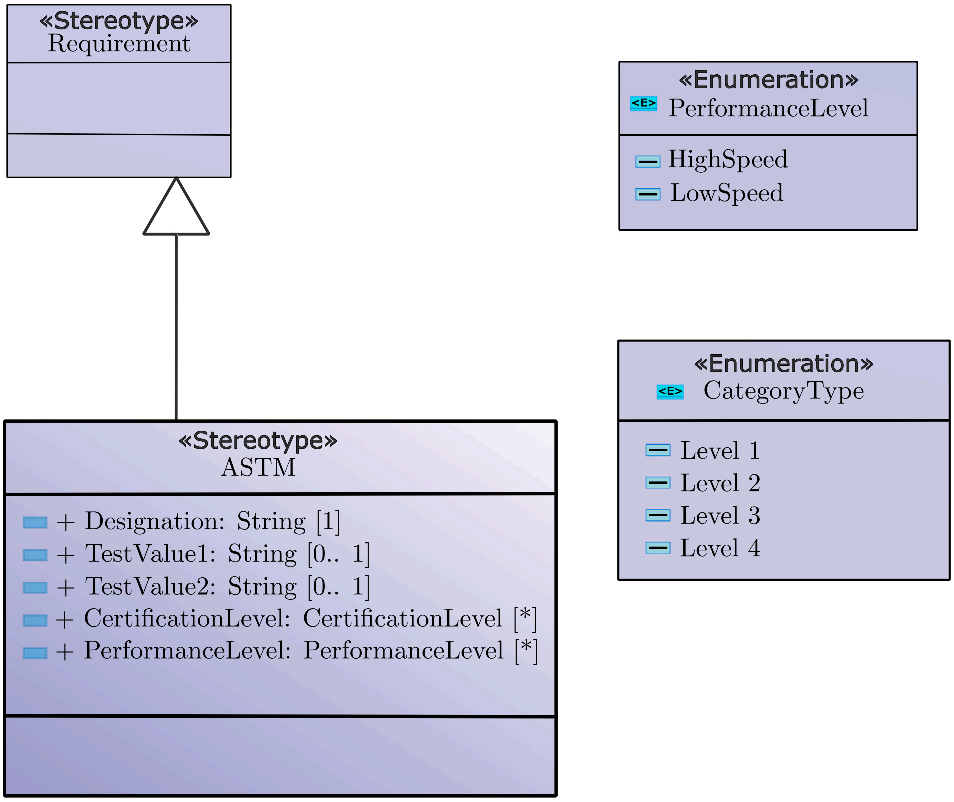


Fig. 5. The SysML graphical representation of the user-defined ASTM stereotype.

Table 3
An example showing the EASA CS-23 hierarchical levels sub-division. A similar sub-division is used to model CS-23, Amendment 5, or later.

	EASA CS-VLA	EASA CS-23, Amendment 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)

of an aircraft during a stall maneuver. It includes provisions for spin prevention, as specified in AMC1 23.2150, and refers specifically to the standard F3180/F3180M-21, *Standard Specification for Low-Speed Flight Characteristics of Aircraft*, section 5.11, *Stall Characteristics, Stall Warning, and Spins*. The applicant must demonstrate acceptable stall characteristics under all flight conditions and configurations specified in CS 23.2150. AMC1 23.2150 provides the necessary interpretative material, offering a less abstract and more practical explanation than the CS 23.2150 paragraph itself. It also highlights that any modification to CS 23.2150 may trigger a new validation activity, requiring the applicant to conduct tests under the flight conditions described in the regulation. The application of formal relationships offers two primary advantages:

- Enhances model traceability by enabling clearer identification of dependencies among regulatory rules. A weak dependency between two elements can be represented using a *Trace* relationship, which indicates that changes to the supplier element (at the arrowhead end) may necessitate modifications to the client element (at the tail end). In contrast, a *Refine* relationship, which denotes a stronger dependency, implies that the client element — such as a Block or another CS requirement — is a more concrete (i.e., less abstract) representation of the supplier element, typically another CS requirement.
- Facilitates the creation of a Certification Case (CC) for any certification artifact under consideration.

SysML representation rules are strictly defined by formal standards, ensuring that each relationship is depicted with a precise and consistent graphical notation. Table 3 presents the hierarchical subdivision used to model EASA certification rules. A similar structure is adopted for CS-23, Amendment 5 and later, which references ASTM documents in specific subparagraphs, labeled with the acronym AMC. Specifically, AMC1 refers to ASTM standards, while AMC2 and AMC3 correspond to CS-23, Amendment 4, and CS-VLA, Amendment 1, respectively. The hierarchical digital model of the EASA CS-23 regulations is primarily based on the CS stereotype, which enables the introduction of as many subdivisions as necessary. The model content is organized into *Packages*, each representing a specific Subpart of the EASA CS-23 documentation. Within each *Package*, all corresponding paragraphs and subparagraphs are included. A single paragraph is modeled as a nested tree of elements that contains all its subparagraphs. Both paragraphs and subparagraphs are represented as SysML classes extended with the user-defined CS profile, which assigns the appropriate attributes needed to describe the EASA requirements.

A set of requirement diagrams has been modeled in the Eclipse Papyrus environment. These diagrams provide a comprehensive graphical representation of the relationships and links between the main paragraphs of EASA CS-23, Amendment 6, and the corresponding ASTM International AMC reference documents. They indicate the specific paragraphs and subparagraphs to which the applicant should refer in order to demonstrate compliance with the high-level requirements. It is important to emphasize that these requirement diagrams are not merely graphical depictions of the current structure of the airworthiness regulations; they can also be operationally employed to generate complex documentation, such as the Compliance Checklist (CC). Fig. 14 presents an example of a requirement diagram.

2.3. Data selection and applicability

This section briefly outlines the scope of the MBSE methodology developed and presented in this article. The substantiation methods and certification artifacts produced by the digital certification framework are applicable to any aircraft architecture — whether conventional or unconventional — certifiable under EASA CS-23 airworthiness regulations. Calculations, simulations, and test data are used to populate certification documents, including Excel tables, technical reports, and figures. The selected conventional architecture is representative of most commuting aircraft currently in operation and encompasses the majority of high-performance, passenger transport aircraft.

The focus of this article is not on specific aircraft certification data or methodologies. The MBSE methodology introduced in this work is agnostic with respect to the configuration selected for conducting certification and substantiation calculations and simulations.

2.4. Certification rules decoding

The certification rules decoding phase represents an essential stage in which the MBSE framework systematically extracts all relevant certification data for the aircraft under examination from the UML file generated by the modeling environment. The MBSE framework described in this study is implemented within the MATLAB programming environment. Fig. 6 illustrates schematically how the MATLAB code performs the decoding phase. During this phase, the code iteratively scans the model and generates code artifacts, including numerical data, function handles, and other relevant elements. The output of this process is a structured variable, consistent with the architecture embodied by the MATLAB-based MBSE framework illustrated in this study as an operative example. The effectiveness of this phase is significantly influenced by the encoding strategies adopted during the modeling phase. Information and data extraction can be facilitated through the strategic use of stereotype definitions, which allows the development of simpler methods to locate the desired information and automatically populate a data structure. This process also involves the manipulation of various data types, such as using a string to define a function handle directly, converting a string to a numerical value, or retaining the string for convenient use within the text of the automatically generated report. Broadly speaking, this process parses a large text file, such as the UML, by exploiting user-defined stereotype fields as target expressions to be located within the text. Once the desired string is found, data extraction depends on the tools available in the chosen programming environment—whether it is Python, C++, or MATLAB.

2.5. Certification test case

The digital certification framework provides tools and facilities for testing the aircraft under examination in accordance with the applicable airworthiness regulations. Fig. 7 presents a general representation of the test case routine logic. The routine accepts all necessary input data to initialize the test. Specifically, it includes a data structure containing information extracted from the SysML model, the aircraft data structure, and other test case-specific data. The output of this process is a partial or complete report generated automatically. This report incorporates additional certification artifacts, such as figures, tables, and other relevant information specific to the test. The code is designed to collect information in a single data collector, ready for further retrieval in subsequent code execution phases.

The standard V&V capabilities of SysML-based tools are inadequate for conducting aviation-specific V&V activities. MATLAB and Simulink have been employed to address this limitation; however, doing so necessitated the development of a rigidly programmed infrastructure. These tools are designed to distinguish between requirements and aircraft certification performance metrics, determining whether specific certification criteria have been met. Constructing such an infrastructure

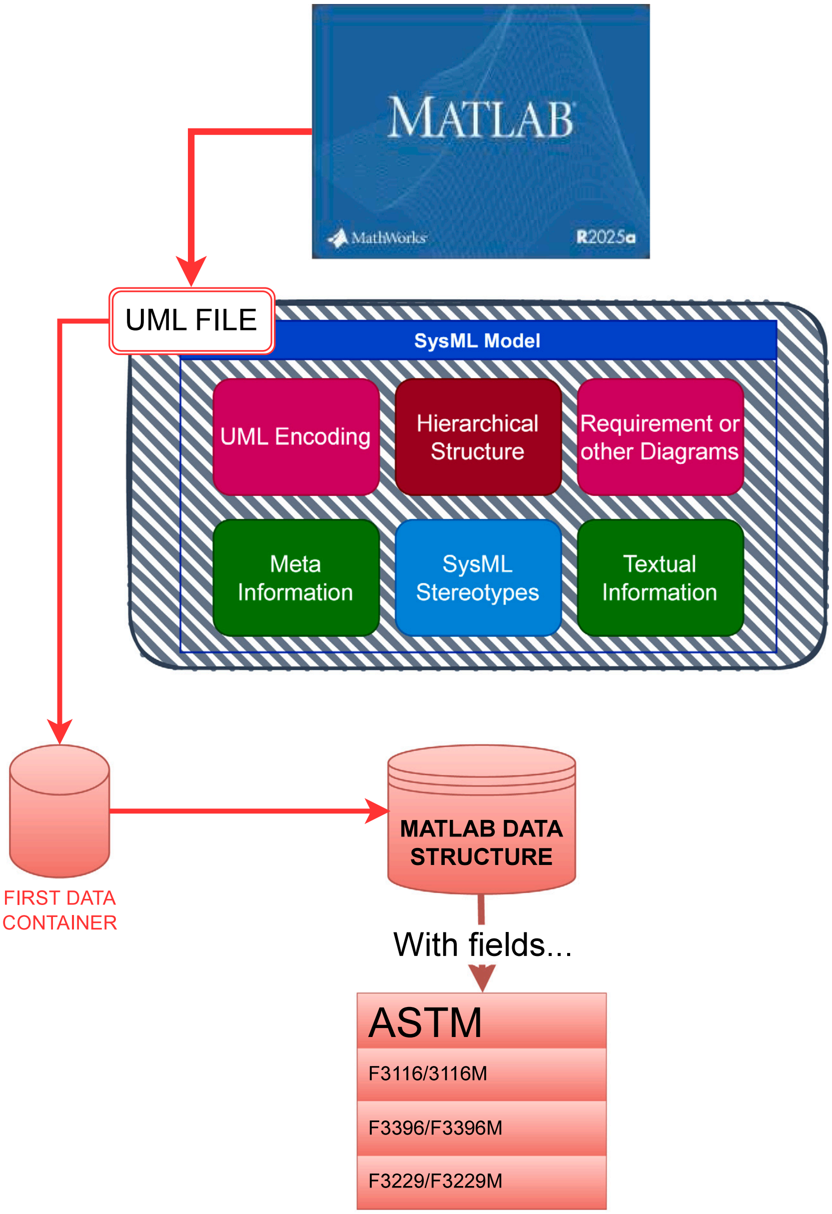


Fig. 6. A schematic representation of the MATLAB decoding phase. The example demonstrates how the MATLAB decoding routine extracts data from the UML file and organizes the relevant information into a structured MATLAB variable. The example provided in the figure is relative to some of the ASTM structured variable fields.

is inherently complex, requiring highly experienced personnel, and carries a significant risk of error.

The management of a certification program can no longer depend on tools characterized by low repeatability and reliability, such as Excel spreadsheets and simple text files. The technology proposed in this research generalizes the certification approach, standardizing the final output regardless of the aircraft's architecture, aerodynamic characteristics, or propulsion type. The MBSE approach presented in this work places the certification material at the center of the complex process required to certify a general aviation aircraft. This enables both the applicant and the Regulatory Agency to exchange certification artifacts digitally, thereby enhancing clarity, coherence, consistency, and potentially transforming the cultural approach to certification. Moreover, information can be more effectively communicated to non-technical personnel within a self-contained modeling environment, given that all the stakeholders have sufficient familiarity with the adopted MBSE tools. Section 1.3 in the Introduction discusses this point in greater detail.

