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A MODEL-BASED TRACEABILITY PROCESS FOR AEROSPACE CERTIFICATION

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A MODEL-BASED TRACEABILITY PROCESS FOR AEROSPACE CERTIFICATION

Daniel Rondon Pleffken

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I dedicate this work to my Lord Jesus Christ, my wife Gabriela, and my children.

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"Teach us to number our days, that we may gain a heart of wisdom."

Psalm 90:12

Resumo

A evolução acelerada dos sistemas aeronáuticos, aliada à fragmentação regulatória, impõe desafios expressivos aos processos de certificação, que exigem verificação e validação rigorosas para garantir a conformidade e a segurança. A ausência de um modelo estruturado que conecte de forma transparente os requisitos regulatórios às evidências de atendimento enfraquece a rastreabilidade, prejudica a padronização e dificulta auditorias eficazes. Para enfrentar esses obstáculos, esta tese propõe um processo de rastreabilidade regulatória baseado em modelos, estruturado segundo o paradigma Design Science Research (DSR) e fundamentado nos princípios do Model-Based Systems Engineering (MBSE). Através de uma Revisão Sistemática da Literatura (PRISMA), foram analisados os processos de certificação, revelando lacunas metodológicas e a necessidade de harmonização normativa. Com base nesses achados, desenvolveu-se um modelo estruturado em SysML voltado à rastreabilidade regulatória, integrando requisitos, artefatos de verificação e fluxos de conformidade. Além disso, explora-se o conceito de rastreabilidade, contribuindo para a gestão continuada em ambientes digitais. Foi conduzido um estudo de caso exploratório e simulado envolvendo a certificação de uma aeronave eVTOL, evidenciando benefícios em termos de clareza conceitual e alinhamento com estruturas compatíveis com fluxos digitais de verificação. A solução proposta é potencialmente adaptável a diferentes domínios regulatórios, oferecendo a fabricantes e autoridades uma abordagem digital para rastreabilidade que melhora a transparência na certificação. Assim, esta pesquisa contribui para o avanço das metodologias de certificação, promovendo interoperabilidade normativa, verificação contínua e transformação digital.

Abstract

The accelerated evolution of aeronautical systems, combined with regulatory fragmentation, poses significant challenges to certification processes, which demand rigorous verification and validation to ensure compliance and safety. The absence of a structured model that transparently connects regulatory requirements to compliance evidence weakens traceability, undermines standardization, and hinders the effectiveness of audits. To address these challenges, this thesis proposes a model-based regulatory traceability process, structured according to the Design Science Research (DSR) paradigm and grounded in the principles of Model-Based Systems Engineering (MBSE). A Systematic Literature Review (PRISMA) was conducted to analyze the certification process, revealing methodological gaps and a pressing need for regulatory harmonization. Based on these findings, a SysML-based traceability model was developed to integrate requirements, verification artifacts, and compliance workflows. Furthermore, the research explores the conceptual foundations of traceability, contributing to the ongoing management of certification data in digital environments. An exploratory and simulated case study involving the certification of an eVTOL aircraft was carried out, demonstrating the benefits of the proposed process in terms of conceptual clarity and alignment with structures compatible with digital verification flows. The proposed solution is potentially adaptable to multiple regulatory domains, offering manufacturers and authorities a digital traceability approach that enhances transparency in certification. Thus, this research contributes to the advancement of certification methodologies by promoting regulatory interoperability, continuous verification, and digital transformation.

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List of Abbreviations and Acronyms

14 CFR	Title 14 of the Code of Federal Regulations
ACM	Acceptable Means of Compliance
AD	Airworthiness Directive
AEG	Aircraft Evaluation Group
AFHA	Aircraft Functional Hazard Assessment
AI	Artificial Intelligence
AIs	Action Items
ALM	Application Lifecycle Management
ANAC	National Civil Aviation Agency
AoA	Angle-of-Attack
ARC	Airworthiness Review Certificate
ARP	Aerospace Recommended Practices
ASA	Aircraft Safety Assessment
ASILs	Automotive Safety Integrity Levels
ATC	Additional Technical Condition
AVS	Aviation Safety
BASA	Bilateral Aviation Safety Agreement
BS	Build Strategy
CAA	Civil Aviation Authority
CAAC	Civil Aviation Administration of China
CAMO	Continuing Airworthiness Management Organization
CAMP	Continuous Airworthiness Maintenance Program
CASA	Civil Aviation Safety Authority
CASS	Continuous Analysis and Surveillance System

CB	Certification Basis
CCA	Common Cause Analysis
CCL	Compliance Checklist
CM	Certification Manager
CRI	Certification Review Items
CRM	Crew Resource Management
CS	Certification Specifications
CPI	Certification Process Improvement
CRL	Certification Readiness Level
CVR	Cockpit Voice Recorders
CVE	Certification Verification Engineer
DAL	Design Assurance Level
DAS	Design Assurance System
DER	Designated Engineering Representative
DIGACE	Digital Innovative General Aviation Certification Environment
DOA	Design Organization Approval
DSR	Design Science Research
EASA	European Union Aviation Safety Agency
EMAR	European Military Airworthiness Requirement
ELOS	Equivalent Level of Safety
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FDR	Flight Data Recorders
FHA	Functional Hazard Assessment

FTFR	Fuel Tank Flammability Reduction
GM	Guidance Material
GTF	Geared Turbofan
HLR	High-Level Software Requirement
ICA	Instructions for Continued Airworthiness
ICAN	International Commission for Air Navigation
ICAO	International Civil Aviation Organization
IFI	Industrial Development and Coordination
IFR	Instrument Flight Rules
JAA	Joint Aviation Authorities
LA	Logical Architecture
LLRs	Low-Level Requirements
LoI	Level of Involvement
MBSA	Model-Based Safety Assessment
MBSE	Model-Based Systems Engineering
MCAS	Maneuvering Characteristics Augmentation System
MoCs	Means of Compliance
NAA	National Aviation Authorities
NLP	Natural Language Processing
OA	Operational Analysis
ODA	Organization Designation Authorization
OEMs	Original Equipment Manufacturers
OMG	Object Management Group
OPs	Overarching Properties
PA	Physical Architecture

PASA	Preliminary Aircraft Safety Assessment
PCM	Project Certification Manager
PSSA	Preliminary System Safety Assessment
PSCP	Project Specific Certification Plan
PSP	Partnership for Safety Plan
RM	Requirements Management
RPAS	Remotely Piloted Aircraft Systems
SARPs	International Standards and Recommended Practices
SA	System Needs Analysis
SC	Special Condition
SE	Systems Engineering
SEI	Safety Emphasis Item
SFAR	Special Federal Aviation Regulation
SFHA	System Functional Hazard Assessment
SSA	System Safety Assessment
SSD	Significant Standards Difference
STANAGs	Standardization Agreements
STC	Supplemental Type Certificate
STCP	Supplemental Type Certification Procedure
STPA	System-Theoretic Process Analysis
TCAA	Transport Canada Civil Aviation
TC	Type Certificates
TCDS	Type Certificate Data Sheet
TCH	Type Certificate Holder
TIA	Type Inspection Authorization

TIP	Technical Implementation Procedures
ToR	Terms of Reference
UAM	Urban Air Mobility
UPRT	Upset Prevention and Recovery Training
VFR	Visual Flight Rules

Contents

1 Introduction

Recent technological advances have introduced structural changes in the aerospace industry. While these technological innovations expand development possibilities, they also introduce challenges in certification processes, regulatory compliance, and traceability of artifacts that demonstrate requirements fulfillment. As systems become more complex, traditional document-based approaches struggle to maintain consistent and auditable compliance records throughout the product lifecycle.

A critical case that highlights these vulnerabilities is the Boeing 737 MAX crisis. Following two fatal accidents, investigations identified systemic failures in the certification process, primarily related to the absence of a structured traceability system. Effective traceability process establishes direct connections between regulatory requirements and corresponding technical documentation, such as design artifacts, test results, and operational procedures. The lack of this explicit connection among regulatory requirements, technical documentation, and Federal Aviation Administration (FAA) oversight prolonged the recertification process for nearly 20 months, underscoring the cost of inadequate regulatory oversight in both economic and operational terms, and highlighting the limitations of document-based compliance models (U.S. Government Accountability Office, 2020; NTSB, 2020; House of Representatives, 2020).

Model-Based Systems Engineering (MBSE) has emerged as a methodology. Unlike traditional approaches, which disperse information across multiple documents and formats, MBSE is based on a consolidated digital model that serves as a single authoritative reference throughout the entire development process. This strategy significantly enhances traceability, ensuring that requirements, design elements, and verification activities remain interconnected improving auditable (Kaslow *et al.*, 2017). Figure 1.1 illustrates this transition, showing how MBSE consolidates previously fragmented information into a cohesive digital environment (Ackva; Tschirner, 2015).

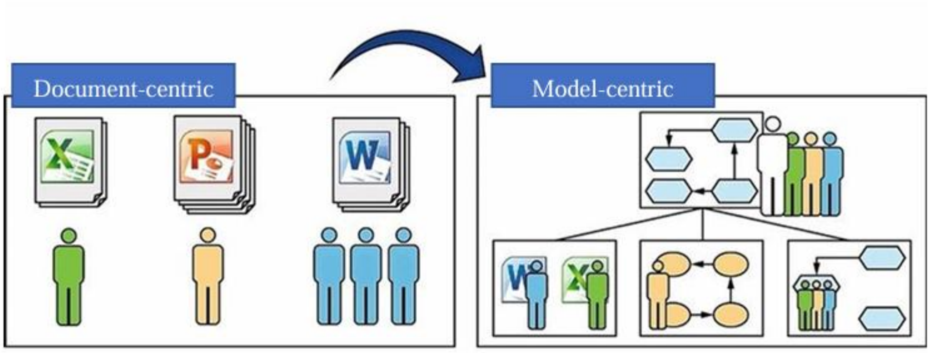


Figure 1.1 – Transition from document-centric engineering to model-based systems engineering (Adapted from Ackva; Tschirner, 2015).

The lack of formalized traceability standards, particularly in certification, limits regulatory consistency. Such variability introduces additional complexity in maintaining regulatory consistency, especially when dynamic and well-structured compliance records are lacking. Without standardized records, it becomes challenging to ensure that all safety requirements are consistently met across different implementations.

1.1 Contextualization

Before a new aircraft design can be certified, it must demonstrate compliance with the requirements established by the relevant regulatory authority, in accordance with the guidelines of the International Civil Aviation Organization (ICAO) (ICAO, 2023). The European Union Aviation Safety Agency (EASA) certification process for a new aircraft or modifications to an existing design typically follows main stages:

- **Technical Familiarization and Certification Basis Definition:** The regulatory authority and the manufacturer agree on the applicable certification requirements.
- **Establishment of the Certification Program:** The methods for demonstrating compliance with each requirement are defined.
- **Verification Phase:** In this stage, the manufacturer demonstrates compliance through testing or analysis supported by results. Structural validation, for example, involves a range of tests, from material testing to full-scale static and fatigue tests, culminating in flight tests under various conditions. Figure 1.2 illustrates the ‘test pyramid’ a widely recognized structure for organizing verification strategies across system levels.

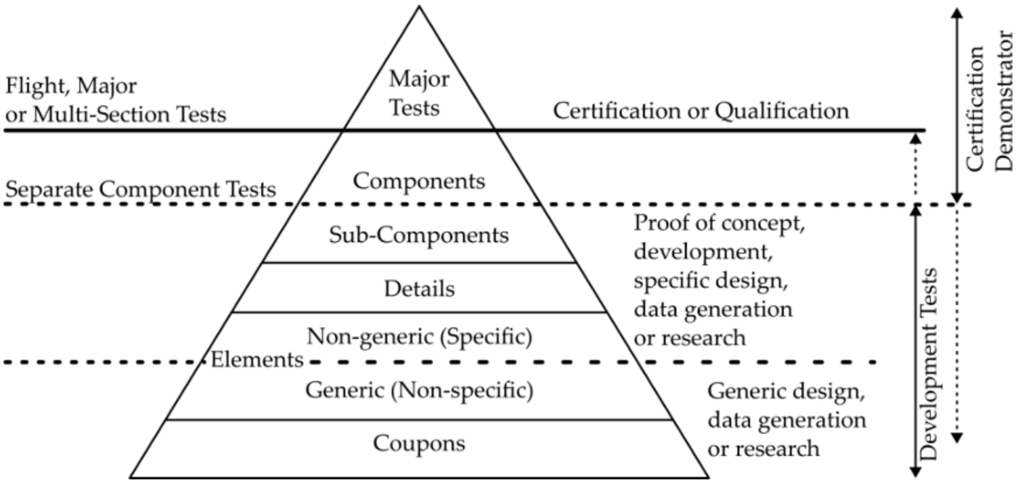


Figure 1.2 – Test pyramid (Adapted from Breuer, 2016).

- **Project Closure and Type Certificate Issuance:** Once compliance is demonstrated, the Type Certificate is issued. Additionally, both the design organization and production organization must be formally approved by the regulatory authority as part of the certification process (EASA, 2023).

Since its establishment in 1944, ICAO has guided the development of global aviation safety regulations, supporting the transition from rule-driven to objective-driven regulatory approaches (ICAO, 2023). This shift is evident in FAA regulations (e.g., 14 CFR Part 23, Part 25, and Part 27) and their EASA counterparts (e.g., CS-23, CS-25, CS-27), as well as in the introduction of special conditions for new aircraft categories, such as electric vertical takeoff and landing (eVTOL) aircraft. However, regulatory fragmentation remains a challenge. For instance, while EASA regulates eVTOLs through a dedicated process (e.g., SC-VTOL-01), the FAA classifies them as "Powered-Lift" aircraft, applying a certification pathway that does not strictly follow Part 23 requirements (United States, 2020; EASA, 2023). In multinational certification scenarios, these discrepancies can result in duplicative validation procedures, delays in certification approval, and misalignments in international safety oversight.

Beyond regulatory harmonization challenges, the transition to performance-based certification further underscores the need for traceability mechanisms. Traditional, paper-based methods often require labor-intensive manual reviews, which disrupt the continuity of records, introduce risks to data integrity, and extend the certification timeline. With the rise of disruptive technologies such as AI-driven avionics and autonomous systems, the absence of a consistent process poses a significant obstacle to timely and verifiable compliance in dynamic certification environments (Glinski *et al.*, 2022).

1.2 Research Problem

Given the contextualized scenario outlined in Section 1.1, the following concern arises:

How can MBSE be applied to regulatory traceability in aerospace certification while ensuring compliance and regulatory alignment across jurisdictions?

This research analyzed the current MBSE process that can support regulatory traceability in Systems Engineering (SE).

1.3 Hypothesis

A model-based regulatory traceability process, grounded in MBSE principles, can improve the alignment between certification requirements, Means of Compliance (MoCs), and verification activities.

1.4 Research Objectives

General Objective

To develop a model-based traceability process for aerospace certification.

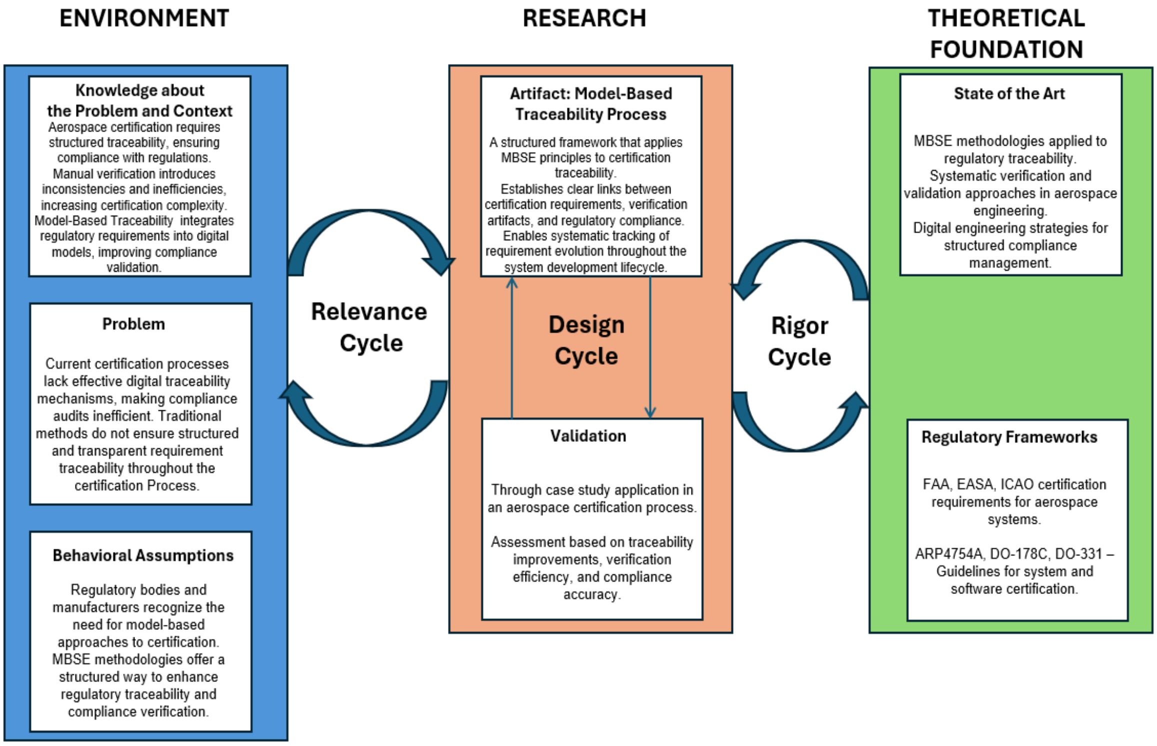
Specific Objectives

1. Analyze certification process and propose a mapping to support traceability and interoperability.
2. Develop a structured compliance process that integrates regulatory requirements, MoCs, corresponding technical documentation and validation activities within a model-based environment.
3. Exemplify the proposed model-based traceability process through a simulated regulatory scenario focused on the eVTOL domain.

1.5 Design Science Research and Structure of the Document

This thesis adopts the Design Science Research (DSR) paradigm to develop and validate a Model-Based Traceability Process that enhances regulatory compliance and digital traceability in aerospace certification processes. The methodology is structured around the Three-Cycle Model of DSR proposed by Hevner (2007), ensuring a balance between scientific rigor and practical relevance. The overall structure of this research reflects the integration of three interrelated research cycles, as illustrated in Figure 1.3.

- **Relevance Cycle**: Establishes a direct connection with real-world aerospace certification challenges by incorporating requirements from the FAA, EASA, ICAO and industry needs. The research problem and objectives (Chapter 1) stem from shortcomings identified in traditional certification methods (ICAO, 2023; EASA, 2023; United States, 2020).
- **Rigor Cycle**: Provides the theoretical foundation necessary to develop the process, drawing on MBSE principles, regulatory compliance structures, and digital traceability techniques. Chapter 2 and Chapter 3 presents theoretical background and literature review that support this research (Estefan, 2007; Friedenthal, Moore e Stein, 2015; Glinski *et al.*, 2022).
- **Design Cycle**: Encompasses the iterative design, development, and assessment of the proposed process. Chapter 4 describes the methodology and explains how the process is structured, exemplified (Chapter 5) through a case study (Hevner, 2007; Peffers *et al.*, 2007).



Knowledge about the Problem and Context
Aerospace certification requires structured traceability, ensuring compliance with regulations. Manual verification introduces inconsistencies and inefficiencies, increasing certification complexity. Model-Based Traceability integrates regulatory requirements into digital models, improving compliance validation.

Problem
Current certification processes lack effective digital traceability mechanisms, making compliance audits inefficient. Traditional methods do not ensure structured and transparent requirement traceability throughout the certification Process.

Behavioral Assumptions
Regulatory bodies and manufacturers recognize the need for model-based approaches to certification. MBSE methodologies offer a structured way to enhance regulatory traceability and compliance verification.

Artifact: Model-Based Traceability Process
A structured framework that applies MBSE principles to certification traceability. Establishes clear links between certification requirements, verification artifacts, and regulatory compliance. Enables systematic tracking of requirement evolution throughout the system development lifecycle.

Validation
Through case study application in an aerospace certification process.
Assessment based on traceability improvements, verification efficiency, and compliance accuracy.

State of the Art
MBSE methodologies applied to regulatory traceability. Systematic verification and validation approaches in aerospace engineering. Digital engineering strategies for structured compliance management.

Regulatory Frameworks
FAA, EASA, ICAO certification requirements for aerospace systems.
ARP4754A, DO-178C, DO-331 – Guidelines for system and software certification.

Figure 1.3 – Application of the Design Science Research (DSR) framework in this study (Developed by the author based on Hevner, 2007; Peffers *et al.*, 2007).

The thesis is organized into six chapters:

- **Chapter 1 – Introduction**: Presents the research context, problem statement, hypothesis, and objectives, and introduces the DSR-based methodological approach adopted in the study. It contextualizes the challenges of regulatory traceability in aerospace certification and motivates the adoption of MBSE as a strategy to enhance compliance structuring and integration.
- **Chapter 2 – Theoretical Framework**: Provides a comprehensive overview of aerospace certification principles and regulatory structures, including the evolution of airworthiness and the roles of key authorities. It also examines the conceptual foundations of MBSE, digital traceability, and the emerging paradigm of regulatory automation, establishing the basis for the proposed process.
- **Chapter 3 – Literature Mapping**: Applies the PRISMA methodology to conduct a systematic mapping and synthesizes key thematic contributions from 21 selected studies. It identifies research gaps related to traceability, verification, and compliance automation in MBSE-based certification processes, and positions the proposed process as a response to these gaps within the academic and regulatory landscape.
- **Chapter 4 – Methodology**: Structures the development of the Integrated Regulatory Traceability Process within a DSR cycle. It details the construction of the Authority Regulatory Model using SysML and implements the integration of MBSE principles to organize regulatory requirements, MoCs, and corresponding verification evidence within a model-based environment.
- **Chapter 5 – Analysis**: This chapter applies the Model-Based Traceability Process to a simulated eVTOL certification scenario, evaluating its capacity to structure regulatory traceability, support preliminary MoC assignment, and organize compliance verification. The analysis examines the integration of MBSE with regulatory constructions and assesses the model’s ability to enable bidirectional traceability across certification artifacts. The chapter concludes by summarizing key findings, acknowledging process limitations, and proposing potential refinements in the context of ongoing regulatory digitalization.

- **Chapter 6 – Conclusions and Future Work**: This chapter synthesizes the research findings, supporting the research hypothesis through structured confirming the viability of the Model-Based Traceability Process for enhancing regulatory traceability in aerospace certification. It discusses the process’s applicability, scalability, and current limitations, and provides recommendations for future work focused on adaptive certification models, digital auditing processes, and prospective implementation in broader and more complex aerospace regulatory environments.

2 Theoretical Framework

This chapter establishes the theoretical foundation for the model-based traceability process proposed in this thesis. It begins by tracing the historical evolution of airworthiness and certification practices, emphasizing the role of international regulatory harmonization. It then examines Systems Engineering, particularly through MBSE. The chapter also explores the implications of digital transformation and regulatory automation for enhancing regulatory transparency, compliance auditability, and process efficiency in certification oversight.

Model-Based refers to the formalized use of structured, digital models to support system requirements, design, analysis, verification, and validation throughout the system lifecycle. This approach replaces traditional document-based methods and enhances integration, consistency, and traceability across engineering domains (INCOSE, 2015, p. 121).

Traceability refers to the ability to identify and document the derivation paths and relationships between stakeholder needs, system requirements, design elements, implementation components, and verification artifacts. This capability enables impact analysis, compliance monitoring, and consistent verification across the system lifecycle (INCOSE, 2015, p. 112).

Process is defined as a structured set of interrelated or interacting activities that transform inputs into outputs by using resources under controlled conditions, with the purpose of consistently achieving specific objectives throughout the system life cycle (ISO; IEC; IEEE, 2015).

Aerospace Certification refers to the formal regulatory process by which a competent aviation authority confirms that an aircraft, system, or component complies with applicable airworthiness and safety requirements. It involves establishing a certification basis, executing verification activities, and providing compliance evidence for operational approval (United States, 2024a).

2.1 Airworthiness

Flight safety is supported by three interrelated pillars: the human element (including pilots, air traffic controllers, engineers, and technicians), the operational environment (meteorology, airport infrastructure, and airspace management), and the aircraft itself (design, certification, and maintenance). Failures in any of these pillars can compromise the integrity of air operations. Airworthiness, defined as the aircraft's sustained ability to meet all essential requirements to operate safely (De Florio, 2016), encompasses three fundamental aspects:

1. Safe operational conditions: Operating the aircraft within prescribed limits to mitigate risks to crew, passengers, and third parties.
2. Regulatory compliance: Adhering to design, manufacturing, and testing standards as defined by competent certification authorities.
3. Defined operational boundaries: Establishing certified flight envelopes that consider structural loads, operational modes (VFR/IFR), and environmental conditions.

To ensure compliance with these aspects, regulatory agencies apply comprehensive certification processes. These include evaluations of structural integrity, performance, flight characteristics, fatigue behavior, and aeroelastic phenomena such as flutter. While these processes are critical to aviation safety, they can also become increasingly complex and financially demanding. For small or medium-sized companies, certification costs may even compromise the economic feasibility of aircraft development (Almeida, 2022).

Importantly, airworthiness is not a static condition, it must be maintained throughout the aircraft's operational life. This involves periodic inspections, preventive and corrective maintenance, and compliance with Airworthiness Directives (ADs), which mandate corrective actions to address identified safety issues. This continuous cycle reinforces operational safety and ensures ongoing conformity with evolving regulatory requirements.

2.1.1 History and the Evolution of Flight Safety

Since the dawn of powered flights, safety has been a central concern. Early aviation was marked by rudimentary designs, limited testing, and the absence of formal regulations, factors that led to frequent fatal accidents. To address these risks, certification standards gradually emerged, introducing stringent safety requirements and systematic verification practices.

These standards evolved from fragmented regional frameworks into globally harmonized models, shaped by technological progress and insights from major accidents. ICAO emphasizes that enduring safety improvements stem from standardized, data-driven certification processes (ICAO, 2013). The FAA reinforces this by incorporating accident investigations into both policy and oversight (United States, 2017), while the Flight Safety Foundation documents how historical events have influenced international safety standards (Flight Safety Foundation, 2024).