2.6. Data reporting

This study describes the general features of the MBSE digital certification framework developed using the MATLAB/Simulink programming environment. The primary objective of the DIGACE research project is to develop a tool capable of generating certification technical reports with minimal user intervention for corrections or additions. Fig. 8 shows a generic implementation of this report generation tool. The data reporting phase, combined with strategically structured data storage, represents a core industry-oriented application. This capability

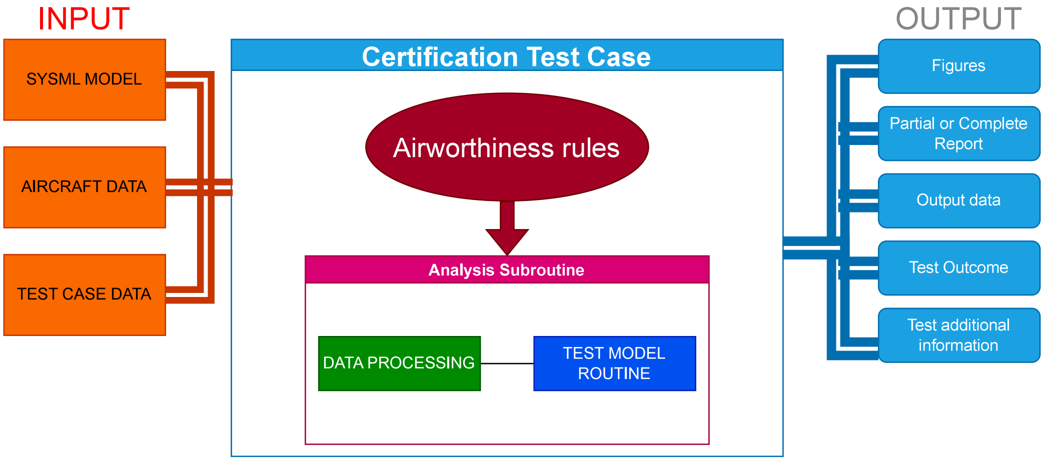


Fig. 7. A schematic representation of a generic test case phase. The DIGACE research project implemented a similar structure using the MATLAB/Simulink programming environment.

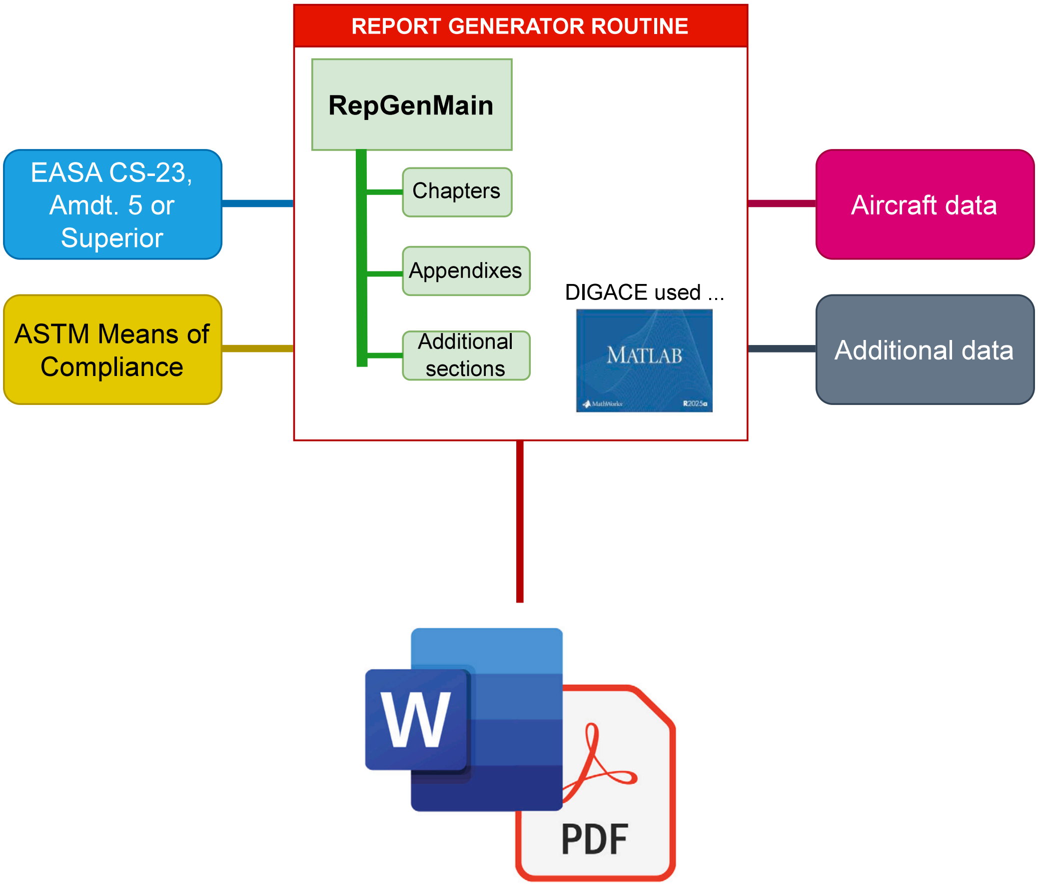


Fig. 8. A schematic representation of a generic data reporting phase. The DIGACE research project implemented a similar structure using the MATLAB/Simulink programming environment.

can positively affect both the time and cost associated with certification, particularly in the case of nonconventional architectures, where development costs are inherently high and lifecycle complexities are best managed using digital, integrated tools. Once the data is available and the Certification Specifications-based routines have completed execution, the Report Generator routine uses this data to produce the certification report in various file formats.

In a practical context, this feature enables a fundamental shift in how complex documents are prepared and issued within a design organization. Information sharing becomes coherent and consistent, owing to the unambiguous origin of both the data and the resulting documentation. Moreover, the transmission of this information to regulatory agencies is more efficient, thereby simplifying the revision process. This approach aligns with the current industry trend of maintaining a document-oriented certification process within a blended environment, where MBSE methodologies are partially implemented and adopted, with the recognition that full adoption by regulatory and industry partners is unlikely.

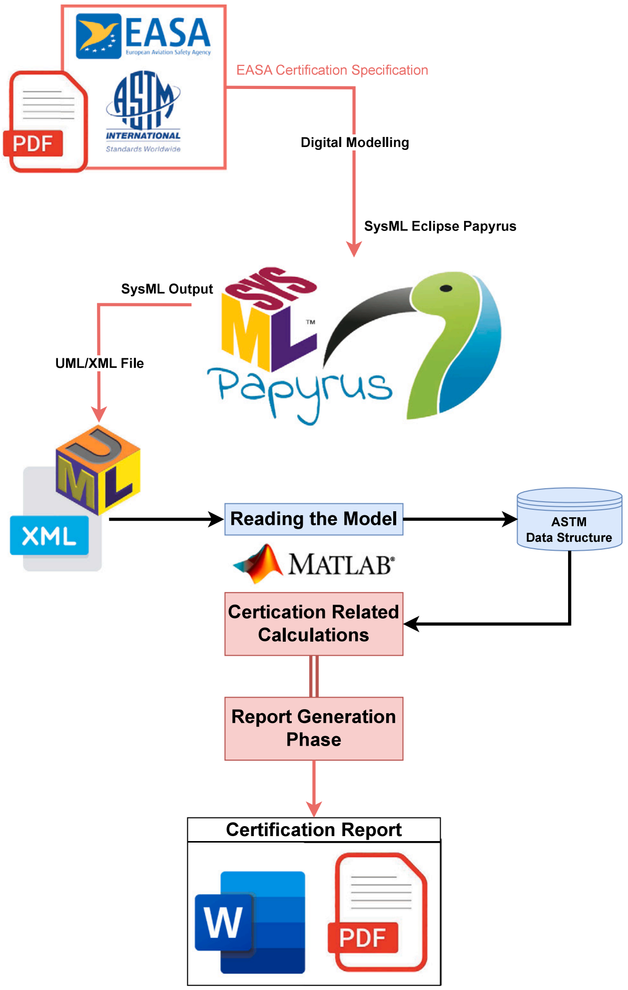


Fig. 9. A schematic representation of the MBSE integrated, digital framework for CS-23 aircraft certification. The final output is a certification document, typically in the form of a technical report.

3. MBSE framework

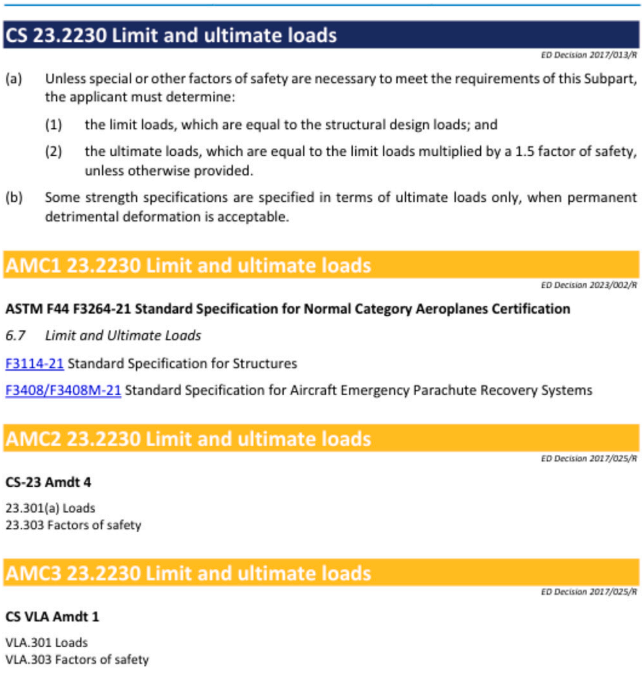
This section summarizes the MBSE developed framework. Fig. 9 presents a schematic representation of the integrated MBSE framework. Among the various phases, the modeling stage is the most time-consuming and resource-intensive. A SysML model can incorporate all relevant information from CS-23 and ASTM documents. The final output is a UML-compliant model in which both textual information and data are structured and ready for parsing. Similar to other programming languages, MATLAB provides tools to efficiently read this information and convert it into MATLAB variables for further processing. Functions, data, and other relevant information are automatically extracted. A structured variable collects all data and results, which can then be automatically inserted into the certification report. The report generation phase constitutes the final stage of the framework's execution. Philosophically, this step may be viewed as a return to a document-based perspective. Automatically generating a document from the model and calculation output remains a valuable feature, recognized by established commercial MBSE tools, even though it represents a compromise between document- and model-based approaches. The MBSE digital framework is structured around the following phases:

- **Modeling Phase.**
  The description provided in this section is sufficiently detailed to enable readers to reproduce the modeling strategy adopted in a SysML modeling environment. Although this phase can be lengthy and labor-intensive, the resulting model has yielded an unprecedented and in-depth understanding of the current system of Certification Specifications published by EASA. The analysis of the Consensus Standards documentation revealed inconsistencies and a lack of traceability or linkage among various paragraphs and subparagraphs. Many high-level (i.e., less concrete) requirements in the CS-23, Amendment 6 document are not properly connected to the corresponding substantiation means outlined in the ASTM standards.
- **Model-Reading Phase.**
  A MATLAB routine is used to read the information contained in the UML file. This file follows an XML-inspired syntax, making it compatible with standard parsing strategies. MATLAB offers tools well suited to the objectives of this work, particularly the use of regular expressions for efficient data extraction. This step represents the initial phase of the framework's execution and is essential for organizing all certification-related information into a structured variable. Section 3.2 gives an overview of the general ideas behind this phase.
- **Certification Specification Phase.**
  This phase focuses on verifying compliance with EASA CS-23 airworthiness requirements through a structured set of simulation-supported and physical test cases. Leveraging a digital model of the aircraft, the verification activities are aligned with AMC and harmonized with ASTM standards recognized by EASA. This phase systematically validates key performance and safety

criteria—such as flight performance and controllability (Subpart B), structural integrity under design loads (Subpart C), and the reliability and functionality of essential onboard equipment (Subpart F). This phase enables traceable, simulation-supported validation of compliance, forming a key element of the integrated certification workflow based on digital evidence and regulatory alignment.