An example is the structural failure of the de Havilland Comet in the 1950s (Figure 2.1), which led to critical advances in fatigue analysis. These included rounded window designs and mandatory cyclic pressurization tests, now codified in regulations such as 14 CFR § 25.571. The case also underscored the importance of both lab and in-flight fatigue testing, practices still fundamental to modern airworthiness certification (Boeing, 2023).

Figure 2.1 – Structural failure of the de Havilland Comet due to fatigue cracks initiated at square-cornered windows (Boeing, 2023).

Between 1956 and 1996, a series of critical accidents led to major regulatory and technological advances in civil aviation safety.

The 1956 mid-air collision over the Grand Canyon, caused by the absence of radar during visual flight operations, led to the creation of the FAA and the modernization of air traffic control systems. In 1960, the TAA Flight 538 accident, where no flight data were available, triggered the mandatory installation of Cockpit Voice Recorders (CVRs) and Flight Data Recorders (FDRs), formalized in ICAO Annex 6 and 14 CFR §121.359.

In 1974, the crash of Turkish Airlines Flight 981, caused by a cargo door design flaw and insufficient system redundancy, resulted in new regulations mandating positive locking mechanisms and fail-safe alert systems (14 CFR §25.783). The 1977 Tenerife disaster exposed serious shortcomings in cockpit communication and crew coordination, leading to standardized phraseology, common language protocols, and the widespread adoption of Crew Resource Management (CRM).

The 1979 crash of American Airlines Flight 191, due to improper maintenance and pylon detachment, resulted in AD 79-12-07 and new restrictions on joint engine/pylon removal (14 CFR Part 121). The 1983 Air Canada Flight 797 accident prompted new fire safety requirements, including smoke detectors, emergency lighting, and stricter flammability standards (14 CFR §25.853). In 1985, Delta Flight 191 highlighted the dangers of undetected microbursts, prompting mandatory wind shear detection systems (14 CFR §121.358) and enhanced pilot training (14 CFR §§121.409 and 121.423).

The 1986 Cerritos mid-air collision resulted in the mandatory use of TCAS II and Mode C transponders (14 CFR §121.356). In 1988, structural failure on Aloha Airlines Flight 243 due to fatigue and corrosion led to the Aging Aircraft Safety Act (1991) and updated damage tolerance requirements (14 CFR §121.1109). Between 1991 and 1994, a series of rudder malfunctions prompted a redesign of the flight control system and revisions to certification criteria (14 CFR §25.671). The 1996 crash of ValuJet Flight 592, involving hazardous materials, led to stricter cargo compartment regulations and required fire detection and suppression systems.

A major regulatory inflection occurred with the crash of TWA Flight 800. As illustrated in Figure 2.2, the mid-air explosion of the aircraft’s center fuel tank, likely triggered by electrical arcing in the presence of flammable vapors, resulted in the issuance of the Fuel Tank Flammability Reduction (FTFR) Rule and Special Federal Aviation Regulation (SFAR) 88. These mandates introduced strict requirements for identifying and mitigating ignition sources in fuel tanks, including mandatory flammability analyses, improved maintenance protocols, and the implementation of inerting or oxygen-reduction systems. The TWA 800 investigation significantly reshaped fuel system design standards and remains a key reference in current certification practices.

Figure 2.2 – TWA Flight 800 Wreckage Reconstruction (NTSB, 1996).

In 1998, the Swissair Flight 111 accident was caused by an electrical fire involving flammable insulation materials. This event led to the prohibition of MPET-covered insulation blankets and prompted a revision of flammability testing protocols under 14 CFR §25.853. Following the investigation, certification criteria for thermal and acoustic insulation were updated to reflect more realistic fire propagation scenarios.

On September 11, 2001, coordinated terrorist attacks exposed critical vulnerabilities in flight deck security. In response, the FAA mandated reinforced cockpit doors (14 CFR §25.795) and formally incorporated unlawful interference protection into both aircraft certification and operational standards.

In 2009, the crash of Air France Flight 447, triggered by Pitot tube icing and compounded by inadequate manual recovery, led to significant regulatory action. Affected probes were replaced through FAA and EASA ADs and Upset Prevention and Recovery Training (UPRT) became mandatory for flight crews under 14 CFR §121.423. The accident highlighted the importance of reliable sensor data and reinforced the need for pilot training in loss-of-control scenarios.

A major turning point in modern certification was marked by the Boeing 737 MAX accidents: Lion Air Flight 610 (2018), depicted in Figure 2.3, and Ethiopian Airlines Flight 302 (2019). The Maneuvering Characteristics Augmentation System (MCAS), designed to enhance pitch stability, relied on a single Angle-of-Attack (AoA) sensor without redundancy or override logic.

In response, MCAS was comprehensively redesigned, and regulatory oversight was significantly reinforced. The U.S. Congress enacted the Aircraft Certification, Safety, and Accountability Act (2020), shifting the balance between manufacturers and authorities. Key reforms included enhanced software traceability, broader safety assessments, and tighter integration between engineering practices and regulatory verification (U.S. GAO, 2020; NTSB, 2020; House of Representatives, 2020).

Figure 2.3 – Lion Air Flight JT610 Wreckage Recovery (Adimaja, 2018).

Continuous reviews of airworthiness requirements reflect lessons learned from accidents and incidents, reinforcing the need for design traceability, regulatory transparency and ongoing verification of operational safety. Despite global growth in air traffic, fatal accident rates have steadily declined, driven by stricter certification protocols, technological advancements, and enhanced operational standards (ICAO, 2013; NTSB, 2001).

As shown in Figure 2.4, accident rates have dropped over time even as flight operations increased. This trend is attributed to more rigorous airworthiness standards, improved oversight practices, and greater investments in pilot training and crew resource management (ICAO, 2013; United States, 2017). Regulatory frameworks have thus enabled the safe integration of innovations by requiring thorough validation prior to operational deployment.

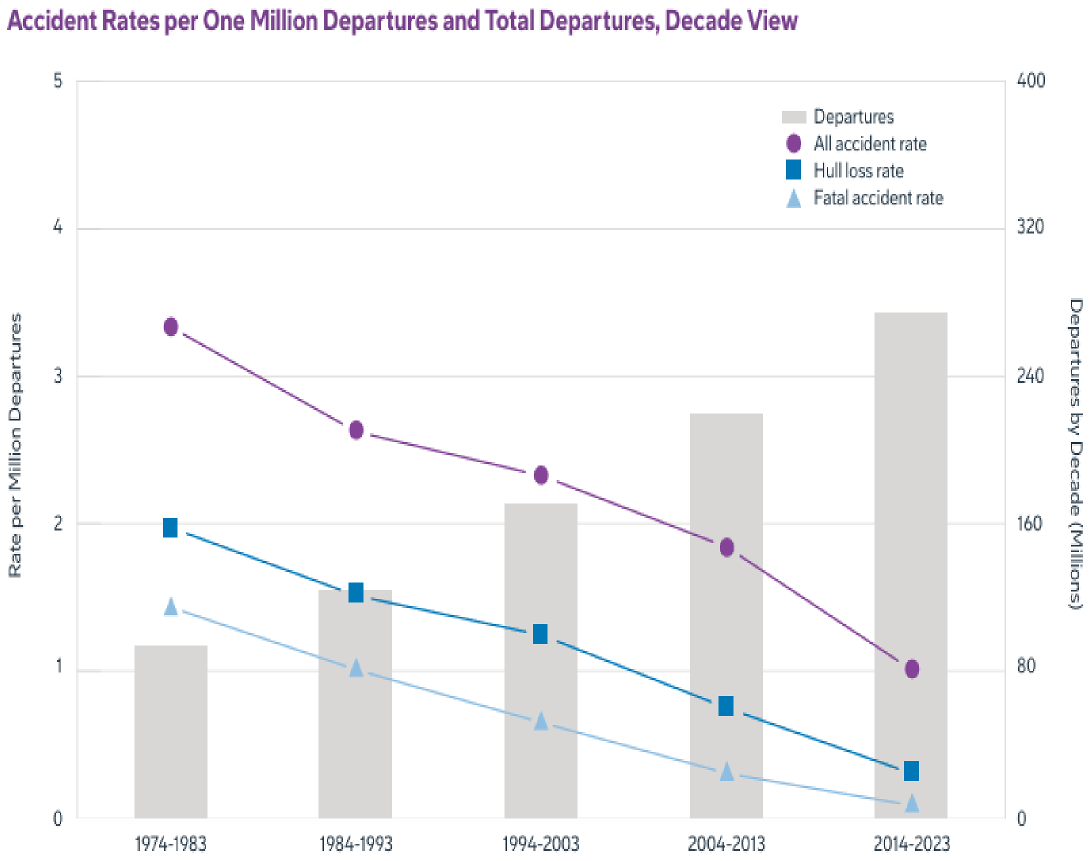
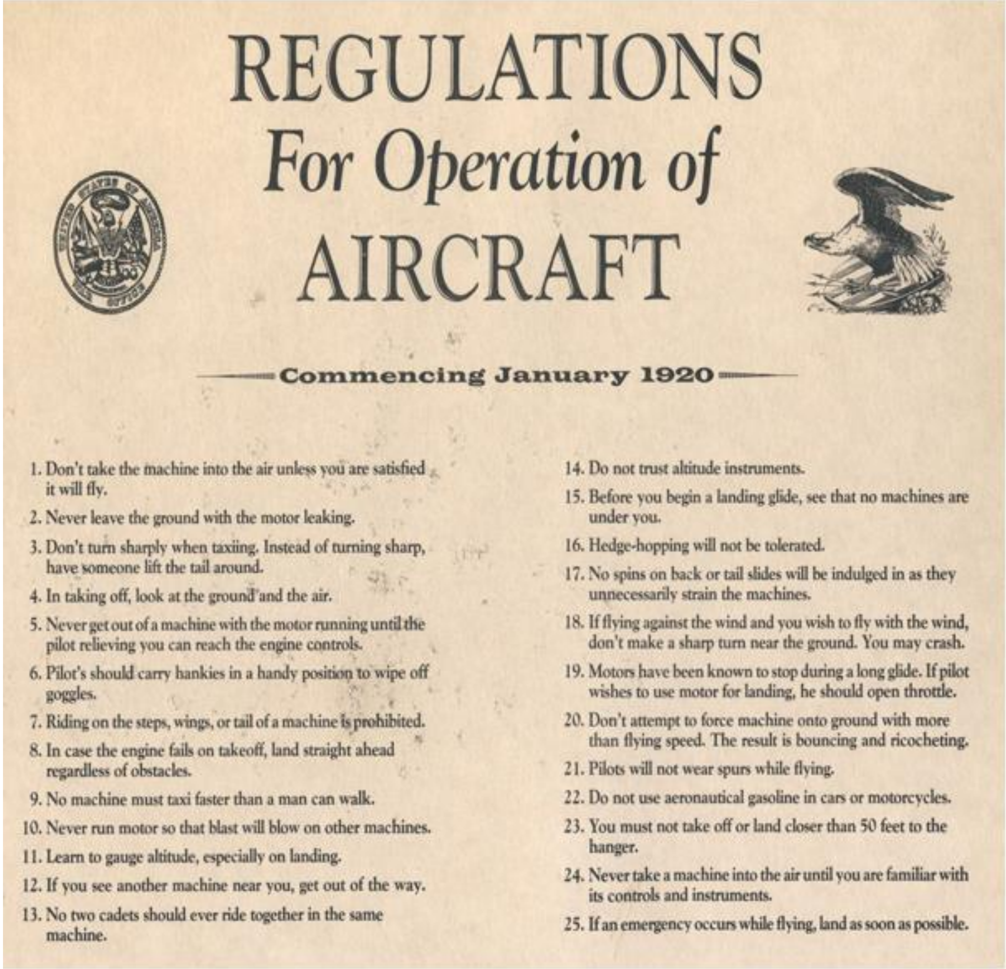


Figure 2.4 – Evolution of Fatal Accident Rate and Number of Departures per Decade (Boeing, 2023).

Since its establishment, ICAO has played a central role in harmonizing technical standards globally, with a focus on operational safety, interoperability, and environmental sustainability. As of 2025, ICAO publishes International Standards and Recommended Practices (SARPs) across 19 annexes, covering key areas such as aircraft certification (Annex 8), air traffic services, and crew licensing. These SARPs are periodically updated and serve as the foundation for national regulations issued by authorities.

The evolution of these standards reflects both technological advances and the integration of lessons learned from accident and incident investigations. According to De Florio (2016), this feedback loop enhances regulatory precision and risk mitigation. Figure 2.5 shows early aircraft operation rules from 1920, reflecting the rudimentary and practical nature of initial flight safety regulations.

Through ICAO’s initiatives, this standardization process has enhanced operational safety and strengthened global coordination in aircraft certification. The resulting regulatory architecture enables consistent oversight among diverse Civil Aviation Authorities, supporting a globally interoperable and resilient aviation system.



REGULATIONS
For Operation of
AIRCRAFT

Commencing January 1920

1. Don't take the machine into the air unless you are satisfied it will fly.
2. Never leave the ground with the motor leaking.
3. Don't turn sharply when taxiing. Instead of turning sharp, have someone lift the tail around.
4. In taking off, look at the ground and the air.
5. Never get out of a machine with the motor running until the pilot relieving you can reach the engine controls.
6. Pilot's should carry hankies in a handy position to wipe off goggles.
7. Riding on the steps, wings, or tail of a machine is prohibited.
8. In case the engine fails on takeoff, land straight ahead regardless of obstacles.
9. No machine must taxi faster than a man can walk.
10. Never run motor so that blast will blow on other machines.
11. Learn to gauge altitude, especially on landing.
12. If you see another machine near you, get out of the way.
13. No two cadets should ever ride together in the same machine.
14. Do not trust altitude instruments.
15. Before you begin a landing glide, see that no machines are under you.
16. Hedge-hopping will not be tolerated.
17. No spins on back or tail slides will be indulged in as they unnecessarily strain the machines.
18. If flying against the wind and you wish to fly with the wind, don't make a sharp turn near the ground. You may crash.
19. Motors have been known to stop during a long glide. If pilot wishes to use motor for landing, he should open throttle.
20. Don't attempt to force machine onto ground with more than flying speed. The result is bouncing and ricocheting.
21. Pilots will not wear spurs while flying.
22. Do not use aeronautical gasoline in cars or motorcycles.
23. You must not take off or land closer than 50 feet to the hanger.
24. Never take a machine into the air until you are familiar with its controls and instruments.
25. If an emergency occurs while flying, land as soon as possible.

Figure 2.5 – Early Aviation Safety Rules Issued by the U.S. Department of Commerce in 1920 (U.S. Department of Commerce – Aeronautics Branch, 1920).

To ensure regulatory control over civil aviation, individual states have established specialized airworthiness authorities responsible for certifying aircraft, operators, and infrastructure in accordance with ICAO standards. This institutional approach has historical roots in maritime inspection systems, most notably, the classification practices introduced by Edward Lloyd in the 17th century, which assessed ships based on their structural condition and operational performance. These classification systems laid the foundation for modern conformity assessment processes.

With the expansion of air transport in the early 20th century, the need for formal verification of airworthiness became critical. Manufacturers and operators require independent certification to confirm an aircraft's suitability for commercial service. Over time, this led to the development of increasingly sophisticated certification process managed by national and regional aviation authorities.

Among global regulators, the FAA (United States) and EASA (Europe) stand as leading reference authorities. Beyond enforcing compliance, they shape technical standards, foster innovation, and facilitate the safe integration of emerging technologies into aviation systems (Petrović, 2023).

Established in 1958, the FAA oversees civil aviation in the United States, with a mission to ensure the safety and efficiency of both commercial and general aviation operations (United States, 2023c). Its core airworthiness responsibilities include supervising the issuance of Type Certification (TC) and monitoring continued airworthiness to ensure compliance with safety standards; approving organizations involved in the design, production, and maintenance of aircraft; conducting inspections and audits to verify regulatory adherence; and developing and updating regulations. Additionally, the FAA manages safety programs and issues ADs in response to identified operational risks.

Figure 2.6 outlines the FAA's organizational structure, including divisions for aviation safety (AVS), air traffic services, infrastructure, and commercial space. This integrated model sustains high regulatory standards and supports technological advancement in U.S. civil aviation.

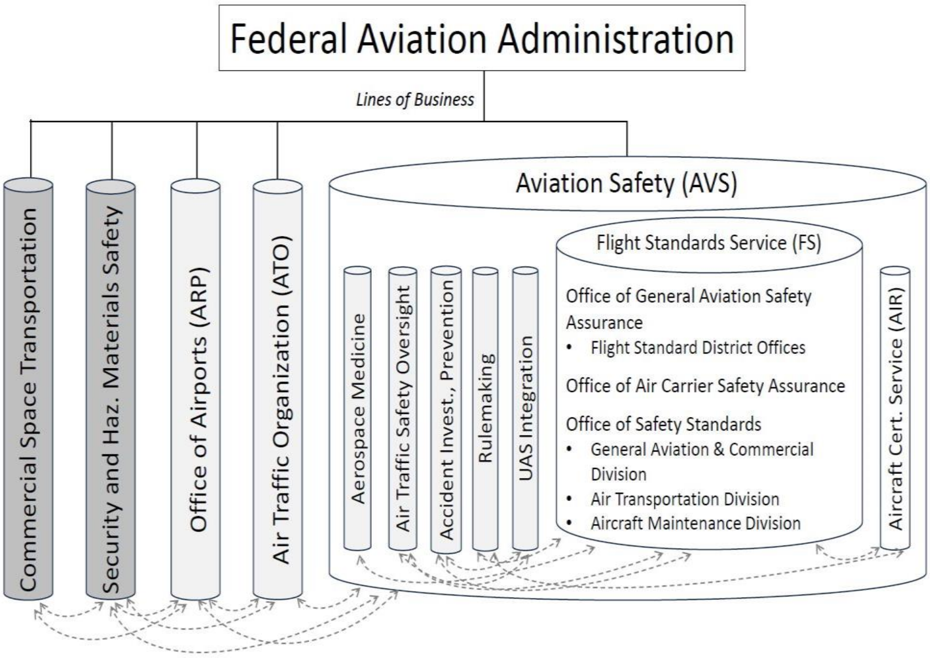


Figure 2.6 – Organizational Structure of the FAA Focusing on Aviation Safety (AVS) (United States, 2023d).

Beyond the FAA, several national civil aviation authorities, such as EASA (Europe), ANAC (Brazil), CAAC (China), CASA (Australia), TCCA (Canada) and CAA (United Kingdom), develop and enforce airworthiness regulations within their jurisdictions while actively participating in the global harmonization of certifications.

Coordinated by ICAO, these agencies collaborate through working groups, joint rulemaking, and bilateral or multilateral validation agreements. These mechanisms promote mutual recognition, minimize redundant efforts, and foster regulatory convergence in complex aerospace programs.

Such alignment supports uniform safety standards, enables cross-border operations, and facilitates oversight amid emerging technologies like electric propulsion, unmanned systems, and advanced automation. Nevertheless, persistent differences in regulatory interpretation, compliance documentation, and traceability practices pose challenges for multinational certification efforts.

2.1.2 Airworthiness Requirements

Historically, civil aviation airworthiness requirements were developed independently by each nation, resulting in regulatory fragmentation that hindered international certification and complicated the export and mutual validation of aeronautical products (ICAO, 2020). In Europe, efforts to address this began in the 1970s with the Joint Aviation Requirements (JARs), introduced by the Joint Aviation Authorities (JAA) to reduce inconsistencies and promote cross-border recognition.

The establishment of the EASA in 2002 centralized regulatory authority across Europe and replaced the JARs with Certification Specifications (CS). These specifications define technical criteria for certification and are supplemented by Acceptable Means of Compliance (AMC) and Guidance Material (GM), providing applicants with structured pathways to demonstrate conformity (EASA, 2023).

In the United States, the FAA governs civil aviation regulation through Title 14 of the Code of Federal Regulations (14 CFR). This framework spans the entire product lifecycle, from design and certification to operation, maintenance, and continued airworthiness.

To foster regulatory convergence and minimize duplication, the U.S. and the EU signed the Bilateral Aviation Safety Agreement (BASA) in 2011. The agreement facilitates mutual recognition of type certifications, maintenance procedures, and personnel licensing (United

States; EASA, 2011). However, divergences persist, particularly regarding emerging technologies and the adoption of performance-based regulatory models.

To support applicants, both the FAA and EASA issue supplementary documents, such as Advisory Circulars (ACs), AMCs, and GMs, that provide interpretive guidance during certification reviews and audits. Despite harmonization efforts, residual discrepancies are managed through coordination procedures and reflected in artifacts like the Type Certificate Data Sheet (TCDS).

In November 2023, the FAA and EASA jointly updated the Technical Implementation Procedures (TIP), reaffirming their commitment to regulatory cooperation and technical alignment (EASA, 2023). Concurrently, Resolution No. 18/2025 of the EU Council of Ministers reinforced operational safety across Member States, aligning with Regulation (EU) 2018/1139 and strengthening the regulatory role of national authorities.

Given this context, a comparative analysis of current regulatory documents from EASA and the FAA is essential. Despite variations in terminology, structure, and procedures, both systems aim to ensure the technical compliance necessary for safe and certifiable operations. Table 2.1 provides a detailed comparison between EASA's Certification Specifications and the corresponding parts of Title 14 CFR, covering aircraft categories, rotorcraft, balloons, engines, propellers, environmental systems, operational equipment, and unmanned aircraft systems.

Table 2.1 – Comparative Overview of EASA Certification Specifications (CS) and Corresponding FAA Title 14 CFR Parts for Aircraft and Related Products.

Application Area	**EASA Certification Specifications (CS)**	**FAA – 14 CFR Part**	**Remarks**
Large Airplanes	CS-25	Part 25	Pertains to transport category airplanes.
Small Airplanes	CS-23	Part 23	Covers normal, utility, aerobatic, and commuter category airplanes.
Rotorcraft	CS-27 (Small), CS-29 (Large)	Part 27 (Normal), Part 29 (Transport)	CS-27 and Part 27 address normal category rotorcraft; CS-29 and Part 29 pertain to transport category rotorcraft.
Sailplanes and Powered Sailplanes	CS-22	Not Applicable	EASA provides specific certification specifications for sailplanes and powered sailplanes; the FAA does not have an equivalent regulation.
Balloons	CS-31GB (Gas Balloons), CS-31HB (Hot Air Balloons)	Part 31	Both agencies provide regulations for manned free balloons.
Engines	CS-E	Part 33	Establish airworthiness standards for aircraft engines.
Propellers	CS-P	Part 35	Sets forth airworthiness standards for propellers.
Environmental Standards (Noise)	CS-36	Part 36	Specifies noise certification standards for various aircraft types.

Table 2.1 – Comparative Overview of EASA Certification Specifications (CS) and Corresponding FAA Title 14 CFR Parts for Aircraft and Related Products. (cont.).

Application Area	**EASA Certification Specifications (CS)**	**FAA – 14 CFR Part**	**Remarks**
Environmental Standards (Fuel Venting and Exhaust Emissions)	CS-34	Part 34	Addresses fuel venting and exhaust emissions requirements for turbine engine-powered airplanes.
Equipment and Instruments	CS-ETSO	Part 21, Subpart O (Technical Standard Orders)	CS-ETSO and Part 21, Subpart O, outline the approval process for aviation equipment and instruments based on technical standard orders.
Operational Suitability Data (OSD)	Part 21, Subpart B	Not Applicable	EASA requires OSD as part of certification; FAA addresses some related elements across various guidance documents but lacks an equivalent structured requirement.
Unmanned Aircraft Systems (UAS)	CS-UAS	Part 107	CS-UAS covers airworthiness certification; Part 107 governs only operational rules for small UAS without design certification requirements.
Certification of Aircraft Parts and Appliances	CS-APU	Not Applicable	CS-APU provides specific requirements for APUs; FAA addresses APU certification under 14 CFR Part 25 or Part 33, without a dedicated section.
Additional Airworthiness Specifications for Operations	CS-26	Not Applicable	EASA's CS-26 includes additional airworthiness specifications to ensure safety in operations; the FAA incorporates similar requirements within various operational and airworthiness directives rather than a consolidated specification.

2.1.3 Airworthiness Certificate Process

The aircraft Type Certification (TC) process adheres to five canonical phases illustrated in Figure 2.7, as delineated in FAA Order 8110.4C and EASA Part 21. These sequential stages establish a structured process that guides the process from initial design conception through sustained operational oversight, maintaining alignment with established regulatory certification models.

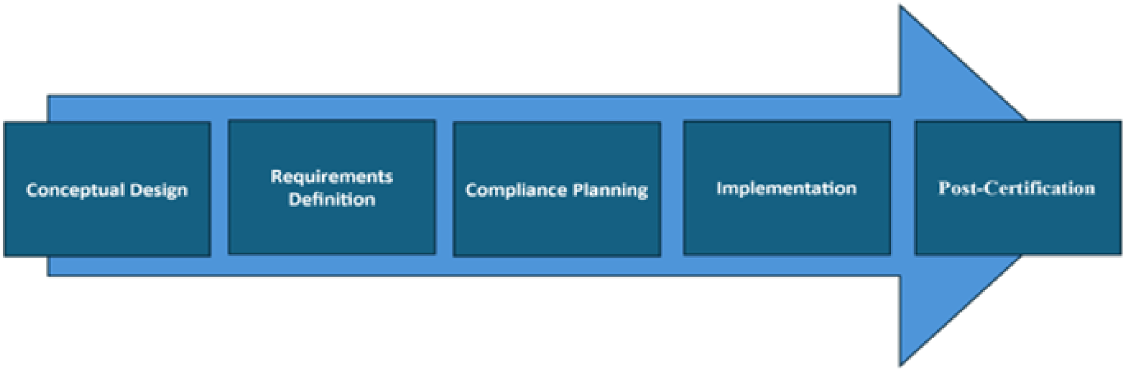


Figure 2.7 – Phases of the aircraft type certification process (Pleffken, 2019).

To obtain a TC, applicants must demonstrate compliance with airworthiness and environmental standards through a structured organizational framework. In the U.S., the FAA regulates this process through FAA Order 8110.37F, which delegates authority to Designated Engineering Representatives (DERs) (United States, 2017). Since 2005, the Organization Designation Authorization (ODA) program has allowed approved organizations to perform certification tasks under specific terms (United States, 2005). Following the Boeing 737 MAX accidents, the FAA implemented reforms to address oversight gaps and improve accountability (DOT OIG, 2021; US Congress, 2020).

Organizations operating under ODA must implement a robust system for managing design control, compliance verification, and corrective actions, as defined in their FAA-approved procedures manual. Compliance is documented through a formal declaration by the ODA Unit Member, but the final issue of the TC remains under FAA authority. Minor Changes and Flight Manual revisions may be approved internally if permitted by the ODA procedures, while Major Changes typically require direct FAA involvement and approval.

For major design modifications, the FAA requires a Supplemental Type Certificate (STC) under 14 CFR Part 21, Subpart E. The FAA evaluates technical data and DER findings but retains final approval authority for STC issuance. Guidance is provided in AC 21-40A.

In EASA, the certification process follows a similar structure under the Design Organization Approval (DOA), defined in Regulation (EU) No. 748/2012, Part 21, Subpart J (EASA, 2020). EASA employs a risk-based Level of Involvement (LoI) model, tailoring oversight based on design complexity and applicant history (EASA, 2022).

After obtaining a TC or STC, the holder may apply for an airworthiness certificate for modified aircraft, conduct installations as specified in the approved data, and request production approval under 14 CFR Part 21, Subpart G. Export coordination follows the TIPs, addressing regulatory differences through Significant Standards Differences (SSDs) and Safety Emphasis Items (SEIs).

Applicants must also submit Instructions for Continued Airworthiness as required by 14 CFR § 23.1529, detailing maintenance procedures, interface specifications, and operational instructions (United States, 2010). If the ICA is incomplete at certification, a compliance plan must outline the timeline for finalizing the documentation before service entry (United States, 2024d).

A TC confirms that a product design meets airworthiness and environmental standards, but operational approval requires a Certificate of Airworthiness (CoA) under 14 CFR § 21.41, which authorizes entry into service by verifying that the aircraft conforms to the approved type design and is in a condition for safe operation (United States, 2023).

Continued Airworthiness and Continuing Airworthiness are distinct but interconnected regulatory responsibilities. Continued Airworthiness focuses on maintaining the integrity of the certified type design through ICAs and mandatory ADs issued to address identified safety risks (ICAO, 2014; De Florio, 2016).

Continuing Airworthiness ensures that each aircraft remains in a safe operational condition through ongoing maintenance, inspections, and recordkeeping managed by operators, CAMOs, and maintenance organizations (De Florio, 2016).

In the U.S., Continued Airworthiness is governed by 14 CFR §21.50 (ICAs) and Part 39 (ADs), while operator responsibilities under Continuing Airworthiness are specified in Parts 91 and 121, which include programs such as the Continuous Analysis and Surveillance System (CASS) (United States, 2023c). In Europe, EU Regulation No. 1321/2014 covers both Continued and Continuing Airworthiness, encompassing Parts M, 145, CAMO, 66, and 147 (EASA, 2014).

ICAO Annexes 6 and 8 reinforce this framework by promoting data sharing between the State of Design and State of Registry and mandating Reliability-Centered Maintenance programs (ICAO, 2018; 2022).

Maintenance and inspection programs are structured using methods like MSG-3, aligning tasks with system criticality and operational risks (Kincaid; Wise, 2012). Recordkeeping ensures regulatory compliance and traceability of life-limited parts, as required by 14 CFR §91.417 and EASA Part M (United States, 2023a; EASA, 2014).

Together, these elements form a comprehensive framework that integrates Continued and Continuing Airworthiness, linking design integrity with operational safety throughout the aircraft lifecycle. Figure 2.8 shows the Integration of Airworthiness Regulatory Standards and Certification Processes.

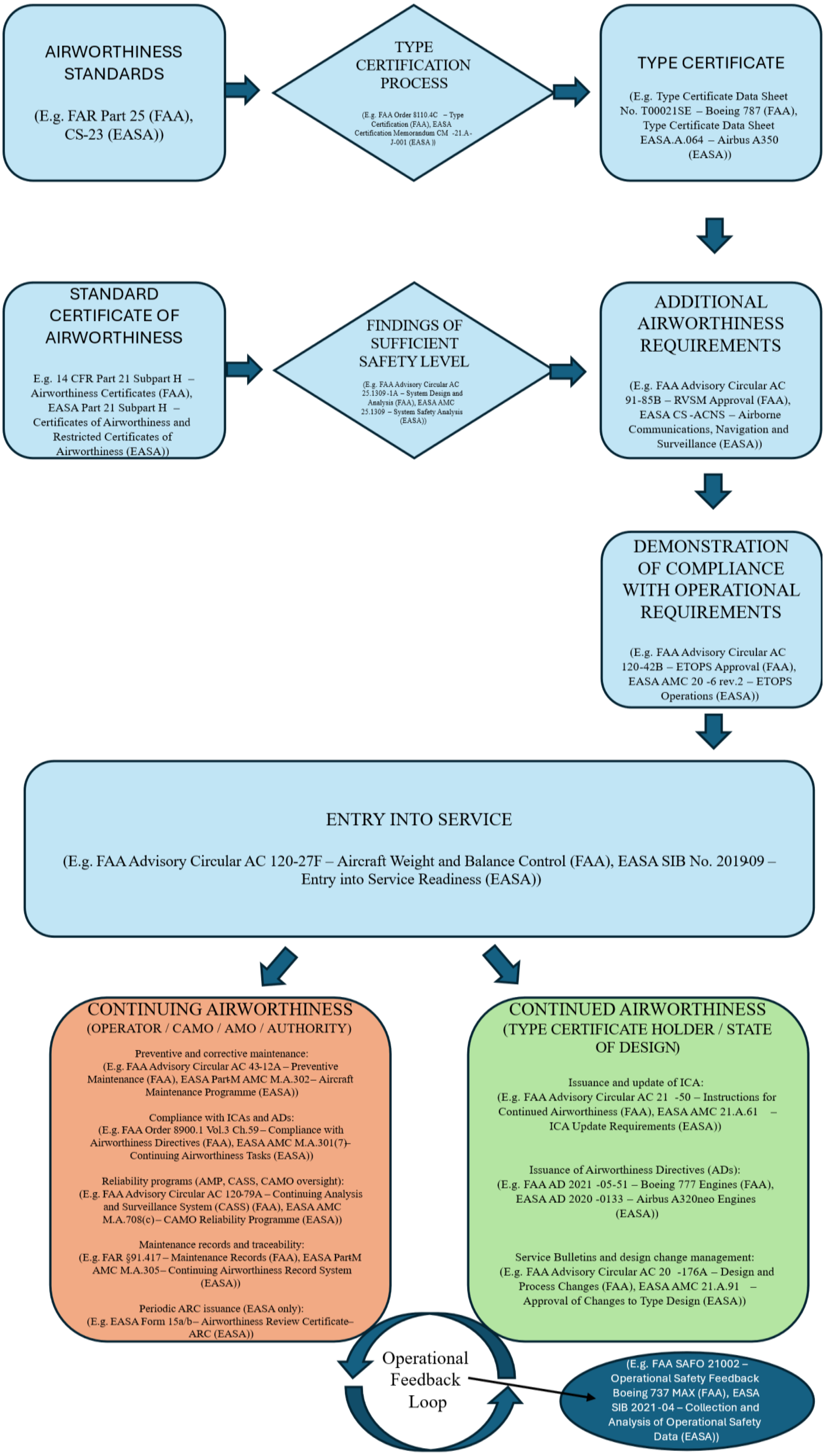


Figure 2.8 – Integration of Regulatory Airworthiness Standards and Certification Processes (Pleffken, 2020).

2.2 Systems Engineering Evolution and Model-Based Certification

The certification of modern aeronautical systems requires a systems engineering approach capable of managing system complexity, regulatory constraints, and stringent safety objectives across all lifecycle stages. This subchapter examines the transition from classical Systems Engineering (SE) practices, centered on functional decomposition, interface management, and verification planning, to model-based approaches that embed regulatory logic within the engineering process.

The content is organized into three interrelated sections. The first outlines the historical foundations and institutional development of SE in aerospace programs. The second focuses on the consolidation of requirements engineering and the role of compliance traceability in certification. The third introduces MBSE as a strategic enabler of integrated, auditable, and digitally traceable certification workflows.

2.2.1 Evolution of Aeronautical Systems and Certification Processes

Systems Engineering is grounded in systems thinking, an interdisciplinary approach that seeks to understand the dynamic interactions, interdependencies, and feedback mechanisms among the components of a system. Unlike reductionist methods that isolate individual parts, system thinking examines the system holistically, recognizing that emergent properties arise from the complex interplay among elements. Originating from General Systems Theory (Bertalanffy, 1968), this perspective has become indispensable in aerospace domains, where failures often trigger cascading and catastrophic consequences.

The foundations of aeronautical SE trace back to the 19th century, when pioneers such as Sir George Cayley conceptualized flight as a system of interdependent components, lift, propulsion, and control, thus laying the groundwork for a functional decomposition approach to design (Anderson, 2002). Subsequent innovators, including Alberto Santos Dumont and the Wright brothers, demonstrated the practical integration of aerodynamics, structural design, propulsion mechanisms, and flight control systems.

With the advancement of aviation technology, particularly during and after World War II, system complexity escalated dramatically. The introduction of jet propulsion, pressurized cabins, and increasingly sophisticated onboard electronics demanded structured engineering methodologies. Mechanistic and compartmentalized industrial paradigms such as Taylorism and Fordism proved inadequate in managing these interdependencies (Checkland, 1999). This gap catalyzed the emergence of SE as a formal discipline, influenced by systemic thinking and Cybernetics (Wiener, 1948), which conceptualized the aircraft as a regulated system subject to technical, operational, and safety constraints (Sage; Armstrong Jr., 2000).

SE was initially institutionalized in large-scale projects involving missiles and satellites. Bell Telephone Laboratories and the U.S. Department of Defense played a critical role in formalizing its principles, introducing essential concepts such as requirements engineering, interface control, and integrated verification and validation (NASA, 2007).

In the civil aviation and space sectors, SE enabled the orchestration of complex development efforts. The Apollo Program stands as a seminal example, where the successful integration of thousands of subsystems into a unified mission architecture underscored the primacy of systems management over isolated innovations (NASA, 2007). In commercial aviation, aircraft such as the Airbus A320 and Boeing 787 underscored the indispensability of structured SE methods. While pioneering in their technological features, these programs also revealed the vulnerabilities of fragmented engineering practices, which led to budget overruns, schedule slippages, and extensive rework (Dörfler; Baumann, 2014; Paul, 2018).

In Brazil, the certification of the Embraer E190-E2 demonstrated the strategic relevance of mature SE practices. The integration of redesigned wings, next-generation geared turbofan engines, and advanced avionics was validated through a comprehensive flight test campaign exceeding 2,000 hours (Embraer Press Release, 2018).

These developments catalyzed the adoption of structured, safety-oriented frameworks. In civil aviation, SAE ARP4754A updated to ARP4754B (2023) and harmonized with EUROCAE ED-79A, provides a foundational reference for aircraft and systems development, from top-level requirements to system integration and verification (SAE International, 2023).

Figure 2.9 illustrates the V-Model formalized in ARP4754B, representing the aircraft development lifecycle. It aligns requirement decomposition (left branch) with progressive verification activities (right branch), ensuring traceability from system-level safety objectives.

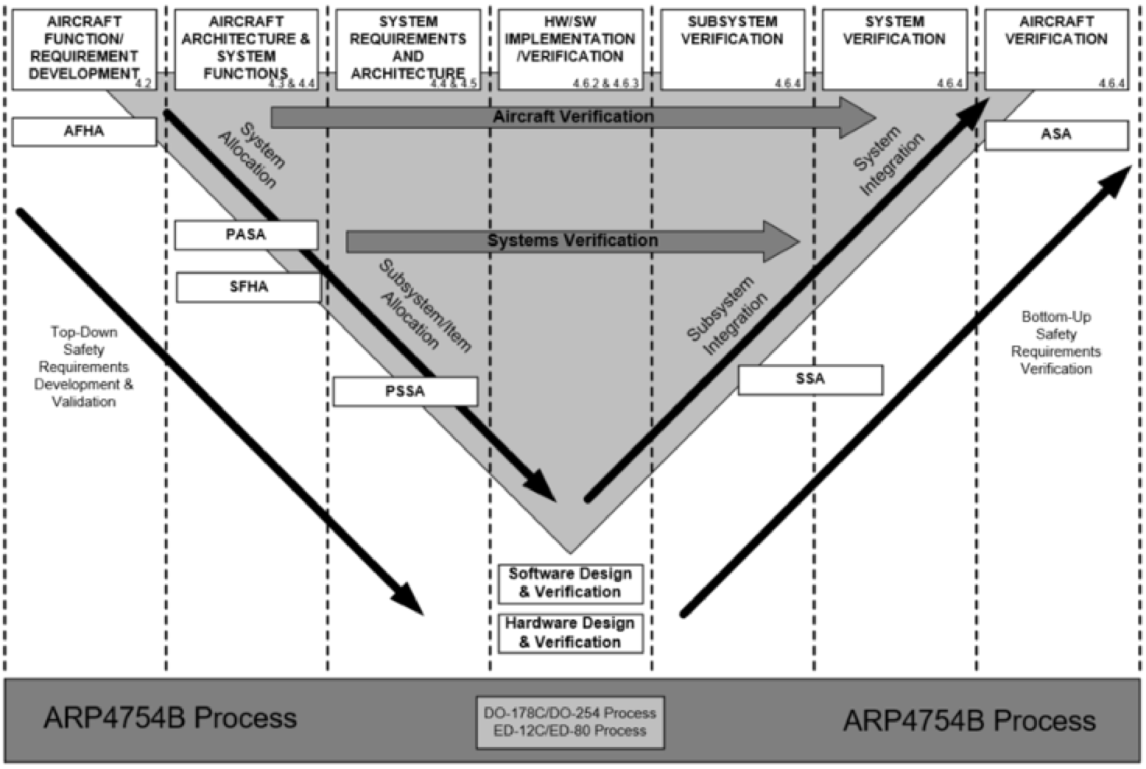


Figure 2.9 – V-Model for Development and Verification of Aircraft Systems According to ARP4754B (SAE International, 2023).

The adoption of the ARP4754B V-Model facilitates a traceable and auditable development process in which safety and performance requirements are systematically allocated and verified at each hierarchical level of the system architecture. This structured framework reinforces alignment between engineering activities and regulatory expectations throughout the aircraft lifecycle.

In parallel, software and hardware development activities adhere to RTCA DO-178C and DO-254, ensuring rigorous verification and validation of functional design, implementation, and integration (RTCA, 2000, 2011).

While these standards maintain a verification-centric approach focused on determinism and structured development processes, established frameworks such as ARP 4754B and ARP 4761A emphasize functional decomposition and traceability, but they remain centered on deterministic verification and safety assessment. Recent initiatives, such as SAE AIR 6988 and ASTM F3330, are exploring more proactive strategies for emerging technologies such as adaptive systems and artificial intelligence. However, these frameworks remain exploratory and are not yet accepted as formal means of compliance by regulatory authorities (SAE International, 2010).

The Boeing 737 MAX accidents (2018–2019) underscore the limitations of conventional certification approaches in managing complex, interdependent systems, where inadequate integration of critical subsystems and deficiencies in hazard analysis contributed to unintended system behaviors (House of Representatives, 2020). The incident highlighted the need for comprehensive, end-to-end systems analysis that considers not only individual components but also their interactions and emergent behaviors in operational contexts.

SE has become a cornerstone in managing complex aerospace systems, structuring the integration of technical, programmatic, and regulatory requirements across the lifecycle (INCOSE, 2023). ISO/IEC/IEEE 15288:2023 outlines SE processes including requirement analysis, functional decomposition, and verification planning, ensuring regulatory alignment. SE systematically coordinates critical subsystems like avionics, propulsion, and flight controls, aligning safety objectives with certification criteria. Blanchard and Fabrycky (2011) emphasize SE’s role in transforming stakeholder needs into verifiable, auditable architectures essential in mission-critical systems.

2.2.2 Requirements Engineering and Compliance Traceability

ISO/IEC/IEEE 29148:2018 establishes a comprehensive framework for eliciting, specifying, validating, and managing requirements throughout the system lifecycle, emphasizing clarity, consistency, and verifiability across all abstraction levels (ISO; IEC; IEEE, 2018). In aerospace certification, these principles are refined in SAE ARP4754B (2021), which extends requirements engineering through model-based methodologies like MBSE and Model-Based Safety Assessment (MBSA). This approach enables structured traceability between operational, functional, and safety requirements and their verification artifacts (SAE International, 2021).

For airborne software, RTCA DO-178C specifies stringent development and verification criteria, structured around Design Assurance Levels (DALs). It mandates bidirectional traceability from software requirements to implementation and verification artifacts, ensuring transparency, auditability, and consistency throughout the software development lifecycle (RTCA, 2011).

Collectively, these standards support a SE approach tailored to the increasing complexity, automation, and criticality of modern aeronautical systems. Engineering requires in this context not only safeguards operational safety but also sustains the Type Certification process through a hierarchical structure, from high-level regulatory and mission requirements to detailed, verifiable specifications (ISO; IEC; IEEE, 2018).

Top-level system requirements are allocated to subsystems such as embedded software, avionics hardware, and human–machine interfaces. ARP4754B formalizes this process by emphasizing structured decomposition from the aircraft level down to individual components, ensuring vertical consistency and enabling systematic compliance verification across the development lifecycle (SAE International, 2021).

Each level of requirement must undergo validation to ensure it accurately reflects operational needs, and verification to confirm that the implementation meets its specifications. This dual process, emphasized in ARP4754B, remains a cornerstone of certification. Validation assesses relevance and completeness, while verification uses test results, analyses, and design documentation to substantiate compliance (SAE International, 2021). Defining high-quality requirements is a critical challenge in aerospace programs. Ambiguous, incomplete, or conflicting requirements are leading contributors to design errors, rework, and safety risks. Effective requirements must be clear, necessary, verifiable, and traceable, especially when derived from safety analyses, supporting objective compliance assessments during certification audits. Figure 2.10 depicts the V-Model's flow from capability documents to baselines, integrating validation, verification, and risk management.

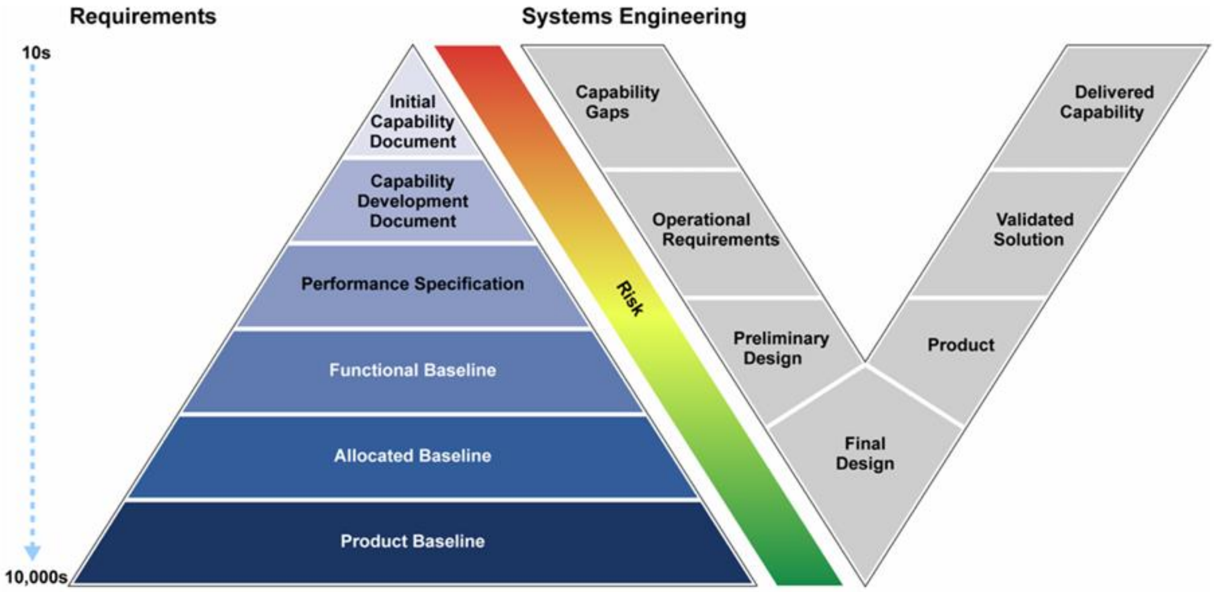


Figure 2.9 – Application of Systems and Requirements Engineering in Successful vs. Problematic Programs (U.S. Government Accountability Office, 2016).

The structured hierarchy of requirements, aligned with SE principles and grounded in documented system-level objectives and capability definitions, is essential for managing complex aerospace programs. As illustrated in Figure 2.11, the V-Model organizes the flow from high-level capability documents to product baselines, integrating risk management, systems engineering, and verification processes. This visual framework reinforces the principles established in ISO/IEC/IEEE 29148:2018 and SAE ARP 4754B. Projects that implement disciplined decomposition, baseline management, and early-stage traceability tend to achieve greater coherence, completeness, and efficiency throughout the verification and certification process.

Traceability evaluates the quality and completeness of system requirements, identifying omissions, ambiguities, or inconsistencies that may propagate errors. An FAA report linked deficient requirement definition processes to delays, rework, and operational risks in certified programs (2009-2015), emphasizing the importance of structured peer reviews, simulation-based validation, and prototyping before baseline finalization (United States, 2016).

To mitigate such risks, aerospace programs increasingly conduct multidisciplinary requirement reviews involving SE, safety, and certification experts. This integrated approach, aligned with SAE ARP4754B and FAA best practices, assesses clarity, consistency, and traceability before detailed design (SAE International, 2021; United States, 2016). Automated tools for textual analysis further detect ambiguities and structural gaps early in the verification process, as endorsed by NASA (NASA, 2016).

Standards like RTCA DO-178C and SAE ARP4754B mandate comprehensive documentation linking regulatory, functional, safety, and interface requirements to verification outcomes (RTCA, 2011; SAE International, 2021). Bidirectional traceability, from requirements to artifacts and back, is essential for managing complexity and substantiating compliance (Dick; Hull; Jackson, 2017; INCOSE, 2015).

Compliance traceability formalizes these links through matrices correlating each requirement with derived artifacts, verification methods, and observed results, reinforcing auditability (INCOSE, 2015; United States, 2016).

RTCA DO-178C exemplifies traceability enforcement by mandating explicit links between High-Level Requirements, Low-Level Requirements, source code, and verification activities, preventing unintended functionality in safety-critical software (RTCA, 2011). Traceability serves three key objectives in the certification process:

- Integrity: Ensuring every requirement is properly implemented and verified.

- Absence of Unintended Functionality: Preventing the inclusion of extraneous or undocumented functionality.
- Change Management: Supporting structured impact analysis for modified requirements.

In safety-critical systems, SAE ARP4754B and EASA CM SWCEH-001 emphasize traceability through safety assessments, linking hazards, architectural elements, and verification evidence to mitigate risks identified in Functional Hazard Assessments (FHAs) and System Safety Assessments (SSAs) (SAE International, 2021; EASA, 2022).

SAE ARP4754B requires traceability from safety analyses to top-level safety objectives, ensuring vertical consistency (hierarchical traceability from aircraft-level needs to components) and horizontal consistency (cross-domain integration across software, hardware, and human-machine interfaces). Compliance matrices map regulatory standards, such as 14 CFR § 25.1309 or RTCA DO-160, to internal verification records, serving as auditable evidence of regulatory fulfillment (United States, 2016; RTCA, 2010).

Integrating MBSE with SysML embeds requirements directly into models, establishing trace links from functional objectives to verification strategies. NASA’s OpenMBEE consolidates models, requirements, and test evidence, reinforcing the model-centric approach advocated by SAE ARP4754B, which explicitly links SysML diagrams to regulatory artifacts, enhancing both horizontal and vertical traceability (SAE International, 2021; NASA, 2016).

Despite advancements, maintaining high-integrity traceability remains a challenge. AI and NLP-based trace link recommendations show potential in mitigating risks of inconsistent traceability chains (Jesus; Soares, 2017). NASA (2024) suggests treating datasets, model architectures, and training parameters as traceable artifacts to preserve accountability in learning-enabled systems.

2.2.3 Model-Based Systems Engineering

Since the mid-2010s, academic and institutional studies have increasingly highlighted MBSE’s potential. Kaslow, Bass, and Graham (2017) demonstrated the use of SysML in small-scale space missions, capturing functional interfaces, requirements, and verification artifacts in a unified model. Bendarkar *et al.* (2022) advanced this concept by integrating architectural modeling with regulatory interpretation, mapping 14 CFR Part 25 requirements into SysML diagrams and directly linking them to system components and verification evidence, establishing end-to-end traceability from regulatory mandates to artifacts that substantiate compliance.

In Europe, the DIGACE initiative (Mirabella *et al*., 2024) proposes a comprehensive MBSE framework for CS-23 certification, integrating regulatory clauses, verification evidence, and compliance justifications within a unified digital platform. The framework incorporates automated checklists, traceability matrices, and structured technical submissions to streamline certification processes. Although DIGACE emphasizes digital integration, it does not explicitly align SAE ARP4761A with SysML as a direct standard practice. However, it facilitates digital audits by linking MATLAB/Simulink outputs to regulatory requirements, enabling traceability of simulation data to verification evidence.

In the United States, NASA has advanced MBSE in electrified and advanced aircraft systems. Glinski *et al*. (2022) proposed a framework that embeds regulatory constraints within system design models, enabling early detection of compliance gaps and structured evidence generation. Similarly, Gregory *et al*. (2020) demonstrated how MBSE mitigates informational gaps in complex programs by unifying safety objectives, operational constraints, and verification criteria within cohesive digital models.