- **Subpart B phase.**
  This phase begins immediately following the model-reading stage. After extracting the airworthiness regulations from the UML file containing the CS-23/ASTM requirements, the code organizes the data into structured variables. These variables are then used to inform subsequent functions and scripts by providing values, function handles, and other relevant parameters. The code subsequently executes simulations to verify compliance with Subpart B requirements. As a demonstrative example of the capabilities of the digital automatic certification framework, this study reports an example concerning climb airworthiness requirements. The ASTM document F3179/F3179M-20, *Standard Specification for Performance of Aircraft*, contains the majority of the performance-based requirements referenced in this work. Section 3.3.1 describes in more detail this phase.
- **Subpart C phase.**
  This phase begins immediately after the model-reading stage. The code extracts information from the structured variable containing the CS-23/ASTM requirements and integrates it into functions and scripts. These values differentiate among various sets of requirements, enabling the application of the framework to a wide range of aircraft configurations, all within the constraints of CS-23. Examples from this phase include Subpart C of CS-23, which is based on the ASTM document F3116/F3116M-23A, *Standard Specification for Design Loads and Conditions*. Section 3.3.2 describes this execution phase, with an example that shows how the code automatically draws the maneuvering and gust flight envelope.
- **Subpart F phase.**
  This phase begins immediately after the model-reading stage. Once again, the performance-based requirements extracted from the UML file are applied to evaluate the aircraft's systems and subsystems. The ASTM document F3227/F3227M-25, *Standard Specification for Environmental Systems in Aircraft*, contains the majority of the performance-based requirements referenced in this context. Section 3.3.3 provides a clearer depiction of tests and performed calculations during this phase, with an example concerning cabin depressurization requirements.

- **Report Generation Phase.**
  The objective of this work is to demonstrate the digital framework's capability to generate reports and certification artifacts automatically. MATLAB provides an API that enables the creation of documents in Microsoft Word or PDF format. The final output of the MATLAB code execution is a comprehensive certification technical report, prepared for submission in accordance with the Flight Loads requirements. The report includes the flight envelope, as well as shear, bending, and torsion diagrams, to address the limit forces and moments. These elements, along with other flight loads calculations, are essential to ensure the required structural strength is achieved without significantly increasing the aircraft's weight. Section 3.4 presents excerpts from the generated reports.



CS 23.2230 Limit and ultimate loads

ED Decision 2017/013/R

(a) Unless special or other factors of safety are necessary to meet the requirements of this Subpart, the applicant must determine:

  (1) the limit loads, which are equal to the structural design loads; and

  (2) the ultimate loads, which are equal to the limit loads multiplied by a 1.5 factor of safety, unless otherwise provided.

(b) Some strength specifications are specified in terms of ultimate loads only, when permanent detrimental deformation is acceptable.

AMC1 23.2230 Limit and ultimate loads

ED Decision 2023/002/R

ASTM F44 F3264-21 Standard Specification for Normal Category Aeroplanes Certification

6.7 Limit and Ultimate Loads

F3114-21 Standard Specification for Structures

F3408/F3408M-21 Standard Specification for Aircraft Emergency Parachute Recovery Systems

AMC2 23.2230 Limit and ultimate loads

ED Decision 2017/025/R

CS-23 Amdt 4

23.301(a) Loads
23.303 Factors of safety

AMC3 23.2230 Limit and ultimate loads

ED Decision 2017/025/R

CS VLA Amdt 1

VLA.301 Loads
VLA.303 Factors of safety

Fig. 10. An extract from the EASA CS-23, Amendment 6, Certification Specifications. The figure shows all the AMCs suggested by EASA to the applicant.

3.1. Modeling phase

The modeling phase involves the creation of a digital model that serves as the foundation for the framework's development. The digital model is formalized using SysML, with Papyrus employed as the modeling environment. Fig. 10 presents a page extracted from CS-23, Amendment 6. This page includes paragraphs and subparagraphs categorized as AMC and *Guidance Material*, which reference three distinct types of consensus standards documents:

- **ASTM**
  The documents published by ASTM International constitute one category of consensus standards. This system of documents, maintained and regularly updated by ASTM Committee F44 on GA Aircraft on behalf of the Federal Aviation Administration (FAA), is now widely accepted for the certification of general aviation aircraft. In alignment with the objective of harmonizing certification requirements across international aviation markets, EASA has accepted ASTM documents as a means of compliance since Amendment 5 of CS-23. In the CS-23 document — available for free download from the EASA website — applicants can refer to AMC1 under each paragraph to identify the corresponding ASTM reference documents.
- **CS-23 Amdt. 4**
  Although EASA advises new applicants that ASTM documents constitute the primary acceptable set of reference consensus standards, a transitional framework has been established to ease the shift from earlier certification rules. This approach is intended to prevent undue burden on aircraft manufacturers during the adoption process. CS-23, Amendment 4, is scheduled for discontinuation in future versions of CS-23. Nevertheless, it remains accepted — exclusively for aircraft intended for operations within Europe — and is designated as AMC2 in CS-23, Amendment 6, which is the current version at the time of writing.
- **CS-VLA**
  Finally, for Very Light Aircraft (VLA), EASA permits new applicants to select a third certification reference basis. These aircraft

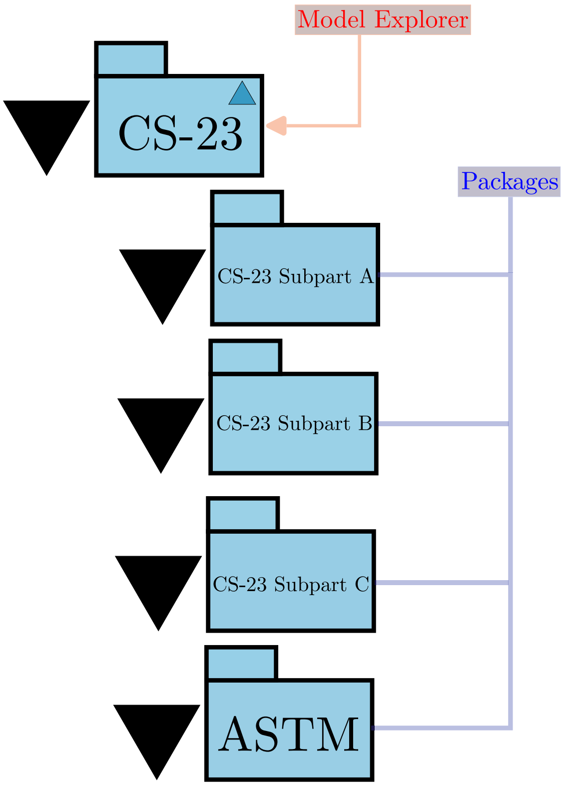


Fig. 11. The Eclipse Papyrus model explorer tab represents the hierarchical tree structure of the SysML model. The model root is distinctly identifiable, and packages and sub-packages are conveniently organized to host the CS-23 contents.

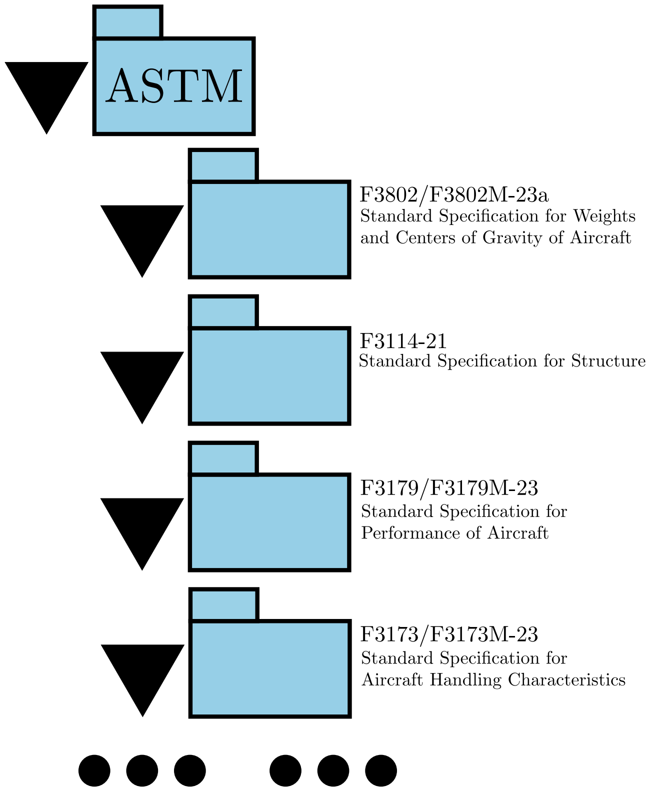


Fig. 12. An expanded view of the Eclipse Papyrus model explorer tab. The figure shows ASTM International documents packages and sub-packages.

> typically incorporate simple and proven technologies and are characterized by limited project scope and reduced development costs. Accordingly, applicants may adopt CS-VLA, Amendment 1, as the certification basis for a new TC, provided that the aircraft remains well within the standard's limitations. The new TC is not valid outside the boundaries of Europe. If the applicant intends to market the aircraft internationally, the vehicle must be recertified in accordance with the regulations established by the aviation authority of the target country. This set of requirements, as outlined in CS-23, Amendment 6, is designated under the label AMC3.

The final SysML model presented in this work incorporates the entirety of CS-23, Amendment 6, but includes only the AMC1 documents, with a focus on the ASTM consensus standards. To implement the hierarchical tree structure of the SysML model, each Package element corresponds to a CS-23 Subpart and contains all associated paragraphs and subparagraphs. Each Class element represents individual paragraphs or subparagraphs, following the textual order and logical subdivisions of the regulation. Stereotypes are applied to extend and enrich the Class elements, inheriting properties from the SysML Requirements element while introducing additional attributes specific to the certification framework.

A similar modeling strategy can be applied to ASTM documents. Each Package element represents a complete ASTM document; that is, each Package corresponds to a fully modeled standard. The internal elements of the document are modeled as Class elements, with the appropriate stereotype applied, as described previously.

Fig. 11 schematically illustrates the hierarchical tree structure of the model, providing an immediate visual understanding of its internal organization. The root of the model is positioned at the top, with all Package elements systematically arranged beneath it. Each Package is labeled with the name of the corresponding CS-23 Subpart. ASTM International documents are organized into dedicated Package elements, which preserve and encapsulate all dependencies and relationships among the corresponding model elements. Fig. 12 presents an example of an expanded view of the model explorer tab. Finally, Fig. 13 illustrates the hierarchical tree structure of Subpart A, with the CS stereotype applied to the Class elements.

The Refinement relationship is the only SysML relationship considered in this work. While a broader set of relationships could enhance the model's readability — enabling features such as grouping related paragraphs and subparagraphs by topic according to user-defined criteria — this study focuses on a minimal yet functional structure. Expanding the relationship set would facilitate information retrieval and enrich the representation of the airworthiness regulatory framework. However, the modeling phase is both time- and labor-intensive. Incorporating such a dense network of relationships would have significantly extended the duration of the modeling process, which falls outside the scope of this research.

Fig. 14 presents the CS 23.2230 *Limit and Ultimate Loads* requirement diagram, which corresponds to the CS-23 paragraph shown in Fig. 15. This diagram is one of many developed as part of this research. Notably, it demonstrates the utility of visual modeling in tracing and linking high-level requirements to the applicable means of compliance. However, the value of these diagrams extends beyond this function.

Numerous sources have reported that inconsistencies and gaps in information are prevalent throughout the ASTM document system (Rodrigues et al., 2024; Batuwangala et al., 2018). Although this body of documents provides guidance for hybrid/electric aircraft and other unconventional configurations — and currently represents the only widely recognized AMC for obtaining a new TC in both the United States and the European Union — it presents several significant challenges that may hinder the market introduction of new aircraft (see Markov et al., 2022; Glinski et al., 2022). Moreover, managing these documents

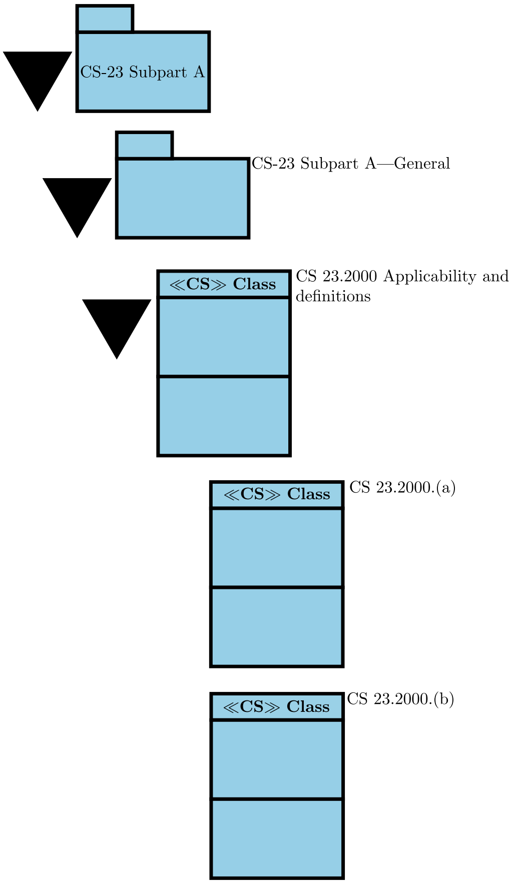


Fig. 13. CS-23 Subpart A expanded view. The hierarchical tree structure and the applied CS stereotype are visible.

is difficult even for Regulatory Authorities, which often delegate this responsibility to external organizations such as the ASTM Consortium, thereby introducing additional layers of inconsistency. The currently active EASA CS-23, Amendment 6, often references ASTM documents that do not fully substantiate the corresponding regulatory paragraphs. This forces applicants to consult additional sources or risk partial non-compliance with the high-level requirements. Addressing this issue through a *Document-Based* approach results in a labor-intensive and repetitive search through the ASTM documentation (Schlickenmaier et al., 2019), in an effort to identify a consistent set of AMCs that adequately support each CS-23 paragraph or subparagraph.

The discussion presented in this section is based on observations derived from AMC1 and AMC2, as outlined in the current amendment to EASA CS-23. Applicants may choose either of these means of compliance to obtain a TC. However, the two differ significantly in several respects, which can lead to confusion and pose challenges in determining the most appropriate certification basis. Regulatory agencies, by contrast, prioritize ensuring an appropriate level of safety when establishing a certification basis. However, the situation described above may pose risks, as it can lead to inconsistencies in the validity of TCs across different countries. This issue is particularly relevant in Europe, where CS-23, Amendment 4, remains accepted by EASA, despite being intended for aircraft operating exclusively within European airspace. Although Regulatory Agencies continue to monitor the implementation of ASTM International Standard documents, their management has proven challenging since their adoption as AMC. The reader is referred to Figs. 14 and 15 for further illustration. Notably, during the development of these figures, the authors observed that CS-23, Amendment 6, exhibits inconsistencies and lacks coherence, indicating potential flaws in its structure. In many instances, AMC1 and AMC2 are not equivalent due to discrepancies in the tracking of ASTM International documents, which often do not align with the derived requirements of AMC2 under CS-23, Amendment 4. To clarify this issue, Fig. 15 presents AMC1 for EASA CS-23, Amendment 6, paragraph 23.2230, titled *Limit and Ultimate Loads*. This paragraph includes a list of reference documents intended to support compliance with the top-level requirement specified in the CS-23 regulation. Unfortunately, the documents cited are insufficient to demonstrate compliance with CS 23.2230. Specifically, the required limit load factors are provided in F3116/F3116M-23a, *Standard Specification for Design Loads and Conditions*, which is not referenced in AMC1. Instead, AMC1 lists only F3408/F3408M, *Standard Specification for Aircraft Emergency Parachute Recovery Systems*, and F3114, *Standard Specification for Structures*. Another illustrative case is presented in Fig. 16. Although AMC1, *Design and Construction Principles*, references only five ASTM documents, the corresponding SysML relationship diagram reveals that the complete set of ASTM documents required to comply with the top-level requirement in EASA CS-23 is as follows:

1. F3061/F3061M-23b *Standard Specification for Systems and Equipment in Small Aircraft*
2. F3232/F3232M-23a *Standard Specification for Flight Controls in Small Aircraft*
3. F3114-21 *Standard Specification for Structures*
4. F3380-19 *Standard Practice for Structural Compliance of Very Light Aeroplanes*
5. F3066/F3066M-23 *Standard Specification for Aircraft Powerplant Installation Hazard Mitigation*
6. F3408/F3408M-21 *Standard Specification for Aircraft Emergency Parachute Recovery Systems*
7. F3083/F3083M-23a *Standard Specification for Emergency Conditions, Occupant Safety and Accommodation*
8. F3233/F3233M-23b *Standard Specification for Flight and Navigation Instrumentation in Aircraft*
9. F3227/F3227M-24 *Standard Specification for Environmental Systems in Aircraft*

EASA CS-23, Amendment 6, adopts ASTM standards to substantiate the high-level requirements outlined in its paragraphs and subparagraphs. However, the inconsistencies identified in this work are likely to have a detrimental impact on applicants who have selected these standards as their certification basis. Moreover, the references typically point to entire documents, making it difficult to trace the specific substantiation requirements necessary to demonstrate compliance with a given CS-23 paragraph.

The MBSE digital certification framework establishes all the required references once and for all, giving applicants adopting these techniques to avoid manual cross-referencing among complex standards. Among the advantages of MBSE approaches, this is perhaps the most impactful, especially if the Regulators decide to establish a proper SysML encoding of the airworthiness rules in advance, adjusting it only for revisions and amendments.

The cases presented in this study are not exhaustive. For the sake of brevity, no additional examples are provided. The key takeaway for the reader is that the MBSE approach translates regulatory requirements into a digital model through the application of the SysML formalism. This methodology enables efficient tracking of requirements and their corresponding means of compliance, thereby facilitating the identification of inconsistencies such as those discussed in this work.

The preceding discussion highlights the advantages that certified production and design organizations, as well as Regulatory Agencies, can derive from this approach. The methodology is robust from both theoretical and practical perspectives, despite the inherent complexity of the underlying technology. From the standpoint of aeronautical

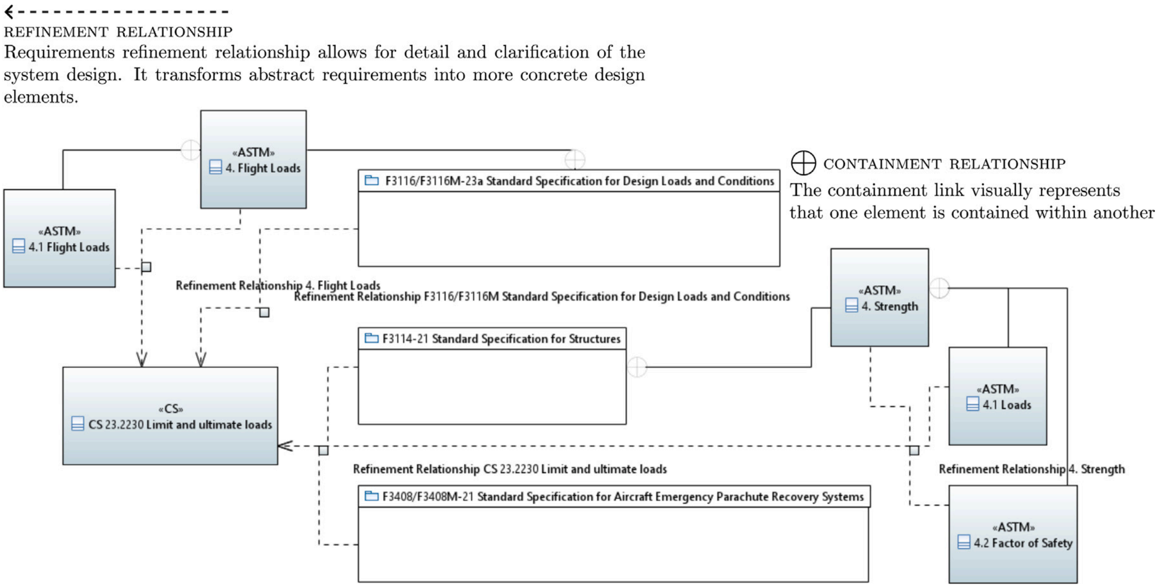
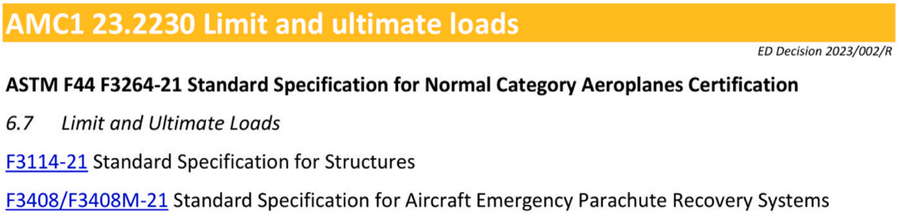


Fig. 14. An example of a Requirement diagram. The example shows the CS 23.2230 *Limit and Ultimate loads* paragraph Requirement diagram.



AMC1 23.2230 Limit and ultimate loads

ED Decision 2023/002/R

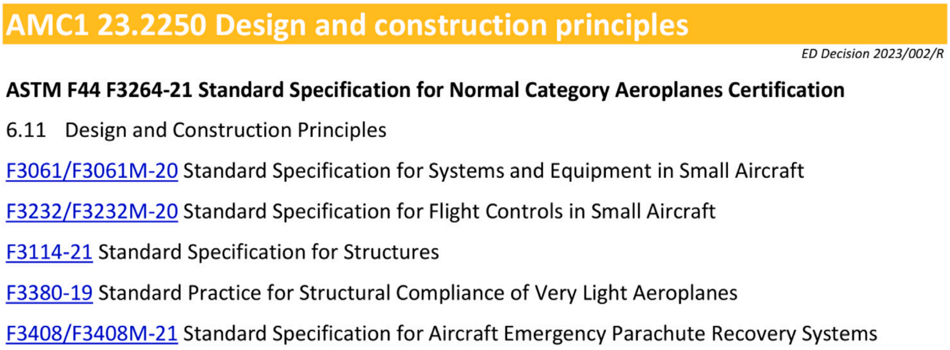
ASTM F44 F3264-21 Standard Specification for Normal Category Aeroplanes Certification

6.7 Limit and Ultimate Loads

F3114-21 Standard Specification for Structures

F3408/F3408M-21 Standard Specification for Aircraft Emergency Parachute Recovery Systems

Fig. 15. The figure presents AMC1 to CS 23.2230, *Limit and Ultimate Loads*, along with key reference documents supporting compliance with the corresponding EASA CS-23 requirement.



AMC1 23.2250 Design and construction principles

ED Decision 2023/002/R

ASTM F44 F3264-21 Standard Specification for Normal Category Aeroplanes Certification

6.11 Design and Construction Principles

F3061/F3061M-20 Standard Specification for Systems and Equipment in Small Aircraft

F3232/F3232M-20 Standard Specification for Flight Controls in Small Aircraft

F3114-21 Standard Specification for Structures

F3380-19 Standard Practice for Structural Compliance of Very Light Aeroplanes

F3408/F3408M-21 Standard Specification for Aircraft Emergency Parachute Recovery Systems

Fig. 16. The figure shows the CS 23.2250 *Design and Construction Principles* Acceptable Means of Compliance 1 (AMC1). The paragraph provides a list of documents useful to comply with the top-level EASA CS-23 requirement.

manufacturers, it is essential to manage aircraft- and certification-related information in a cohesive and timely manner in order to address certification tasks efficiently. Regulatory agencies, on the other hand, would benefit from version sequencing of issued regulations, including clear subdivisions by amendment. Such confinement and separation can be effectively achieved using a packaging logic analogous to well-established programming practices, wherein each amendment is stored in a separate folder to facilitate maintenance. Moreover, the editing of requirements and airworthiness rules would become immediate, with changes automatically propagating throughout the usage chain. As a result, this approach would enhance efficiency, responsiveness, and the timely correction of errors.

3.2. Reading phase

The digital SysML model, which encodes all certification rules within a UML file, can be programmatically accessed to extract data, constraints, numerical values, and formulas directly from the model. This process has been implemented in the MATLAB/Simulink programming environment. Fig. 17 illustrates the conceptual workflow, which is divided into distinct phases. The process begins with the UML file and generates a structured variable containing textual information that can be parsed using regular expressions.