Interoperability between modeling tools, requirements databases, and test platforms is hindered by the absence of universally adopted data exchange standards. While formats like ReqIF, XMI, and OSLC show promise, they lack formal regulatory endorsement and consistent implementation. FAA and EASA are involved in exploration efforts to standardize digital certification workflows. However, formal regulatory endorsement and process integration remain in development, and current regulations do not yet permit the full submission and auditing of digital artifacts.

Major OEMs like Boeing, Airbus, and Embraer have increasingly adopted hybrid MBSE workflows that integrate document-based deliverables with model-centric verification processes. These implementations focus on digital modeling of requirements subject to certification, integration of safety analyses, and structured organization of compliance evidence in SysML-based frameworks. This shift responds to industry demands for verifiable and auditable engineering workflows, underscored by documentation and traceability gaps revealed in the Boeing 737 MAX incidents (House of Representatives, 2020).

Boeing’s Model-Based Enterprise (MBE) exemplifies the institutionalization of MBSE in complex aerospace programs, integrating product, process, and compliance data through structured modeling practices and a comprehensive digital infrastructure. The MBE Diamond, adapted from its transformation initiatives (Farr *et al*., 2020), illustrates the integration of physical and virtual lifecycles. The lower portion represents the traditional V-model, covering physical activities such as requirements definition, design, manufacturing, testing, and certification. The upper portion maps the virtual lifecycle, including MBSE, Model-Based Definition, and Virtual Certification, interconnected by a Digital Thread that ensures traceability and data continuity. This structure enables early validation, model reuse, and regulatory alignment throughout the lifecycle.

This enterprise-level strategy exemplifies how MBSE can extend beyond engineering design to enhance regulatory compliance and certification traceability through a structured, scalable, and digitally integrated framework. Figure 2.11 visualizes the MBE Diamond, linking physical and virtual lifecycles through modeling and simulation, reinforcing traceability and data continuity.

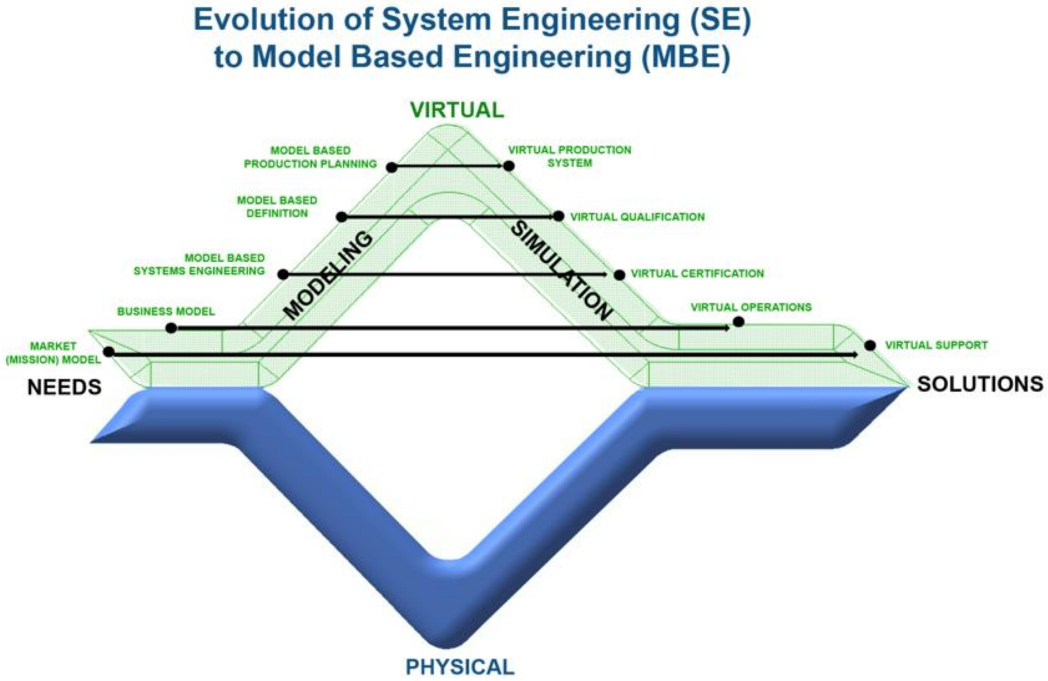


Figure 2.10 – Boeing’s MBE Diamond Framework (Adapted from Farr *et al*., 2020).

Despite methodological advances, MBSE adoption for certification faces challenges, including resistance to digital workflows, a shortage of skilled personnel, and the lack of regulatory recognition for models as certifiable artifacts (Ackva; Tschirner, 2015; Glinski *et al*., 2022).

3 Literature Mapping

This chapter presents a systematic literature mapping aligned with the research objectives, methodological foundations, and epistemological focus of this thesis. The aim is to identify, classify, and critically analyze the state of the art regarding the application of MBSE to enhance regulatory traceability and compliance verification in aerospace certification contexts.

To support replication and methodological rigor, the section follows the PRISMA 2020 protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which structures the review into four stages: identification, screening, eligibility assessment, and final inclusion (Page *et al*., 2021).

To ensure thematic alignment between the systematic review and the core research problem, a set of five Research Questions (RQs) was formulated. These questions were derived directly from the general and specific objectives outlined in Chapter 1. They serve as analytical pillars to guide the search, selection, and interpretation of literature, ensuring conceptual traceability between the review and the intended research contributions.

Table 3.1 presents the mapping between the research objectives and their corresponding RQs, highlighting how the questions operationalize the goals of this thesis.

Table 3.1 – Mapping between Research Objectives and Corresponding Systematic Review Questions.

Objective	Derived Research Question (RQ)
General Objective To develop a model-based traceability process for aerospace certification.	RQ1 – What model-based strategies and digital mechanisms have been proposed to enhance traceability and compliance verification in aerospace certification processes?
Specific Objective 1 Analyze certification process and propose a mapping to support traceability and interoperability.	RQ2 – How do current certification process address regulatory traceability, and what are the opportunities for MBSE-based mappings to improve interoperability?
Specific Objective 2 Develop a structured compliance process that integrates regulatory requirements, MoCs, corresponding technical documentation and validation activities within a model-based environment.	RQ3 – What approaches have been adopted to integrate regulatory requirements, MoCs, and technical documentation into structured compliance processes using MBSE? RQ4 – What are the main technical and institutional barriers that affect the implementation of automated or model-based verification in certification environments?
Specific Objective 3 Exemplify the proposed model-based traceability process through a simulated regulatory scenario focused on the eVTOL domain.	RQ5 – How have model-based traceability approaches been applied in emerging aviation domains such as eVTOLs, and what insights can be drawn from these applications for validation scenarios?

3.1 Process Applied in this Mapping

The systematic mapping process adhered strictly to the PRISMA 2020 protocol, as recommended by Page *et al.* (2021), ensuring methodological transparency, replicability, and consistency with evidence-based research practices. The temporal scope was delimited to the period from 2019 to 2024 to capture the most recent developments in model-based certification, with particular attention to digital compliance, regulatory traceability, and MBSE integration in safety-critical domains.

Databases and Search Strategy

Seven major databases were queried: Scopus, IEEE Xplore, Web of Science, MDPI, ScienceDirect, AIAA Aerospace Research Central (ARC), and NASA Technical Reports Server (NTRS). Google Scholar was used to retrieve relevant grey literature and to apply backward snowballing techniques.

The search strategy employed Boolean combinations of domain-specific keywords, including: "MBSE" OR "model-based systems engineering", "airworthiness" OR "aerospace certification", "traceability", "compliance", "digital certification pipeline", "ARP4754A", "ARP4754B", and "aviation regulation". These expressions were tailored to retrieve publications focused on the application of MBSE to regulatory contexts, certification workflows, and compliance verification strategies.

Inclusion Criteria

- Peer-reviewed journal articles, conference papers, dissertations, and institutional technical reports
- Publications in English
- Studies demonstrating the application of MBSE to aerospace certification, regulatory traceability, V&V, or safety justification
- Case studies involving emerging aviation domains (e.g., eVTOLs, UAS, electrified propulsion).

Exclusion Criteria

- Studies unrelated to certification or lacking a clear MBSE framework
- Theoretical or conceptual works without methodological or empirical validation
- Non-peer-reviewed sources and opinion pieces
- Duplicate records and documents published outside the selected timeframe

Screening and Selection Process

Of the 410 records initially retrieved, 108 duplicates were excluded. A total of 302 records underwent title and abstract screening. Fifty-three full-text documents were assessed for eligibility, from which 21 studies satisfied all inclusion criteria. The exclusions were distributed as follows:

- 150 studies did not address MBSE within airworthiness or certification contexts
- 80 failed to present methodological rigor or reproducible frameworks
- 10 were published in non-English languages
- 5 were identified as non-peer-reviewed or informal publications

Each selected study was analyzed using a structured data extraction template covering bibliographic metadata, research objectives, methodologies, tools, contributions to MBSE-certification integration, and identified technical or methodological gaps.

Thematic Synthesis

The selected studies were grouped into four thematic clusters:

- MBSE-Based Digital Certification Frameworks
- MBSE Integrated with Safety and Verification Strategies
- Applications for Emerging Aviation Technologies (eVTOL, UAS)
- Tool Interoperability and Regulatory Acceptance Barriers

This thematic synthesis provides the foundation for the critical analysis presented in the subsequent sections. Figure 3.1 presents the PRISMA 2020 diagram summarizing the review workflow, including identification, screening, eligibility, and final inclusion stages.

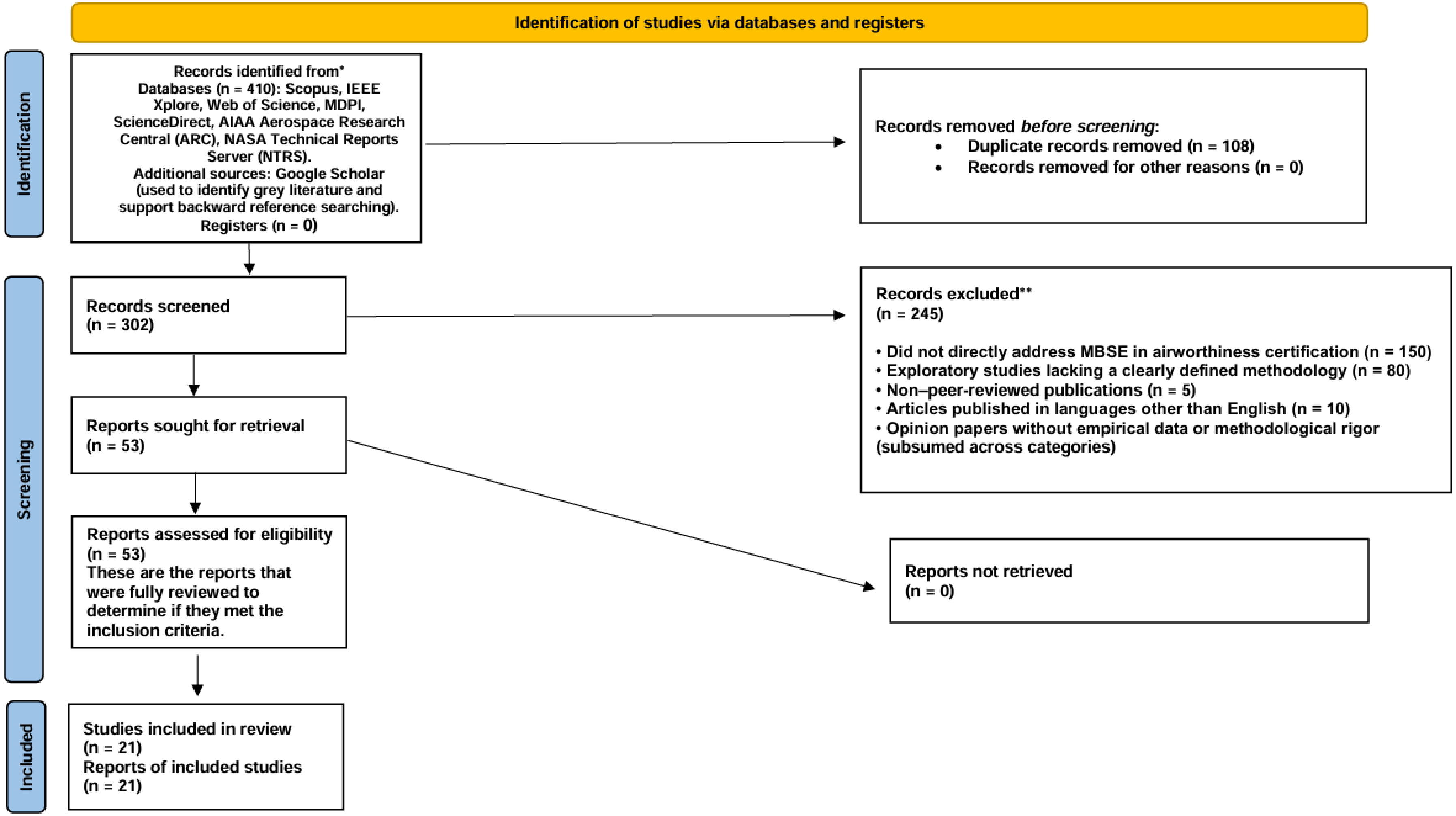


Figure 3.1 – PRISMA 2020 flow diagram applied to the systematic review on MBSE in aerospace certification (Adapted from Page *et al*., 2021).

3.2 Thematic Synthesis and Critical Contributions from the Selected Literature

Following the systematic review protocol detailed in Section 3.1, this section presents a critical analysis of the 21 selected studies. Each was evaluated considering its methodological rigor and contribution to model-based certification, regulatory traceability, and the integration of MBSE within aerospace certification contexts. Through thematic synthesis, four interrelated categories were defined, reflecting the central pillars of this thesis: (1) model-based certification frameworks, (2) MBSE applications to emerging technologies, (3) integration with safety, V&V, and MoC, and (4) standardization, semantics, and regulatory harmonization.

1 - Model-Based Certification Frameworks

This category consolidates studies that employ formal MBSE frameworks, particularly those grounded in SysML, to structure certification workflows, promote end-to-end traceability, and support the systematic generation of compliance artifacts.

Bleu-Laine *et al*. (2019), Fazal *et al*. (2022), and Harrison *et al*. (2021) emphasize SysML-based architectures to map certification evidence across regulatory domains.

Bendarkar *et al*. (2023), Glinski *et al*. (2022), and Mirabella *et al*. (2024) advance techniques for automated requirement extraction, regulatory gap analysis, and the implementation of digital certification pipelines.

These studies support the thesis’s proposition that MBSE can formalize and consolidate regulatory flows, enabling traceable and auditable compliance across complex system architectures.

2 - MBSE for Emerging Aerospace Technologies

This category addresses how MBSE must adapt to the certification of disruptive aviation technologies such as eVTOLs, UAS, and electrified propulsion systems, whose configurations challenge existing regulatory paradigms.

Mou *et al*. (2020) and Ravikanti *et al*. (2024) provide MBSE-based frameworks tailored to eVTOL and UAS certification.

Torrigiani *et al*. (2021), Glinski *et al*. (2022), and Long *et al*. (2021) explore regulatory misalignments and propose model-based strategies to mitigate compliance uncertainty in emerging platforms.

These studies reinforce the thesis’s motivation to develop a flexible and adaptive MBSE-based framework capable of bridging regulatory gaps in the certification of novel aerospace systems.

3 - Integration with Safety, V&V, and Means of Compliance

This thematic axis highlights how MBSE supports the formalization of safety requirements, the implementation of structured V&V processes, and the consolidation of MoC within certification workflows.

Harrison *et al*. (2021), Daw and Beecher (2023), and Villegas *et al*. (2022) present verification strategies grounded in simulations, safety analyses, and structured test planning.

Cartile *et al*. (2023), Haider (2022), and Ali *et al*. (2024) investigate semantic modeling, MBSA, and the automation of safety requirement verification.

Pittini and Kourousis (2023), Husung *et al*. (2021), and Haider (2022) integrate MBSE with safety assessment techniques to reinforce design assurance and lifecycle consistency.

These contributions support the claim that MBSE can embed safety justifications into the system model, enhancing traceability and reinforcing compliance across abstraction levels.

4 - Standardization, Semantics, and Regulatory Harmonization

This final category aggregates studies focused on ontological modeling, vocabulary harmonization, and the use of semantic structures to support cross-authority certification frameworks.

Ma *et al*. (2022), Cartile *et al*. (2023), and Clare and Kourousis (2021) explore the use of formal semantics, ontologies, and lessons from safety incident analyses to enhance regulatory clarity and standard interpretation.

These findings provide the semantic foundation for this thesis’s traceability framework, which depends on consistent, machine-interpretable representations of regulatory obligations.

To support the thematic synthesis, each article was evaluated according to four analytical dimensions: (i) its core methodological contribution (e.g., MBSE, AI, semantic modeling), (ii) the regulatory context addressed (civil, military, UAS, etc.), (iii) the domain of application (e.g., certification, safety, V&V), and (iv) the implementation of formal traceability mechanisms. These dimensions enabled the structured classification of studies, forming the analytical foundation for Table 3.2, which provides a tabular overview of the selected literature by number, title, authorship, and publication year.

Table 3.2 – Studies included in the systematic literature review (2019–2024).

ID	Study Title	Authors	Year of Publication
1	A Model-Based System Engineering Approach to Normal Category Airplane Airworthiness Certification	Bleu-Laine *et al.*	2019
2	Framework for Certification of AI-Based Systems	Gariel *et al.*	2023
3	Certification Considerations of eVTOL Aircraft	Mou *et al.*	2020
4	A Model-Based System Engineering Approach to the Certification of Aircraft Systems	Harrison *et al.*	2021
5	Development of a Language Model for Named-Entity Recognition in Aerospace Requirements	Tikayat Ray *et al.*	2024
6	Harmonizing and Standardizing Military Airworthiness in Europe	Pittini & Kourousis	2023
7	Assuring Safety in a Flexible Aerospace Certification	Daw & Beecher	2023
8	An Extended MBSE Framework for Regulatory Analysis of Aircraft Architectures	Bendarkar *et al.*	2023
9	An MBSE Framework for Regulatory Modeling of Transport Category Airplanes	Fazal *et al.*	2022
10	MBSE-Enabled System Verification of UAS Noise Certification	Ravikanti *et al.*	2024
11	Semantic Modeling Approach Supporting Process Modeling in Aircraft Development	Ma *et al.*	2022
12	MBSE Certification-Driven Design of a UAV MALE Configuration	Torrigiani *et al.*	2021
13	An MBSE Framework to Identify Regulatory Gaps for Electrified Transport Aircraft	Glinski *et al.*	2022
14	Demonstrating a Semantic Approach to Clarifying Regulatory Ambiguity	Cartile *et al.*	2023
15	Learning from Incidents in Aircraft Maintenance and Continuing Airworthiness	Clare & Kourousis	2021
16	Verification and Validation Framework for AFDX Avionics Networks	Villegas *et al.*	2022
17	Applying Model-Based Safety Assessment for Aircraft Landing Gear System Certification	Haider	2022
18	Model-Based Systems Engineering – A New Way for Function-Driven Product Development	Husung *et al.*	2021

Table 3.2 – Studies included in the systematic literature review (2019–2024) (cont.).

ID	Study Title	Authors	Year of Publication
19	Demand Analysis in Urban Air Mobility: A Literature Review	Long *et al.*	2023
20	MBSE Enabled Requirement Verification for a Traceable Regulatory Framework	Ali *et al.*	2024
21	A Model-Based Systems Engineering Approach Towards Aircraft Digital Certification	Mirabella *et al.*	2024

Beyond the extraction of bibliographic metadata, a qualitative synthesis was conducted to examine the conceptual and methodological contributions of each selected study. This synthesis focused on how each work articulates the principles of MBSE with regulatory processes, assessing the extent to which it addresses core elements such as traceability, compliance verification, and certification strategies.

The results of this critical assessment are consolidated in Table 3.3, which synthesizes the main contribution of each study and systematically maps its alignment with the research objectives, guiding hypotheses, and traceability process proposed in this thesis.

Table 3.3 – Summary and Relevance to the Thesis.

ID	Key Contribution	Connection to this Thesis
1	Development of a SysML-based MBSE framework for automating compliance checklists, integrating FAR 23 regulations with ASTM consensus standards in a model-driven certification plan.	Fundamental for demonstrating MBSE's role in enhancing regulatory compliance and traceability.
2	AI-based framework for certifying deep neural networks, focusing on traceability across datasets, training processes, and runtime performance, in scenarios where DO-178 is inapplicable.	Reinforces AI's role in enabling automated traceability and regulatory compliance in aerospace systems.
3	Risk-informed certification strategies for eVTOL architectures, highlighting the mismatch with existing FARs and proposing adaptive frameworks based on consensus standards and operational scenarios.	Shows the need for flexible certification frameworks to integrate emerging aerospace technologies.

Table 3.3 – Summary and Relevance to the Thesis. (cont.).

ID	Key Contribution	Connection to this Thesis
4	Development of an MBSE digital thread to structure compliance with 14 CFR Part 25, enhancing traceability, verification methods, and generation of certification artifacts in powerplant systems.	Highlights the importance of formal verification and methodologies for complex aerospace systems.
5	Development of the aeroBERT-NER model to identify aerospace-specific named entities, enhancing the traceability and standardization of natural language requirements in MBSE contexts	Validates the use of NLP and machine learning to automate requirement extraction and regulatory compliance.
6	Critical review of EMAR-based harmonization of military airworthiness across Europe, highlighting structural and regulatory integration challenges that support traceable certification practices.	Supports the use of MBSE for creating a unified regulatory framework that adapts to military-specific requirements and facilitates harmonization through EMAR adoption across European countries.
7	Demonstrates the use of Overarching Properties (OPs) as alternative Means of Compliance in the certification of a Level A system, leveraging MBSE to support structured assurance arguments in the certification of APU control software and hardware.	MBSE supports flexible safety assessment methodologies in aerospace by enabling OPs to serve as alternative Means of Compliance for novel and critical systems.
8	Extended MBSE framework enabling automated extraction of certification bases and regulatory gap analysis for conventional and electrified aircraft, using enriched SysML regulatory models aligned with 14 CFR Part 25.	Integrates MBSE with automated tools to streamline the identification of regulatory gaps and improve compliance.
9	Proposes a SysML-based regulatory modeling framework for 14 CFR Part 25, improving traceability, transparency, and compliance verification through structured representation of requirements, contexts, and tests.	Improves the transparency of certification processes and reduces documentation complexity for complex aircraft.
10	MBSE-enabled framework for defining and validating noise certification basis for UAS, integrating requirement traceability, compliance modeling, and iterative refinement based on FAA-specific standards and urban eVTOL missions.	Highlights how MBSE can be applied to specialized systems like UAS to ensure compliance with noise certification regulations.

Table 3.3 – Summary and Relevance to the Thesis. (cont.).

ID	Key Contribution	Connection to this Thesis
11	Semantic modeling using the KARMA language to integrate process modeling, static cost verification, and dynamic lifecycle analysis in aircraft system development, enhancing MBSE traceability and reusability.	Demonstrates the synergy between MBSE and semantic models to improve lifecycle traceability and cost efficiency.
12	MBSE-based certification-driven design for a MALE UAV configuration, integrating multidisciplinary requirements, stakeholder scenarios, and regulatory compliance processes in alignment with EASA CS 25 and AMC 20-136.	Validates MBSE's role in managing complex certification tasks for UAVs and electrified aircraft.
13	MBSE-based framework for detecting regulatory gaps in the certification of electrified aircraft by mapping functional requirements to novel physical implementations, enabling formal analysis of Part 25 applicability and coverage.	Aligns MBSE with the needs of electrified aircraft certification and regulatory adaptation for new propulsion systems.
14	Proposes a semantic modeling approach combining ontologies, process mapping, and UML to clarify regulatory ambiguity in aircraft certification, enhancing traceability and model interoperability through formalized terminology structures.	Validates the importance of semantic structures in improving regulatory interpretation and traceability.
15	Critically reviews European regulations on maintenance and continuing airworthiness, identifying systemic gaps in incident learning, and advocating for structured, traceable methods to integrate safety feedback into certification processes.	Strengthens the need for structured methodologies to close gaps in regulatory frameworks and improve compliance.
16	Development of AVVorks framework for verification and validation of AFDX avionics networks using model-supported simulations and formal timing analysis, demonstrating compliance with avionics performance constraints but without extensive integration of traditional MBSE architectures.	Demonstrates how MBSE enhances the reliability of avionics systems and facilitates certification

Table 3.3 – Summary and Relevance to the Thesis.(cont.).

ID	Key Contribution	Connection to this Thesis
17	Application of MBSA to aircraft landing gear and steering systems, supporting compliance with FAR 25.1309 through simulation-based failure injection and integration with updated SAE ARP 4761A guidance.	Highlights MBSA's role in improving safety certification and traceability for critical aircraft systems, especially where virtual testing can replace hazardous or infeasible flight test scenarios.
18	Presents a theoretical foundation for MBSE-driven functional modeling in product development, emphasizing traceability, system decomposition, and integration of requirements, design rationale, and regulatory compliance.	Validates how MBSE bridges gaps between product development and certification through model-driven processes.
19	Systematic review of demand estimation methodologies for Urban Air Mobility (UAM), outlining how operational, economic, and societal constraints drive regulatory requirements and certification priorities for novel platforms such as eVTOLs.	Addresses the regulatory adaptation challenges for novel technologies like eVTOLs and UAM.
20	Proposes a SysML-based framework for requirement verification and regulatory analysis of UAS noise certification, integrating real-world test data with model-based verification to assess the technical feasibility and proportionality of FAA and EASA standards.	Demonstrates how MBSE supports regulatory verification and compliance throughout the product lifecycle.
21	Introduces a fully digital certification pipeline for CS-23 aircraft using MBSE and SysML modeling, enabling automated artifact generation, regulatory traceability, and integration of verification test cases into formal compliance workflows.	Supports the integration of MBSE into digital certification workflows for emerging technologies in aerospace.

3.3 Positioning of this Work

The literature reviewed reveals persistent shortcomings in how traceability is implemented within aerospace certification contexts. Despite growing interest in the use of MBSE for safety-critical systems, most studies continue to treat regulatory, technical, and verification artifacts as disconnected entities. Two major deficiencies became evident across the selected works.

The first concerns the limited integration of regulatory content into model-based environments. While there is progress in modeling functional and safety requirements, few efforts explicitly embed regulatory clauses, compliance strategies, and verification evidence into the same traceable structure. This fragmentation undermines auditability and weakens confidence in digital certification processes. The process proposed here addresses this gap by embedding certification logic into SysML models, enabling consistent and bidirectional traceability from regulatory statements to system design elements and their supporting evidence.

The second challenge involves the disconnect between certification artifacts and the operational life of the system. Most approaches remain focused on pre-delivery phases, overlooking the importance of maintaining traceability after entry into service. This limits the ability to track deviations, support predictive maintenance, or integrate field data into safety assessments. To close this gap, the proposed process incorporates Digital Twins as living extensions of the certified configuration, linking design intent with real-world performance and maintenance records. This connection enhances the transparency and continuity of airworthiness oversight throughout the lifecycle.

Multiple studies highlighted the lack of structured regulatory traceability and the barriers to operational integration of model-based strategies. The themes synthesized in the literature mapping, such as harmonization, auditability, digital verification, and adoption hurdles, provided clear evidence of where current methods fall short.

This thesis demonstrates that model-based traceability can serve as a unifying strategy to address these limitations. By formally connecting regulatory, technical, and operational dimensions, it becomes possible to reinforce confidence in digital compliance and streamline the certification process. In doing so, this work contributes to the evolution of certification practices toward a more integrated, traceable, and auditable future.

4 Methodology

This chapter establishes the methodological foundation for the development of a model-based traceability process for aerospace certification.

The chapter is organized into four sections:

4.1 Materials: Describes the normative and technical sources employed in the process's development, including the SysML modeling environment and FAA Type Certification processes.

4.2 Review of the Current Certification Process: Analyzes the conventional certification workflow, identifying limitations in continuous traceability, compliance formalization, and verification planning, aspects that remain predominantly document-centric and unstructured.

4.3 Development of the Thesis Artefact: Details the construction of the Authority Regulatory Model, encompassing the selection of regulatory documents, the structuring of traceability through SysML.

4.4 Reconfiguration of the Certification Process with MBSE: Demonstrates how the proposed process transforms the traditional certification process, integrating requirements, MoCs, and compliance evidence into an auditable, consolidated, and interoperable model.

4.1 Materials

The modeling environment selected for implementing the MBSE-based artifact is SysML, enabling the structured representation of complex systems, including traceability between requirements, functions, and verification elements.

In addition to the modeling tool, this research relies on the TC process established by the FAA, as defined in FAA Order 8110.4C and related guidance. This process serves as the baseline for understanding the sequential phases, roles, and deliverables expected in civil certification projects.

4.1.1 Systems Modeling Language

MBSE employs a variety of diagram types to represent both the structural and behavioral aspects of complex systems. SysML, currently the most widely adopted language in MBSE practice, defines nine primary diagram types, which are conventionally grouped into two main categories: structural diagrams and behavioral diagrams.

Structural diagrams aim to capture the static architecture and interrelationships of system components. The five SysML diagram types in this category are:

Requirement Diagram: Captures system requirements and their hierarchical relationships, enabling traceability throughout the development lifecycle.

Block Definition Diagram (BDD): Describes the system’s structural elements, their properties, and relationships using blocks and associations.

Internal Block Diagram (IBD): Details the internal structure of blocks, emphasizing ports, flows, and connectors.

Parametric Diagram: Expresses quantitative constraints among system parameters, facilitating trade-off and performance analysis.

Package Diagram: Organizes model elements into cohesive packages, supporting modularity and manageability in large-scale projects.

Figure 4.1 illustrates these five structural diagram types offering a consolidated view of the core SysML constructs used to model the static aspects of a system.

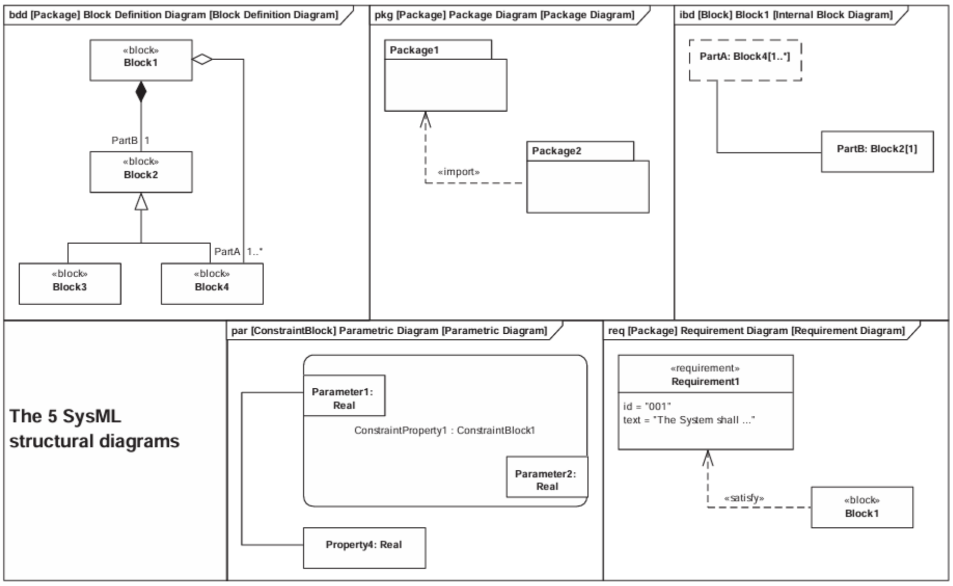


Figure 4.1 – SysML structural diagrams (Holt; Perry, 2019).

Behavioral diagrams represent the dynamic aspects of the system, capturing interactions, processes, and event-driven behavior. The four SysML diagram types in this category are:

Use Case Diagram: Depicts functional capabilities of the system and its interactions with external actors.

Activity Diagram: Models the flow of control and data through sequential or concurrent system activities.

Sequence Diagram: Shows the chronological exchange of messages among components or actors.

State Machine Diagram: Represents the discrete states of a system component and the transitions triggered by events or conditions.

Figure 4.2 presents examples of these four behavioral diagram types highlighting the mechanisms by which SysML captures the system's functional and dynamic perspectives. These representations support the modeling of use scenarios, logic flows, reactive states, and time-based interactions essential for certification-oriented analysis.

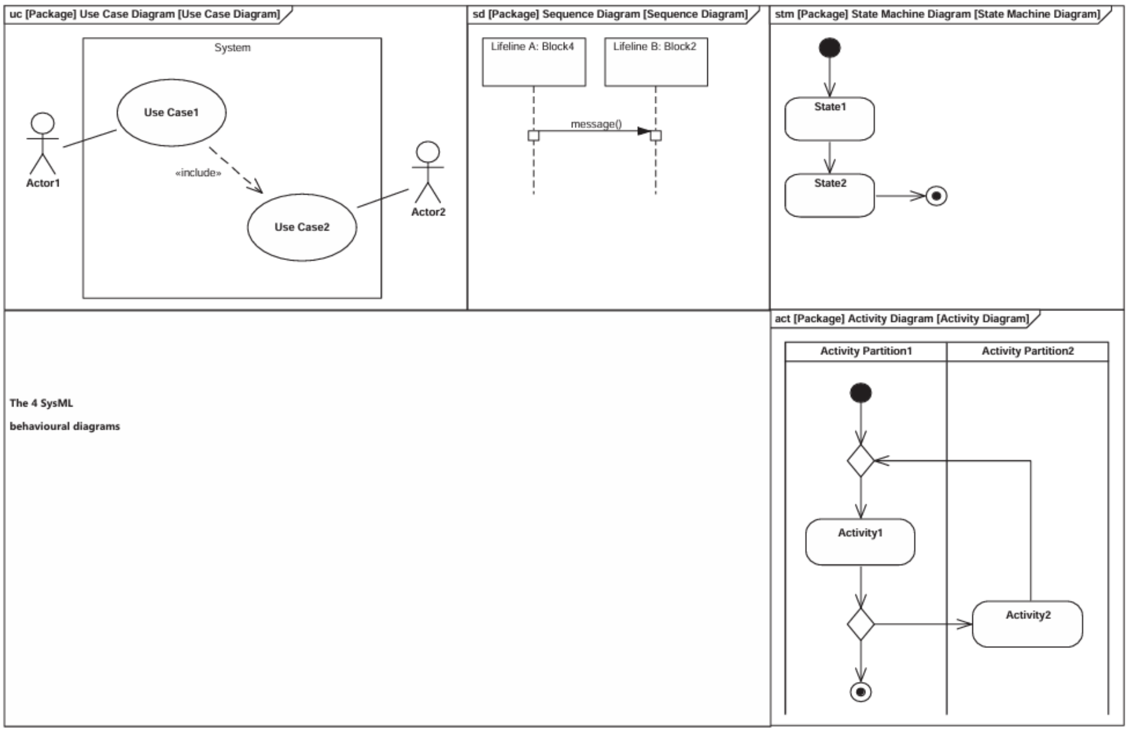


Figure 4.2 – SysML behavioural diagrams (Holt; Perry, 2019).

4.1.2 FAA Type Certification Process

The TC process conducted by the FAA is structured into five distinct phases, as defined in the FAA Order 8110.4 and the Certification Process Improvement Guide. Each phase involves specific technical objectives, formal deliverables, and structured interactions between the FAA and the applicant (United States, 2017).

Phase I – Conceptual Design

In this phase, the applicant presents an initial design concept with potential for certification. Preliminary discussions are held to identify broad safety objectives, anticipated risks, and areas of regulatory attention. Early coordination is encouraged to align expectations and clarify technical or procedural complexities before formal project initiation.

Phase II – Requirements Definition

This stage focuses on identifying the applicable certification basis, including relevant sections of 14 CFR (e.g., Part 23, Part 25), as well as any Special Conditions, exemptions, or Equivalent Level of Safety findings. The applicant and the FAA collaboratively define the Project Specific Certification Plan as a detailed roadmap for compliance activities. The PSCP is developed within the framework of the Partnership for Safety Plan, which outlines the general working agreement between the FAA and the organization.

Phase III – Compliance Planning

During this phase, the PSCP is finalized. Compliance methods are defined, documentation protocols are clarified, and alignment is achieved regarding engineering conformity plans and certification milestones. The FAA and the applicants confirm the proposed MoCs, establish the Certification Plan Agreement, and formalize conformity documentation.

In the FAA jurisdiction, MoCs are technically sound methods deemed sufficient to satisfy the provisions of Title 14 of the CFR. Although alternative approaches may be proposed, they require detailed justification and formal approval, as outlined in various ACs.

Table 4.1 classifies these MoCs based on their nature and the supporting documentation typically required. This structure underpins the framework’s logic for associating technical artifacts with their respective compliance strategies.

Table 4.1 – MoCs for aircraft requirements (De Florio, 2016).

Type of Compliance	**Means of Compliance**	**Associated Compliance Documents**
Engineering evaluation	MoC0: - Compliance statement - Reference to Type Design documents - Election of methods, factors etc. - Definition	- Type Design documents - Recorded statements
	MoC1: Design review	- Description -Drawings
	MoC2: Calculation/Analysis	- Substantiation reports
	MoC3: Safety assessment	- Safety analysis
Tests	MoC4: Laboratory tests	- Test programs - Test reports - Test interpretations
	MoC5: Ground tests	
	MoC6: Flight tests	
	MoC8: Simulation	
Inspection	MoC7: Design inspection/audit	- Inspection or audit reports
Equipment qualification	MoC9: Equipment qualification	- Note: Equipment qualification is a process which may include all previous means of compliance

Phase IV – Implementation

This phase encompasses the execution of all verification activities planned in the PSCP. These include engineering analyses, ground and laboratory tests, and flight tests. FAA designees, such as DERs, may witness or approve these activities under FAA oversight. The issuance of a Type Inspection Authorization, when applicable, allows FAA-conducted or FAA-authorized flight tests. All supporting evidence, including test results, inspection reports, and compliance checklists, must be submitted. Upon completion, a Certification Summary Report is compiled to consolidate the entire compliance demonstration.

Phase V – Post-Certification

Following technical approval, the FAA issues the TC and the associated TCDS, which formally defines the product’s configuration and limitations. This phase also includes evaluation by the Aircraft Evaluation Group, with a focus on operational suitability, ICA, and maintenance documentation. Any post-certification items, such as safety-related updates, corrective actions, or airworthiness directives, are also addressed during this stage.

The FAA model relies on delegation mechanisms such as the DER and ODA systems. While the ODA framework enables organizations to perform specific certification functions, it is structured as a delegation contract rather than a formal regulatory approval of the internal assurance system (United States, 2013).

Figure 4.3 provides an overview of the FAA’s certification process, illustrating key activities, deliverables, and formal checkpoints across the five phases. The diagram is adapted from internal FAA documentation and serves as a reference for applicants and regulatory stakeholders.

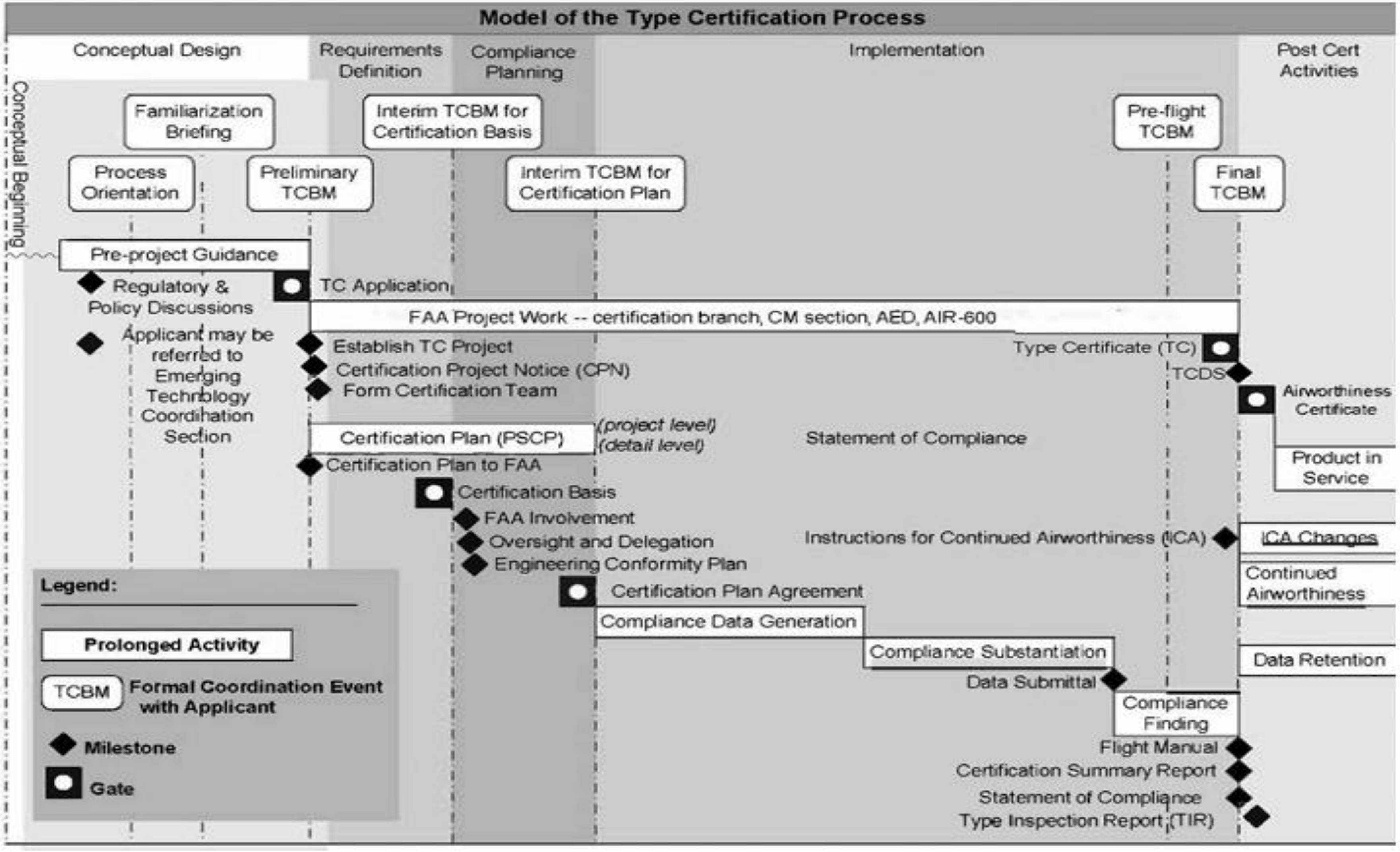


Figure 4.3 – FAA Type Certification Process Model (United States, 2007).

4.2 Review of the Current Certification Process

Figure 4.4 presents a structured depiction of the TC process, segmented into eight steps that encompass the regulatory practices. The flowchart shows the core activities, decision points, and deliverables integral to the certification process, highlighting the distinct roles of the applicant and the certifying authority.

The flowchart illustrates some feedback loops that may arise due to inadequately defined requirements, misaligned MoCs, or unresolved nonconformities during the verification stage.

The subsections (4.2.1 to 4.2.8) provide an examination of each stage, outlining its objectives, regulatory process, and deliverables.

4.2.1 Establish Certification Basis

Identify applicable regulatory requirements and establish the certification basis. At this stage, the certification authority determines the applicable regulations for the specific project. Certification initially focuses on minimum safety requirements, establishing a matrix of requirements and their respective MoCs. This process is iterative and involves alignment with the applicant to ensure that essential requirements are identified and documented. This stage corresponds to Phases I and II - FAA.

4.2.2 Define Preliminary Means of Compliance

Develop preliminary MoCs to demonstrate compliance with established requirements. In this step, the developer proposes preliminary methods for demonstrating compliance and submits them to the certification authority for review. The objective is to ensure that each requirement identified in the matrix has a suitable verification method, aiming to reduce ambiguities and align expectations between the developer and the certification authority. This stage corresponds to Phase II - FAA.

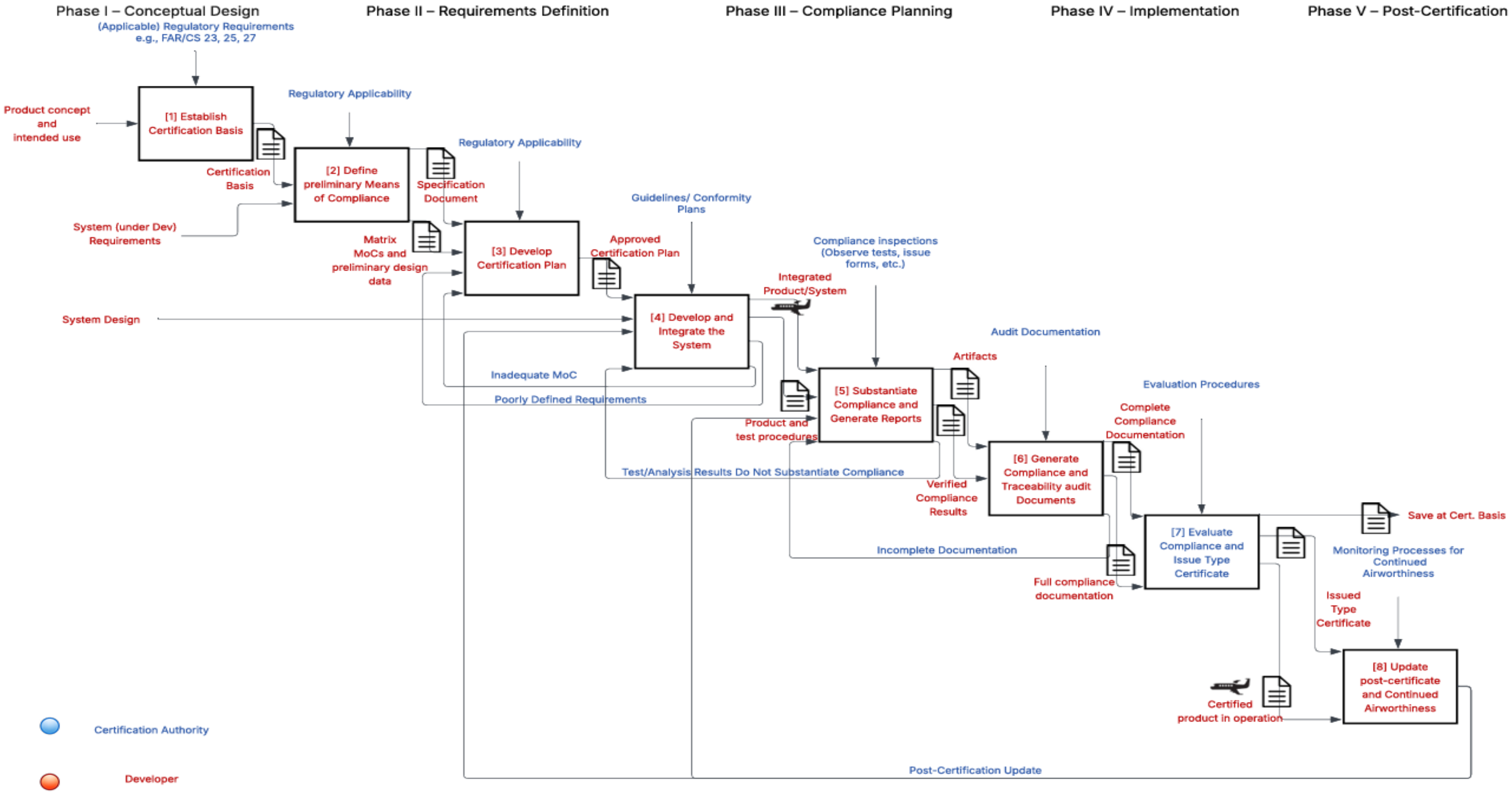


Figure 4.4 – Type Certification Process Flow.

4.2.3 Develop Certification Plan

Formalize the certification plan, including schedule, artifacts, and compliance procedures. The certification plan consolidates the defined MoCs and establishes a schedule for verification and validation activities. During this stage, the developer must ensure that all necessary artifacts for submission are organized, including design specifications, test plans, and compliance analysis. The certification authority reviews and approves the plan before implementation begins. This stage corresponds to Phase III - FAA.

4.2.4 Develop and Integrate the System

Execute system development and subsystem integration in accordance with the established MoCs. During this step, testing and compliance analysis are conducted simultaneously with system development. Each subsystem is verified according to the approved MoCs, and the results are documented for inclusion in the final certification package. Issues identified may result in MoC revisions and adjustments to the certification plan. This stage corresponds to Phases III and IV - FAA.

4.2.5 Substantiate Compliance and Generate Reports

Validate test results and generate compliance reports. Reports are generated based on data collected during testing and analysis, linking each MoC to the requirements established in the certification matrix. The developer must ensure that all data is structured in an auditable and verifiable format, allowing the certification authority to clearly trace compliance. This stage corresponds to Phase IV - FAA.

4.2.6 Generate Compliance and Traceability Audit Documents

Compile all compliance documentation and traceability evidence. At this stage, all reports, artifacts, and compliance evidence are organized into a single package, allowing the certification authority to conduct traceability audits. This package must ensure that all requirements have been met, and that the documentation is complete and consistent with the approved certification plan. This stage corresponds to Phase IV - FAA.

4.2.7 Evaluate Compliance and Issue Type Certificate

Evaluate final compliance and issue the Type Certificate. The certification authority conducts a final review of the compliance documentation, verifying the complete traceability of MoCs, requirements, and evidence. Once approved, the Type Certificate is issued, formalizing the acceptance of the product for commercial operation. This stage corresponds to Phases IV and V – FAA.

4.2.8 Update Post-Certificate and Continued Airworthiness

Monitor continued compliance after the issuance of the Type Certificate. After the issuance of the Type Certificate, the product enters a phase of continuous monitoring. The developer must update the MoCs, and documentation as new guidelines or operational issues arise, keeping the certification authority informed and ensuring operational safety. This stage corresponds to Phase V – FAA.

4.3 Implementation and Integration of the Model-Based Traceability Process

Figure 4.5 presents a structured depiction of the Authority Regulatory Model development process, segmented into six sequential steps encompassing the alignment of regulatory process with SysML-based traceability structures. The flowchart delineates the activities, to the model construction, emphasizing the conversion of regulatory texts into structured, traceable model elements.

The subsections (4.3.1 to 4.3.6) provide a detailed examination of each step, outlining its primary objectives, regulatory focus, and expected outputs, facilitating a cohesive integration of regulatory content into the Authority Regulatory Model.