The data extraction process converts this textual information into usable data, which is logically organized within a structured variable. This variable includes function handles, numerical values, units of

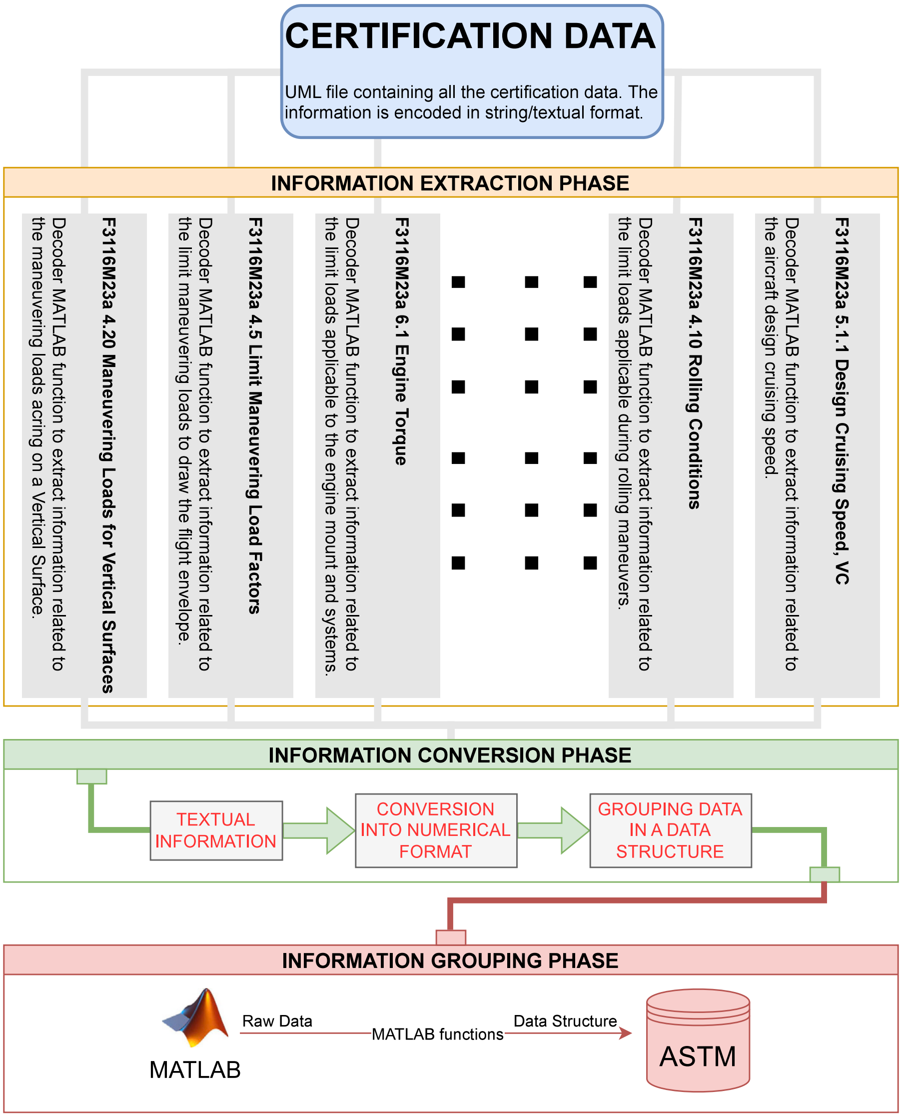


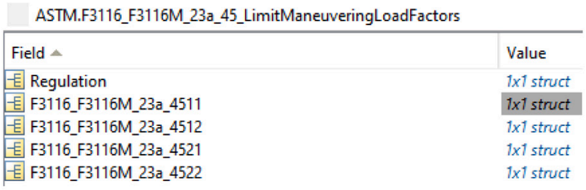
Fig. 17. The decoding and encoding phases involve extracting and analyzing UML data using MATLAB functions. Initially encoded as MATLAB strings, certification-relevant information is converted into numerical values or function handles, then structured into variables for further processing and analysis.

> 4.5 *Limit Maneuvering Load Factors:*
>
> 4.5.1 The positive limit maneuvering load factor n may not be less than:
>
> 4.5.1.1 $2.1+\frac{24{,}000}{W+10{,}000}$, where W = design maximum take-off weight (lb), except that n need not be more than 3.8;
>
> 4.5.1.2 6.0 for airplanes approved for aerobatics.
>
> 4.5.2 The negative limit maneuvering load factor may not be less than:
>
> 4.5.2.1 0.4 times the positive load factor;
>
> 4.5.2.2 0.5 times the positive load factor for airplanes approved for aerobatics.
>
> 4.5.3 Maneuvering load factors lower than those specified in this section may be used if the airplane has design features that make it impossible to exceed these values in flight.

Fig. 18. Excerpt from ASTM F3116/F3116M, *Standard Specification for Design Loads and Conditions*, detailing how applicants may define limit maneuvering loads based on design constraints and intended use. It focuses on both aerobatic and non-aerobatic aircraft.

measure, and supplementary textual content. Information regarding units of measure can be used to initialize validation procedures, ensuring that the code operates with consistent and accurate values—for example, forces expressed in newtons and masses in kilograms. The extracted textual information is subsequently used to complete the certification report by incorporating the relevant airworthiness rule text, with automatic references to the corresponding paragraphs or subparagraphs.

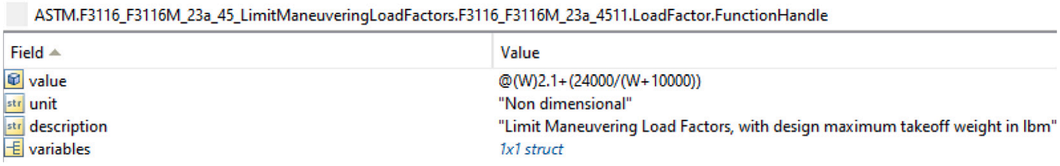
For example, Fig. 18 presents the airworthiness requirements used to construct the maneuvering flight envelope, applicable to CS-23 normal and aerobatic category aircraft. During the preliminary design phase, the maneuvering flight envelope defines the structural operational limits, enabling engineers to size both primary (critical) and secondary (non-critical) structural components with appropriate safety margins. This ensures structural integrity without exceeding weight constraints that could compromise the aircraft's in-flight performance. To initialize a function capable of automatically calculating both positive and negative limit maneuvering load factors — including those applicable to aerobatic and non-aerobatic configurations — a structured variable is used to store all relevant values. This variable also derives function handles based on the recommended calculation formula for positive limit maneuvering load factors.



ASTM.F3116_F3116M_23a_45_LimitManeuveringLoadFactors

Field	Value
Regulation	1x1 struct
F3116_F3116M_23a_4511	1x1 struct
F3116_F3116M_23a_4512	1x1 struct
F3116_F3116M_23a_4521	1x1 struct
F3116_F3116M_23a_4522	1x1 struct

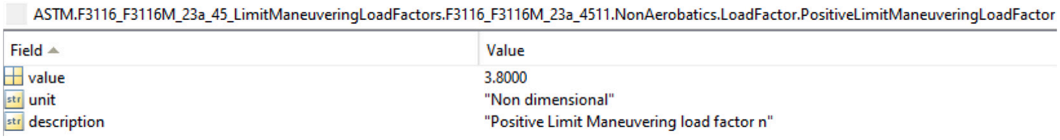
(a) *Paragraph and Subparagraphs ASTM structure*



ASTM.F3116_F3116M_23a_45_LimitManeuveringLoadFactors.F3116_F3116M_23a_4511.LoadFactor.FunctionHandle

Field	Value
value	@(W)2.1+(24000/(W+10000))
unit	"Non dimensional"
description	"Limit Maneuvering Load Factors, with design maximum takeoff weight in lbm"
variables	1x1 struct

(b) *Function handle automatically generated*



ASTM.F3116_F3116M_23a_45_LimitManeuveringLoadFactors.F3116_F3116M_23a_4511.NonAerobatics.LoadFactor.PositiveLimitManeuveringLoadFactor

Field	Value
value	3.8000
unit	"Non dimensional"
description	"Positive Limit Maneuvering load factor n"

(c) *Limit maneuvering load factor (numerical value)*

Fig. 19. A structured variable named `ASTM` illustrates the data collection process, with fields mirroring the hierarchy of F3116/F3116M, *Standard Specification for Design Loads and Conditions*. MATLAB functions generate function handles via string concatenation, and regular expressions extract numerical data, as shown in the final figure.

Fig. 19 illustrates how the MATLAB code encapsulates information within a structured variable to initialize flight load calculations and apply the relevant certification specifications. Fig. 19(a) shows how the code automatically and systematically arranges the structured variable to reflect the organization of the airworthiness rules, preserving the correspondence with the original regulatory text. Fig. 19(b) illustrates the capability to encapsulate formulas and mathematical expressions directly into MATLAB function handles. Finally, Fig. 19(c) demonstrates how numerical values embedded in the airworthiness rules are extracted as string variables and automatically converted into numerical values, ready for use in certification calculations. This structured variable remains continuously accessible, ensuring that all functions rely solely on the digital model. At the core of the MBSE logic is the digital representation of the airworthiness rules—the UML file. Consequently, any modifications to the UML file are automatically reflected in the certification calculations.

3.3. *Certification specifications phase*

3.3.1. *Subpart B phase*

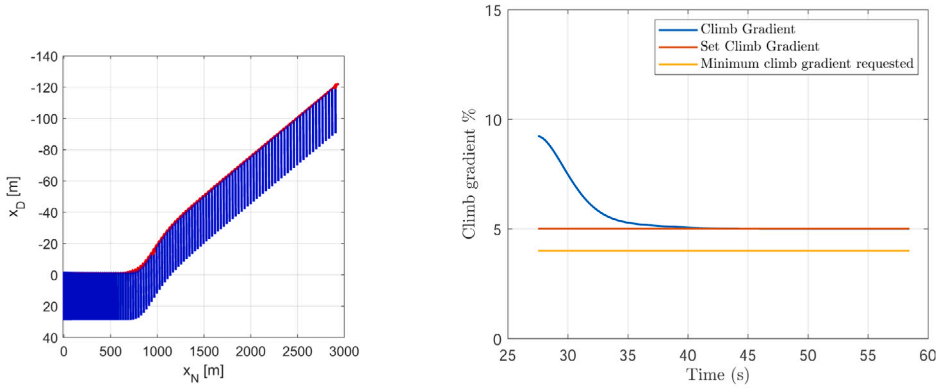
This subsection presents an example of the process applied to CS-23 Subpart B. Subpart B outlines the requirements related to flight characteristics and handling qualities, including stall behavior, controllability, maneuverability, and stability. For instance, Article CS 23.2120, *Climb Requirements*, specifies the certification criteria pertaining to climb performance. This article examines three maneuvers influenced by the aircraft's climb performance: climb with all engines operating, climb following a critical loss of thrust, and balked landing. The configurations for these flight tests are derived from ASTM document F3179/F3179M-20, *Standard Specification for Performance of Aircraft*. The results presented in this subsection are intended solely for illustrative purposes. It is important to emphasize that certification maneuvers conducted during an actual flight test program differ significantly in both execution and numerical outcomes from those reported in this study. The primary objective here is to demonstrate the capabilities of the digital certification framework using simulation data as a theoretical example.

As prescribed by the regulation, the all-engines-operating climb simulation is performed with takeoff power applied to each engine, landing gear extended, wing flaps set to the takeoff position, and a climb speed not less than the greater of $1.1 \cdot V_{MC}$ and $1.2 \cdot V_{S1}$, resulting in a minimum climb speed of $43.56\,\mathrm{m\,s^{-1}}$. The regulation requires demonstrating a steady climb gradient of at least 4.00% following takeoff. Fig. 20(a) presents the simulated climb trajectory, while Fig. 20(b) illustrates the corresponding climb gradient. The results confirm that the gradient stabilizes at approximately 5.00%, which exceeds the minimum requirement specified by the regulation. The second simulation models the climb following a critical loss of thrust. According to CS-23, a steady climb gradient of at least 1.00% must be demonstrated at an altitude of 122.00 m (400.00 ft) above the takeoff point. The test is conducted under the following conditions: one engine inoperative; the remaining engines operating at takeoff power; landing gear retracted; wing flaps in the takeoff position; and a climb speed equal to that achieved at an altitude of 15.00 m (50.00 ft). Fig. 20(c) displays the trajectory during the simulated loss-of-thrust scenario, while Fig. 20(d) confirms that the climb gradient meets the regulatory requirement.