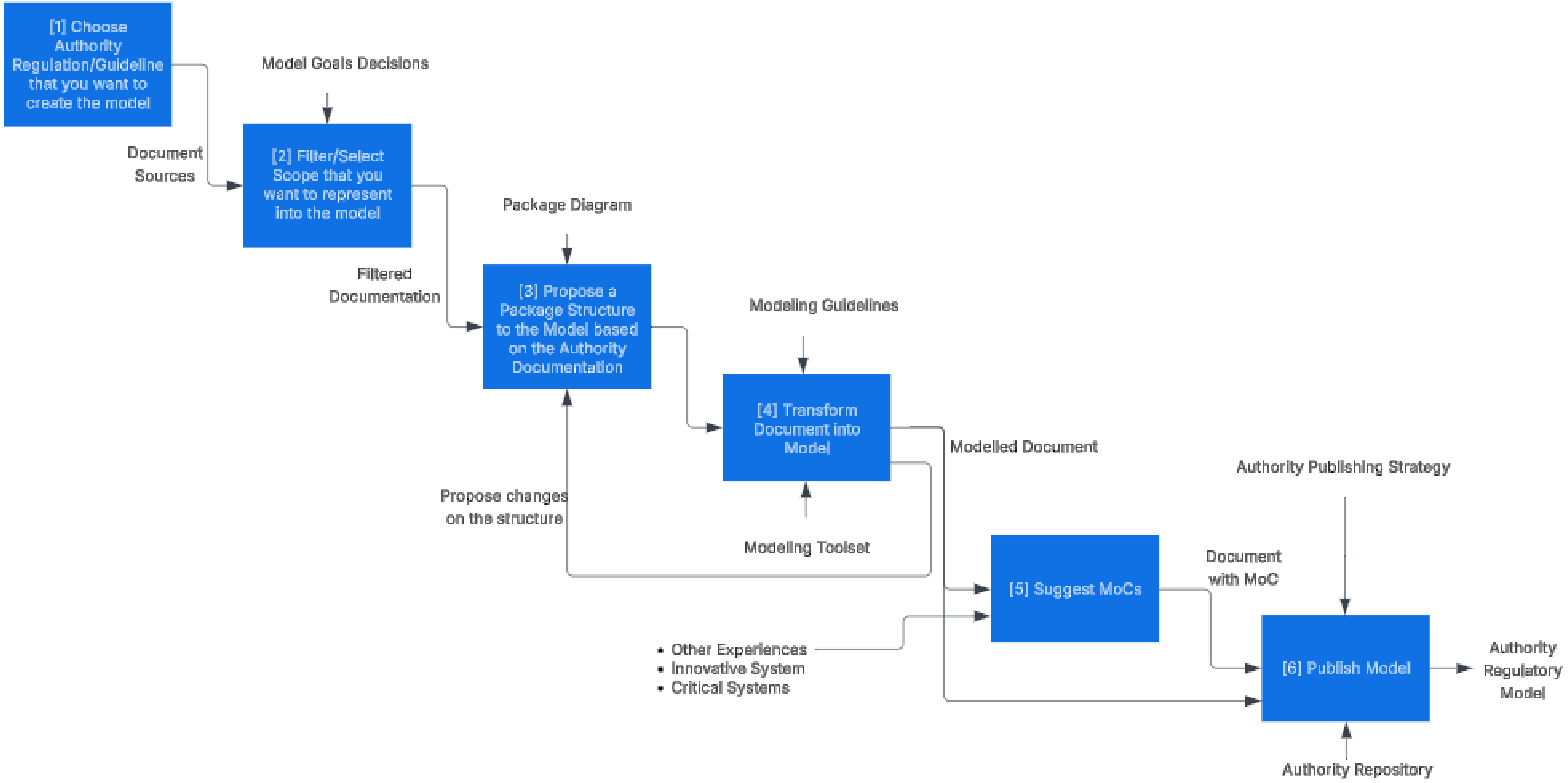


Figure 4.5 – Sequential Development Flow of the Authority Regulatory Model

4.3.1 Choose Authority Regulation/Guideline that you Want to Create the Model

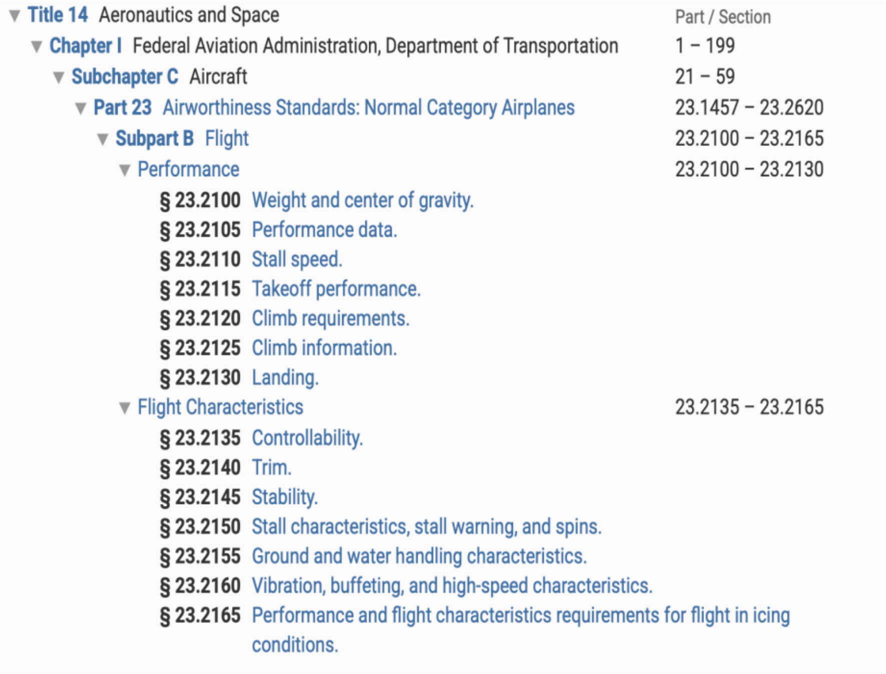
The initial step in constructing the Authority Regulatory Model involves selecting a specific regulatory document issued by a certification authority. This document serves as the foundational reference for the model-based transformation and can include regulations, procedural guides, or certification process.

Rather than replicating the entire regulatory corpus, the objective can be strategically select a document that is both operationally relevant and structurally suitable for traceability modeling. This targeted approach ensures that the selected document effectively defines the scope, structure, and verification pathways to be systematically represented in the model, establishing a clear process for the subsequent development phases.

4.3.2 Filter/Select Scope that you Want to Represent into the Model

This step focuses on identifying segments that are operationally significant, verifiable, and critical to the certification process.

To contextualize the selection process, Figure 4.6 present Structure of Title 14, Code of Federal Regulations, Aircraft Subchapter illustrates the overarching structure of Title 14, highlighting the location of the certification requirements relevant to this study.



	Part / Section
▼ **Title 14** Aeronautics and Space	
▼ **Chapter I** Federal Aviation Administration, Department of Transportation	1 – 199
▼ **Subchapter C** Aircraft	21 – 59
▼ **Part 23** Airworthiness Standards: Normal Category Airplanes	23.1457 – 23.2620
▼ **Subpart B** Flight	23.2100 – 23.2165
▼ Performance	23.2100 – 23.2130
§ 23.2100 Weight and center of gravity.	
§ 23.2105 Performance data.	
§ 23.2110 Stall speed.	
§ 23.2115 Takeoff performance.	
§ 23.2120 Climb requirements.	
§ 23.2125 Climb information.	
§ 23.2130 Landing.	
▼ Flight Characteristics	23.2135 – 23.2165
§ 23.2135 Controllability.	
§ 23.2140 Trim.	
§ 23.2145 Stability.	
§ 23.2150 Stall characteristics, stall warning, and spins.	
§ 23.2155 Ground and water handling characteristics.	
§ 23.2160 Vibration, buffeting, and high-speed characteristics.	
§ 23.2165 Performance and flight characteristics requirements for flight in icing conditions.	

Figure 4.6 – Structure of Title 14, Code of Federal Regulations – Aircraft Subchapter.

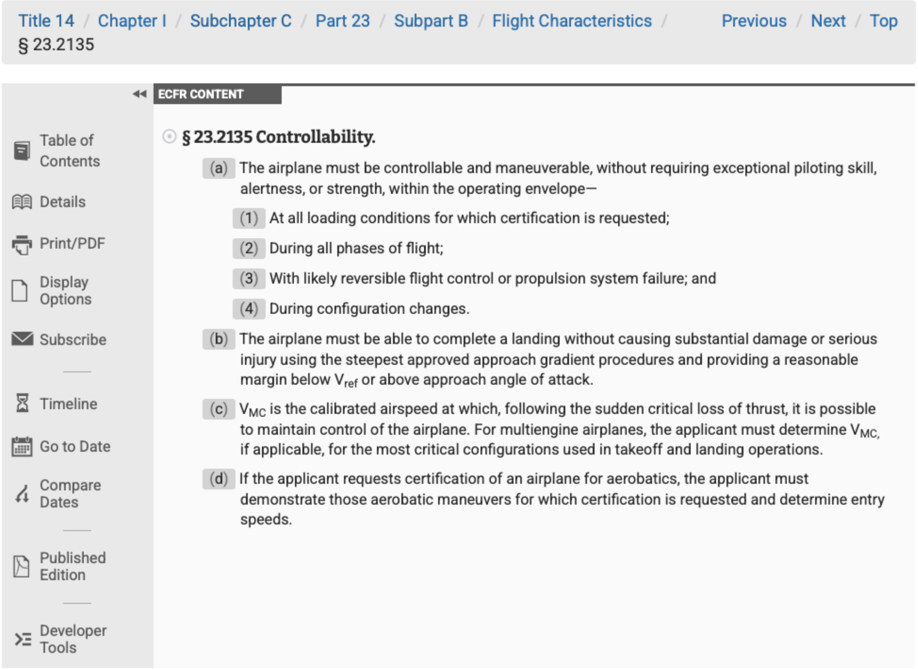
Once the regulatory structure is established, the scope is further refined by focusing on regulatory parts. In this model, the selected scope was narrowed to Subpart B, Performance and Flight Characteristics, which is presented in Figure 4.7, Overview of Subpart B, Performance and Flight Characteristics Requirements. This section encompasses essential criteria related to aircraft performance, stall characteristics, and controllability.

▼ **Subpart B** Flight 23.2100 – 23.2165
▼ Performance 23.2100 – 23.2130
§ 23.2100 Weight and center of gravity.
§ 23.2105 Performance data.
§ 23.2110 Stall speed.
§ 23.2115 Takeoff performance.
§ 23.2120 Climb requirements.
§ 23.2125 Climb information.
§ 23.2130 Landing.
▼ Flight Characteristics 23.2135 – 23.2165
§ 23.2135 Controllability.
§ 23.2140 Trim.
§ 23.2145 Stability.
§ 23.2150 Stall characteristics, stall warning, and spins.
§ 23.2155 Ground and water handling characteristics.
§ 23.2160 Vibration, buffeting, and high-speed characteristics.
§ 23.2165 Performance and flight characteristics requirements for flight in icing conditions.

Figure 4.7 – Overview of Subpart B – Performance and Flight Characteristics Requirements.

To demonstrate the practical application of this scoping process, the specific requirements for Controllability (§23.2135) were selected as the modeling focus. Figure 4.8 detailed view of §23.2135, Controllability Requirements provides a comprehensive breakdown of the controllability requirements, segmented into paragraphs (a) through (d), showcasing how specific regulatory content is isolated for targeted modeling.

This structured filtering ensures that only regulatory sections with clear compliance requirements and verification logic are selected, forming the foundational scope for the subsequent modeling steps.



§ 23.2135 Controllability.

(a) The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope—

(1) At all loading conditions for which certification is requested;

(2) During all phases of flight;

(3) With likely reversible flight control or propulsion system failure; and

(4) During configuration changes.

(b) The airplane must be able to complete a landing without causing substantial damage or serious injury using the steepest approved approach gradient procedures and providing a reasonable margin below V_{ref} or above approach angle of attack.

(c) V_{MC} is the calibrated airspeed at which, following the sudden critical loss of thrust, it is possible to maintain control of the airplane. For multiengine airplanes, the applicant must determine V_{MC}, if applicable, for the most critical configurations used in takeoff and landing operations.

(d) If the applicant requests certification of an airplane for aerobatics, the applicant must demonstrate those aerobatic maneuvers for which certification is requested and determine entry speeds.

Figure 4.8 – Detailed View of §23.2135 – Controllability Requirements.

4.3.3 Propose a Package Structure to the Model based on the Authority Documentation

This phase establishes the hierarchical and semantic organization of the regulatory content within the model. The objective is to structure the content in a way that not only mirrors the source documentation but also introduces modularity and traceability for future use.

Instead of treating the document as a linear sequence of paragraphs, the content is organized into functional domains, regulatory topics, and certification phases, creating a layered structure that facilitates modular expansion and targeted analysis:

- Functional Domains: Propulsion, Avionics, Flight Controls.
- Regulatory Topics: Airworthiness, Environmental Protection, Performance.
- Certification Phases: Compliance Planning, Test Evidence, Verification Reporting.

For instance, in modeling Part 23, the structure depicted in Figure 4.9 organizes the Flight Characteristics content into discrete sections such as Controllability (§23.2135), Trim (§23.2140), and Stability (§23.2145), each serving as a distinct package with its own set of requirements and MoCs.

This approach ensures that the model can be expanded and integrated with other regulatory artefacts, such as tailored certification items, verification sources, and authority guidance, supporting comprehensive traceability across the certification lifecycle.

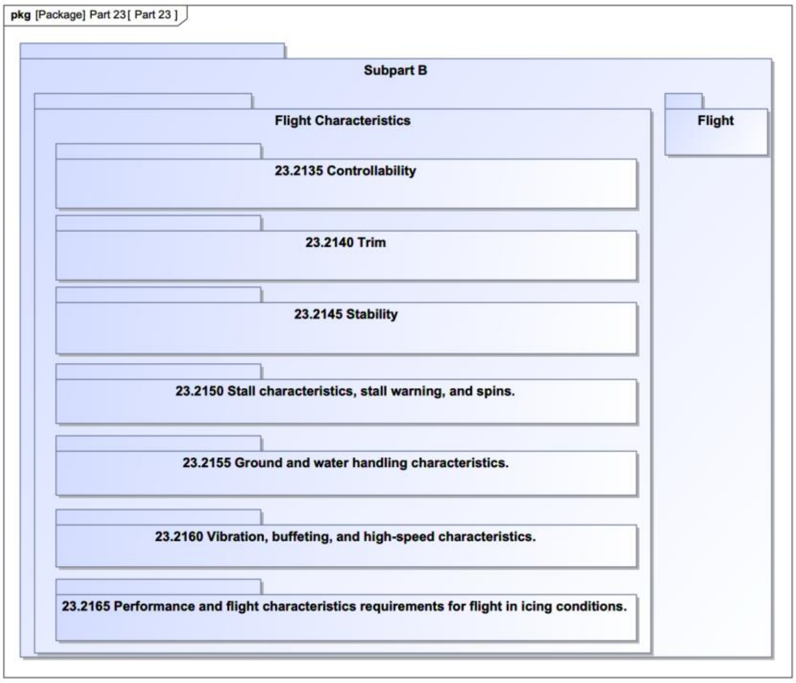


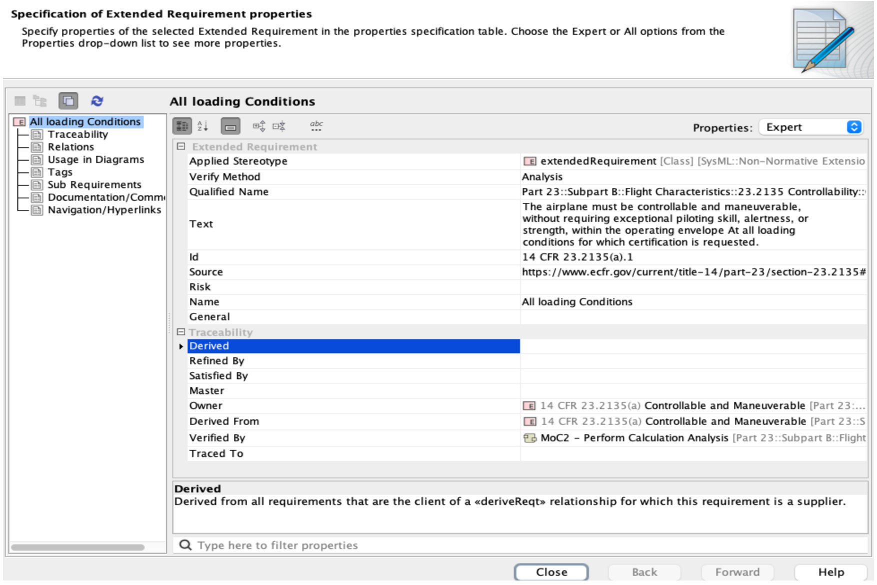
Figure 4.9 – Package Structure for Part 23 Requirements.

4.3.4 Transform Document into Model

In this phase, the regulatory content is systematically transformed into structured model elements, establishing a traceable and auditable process using SysML, a modeling language, or similar modeling tools. Each element is formalized to maintain consistency, modularity, and verification logic. The transformation process involves the following key attributes:

- Unique Identifier: Assigns a specific identifier to each clause.
- Requirement Text: Captures the precise regulatory language, ensuring fidelity to the source document.
- Classification: Organizes content by domain, facilitating targeted analysis.
- Attributes: Defines critical parameters such as applicability, criticality, and intended verification methods.
- Relationships: Establishes connections between requirements, MoCs, and system functions, enabling structure traceability.

For instance, the requirement “The airplane must maintain lateral-directional stability in all loading conditions” from §23.2150 is converted into a SysML Requirement element. It is then linked to its corresponding system function (e.g., Flight Control) and verification method (e.g., flight test XYZ-TP-12). Figure 4.10 illustrates how requirement properties are systematically organized in the model, demonstrating the traceability paths from regulatory clauses to verification artifacts.



Specification of Extended Requirement properties

Specify properties of the selected Extended Requirement in the properties specification table. Choose the Expert or All options from the Properties drop-down list to see more properties.

All loading Conditions

Extended Requirement	
Applied Stereotype	extendedRequirement [Class] [SysML::Non-Normative Extensio
Verify Method	Analysis
Qualified Name	Part 23::Subpart B::Flight Characteristics::23.2135 Controllability::
Text	The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope At all loading conditions for which certification is requested.
Id	14 CFR 23.2135(a).1
Source	https://www.ecfr.gov/current/title-14/part-23/section-23.2135#
Risk	
Name	All loading Conditions
General	
Traceability	
Derived	
Refined By	
Satisfied By	
Master	
Owner	14 CFR 23.2135(a) Controllable and Maneuverable [Part 23:...
Derived From	14 CFR 23.2135(a) Controllable and Maneuverable [Part 23::S
Verified By	MoC2 – Perform Calculation Analysis [Part 23::Subpart B::Flight
Traced To	

Derived
Derived from all requirements that are the client of a «deriveReqt» relationship for which this requirement is a supplier.

Figure 4.10 – Requirement Properties in the Model.

4.3.5 Suggest MoCs

After establishing the structured model of regulatory requirements, the next step involves assigning appropriate MoCs to each requirement. This step connects the regulatory intent with specific verification methods, creating a structured compliance matrix that can be audited and validated. MoCs can be derived from multiple sources, including:

- Regulatory Guidance: Official ACs.
- Past Certifications: Proven test plans and analysis methods.
- Engineering Best Practices: Analytical models, similarity analyses, and simulation process.
- Each MoC is systematically linked to its corresponding requirement in the model, forming a verification structure that includes:
- MoC Type: Defines the method of compliance.
- Evidence Source: Specifies the documentation or data supporting the MoC.
- Verification Status: Indicates the acceptability of the MoC.

Figure 4.11 illustrates how the requirement “All loading conditions” derived from §23.2135(a) is linked to its corresponding MoC, which in this case is a calculation analysis method. This visual representation emphasizes how verification activities are systematically embedded into the model, facilitating traceability and compliance validation.

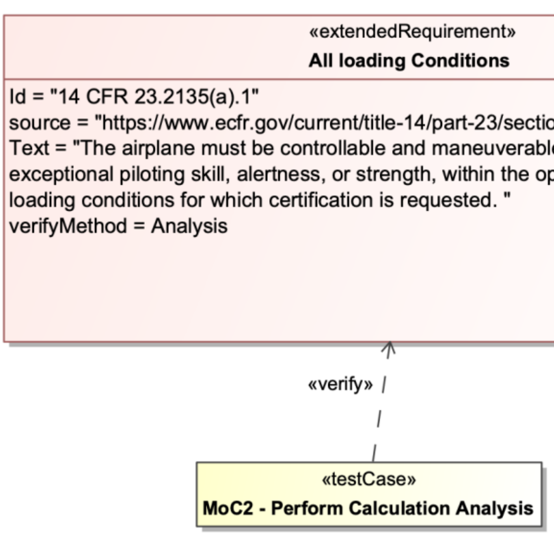


Figure 4.11 – MoC Assignment to a Modelled Requirement.

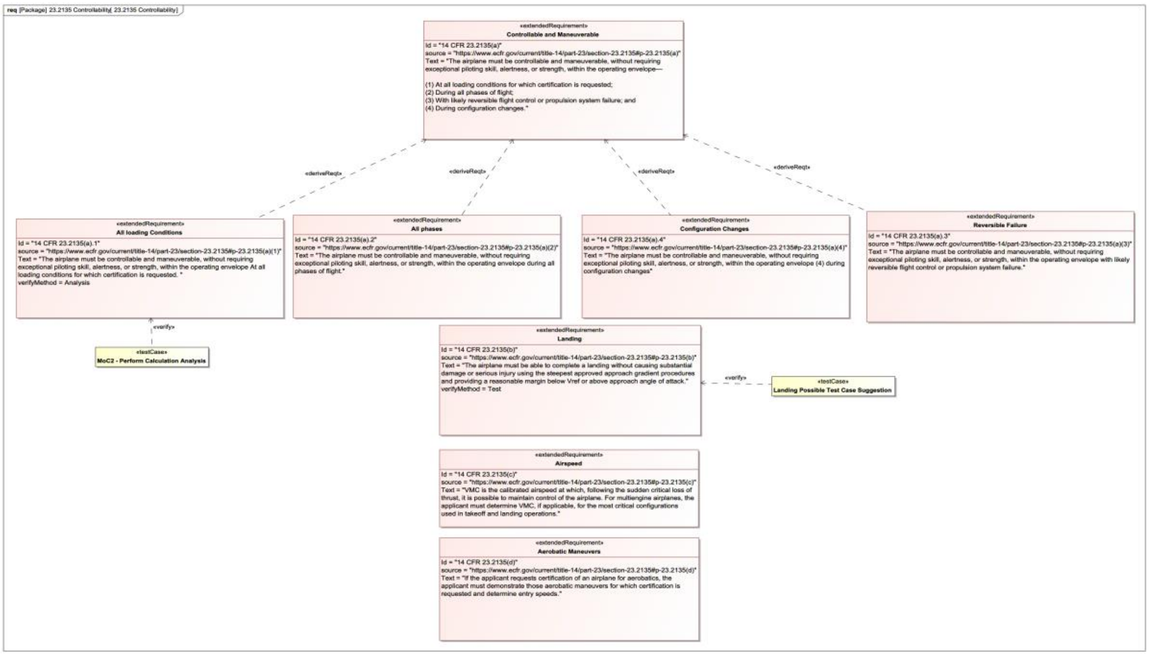
4.3.6 Publish Model

After the model is fully developed and verified, it is prepared for institutional publication. Publication in this context refers to making the model accessible to relevant stakeholders, which can occur in multiple forms:

- Internal Reference: As a structured artefact for certification teams, providing a digital reference for ongoing and future projects.
- Submission to Authorities: As a formalized document submitted to regulatory bodies for review and potential approval.
- Certification Baseline: As a documented baseline for project certification planning, including traceability matrices and MoC assignments.

The publication process involves implementing version control, documenting modeling logic, and validating content through subject-matter experts or regulatory reviewers. Successful publication can evolve into a Reusable Authority Model, enabling future assignments of MoCs, audit preparations, and potentially regulatory automation.

Figure 4.12 presents the output Structure of the 23.2135 Controllability Branch illustrates the final model output for the controllability requirement, showing four derived requirements structured in accordance with FAA guidance. This representation demonstrates how regulatory content is modularized, interconnected, and prepared for institutional use, establishing a digital certification baseline.



Id = "14 CFR 23.2135(a)"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(a)"
Text = "The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope—

(1) At all loading conditions for which certification is requested;
(2) During all phases of flight;
(3) With likely reversible flight control or propulsion system failure; and
(4) During configuration changes."

Id = "14 CFR 23.2135(a).1"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(a)(1)"
Text = "The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope At all loading conditions for which certification is requested. "
verifyMethod = Analysis

Id = "14 CFR 23.2135(a).2"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(a)(2)"
Text = "The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope during all phases of flight."

Id = "14 CFR 23.2135(a).4"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(a)(4)"
Text = "The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope (4) during configuration changes"

Id = "14 CFR 23.2135(a).3"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(a)(3)"
Text = "The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope with likely reversible flight control or propulsion system failure."

Id = "14 CFR 23.2135(b)"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(b)"
Text = "The airplane must be able to complete a landing without causing substantial damage or serious injury using the steepest approved approach gradient procedures and providing a reasonable margin below Vref or above approach angle of attack."
verifyMethod = Test

Id = "14 CFR 23.2135(c)"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(c)"
Text = "VMC is the calibrated airspeed at which, following the sudden critical loss of thrust, it is possible to maintain control of the airplane. For multiengine airplanes, the applicant must determine VMC, if applicable, for the most critical configurations used in takeoff and landing operations."

Id = "14 CFR 23.2135(d)"
source = "https://www.ecfr.gov/current/title-14/part-23/section-23.2135#p-23.2135(d)"
Text = "If the applicant requests certification of an airplane for aerobatics, the applicant must demonstrate those aerobatic maneuvers for which certification is requested and determine entry speeds."

Figure 4.12 – Output Structure of the 23.2135 Controllability Branch.

4.4 Changes of the Certification due to the Implementation of MBSE

The reconfiguration of the certification process leverages the proposed MBSE process to transition from a document-centric workflow to an integrated, model-based structure. This transformation consolidates regulatory requirements, MoCs, and compliance evidence into a single, auditable model, enhancing traceability and regulatory oversight.

Figure 4.13 outlines the reconfigured certification process, structured into eight sequential steps that guide the transition from requirement identification to post-certification monitoring. The following subsections detail each step, providing a systematic approach to implementing the MBSE process in the certification context.

4.4.1 Establish Certification Basis

This initial step establishes the regulatory process that will govern the certification project. It involves identifying the primary certification authority and regulatory requirements and establishing the certification basis that will serve as the baseline for the model-based transformation.

The objective is to ensure that all regulatory content integrated into the model aligns with the specific structure, terminology, and verification logic prescribed by the chosen authority. This alignment creates a cohesive structure for subsequent model development phases and ensures that the regulatory foundation is consistent throughout the certification process. This stage corresponds to Phases I and II - FAA.

To implement this step within a model-based environment, a structured procedure is followed to ensure regulatory consistency and traceability. The process begins by identifying the applicable certification authority and selecting the relevant regulatory documents, such as sections of the Code of Federal Regulations, advisory circulars, or consensus-based technical standards issued by recognized organizations like ASTM or SAE. These references are then organized within the modeling tool in a modular structure, typically using packaged files that preserve the logical hierarchy of the original documents.