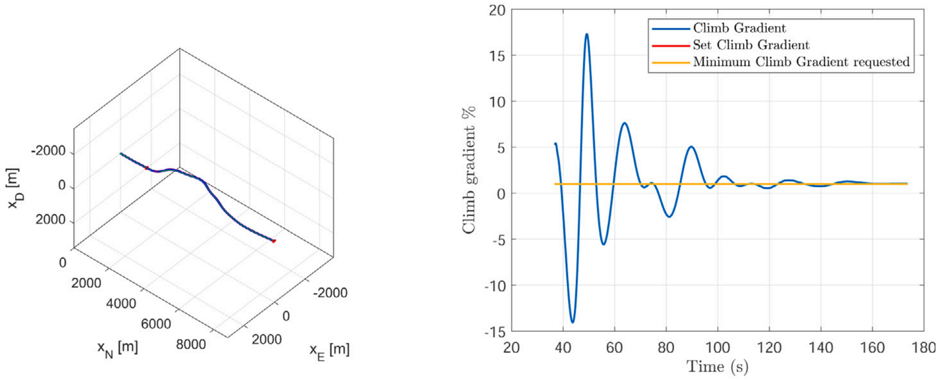
The final simulation concerning climb performance addresses the balked landing maneuver. In accordance with CS-23, a minimum climb gradient of 3.00% must be demonstrated. The test is conducted under the following conditions: for each engine, no more power than that available eight seconds after initiating movement of the power controls from the minimum flight idle position; landing gear extended; wing flaps in the landing position; and a climb speed equal to V_{REF}, appropriate for the given configuration. Fig. 20(e) presents the altitude profile during the balked landing maneuver, while Fig. 20(f) demonstrates that a climb gradient of 4.00% is achieved and maintained, thereby satisfying the CS-23 requirements. The simulations show compliance with all the requirements prescribed for the climb phase.

3.3.2. *Subpart C phase*

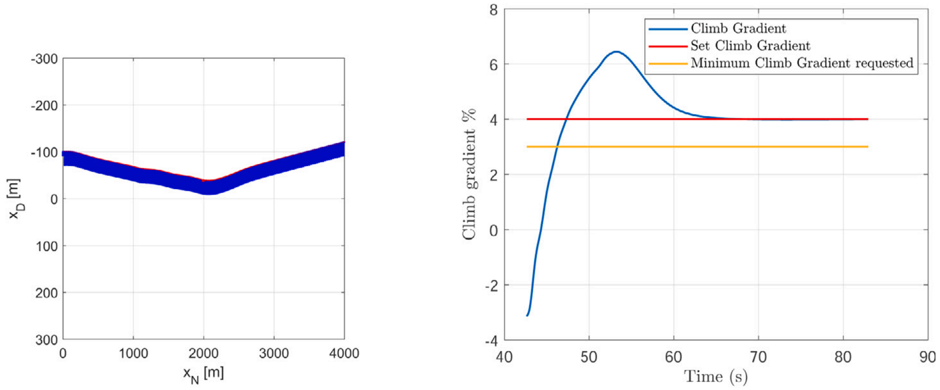
The purpose of this section is to summarize the process in its entirety, providing the reader with a clear and comprehensive understanding of the overall workflow. The Flight Loads Certification



(a) *Climb trajectory* (b) *Gradient of climb*



(c) *Loss of thrust trajectory* (d) *Gradient of climb during loss of thrust*

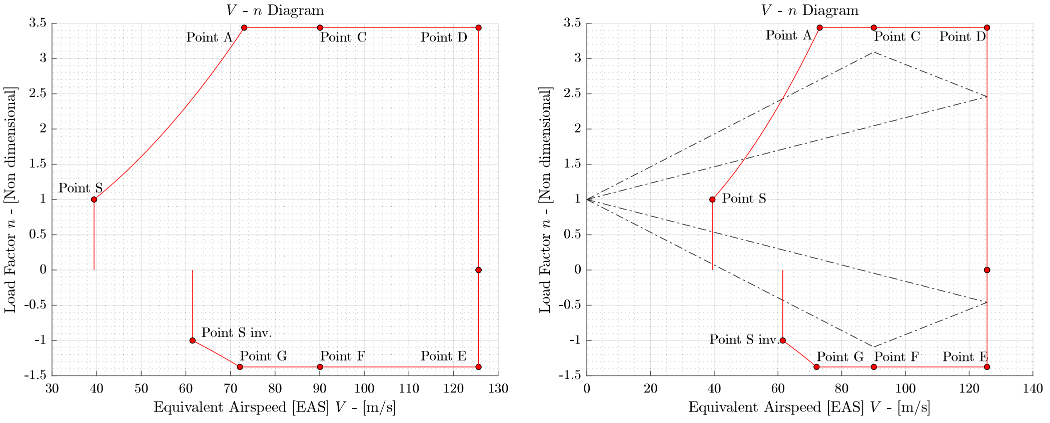


(e) *Balked landing trajectory* (f) *Gradient of climb during balked landing*

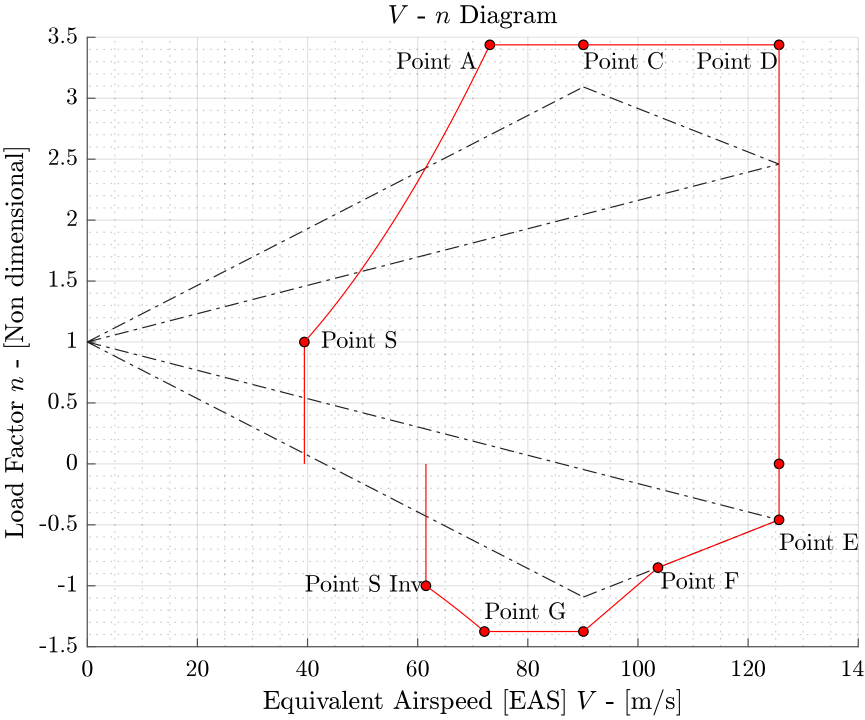
Fig. 20. Representation of selected results from the climb test simulations: Fig. 20(a) shows the altitude profile during a climb conducted under the conditions specified by the ASTM standard. Fig. 20(b) illustrates the corresponding climb gradient, which exceeds the minimum required value. Figs. 20(c) and 20(d) present the trajectory and climb gradient during a simulated loss-of-thrust scenario. Figs. 20(e) and 20(f) depict the altitude profile and climb gradient during a balked landing maneuver. Additionally, the blue lines beneath the trajectories in Figs. 20(a) and 20(e) represent ellipsoids used to aid in the three-dimensional visualization of the aircraft. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Report must include all necessary information to demonstrate compliance with CS-23/FAR 23 Subpart C, *Structure*. Aviation Regulatory Agencies require aircraft manufacturers to design aerostructures based on robust and well-founded assumptions, employing a consensus-based set of established practices and methodologies. Based on the low-level performance-based requirements outlined in the ASTM standards, engineering calculations demonstrate that the final product meets the necessary criteria for acceptability. CS-23, Amendment 6, applies to normal category aircraft with a passenger seating configuration of 19 or fewer and a maximum takeoff mass of 8618.00 kg (19000.00 lb) or less. This amendment introduces the concept of Aircraft Certification Levels. Applicants may select or negotiate the certification basis that best aligns with the intended TC. Table 4 presents the Certification Levels defined in CS-23, Amendment 6.

For example, ASTM F3116/F3116M, *Standard Specification for Design Loads and Conditions*, defines how applicants should establish limit loads for design purposes. It also provides constraints on the applicability of calculation results when addressing unconventional design



(a) *Example of Flight Envelope* (b) *Example of Flight Envelope with Gust Lines*



(c) *Maneuvering and Gust Flight Envelope*

Fig. 21. Flight Envelope for a Level 4 aircraft, according to ASTM Acceptable Means of Compliance. This article focuses on the concept of digital certification using an MBSE approach. The example provided here illustrates the flexibility of the methodology and represents one comprehensive application.

Table 4
Aircraft certification levels, according to CS-23, Amendment 5, or later.

Aircraft certification level	Number of passengers
Level 1	From 0 to 1 passengers
Level 2	From 2 to 6 passengers
Level 3	From 7 to 9 passengers
Level 4	From 10 to 19 passengers

features—such as tandem wing configurations or canards. These guidelines apply to any aircraft within the normal category. Applicants pursuing a Level 1 or Level 2 TC may refer to additional ASTM documents, such as F3396/F3396M, *Standard Practice for Aircraft Simplified Loads Criteria*, which outlines less demanding requirements. Furthermore, two additional aircraft categorizations assist applicants in selecting the appropriate set of requirements:

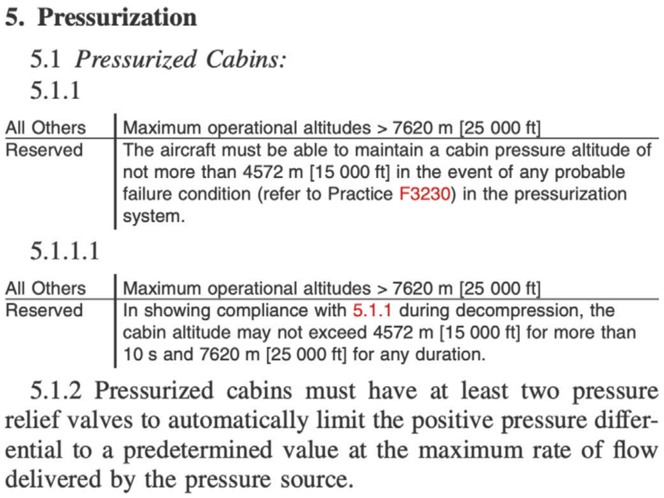
1. **Aircraft Performance Levels**, with the following criteria:
    - *Low-Speed Aircraft* refers to aircraft with a maximum structural cruising speed (or maximum speed for *normal operations*) V_{NO}, or a maximum operating limit speed V_{MO}, less than or equal to 250.00 kn *calibrated airspeed* (KCAS), or a maximum operating limit Mach number M_{MO} less than or equal to 0.6. It is important to note that exceeding the limit load factor at or above these speed thresholds may result in permanent structural damage to the airframe.
    - *High-Speed Aircraft*, for aircraft with V_{NO} or V_{MO} greater than 250.00 kn *calibrated airspeed* or M_{MO} greater than 0.6.
2. **Aircraft Maneuvering Limitations**, resulting in aircraft approved or not approved for Aerobatics, and specifically:
    - Aircraft not certified for aerobatics may be used to perform any maneuver incidental to normal flight, including stalls

(excluding whip stalls), lazy eights, chandelles, and steep turns, provided that the angle of bank does not exceed 60.00°.

- Aircraft certified for aerobatics may perform maneuvers without restriction, except as limited by the provisions established under CS-23 Subpart G, *Flight Crew Interface and Other Information*.

Applicants may utilize the simplified loads criteria outlined in F3396/F3396M, *Standard Practice for Aircraft Simplified Loads Criteria*, or F3409-19e1, *Standard Practice for Simplified Aircraft Loads Determination*, provided that the new aircraft design falls within the specified design limitations. Additional ASTM documents address specific operational loading conditions that are infrequently considered in the certification of normal category aircraft. For example, water loads are covered in F3331-18(2023), *Standard Practice for Aircraft Water Loads*. It is important to note that the documents cited in this paragraph highlight the potential inconsistency within the approved certification documentation framework. While this system offers applicants considerable flexibility in negotiating an appropriate certification pathway with regulatory authorities, the extensive and often fragmented nature of the documentation currently adopted by EASA can be overwhelming—particularly for small aircraft manufacturers. The resulting certification process is highly complex and can pose significant challenges on the path to obtaining a TC (Kurri, 2020). The current regulatory framework tends to disadvantage small aircraft manufacturers, while primarily benefiting larger organizations that possess greater influence in shaping industry consensus standards (Joosen et al., 2022). The content and structure of consensus standard materials have evolved compared to previously accepted documentation, which can introduce challenges and delays in the certification process. These changes often result in increased costs and extended time to market (Di Camillo, 2024). Specifically, aeronautical firms are likely to face an increased need for detailed upfront planning in the development of the *Project Specific Certification Plan* (PSCP). Additionally, the *TC Data Sheet* (TCDS) will likely include only high-level requirements, consistent with the structure of the EASA CS-23 Easy Access documents. Furthermore, post-certification modifications may prove challenging, as obtaining approval for changes after the issuance of the complete TC is expected to be a cumbersome process. For larger-scale projects, such as commercial aircraft certified under CS-25, the administrative burden is expected to increase over time due to safety enhancement directives issued by Regulatory Agencies (Correia, 2020; Lercel et al., 2024). A similar trend may also apply to emerging unmanned systems, which are subject to certification under the current regulatory framework (Kasprzyk, 2022). From the perspective of an aircraft manufacturer, digital certification offers some advantages, including more efficient management and tracking of requirements, certification inputs and outputs, and other related artifacts (Xanala, 2023).

This section illustrates and explains several applications of digital certification through computational methods, using examples drawn from EASA CS-23, Amendment 6, Subpart C, *Structures*. It is important to note that the outcome of this process is a collection of certification artifacts, which are automatically compiled and inserted into the final certification report. Fig. 21 illustrates one of the certification artifacts generated by the digital framework. Fig. 21(a) shows the Maneuvering Flight Envelope for a normal category aircraft, certifiable under the EASA CS-23 airworthiness regulations. Fig. 21(b) shows the same Flight Envelope with gust lines superimposed. Finally, Fig. 21(c) represents the actual Final Envelope, considering maneuvering and gust limit load factors. The diagrams are automatically drawn with MATLAB functions that accept Input data from the aircraft geometry, aerodynamics, and the applicable digital regulations. The code adapts to the kind of aircraft analyzed and discriminates which certification and airworthiness rules apply to the considered aircraft. Flight envelope diagrams are essential components of the certification workflow. However, in this article, they are presented solely as an example of the framework's adaptability. The digital process supports verification and validation procedures under Subpart B, structural calculations under Subpart C, and compliance checks related to powerplant, systems, and subsystems under Subparts E and F. It automatically identifies the applicable certification specifications and corresponding means of compliance.



5. Pressurization

5.1 *Pressurized Cabins:*

5.1.1

All Others	Maximum operational altitudes > 7620 m [25 000 ft]
Reserved	The aircraft must be able to maintain a cabin pressure altitude of not more than 4572 m [15 000 ft] in the event of any probable failure condition (refer to Practice F3230) in the pressurization system.

5.1.1.1

All Others	Maximum operational altitudes > 7620 m [25 000 ft]
Reserved	In showing compliance with 5.1.1 during decompression, the cabin altitude may not exceed 4572 m [15 000 ft] for more than 10 s and 7620 m [25 000 ft] for any duration.

5.1.2 Pressurized cabins must have at least two pressure relief valves to automatically limit the positive pressure differential to a predetermined value at the maximum rate of flow delivered by the pressure source.

Fig. 22. ASTM F3227/F3227-25 *Standard Specification for Environmental Systems in Aircraft*, paragraph 5. Pressurization, subparagraph 5.1 Pressurized Cabins.

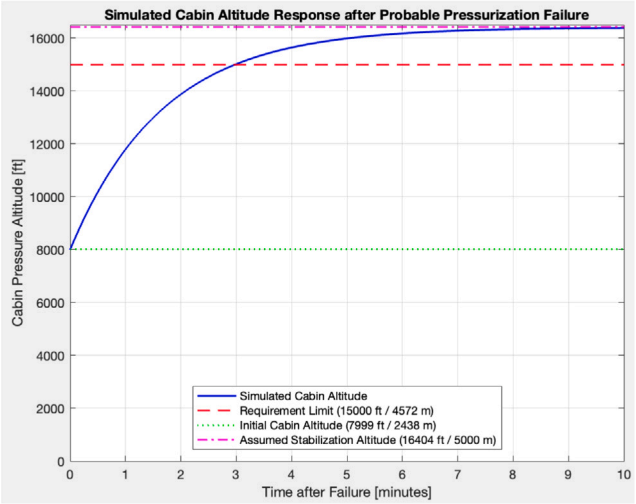
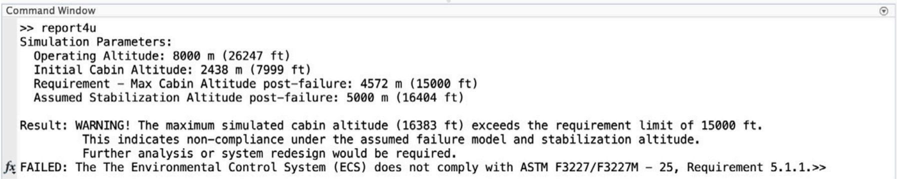


Fig. 23. The MATLAB code produces a graph to show the simulated cabin response after a pressurization failure. In this case, the cabin failed to comply with the ASTM-prescribed limitations.

3.3.3. *Subpart F phase*

This subsection presents an additional example drawn from Subpart F, aiming to provide a comprehensive overview of the aircraft certification process in accordance with ASTM International's performance-based requirements. The example is based on ASTM F3227/F3227-25, *Standard Specification for Environmental Systems in Aircraft*, specifically subparagraph 5.1.1. Fig. 22 presents an excerpt from the ASTM document referenced above. Following the reading phase, the MATLAB code performs the necessary checks to verify the cabin pressurization system. These checks include parameters such as *Remaining Inflow Capacity*, *Effective Leak Area*, *Maximum Operational Altitude*, *Cabin Volume*, among others.



```
>> report4u
Simulation Parameters:
  Operating Altitude: 8000 m (26247 ft)
  Initial Cabin Altitude: 2438 m (7999 ft)
  Requirement - Max Cabin Altitude post-failure: 4572 m (15000 ft)
  Assumed Stabilization Altitude post-failure: 5000 m (16404 ft)

Result: WARNING! The maximum simulated cabin altitude (16383 ft) exceeds the requirement limit of 15000 ft.
         This indicates non-compliance under the assumed failure model and stabilization altitude.
         Further analysis or system redesign would be required.
fx FAILED: The The Environmental Control System (ECS) does not comply with ASTM F3227/F3227M - 25, Requirement 5.1.1.>>
```

Fig. 24. The MATLAB code textual output, used as a check during its execution. This is the output associated with Fig. 23.

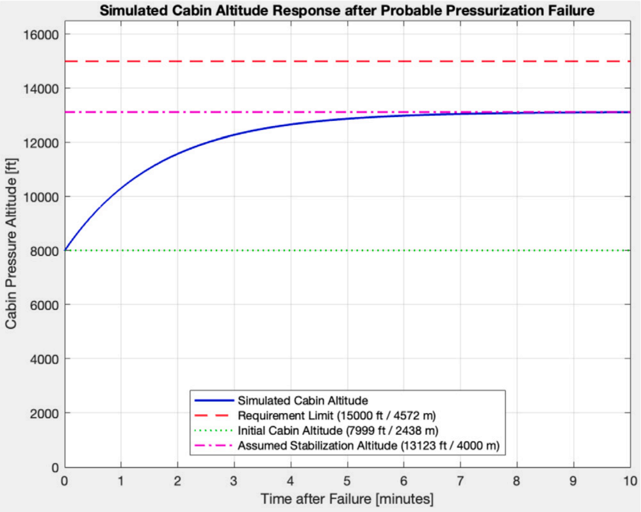


Fig. 25. The MATLAB code produces a graph to show the Simulated Cabin Response after a pressurization failure. In this case, the cabin complies with the ASTM-prescribed limitations.

The code simulates the cabin pressure altitude response under a representative probable failure scenario. The resulting data are collected and evaluated against the applicable requirements to determine whether compliance is achieved. Figs. 23 and 24 present the results of the loss-of-cabin-pressure simulation for a noncompliant configuration, as defined by the ASTM means of compliance. In contrast, Figs. 25 and 26 illustrate the simulation output for a configuration that meets the compliance standards. During execution, the MATLAB code also prints the output to the command window, and this information can be saved to a log file for further analysis.

3.4. Report generation phase

The execution of the MBSE digital certification framework generates data that must be utilized to produce certification artifacts. The most basic form of such an artifact may consist of a Microsoft Excel file — or a comparable digital format, such as a CSV file — containing numerical data. To demonstrate compliance with EASA requirements, the applicant for a new TC must submit various types of certification items and artifacts, including diagrams, documents, and, in some cases, videos. In many instances, it is sufficient to provide accurate and comprehensive documentation of the tests conducted by the applicant.

This section presents the primary output of the digital certification framework: the certification report. For illustrative purposes, only selected excerpts from the EASA CS-23, Subpart C certification report are included.

The first excerpt from the generated report is presented in Fig. 27. As previously noted, the report includes the requirements, the corresponding results, the textual content of the requirements, and a clear indication that the test has been successfully passed. Fig. 28 presents a single page from the automatically generated Flight Loads certification report. Each numerical datum — in this case, design airspeeds — is automatically incorporated into the equations or tables within the report. After the document is generated, the user retains the ability to edit its contents, including the addition or removal of items.

Commercial software implementing MBSE methodologies or adopting the SysML language typically includes embedded report wizards that generate documents from selected portions of the digital model created within their environments. Accordingly, this feature has been incorporated into the MBSE digital certification framework described in this work. The need for efficient, accurate, and rapid document generation will be among the most critical features for the successful adoption of MBSE techniques in practical contexts, where not all stakeholders possess the same level of proficiency with these tools. Lastly, emerging technologies demand more extensive investigation and an integrated, multidisciplinary analytical approach typical of MBSE methodologies. Compared to traditional document-based workflows, the report generated by the digital certification framework presented in this article automatically includes all necessary cross-references to demonstrate compliance with EASA CS-23 requirements, thereby relieving certification personnel from performing these cross-referencing tasks manually.

4. Conclusions and future works

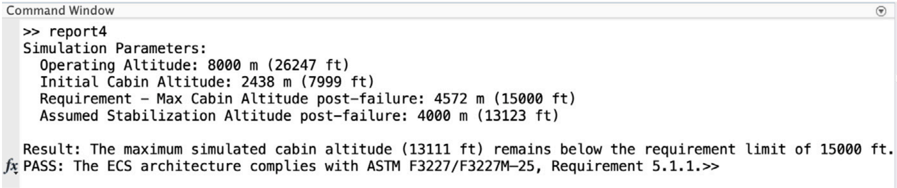
4.1. Conclusions

Within the proposed MBSE framework, a regulatory model encompassing requirements, consensus standards, their interrelationships, and annotations with metadata properties is created, offering flexibility and adaptability for future regulatory artifacts updates. The MBSE digital certification framework presented in this study is designed to reduce the costs associated with the certification process by narrowing the scope and extent of ground and flight testing programs and by integrating simulation tools into the certification loop. Moreover, the use of simulation-based analysis as an acceptable MoC enables the execution of V&V activities before formal certification testing.

Structured data archives are adopted to create certification reports that comply with regulatory requirements. This capability can also benefit EASA by reducing the number of iterations required with applicants, thus streamlining the certification process. The automatic generation of certification artifacts for the certification plan — based on aircraft category — the traceability of specifications and MoCs, and the automated compliance checklist for all CS-23 subparts enabled by simulation capabilities, represents one of the advantages of adopting the proposed MBSE techniques.

Moreover, technology and market demand are evolving more rapidly than in previous years. To navigate this increasingly dynamic environment, it is essential to develop and implement effective strategies that address the complexities associated with the introduction of advanced aircraft concepts, novel design architectures, and expanded flight envelope capabilities and operational limitations. The MBSE framework proposed in this study is designed to adapt to and encompass all the characteristics necessary to determine whether an unconventional aircraft is certifiable.

The SysML model can be expanded at will by the user, incorporating all airworthiness provisions introduced by aviation authorities in the coming years to ensure that these new aircraft models maintain an



```
>> report4
Simulation Parameters:
  Operating Altitude: 8000 m (26247 ft)
  Initial Cabin Altitude: 2438 m (7999 ft)
  Requirement - Max Cabin Altitude post-failure: 4572 m (15000 ft)
  Assumed Stabilization Altitude post-failure: 4000 m (13123 ft)

Result: The maximum simulated cabin altitude (13111 ft) remains below the requirement limit of 15000 ft.
PASS: The ECS architecture complies with ASTM F3227/F3227M-25, Requirement 5.1.1.>>
```

Fig. 26. The MATLAB code textual output, used as a check during its execution. This is the output associated with Fig. 25.