Each regulatory element is represented as a requirement within the model, retaining its numbering, title, and context to maintain fidelity to the source material. Once the documents are structured, the certification basis is formally defined by filtering and selecting the clauses that apply to the system under analysis. In cases involving novel technologies or operational profiles, supplementary materials, such as special conditions, issue papers, or equivalent provisions, are incorporated to complete the regulatory scope.

This organized baseline serves as the foundation for the subsequent integration of compliance elements, allowing for the consistent association of Means of Compliance, system requirements, and verification artifacts. The approach ensures semantic alignment with the authority’s regulatory framework and establishes a transparent and reusable structure that supports the integrity of the digital certification process.

4.4.2 Define Preliminary Means of Compliance

Once the regulatory process is defined, the next step involves decomposing the selected certification requirements into structured, verifiable model elements. This decomposition process facilitates the identification of key regulatory clauses and their allocation to specific system functions or components.

The objective is to systematically organize requirements into a hierarchical structure, categorizing them by domain and associating them with corresponding MoCs. This structured allocation enables traceability and ensures that each requirement is addressed by an appropriate verification method. This stage corresponds to Phase II - FAA.

Once the certification requirements are selected and modeled, this phase focuses on structuring them in a way that supports traceability and early compliance planning. Each requirement is interpreted according to its regulatory context and represented in the model with clear attributes, such as identifier, source, and scope of applicability. These elements are grouped by system domain, such as structures, propulsion, or environmental controls, and organized hierarchically to preserve both the regulatory logic and the technical structure of the project.

Preliminary MoC are then proposed for each requirement. These may include test procedures, simulations, design justifications, or references to recognized standards. Although still subject to refinement, these associations help define the intended verification approach and allow the team to anticipate the evidence needed to demonstrate compliance. When applicable, multiple regulatory sources may be linked to a single requirement to reflect harmonized or complementary rules. By formalizing these connections in the model, this step lays the foundation for an auditable and coherent certification process, ensuring that each requirement can be systematically verified in the following stages.

4.4.3 Develop Certification Plan

The development of the certification plan establishes the structured approach for verifying compliance with the decomposed requirements. This step links each regulatory requirement to a specific MoC, defining the verification methods to be applied and the corresponding compliance evidence to be generated.

The objective is to create a comprehensive compliance matrix that integrates regulatory requirements, MoCs, and verification activities, ensuring that each regulatory clause is systematically addressed and traceable throughout the certification lifecycle. This stage corresponds to Phase III - FAA.

Once the requirements and their preliminary MoC have been defined, the certification plan formalizes how each item will be verified and what evidence must be produced. The process begins by revisiting the regulatory requirements modeled in the previous step and confirming that each one is associated with an appropriate method of compliance. These associations are then organized to reflect their links with system elements and verification strategies, forming a structured and coherent view of the entire compliance framework.

From this structure, a certification plan is derived, typically in the form of a compliance matrix that consolidates key information: regulatory references, verification methods, expected outcomes, and the evidence to be generated. This matrix guides the execution of verification activities and serves as a central reference for internal reviews and regulatory audits. To ensure consistency over time, version control and update mechanisms are incorporated into the model. By anticipating how each requirement will be verified, this step strengthens planning, supports traceability, and contributes to a more transparent and efficient certification process.

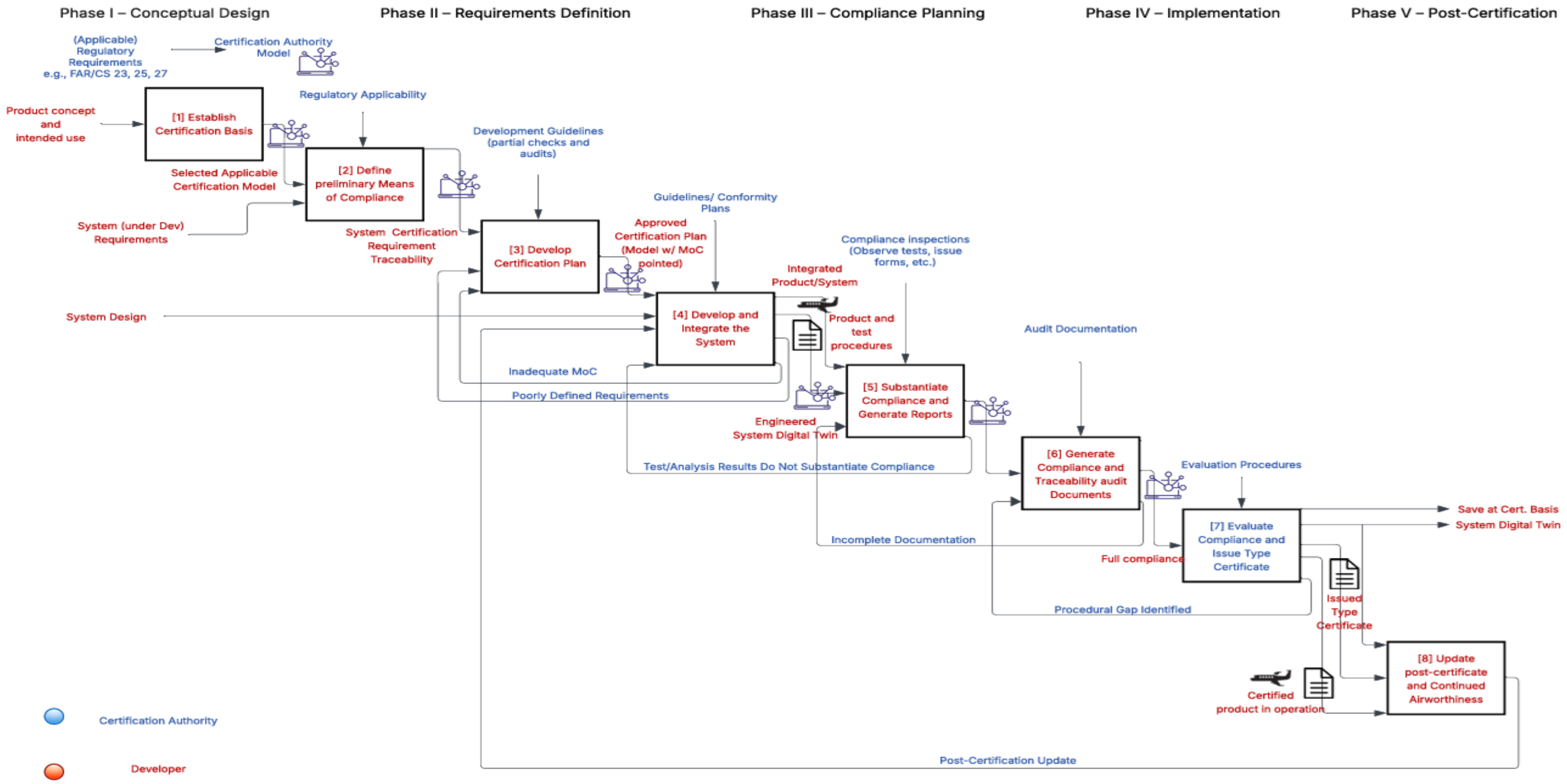


Figure 4.13 – Reconfigured Certification Process Flow Using MBSE.

4.4.4 Develop and Integrate the System

During this phase, the focus shifts to the execution of system development and the integration of subsystems in alignment with the structured certification plan. The objective is to ensure that each component and subsystem adheres to the regulatory requirements and associated MoCs defined in the model.

The development process involves systematic verification of each component against its designated MoCs, collecting compliance evidence to substantiate each verification step. This approach ensures that the system is not only functionally complete but also traceable to regulatory clauses and verification activities. This stage corresponds to Phases III and IV - FAA.

This phase marks the transition from planning to implementation. Subsystems are developed and progressively integrated, following the structure defined in the certification plan and the traceability model. For each component, verification activities are carried out in alignment with the established MoC, whether through tests, simulations, inspections, or analytical assessments, ensuring that all regulatory requirements are addressed as the system evolves.

As verification proceeds, the evidence generated is linked directly to the corresponding requirements within the model. This traceable structure allows the team to monitor progress, identify any gaps early, and maintain consistency between system development and regulatory expectations. The integration process also reinforces cross-domain alignment, helping to ensure that interactions between hardware, software, and operational elements remain coherent and certifiable. By the end of this stage, the system should be not only functionally complete, but also demonstrably compliant with its certification basis, with all evidence organized and traceable within the model environment.

4.4.5 Substantiate Compliance and Generate Reports

This phase consolidates all verification activities and compliance evidence collected during the system integration phase, structuring them into formal reports that substantiate regulatory adherence. The objective is to create comprehensive documentation that clearly links each regulatory requirement to its corresponding MoC and verification evidence. This stage corresponds to Phase IV - FAA.

The compliance reports are structured to include the following key elements:

- Requirement ID: Reference to the specific regulatory clause (e.g., §23.2135).
- MoC Type: Verification method applied (e.g., test, analysis).
- Evidence Source: Documented outcome (e.g., test report, analytical model).
- Verification Status: Compliance status (e.g., passed, failed, pending).

At this stage, all verification activities conducted during system development are consolidated into a structured certification package. The process begins by gathering the verification methods, such as tests, analyses, or inspections, defined earlier in the model. Each activity is linked to its corresponding MoC and supported by evidence demonstrating its execution.

Next, this evidence is associated directly with the mapped regulatory requirements, enabling the construction of a complete traceability path within the modeling environment. This structured linkage ensures that each requirement is clearly connected to the verification method applied and the result obtained.

Finally, all this information is compiled into formal compliance reports. These documents include the requirement ID, the type of MoC used, the source of supporting evidence (such as test reports or analytical models), and the verification status. This structure reinforces transparency, supports audit readiness, and strengthens the overall integrity of the certification process.

4.4.6 Generate Compliance and Traceability Audit Documents

In this step, the focus is on compiling all verification artifacts and compliance evidence into structured audit documents. These documents serve as the formal output of the certification process, providing a comprehensive view of regulatory compliance, verification activities, and traceability paths. This stage corresponds to Phase IV - FAA.

The audit documentation includes:

- Compliance Matrix: Mapping each regulatory requirement to its respective MoC and verification evidence.
- Traceability Report: Detailing the linkage between requirements, MoCs, and evidence, establishing a clear audit trail.

- Verification Summary: Summarizing the verification outcomes, identifying any open items or pending validations.

In this phase, the data consolidated throughout the certification process is organized into a set of formal audit documents. The preparation begins with the generation of a Compliance Matrix, which provides a structured view linking each regulatory requirement to its corresponding Means of Compliance and supporting evidence. This matrix ensures that all applicable clauses have been addressed and verified.

Following that, a Traceability Report is compiled to illustrate how requirements, verification methods, and outcomes are connected within the model. This report serves as a transparent record of the certification logic, allowing both internal and external stakeholders to follow the audit trail and assess the integrity of the compliance process.

A Verification Summary is then assembled to present the status of each requirement, clearly indicating whether the objective was met, is still under evaluation, or requires further action. When implemented within a model-based environment, these documents can often be generated automatically, using structured traceability data embedded in the model itself. This capability helps maintain consistency, minimizes manual effort, and ensures that the final certification package is both complete and auditable.

4.4.7 Evaluate Compliance and Issue Type Certificate

This phase represents the culmination of the certification process, where all compliance evidence is reviewed, and final assessments are conducted to determine conformity with regulatory requirements. The objective is to resolve any remaining nonconformities, validate the traceability structure, and issue the Type Certificate upon successful completion. This stage corresponds to Phases IV and V – FAA.

The evaluation process includes:

- Review of Compliance Matrix: Ensures that all regulatory requirements have been addressed, and corresponding MoCs are substantiated with evidence.
- Traceability Links: Confirms that each requirement is traceable to its respective verification activity and evidence source.
- Resolution of Nonconformities: Identifies and addresses any open items or discrepancies prior to final certification.

In the final stage of the certification process, the complete set of compliance data is subjected to a thorough evaluation by the designated certification authority. The process begins with a detailed review of the Compliance Matrix to confirm that all regulatory requirements have been met and are supported by appropriate MoC and documented evidence. This review ensures that the proposed verification strategy has been correctly executed and that the system complies with its certification basis.

Subsequently, the traceability architecture is verified to confirm the consistency of links between requirements, model elements, and verification artifacts. The objective is to ensure that all elements of the system can be traced back to their regulatory origins and that no gaps remain in the verification chain.

Any identified nonconformities, pending validations, or inconsistencies are formally addressed at this stage. Once all open items are resolved and the system's compliance is fully demonstrated, the Type Certificate may be issued. When supported by a model-based environment, this final evaluation can be accompanied by automatically generated compliance reports, consolidating all traceability information into an auditable, regulator-ready package.

4.4.8 Update Post-Certificate and Continued Airworthiness

Following the issuance of the Type Certificate, the certification process transitions to the post-certification phase, focusing on continued airworthiness and ongoing regulatory compliance. The objective is to maintain the integrity of the certification baseline, manage updates, and address any emerging compliance issues. This stage corresponds to Phase V – FAA.

The post-certification phase involves:

- Monitoring Compliance: Ongoing verification of operational data to detect potential safety issues or regulatory nonconformities.
- Updating the Model: Incorporating updates based on new regulatory guidelines, service bulletins, or field reports.
- Managing Configuration Control: Ensuring that any modifications to the system or its components are properly documented and revalidated as necessary.

In the post-certification phase, the certified model assumes a central role as the authoritative reference for all future updates, effectively becoming the system's regulatory source of truth. This represents a shift from traditional document-centric practices to a model-centric approach, in which compliance artifacts and configuration changes are managed directly within the model environment.

The process begins with continuous monitoring of operational data to identify any emerging safety concerns or deviations from certified performance. When updates are required, whether due to service bulletins, regulatory revisions, or operational findings, these changes can be implemented directly in the model. The integrated structure allows for the automated propagation of updates across affected components, maintaining alignment with the certification baseline.

This approach enhances traceability by preserving historical data, supporting version control, and reducing the risk of inconsistencies between physical modifications and their regulatory documentation. By enabling a continuous feedback loop between the system's real-world behavior and its digital representation, the model supports both continued and continuing airworthiness, ensuring regulatory alignment throughout the lifecycle.

5 Analysis of the Model-Based Traceability Process

This chapter applies the Model-Based Traceability Process within the example of eVTOL certification, integrating SysML to structure the traceability between regulatory requirements, MoCs, and verification evidence. The analysis encompasses the application of the process in the verification processes, including exploratory studies on MoC recommendations using LLMs and the implementation of Digital Twins for continued airworthiness management. Finally, challenges, limitations, and improvement opportunities in complex regulatory environments are discussed.

5.1 Case Description: Regulatory Challenges for eVTOLs

The selection of eVTOL aircraft as the primary case study in this thesis is grounded in its alignment with emerging regulatory challenges and the growing focus on Advanced Air Mobility. eVTOLs introduce operational complexities that diverge from conventional aircraft, including distributed electric propulsion, autonomous capabilities, and low-altitude urban operations. These factors necessitate a robust certification strategy that effectively addresses hybrid regulatory structures and evolving safety standards.

Given the novelty and complexity of eVTOL systems, the need for comprehensive traceability becomes paramount. Certification in such contexts requires meticulous documentation of each regulatory requirement, Means of Compliance, and verification artifact to ensure both correctness and completeness throughout the certification lifecycle. This need for rigorous traceability is particularly evident in scenarios where operational hazards, such as bird strikes, must be addressed.

Before delving into specific regulatory requirements, it is essential to establish a comprehensive operational concept for eVTOL aircraft. Figure 5.1 presents a conceptual model that consolidates key operational domains associated with an eVTOL under certification. These domains include terrain, weather, passenger, vertiport, urban air traffic management, and potential hazards such as bird strikes. Each domain is systematically represented as a SysML block, establishing the foundational structure upon which specific regulatory requirements and MoCs will be mapped.

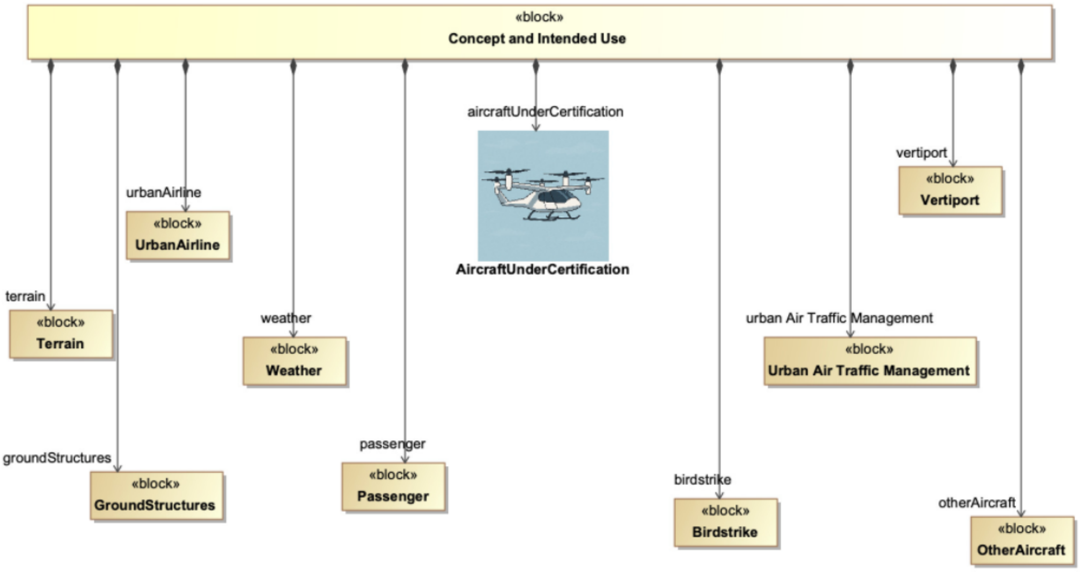


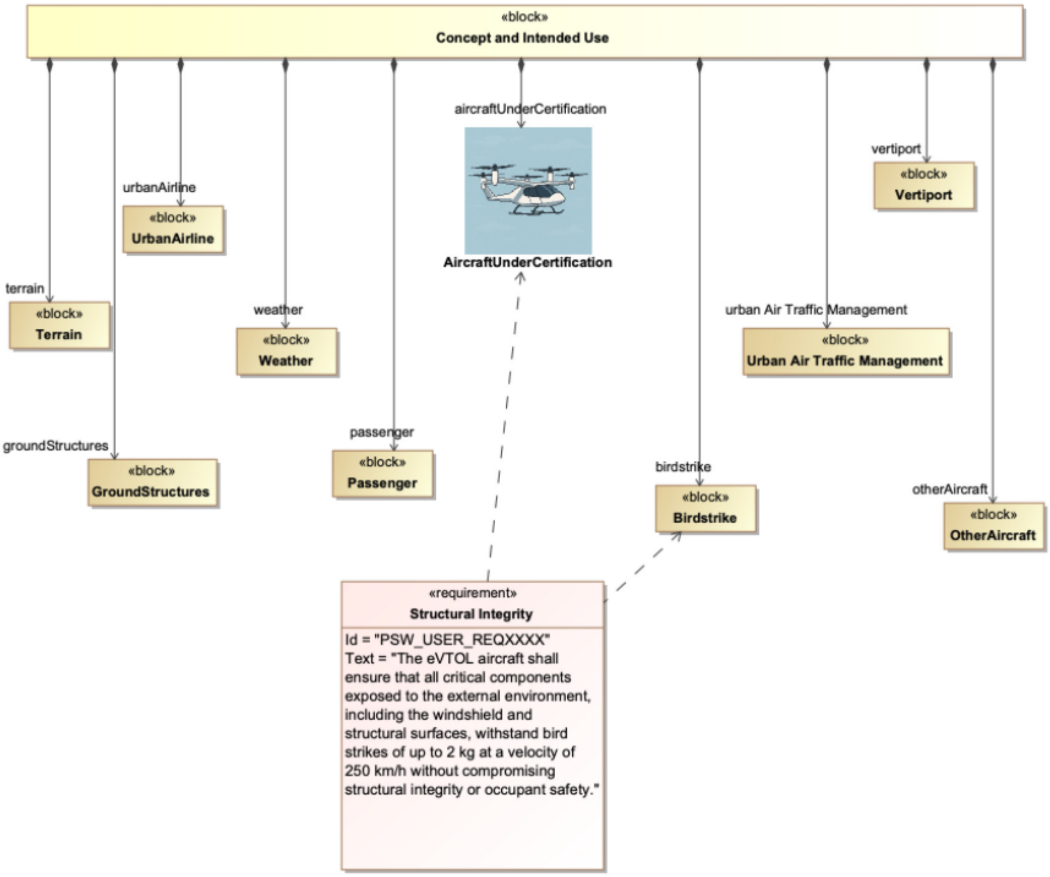
Figure 5.1 – Product Concept and Intended Use: Example of Potential Operational Concept for eVTOL Aircraft and Its Elements.

The rationale for focusing on bird strike protection as a representative certification challenge is rooted in the heightened risk of bird encounters in low-altitude urban operations, a core operational domain for eVTOLs. Bird strikes pose significant safety risks, particularly to critical external components such as windshields, sensors, and structural surfaces.

A typical client requirement in the context of bird strike protection can be articulated as follows:

"The eVTOL aircraft shall ensure that all critical components exposed to the external environment, including the windshield and structural surfaces, withstand bird impacts of up to 2 kg at a speed of 250 km/h without compromising structural integrity or occupant safety."

Within the SysML model, it is possible to associate such requirements with specific model elements, establishing bidirectional traceability between the identified operational hazard (bird strike), the client requirement, and the proposed MoC. Figure 5.2 illustrates how the requirement is linked to the aircraft structure and potential bird strike scenarios, serving as a visual representation of the traceability mechanism within the process.



Id = "PSW_USER_REQXXXX"
Text = "The eVTOL aircraft shall ensure that all critical components exposed to the external environment, including the windshield and structural surfaces, withstand bird strikes of up to 2 kg at a velocity of 250 km/h without compromising structural integrity or occupant safety."

Figure 5.2 – System (Under Development) Requirements: Associating Requirements with Model Elements, Highlighting Bird Strike Protection.

5.1.1 Establish Certification Basis

This initial step establishes the regulatory process that will govern the certification project. It involves identifying the primary certification authority and regulatory requirements and defining the certification basis that will serve as the baseline for the model-based transformation. The objective is to ensure that all regulatory content integrated into the model aligns with the specific structure, terminology, and verification logic prescribed by the chosen authority.

Identification of Regulatory Structure:

- 14 CFR Part 23 – Subpart D: Structural requirements and impact resistance for eVTOL aircraft.
- ASTM F330-21 – Aircraft Impact Tolerance: Test procedures and energy absorption criteria for bird strike impacts.

- AC 21.17-4 – Powered-Lift Aircraft Certification: Guidance specific to eVTOL operations, particularly in urban environments.

Definition of Certification Basis:

The G-1 Issue Paper serves as a formal mechanism to define specific requirements not explicitly covered by existing regulations. In the context of bird strike impact resistance, the aircraft must demonstrate the ability to withstand impacts from birds weighing up to 2 kg at a velocity of 250 km/h, using criteria established in ASTM F330-21 or other MoCs proposed by the applicant and subject to FAA approval.

The selected applicable certification model consolidates these regulatory references, establishing a structured approach for SysML integration. Figure 5.3 illustrates the configuration of the selected regulatory models, encompassing the FAA's G-1 Issue Paper, AC 21.17-4, and ASTM standards relevant to bird strike resistance.

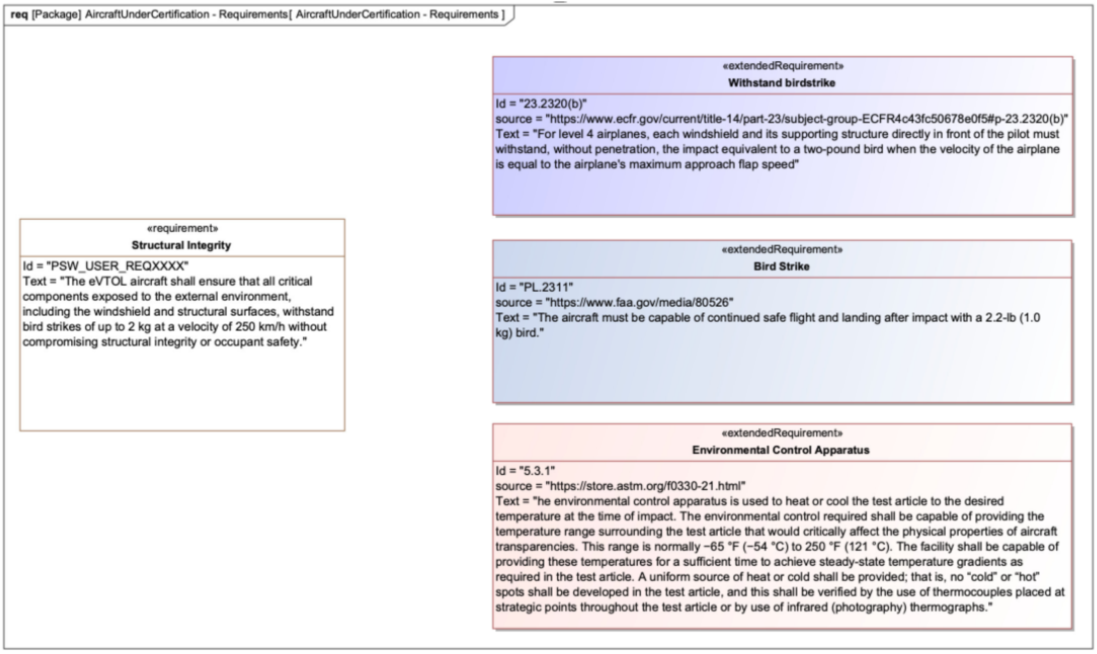
Figure 5.3 – Selected Applicable Certification Model for eVTOL Certification Basis.