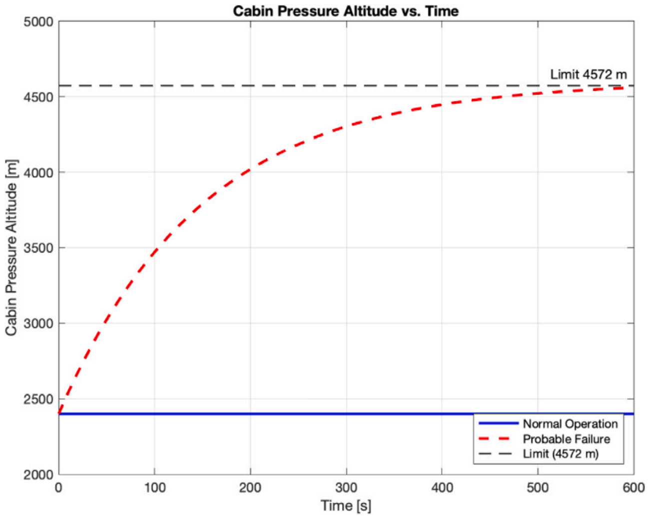


Fig. 27. The MATLAB generated certification report, EASA CS-23 Subpart F.

aviation-rated level of safety under normal operating conditions—an indispensable feature. Methodologies and computational routines will be continuously refined to accommodate evolving requirements and needs, according to simulation and calculation perspectives. This approach aligns with the concept of externally managing the digital certification framework, under the direct supervision and active collaboration of the design organization and the relevant aviation authority overseeing the certification process.

Optimal implementation would require close collaboration between manufacturers and regulators within a secure, potentially cloud-based, digital environment. Shared tools would enable real-time updates to certification artifacts, improving efficiency and responsiveness. However, widespread adoption remains limited due to persistent skepticism within the aviation community regarding fully integrated digital certification ecosystems.

The authors emphasize the need for a blended approach, introducing MBSE tools and methodologies without fully eliminating traditional documentation. A complete transition to MBSE would require a paradigm shift by regulatory agencies, including the issuance of airworthiness specifications and consensus standards as digital models. The forthcoming SysML v2 standard, to be released by OMG, may represent a significant advancement—particularly when integrated with AI-enabled commercial tools that leverage the scripting capabilities of the underlying KerML language. *Dassault Systèmes* will introduce an AI companion in the next iteration of the software, which, combined with the new features of SysML v2 will further enhance the user experience.

4.2. Future works

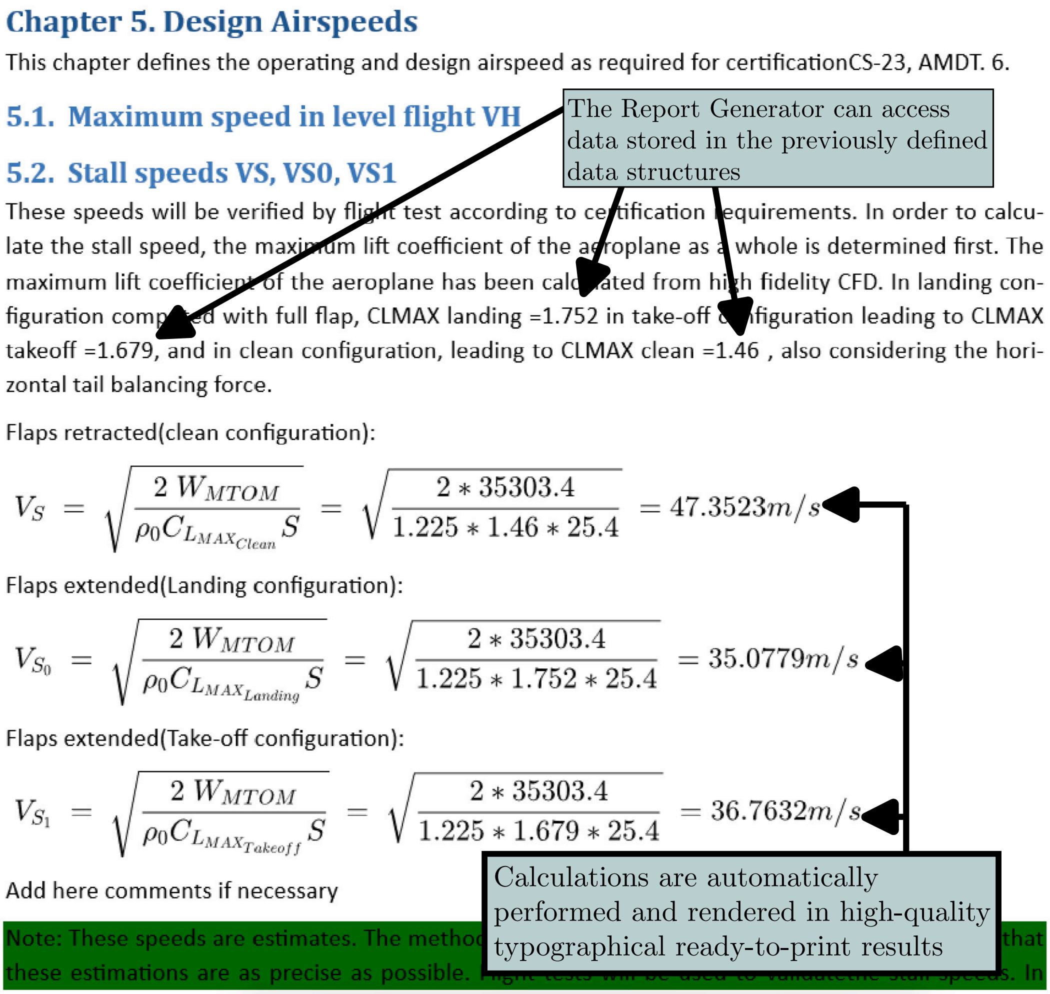
Experience suggests that the principal advantages of the methodologies presented in this work are as follows:

1. With sufficient time and financial resources, the digital certification framework can be flexibly expanded to encompass a wide range of aeronautical applications.
2. The integrated approach enhances overall efficiency by facilitating a continuous exchange of information among stakeholders involved in the certification process.
3. Any modifications or updates to the model are automatically propagated throughout the framework.
4. Containment and version control are straightforward, enabling the development of a controlled environment in which the applicant and Regulatory Agencies can collaborate using the selected certification basis from the outset of the certification process.
5. Technical reports and other certification artifacts are automatically generated as outputs of the digital framework.

These factors must be examined through rigorous implementation and testing, ideally via pilot projects conducted by aeronautical design organizations applying the digital certification workflow in practical settings. Key performance indicators (KPIs) should be defined and systematically applied to collect and analyze the perspectives and preferences of stakeholders in the aviation industry. The digital certification framework proposed in this study can be further improved through the development of a user interface decoupled from the underlying UML model, thereby reducing the costs associated with implementing the MBSE approach to certification.

The SysML model of the EASA certification specifications and ASTM substantiation requirements can be significantly improved by introducing a consistent set of stereotypes to represent the structure of the regulation within the modeling context. These stereotypes would be applied to the SysML *Block* element, enabling the construction of block definition diagrams (BDDs) that represent CS-23 and ASTM paragraphs and subparagraphs. Such a model would be richer in features and broader in scope. However, the modeling effort and the number of working hours required would increase substantially. Within the Eclipse Papyrus modeling environment, the SysML model proposed in this work employs the simpler SysML *Requirement* element due to time constraints. Nonetheless, the model includes nearly all relevant ASTM standards. Furthermore, it could be expanded to incorporate additional consensus standard documents, enabling the comparison of different substantiation methods and certification bases.

Regardless of the modeling strategy employed, it is possible to incorporate extensive certification information within the CS or ASTM stereotypes. Due to time constraints, the capabilities of SysML were not fully utilized, leading to the development of a MATLAB decoding routine that is less stable than what is currently technically feasible. Consequently, if the CS or ASTM requirements change substantially, the code may fail to interpret them reliably. Although the so-called *silent failure* is currently prevented by a built-in error-handling mechanism, this limitation remains inherent to both the SysML model and the code. This further underscores the importance of focusing on the modeling phase, as the quality of the model significantly influences the components of the digital certification framework that operate on it. The issues described in this paragraph can be solved by adopting commercial suites, such as *Dassault Systèmes* CATIA *Magic Systems of Systems Architect* (MSoSA). Although acquisition costs may be prohibitive, the benefits of using such a powerful tool are evident, particularly given that CATIA MSoSA is built around an efficient and effective collaborative, cloud-based environment. The concerns raised in this work regarding M2T transformations for sharing model-encoded information



Chapter 5. Design Airspeeds

This chapter defines the operating and design airspeed as required for certificationCS-23, AMDT. 6.

5.1. Maximum speed in level flight VH

5.2. Stall speeds VS, VS0, VS1

These speeds will be verified by flight test according to certification requirements. In order to calculate the stall speed, the maximum lift coefficient of the aeroplane as a whole is determined first. The maximum lift coefficient of the aeroplane has been calculated from high fidelity CFD. In landing configuration computed with full flap, CLMAX landing =1.752 in take-off configuration leading to CLMAX takeoff =1.679, and in clean configuration, leading to CLMAX clean =1.46 , also considering the horizontal tail balancing force.

Flaps retracted(clean configuration):

$$V_S = \sqrt{\frac{2\,W_{MTOM}}{\rho_0 C_{L_{MAX_{Clean}}} S}} = \sqrt{\frac{2 * 35303.4}{1.225 * 1.46 * 25.4}} = 47.3523m/s$$

Flaps extended(Landing configuration):

$$V_{S_0} = \sqrt{\frac{2\,W_{MTOM}}{\rho_0 C_{L_{MAX_{Landing}}} S}} = \sqrt{\frac{2 * 35303.4}{1.225 * 1.752 * 25.4}} = 35.0779m/s$$

Flaps extended(Take-off configuration):

$$V_{S_1} = \sqrt{\frac{2\,W_{MTOM}}{\rho_0 C_{L_{MAX_{Takeoff}}} S}} = \sqrt{\frac{2 * 35303.4}{1.225 * 1.679 * 25.4}} = 36.7632m/s$$

Add here comments if necessary

Note: These speeds are estimates. The metho that these estimations are as precise as possible. s. In

The Report Generator can access data stored in the previously defined data structures

Calculations are automatically performed and rendered in high-quality typographical ready-to-print results

Fig. 28. The MATLAB-generated certification report, EASA CS-23 Subpart C.

would be considerably mitigated by the capabilities available in CATIA MSoSA.

This study underscores the need to reassess the current certification landscape. The MBSE methodologies and approaches discussed herein have the potential to transform the way aeronautical firms and Regulatory Agencies manage the complex process of issuing new TCs for newly designed aircraft. The aeronautical industry stands to benefit from the adoption of new, lean, and efficient approaches that employ integrated tools to reduce the costs and labor hours associated with certification activities.

As shown in Section 3.1, the regulatory framework introduced by EASA since Amendment 5 may contain inconsistent links between high-level requirements and their corresponding AMCs. This inconsistency can hinder or delay the certification process, particularly when applying for a new TC. The MBSE techniques presented in this work address this issue systematically by constructing a series of requirement diagrams that graphically represent all connections between each CS-23 paragraph and the corresponding ASTM International documents, down to the paragraph and subparagraph level.

Using the SysML model, the applicant can immediately identify all the substantiation methods necessary to demonstrate compliance with high-level requirements. This discussion underscores the importance of coherence and consistency in certification information, ensuring that all stakeholders share a common understanding of certification progress.

Future work will further investigate these issues, introducing tools and capabilities to prevent, identify, and ultimately resolve individual inconsistencies within the currently active regulatory landscape. In this context, the adoption of new digital tools to manage and sustain the certification infrastructure over time appears both necessary and advisable.

Overall, the outlook for adopting MBSE methodologies in this field is promising. Such adoption is expected to positively influence industry performance by increasing the potential for introducing novel and unconventional flying vehicle architectures, even among small aeronautical manufacturers.

However, the airworthiness regulations applicable to these new designs continue to raise unresolved questions that necessitate negotiation among industry stakeholders. The authors of this work aim to further investigate the complexities associated with introducing new regulations for unconventional designs. Building on the tools and techniques developed and illustrated in this study, future efforts will focus on modeling new requirements applicable to emerging technologies, while ensuring the minimum safety level necessary for operating a flying vehicle.

CRediT authorship contribution statement

Pierluigi Della Vecchia: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Claudio Mirabella:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michele Tuccillo:** Writing – review & editing, Visualization, Validation, Software, Data curation, Conceptualization. **Carlo Emanuele Riboldi:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Marco Fioriti:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization. **Fixherald Shahini:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Francesca Roncolini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Claudio Mirabella reports that financial support was provided by Ministry of University and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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