5.1.2 Define Preliminary Means of Compliance

Once the regulatory process is defined, the subsequent step involves decomposing the selected certification requirements into structured, verifiable model elements. This decomposition process enables the identification of key regulatory clauses and their systematic allocation to specific system functions or components.

The objective is to organize these requirements into a hierarchical structure, categorizing them by domain and associating them with corresponding MoCs. This structured allocation ensures traceability and facilitates verification by establishing clear links between each requirement and its designated verification method. This stage corresponds to Phase II - FAA.

Figure 5.4 illustrates the certification requirement traceability model, demonstrating how the bird strike safety requirement can be associated with multiple regulatory bases, including FAA Part 23, ASTM F330-21, and specific Issue Papers. The model establishes a structured linkage between the client requirement for bird strike protection and the imported regulatory process, consolidating them within the eVTOL project scope.



«requirement»
Structural Integrity
Id = "PSW_USER_REQXXXX"
Text = "The eVTOL aircraft shall ensure that all critical components exposed to the external environment, including the windshield and structural surfaces, withstand bird strikes of up to 2 kg at a velocity of 250 km/h without compromising structural integrity or occupant safety."

«extendedRequirement»
Withstand birdstrike
Id = "23.2320(b)"
source = "https://www.ecfr.gov/current/title-14/part-23/subject-group-ECFR4c43fc50678e0f5#p-23.2320(b)"
Text = "For level 4 airplanes, each windshield and its supporting structure directly in front of the pilot must withstand, without penetration, the impact equivalent to a two-pound bird when the velocity of the airplane is equal to the airplane's maximum approach flap speed"

«extendedRequirement»
Bird Strike
Id = "PL.2311"
source = "https://www.faa.gov/media/80526"
Text = "The aircraft must be capable of continued safe flight and landing after impact with a 2.2-lb (1.0 kg) bird."

«extendedRequirement»
Environmental Control Apparatus
Id = "5.3.1"
source = "https://store.astm.org/f0330-21.html"
Text = "he environmental control apparatus is used to heat or cool the test article to the desired temperature at the time of impact. The environmental control required shall be capable of providing the temperature range surrounding the test article that would critically affect the physical properties of aircraft transparencies. This range is normally −65 °F (−54 °C) to 250 °F (121 °C). The facility shall be capable of providing these temperatures for a sufficient time to achieve steady-state temperature gradients as required in the test article. A uniform source of heat or cold shall be provided; that is, no “cold” or “hot” spots shall be developed in the test article, and this shall be verified by the use of thermocouples placed at strategic points throughout the test article or by use of infrared (photography) thermographs."

Figure 5.4 – System - Certification Requirement Traceability Model for Bird Strike Protection.

In Section 5.2.1, an exploratory case will be presented, showcasing the experimental integration of LLMs for MoC recommendation.

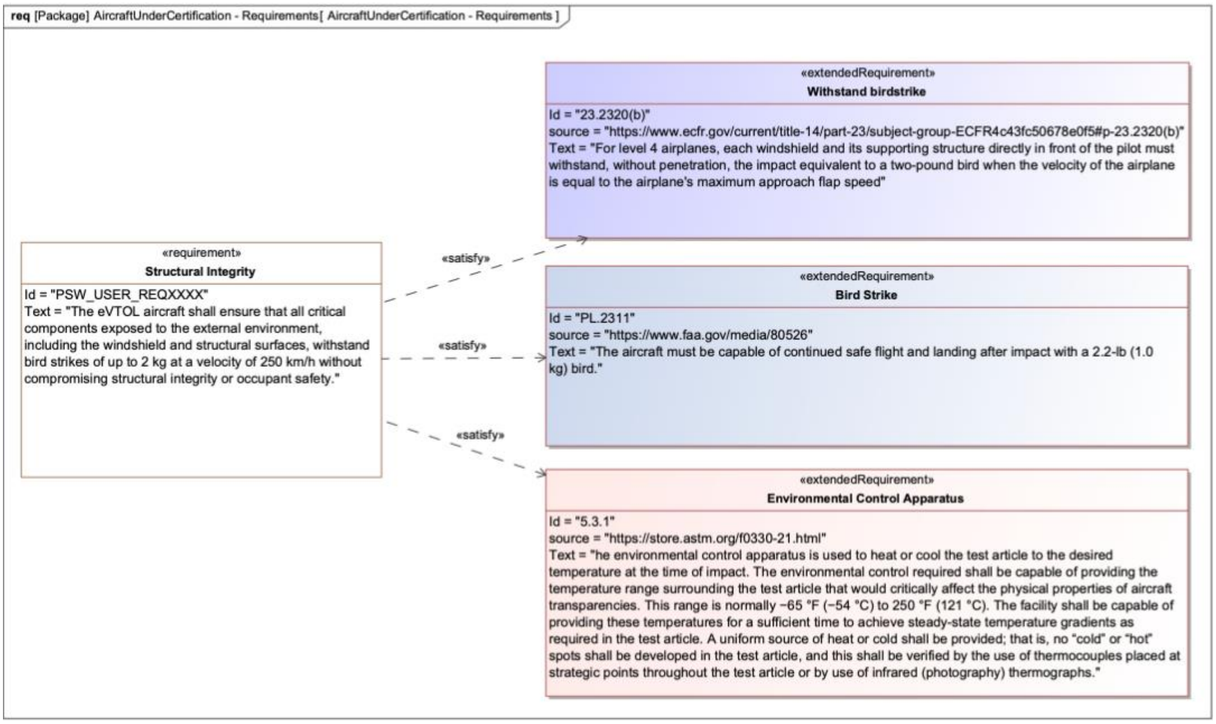
5.1.3 Develop Certification Plan

During this phase, the focus shifts to the execution of system development and the integration of subsystems in alignment with the structured certification plan. The objective is to ensure that each component and subsystem adheres to the regulatory requirements and associated MoCs defined in the model.

The development process involves systematic verification of each component against its designated MoCs, collecting compliance evidence to substantiate each verification step. This approach ensures that the system is not only functionally complete but also traceable to regulatory clauses and verification activities. This stage corresponds to Phases III and IV - FAA.

Traceability in the Model

The association of requirements within the model enables bidirectional traceability between system components and regulatory requirements. This structured approach ensures that each requirement can be traced to its source and associated with MoCs, as illustrated in Figure 5.5.



Id = "PSW_USER_REQXXXX"
Text = "The eVTOL aircraft shall ensure that all critical components exposed to the external environment, including the windshield and structural surfaces, withstand bird strikes of up to 2 kg at a velocity of 250 km/h without compromising structural integrity or occupant safety."

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Text = "For level 4 airplanes, each windshield and its supporting structure directly in front of the pilot must withstand, without penetration, the impact equivalent to a two-pound bird when the velocity of the airplane is equal to the airplane's maximum approach flap speed"

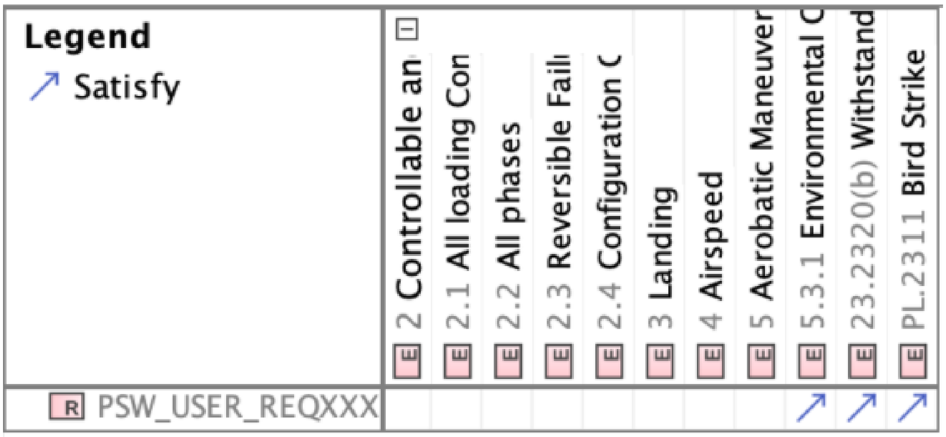
Id = "PL.2311"
source = "https://www.faa.gov/media/80526"
Text = "The aircraft must be capable of continued safe flight and landing after impact with a 2.2-lb (1.0 kg) bird."

Id = "5.3.1"
source = "https://store.astm.org/f0330-21.html"
Text = "he environmental control apparatus is used to heat or cool the test article to the desired temperature at the time of impact. The environmental control required shall be capable of providing the temperature range surrounding the test article that would critically affect the physical properties of aircraft transparencies. This range is normally −65 °F (−54 °C) to 250 °F (121 °C). The facility shall be capable of providing these temperatures for a sufficient time to achieve steady-state temperature gradients as required in the test article. A uniform source of heat or cold shall be provided; that is, no "cold" or "hot" spots shall be developed in the test article, and this shall be verified by the use of thermocouples placed at strategic points throughout the test article or by use of infrared (photography) thermographs."

Figure 5.5 – Traceability Structure for eVTOL Certification Requirements.

Mapping of Regulatory Requirements

Figure 5.6 illustrates the traceability of each system requirement with applicable regulatory bases, including FAA Part 23, ASTM F330-21, and specific Issue Papers. This comprehensive mapping ensures alignment with multiple regulatory process.



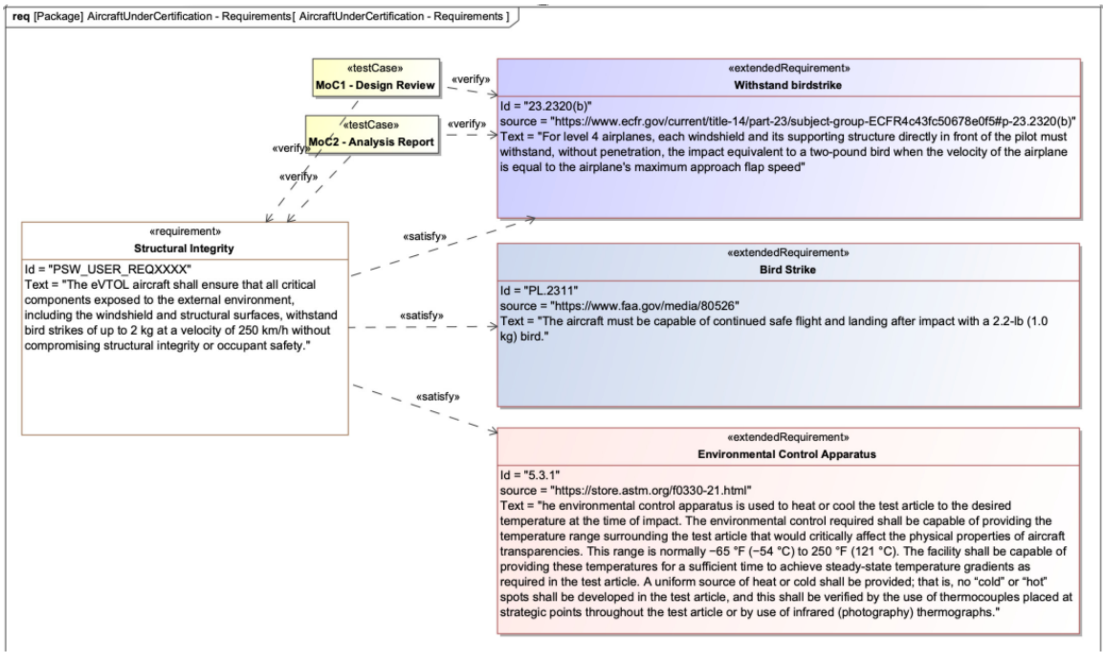
Legend
↗ Satisfy

	2 Controllable an	2.1 All loading Con	2.2 All phases	2.3 Reversible Faili	2.4 Configuration C	3 Landing	4 Airspeed	5 Aerobatic Maneuver	5.3.1 Environmental C	23.2320(b) Withstand	PL.2311 Bird Strike
PSW_USER_REQXXX									↗	↗	↗

Figure 5.6 – Mapping of Regulatory Requirements and System-Level Traceability.

Association of MoCs

Each regulatory requirement is linked to proposed MoCs, establishing a structured verification path. Figure 5.7 demonstrates how each MoC is associated with the specific system requirement, indicating its relevance and verification method.



«extendedRequirement»
Withstand birdstrike
Id = "23.2320(b)"
source = "https://www.ecfr.gov/current/title-14/part-23/subject-group-ECFR4c43fc50678e0f5#p-23.2320(b)"
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«requirement»
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«extendedRequirement»
Bird Strike
Id = "PL.2311"
source = "https://www.faa.gov/media/80526"
Text = "The aircraft must be capable of continued safe flight and landing after impact with a 2.2-lb (1.0 kg) bird."

«extendedRequirement»
Environmental Control Apparatus
Id = "5.3.1"
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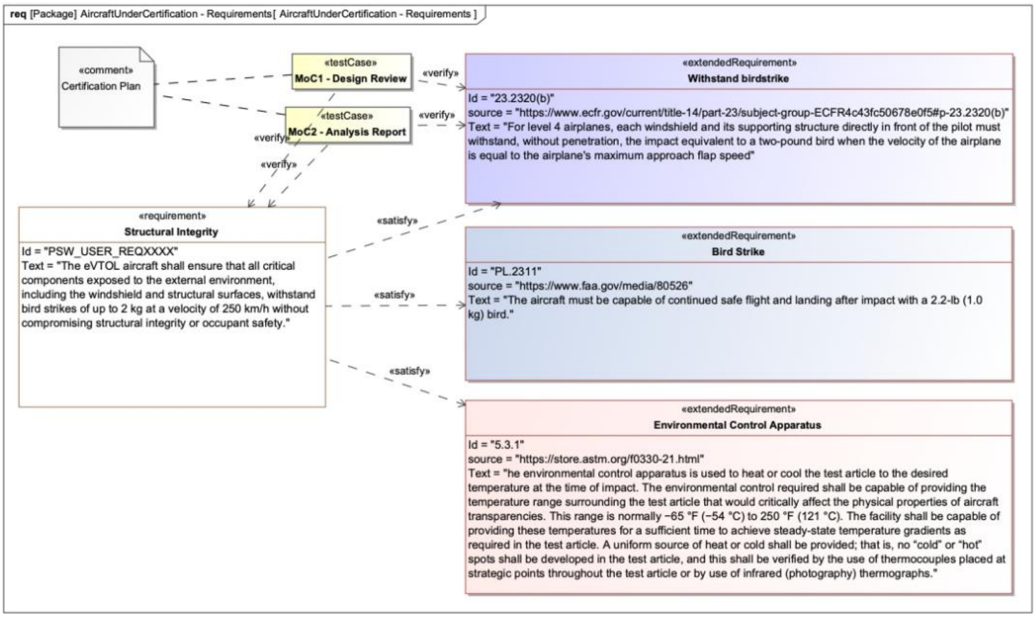
Figure 5.7 – Association of MoCs with System Requirements for Bird Strike Protection.

Certification Plan Documentation

Based on the established links, a comprehensive certification plan can be generated, consolidating MoCs, associated verification methods, and corresponding regulatory requirements. This structured document serves as a foundational reference for compliance verification and audit processes, as shown in Figure 5.8.



Id = "PSW_USER_REQXXXX"
Text = "The eVTOL aircraft shall ensure that all critical components exposed to the external environment, including the windshield and structural surfaces, withstand bird strikes of up to 2 kg at a velocity of 250 km/h without compromising structural integrity or occupant safety."

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source = "https://www.ecfr.gov/current/title-14/part-23/subject-group-ECFR4c43fc50678e0f5#p-23.2320(b)"
Text = "For level 4 airplanes, each windshield and its supporting structure directly in front of the pilot must withstand, without penetration, the impact equivalent to a two-pound bird when the velocity of the airplane is equal to the airplane's maximum approach flap speed"

Id = "PL.2311"
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Figure 5.8 – Certification Plan Generation Based on Traceability and MoC Associations.

5.1.4 Develop and Integrate the System

During this phase, the focus transitions to the execution of system development and the integration of subsystems in alignment with the structured certification plan. The objective is to ensure that each component and subsystem adheres to the regulatory requirements and associated MoCs defined in the model.

The development process involves systematic verification of each component against its designated MoCs, collecting compliance evidence to substantiate each verification step. This approach ensures that the system is not only functionally complete but also traceable to regulatory clauses and verification activities. This stage corresponds to Phases III and IV - FAA.

A pivotal aspect of this phase is the development of the Engineered System Digital Twin, a comprehensive digital representation of the eVTOL system that consolidates structural, functional, and operational data. This digital twin not only serves as a reference for verifying component integration and regulatory compliance but also establishes a foundation for its subsequent utilization in continued and continuing airworthiness assessments, as further explored in Section 5.2.2 – Digital Twins for Continuing and Continued Airworthiness.

The digital twin process facilitates ongoing monitoring, predictive maintenance, and post-certification verification, aligning with emerging regulatory trends in digital oversight and lifecycle management.

5.1.5 Substantiate Compliance and Generate Reports

This phase consolidates all verification activities and compliance evidence collected during the system integration phase, structuring them into formal reports that substantiate regulatory adherence. The objective is to create comprehensive documentation that clearly links each regulatory requirement to its corresponding MoC and verification evidence. This stage corresponds to Phase IV - FAA.

The compliance reports are structured to include the following key elements:

Requirement ID: Reference to the specific regulatory clause (e.g., §23.2135).

MoC Type: Verification method applied (e.g., test, analysis).

Evidence Source: Documented outcome (e.g., test report, analytical model).

Verification Status: Compliance status (e.g., passed, failed, pending).

Establishing Test Procedures

The manufacturer can develop a structured package containing detailed descriptions of each test procedure using sequence diagrams, as illustrated in Figure 5.9. These procedures are linked to specific system components and certification requirements, establishing a clear traceability path.

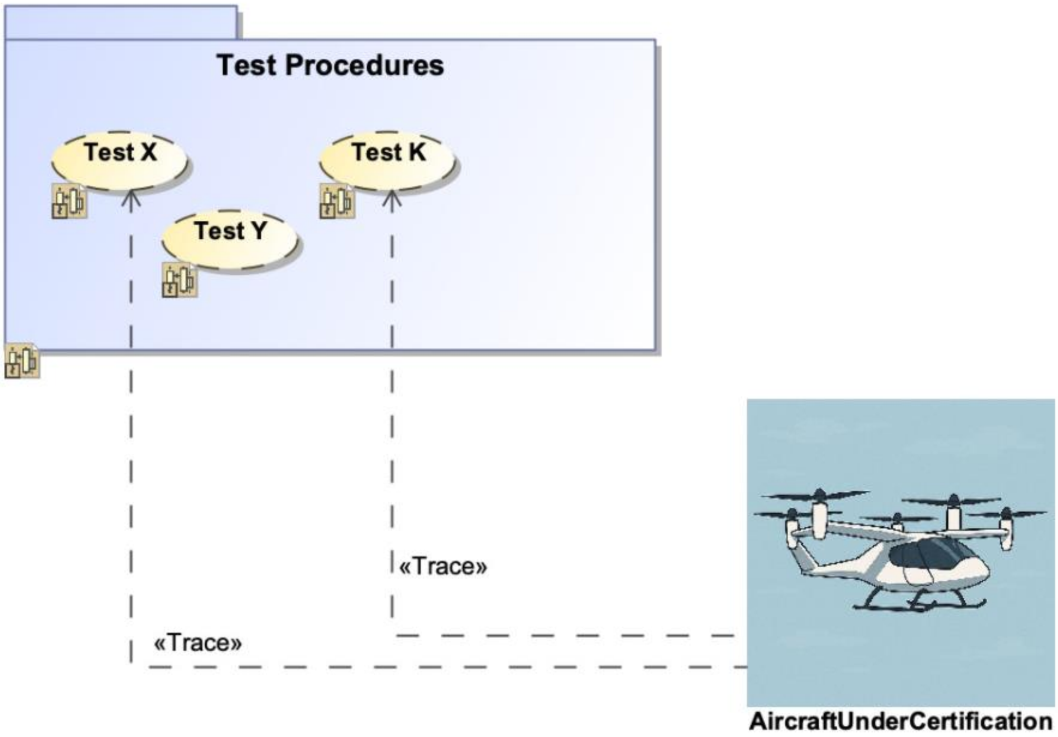


Figure 5.9 – Test Procedures and System Traceability.

Linking Test Reports to Compliance Evidence

It is essential to associate each test procedure with its respective test report, documenting the outcomes and providing direct links to the evidence supporting each verification activity. Figure 5.10 exemplifies how test reports are integrated into the model, enabling seamless access to compliance evidence.

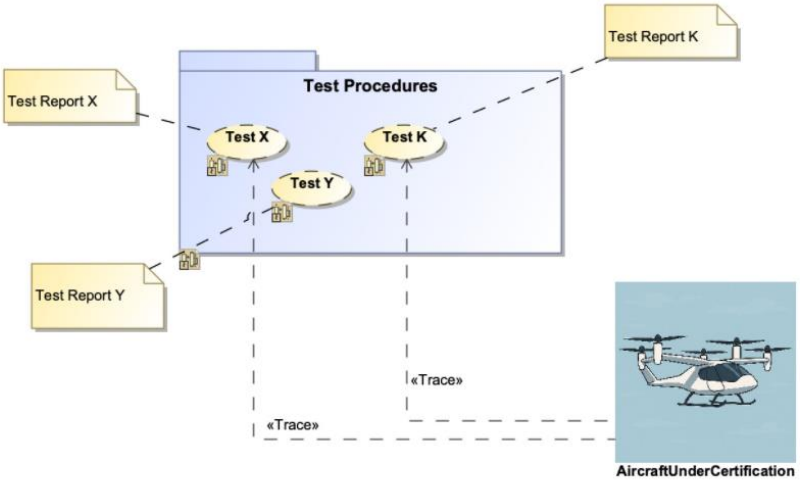
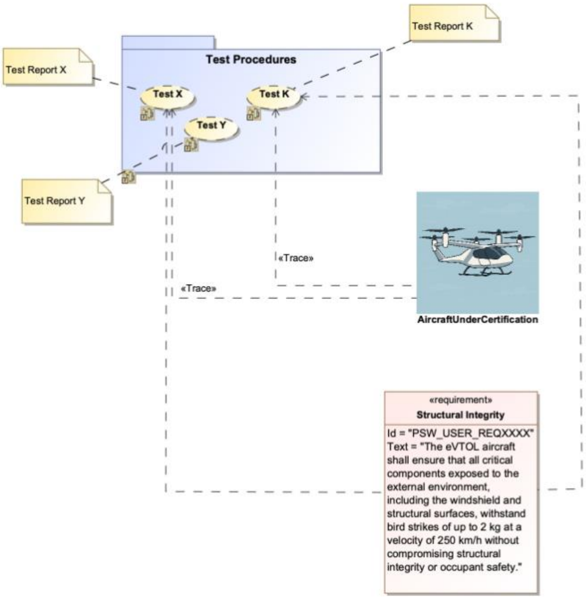


Figure 5.10 – Linking Test Reports to Compliance Evidence.

Compliance with System Requirements

Each test is then mapped to the corresponding system requirement, verifying whether the test adequately satisfies the requirement. Figure 5.11 illustrates this verification process, demonstrating how specific tests are associated with regulatory clauses and MoCs.



Id = "PSW_USER_REQXXXX"
Text = "The eVTOL aircraft shall ensure that all critical components exposed to the external environment, including the windshield and structural surfaces, withstand bird strikes of up to 2 kg at a velocity of 250 km/h without compromising structural integrity or occupant safety."

Figure 5.11 – Verification of Compliance with System Requirements.

Comprehensive Traceability and Reporting

The final step involves consolidating all compliance data into a comprehensive report that illustrates the traceability from the regulatory requirement to the proposed MoC, the associated tests, and the resulting evidence. This process ensures transparency and accountability throughout the certification lifecycle, as shown in Figure 5.12.

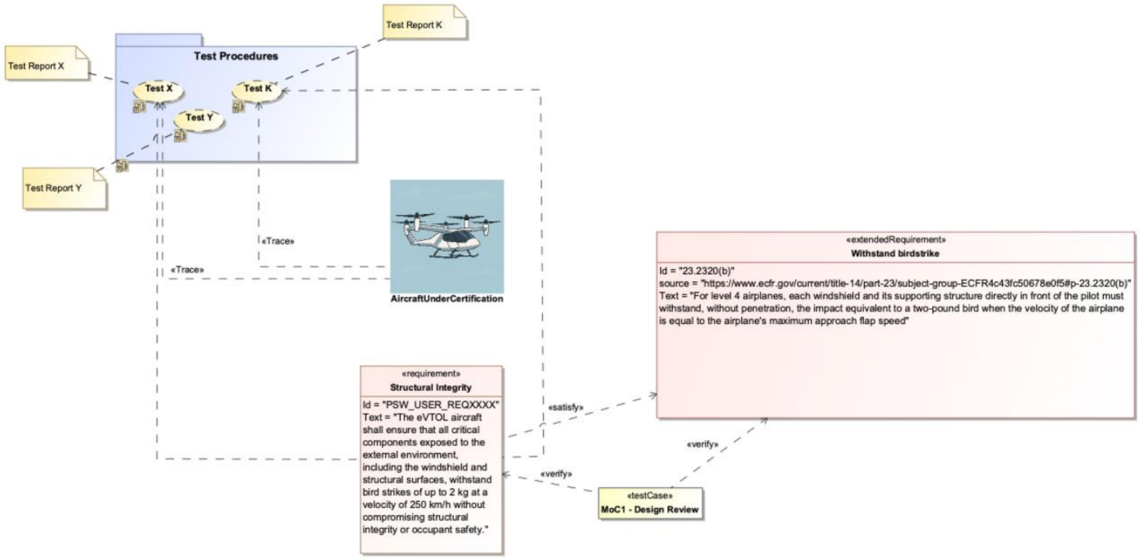


Figure 5.12 – Comprehensive Traceability and Reporting Structure.

5.1.6 Generate Compliance and Traceability Audit Documents

In this step, the focus shifts to compiling all verification artifacts and compliance evidence into structured audit documents. These documents serve as the formal output of the certification process, providing a comprehensive view of regulatory compliance, verification activities, and traceability paths. This stage corresponds to Phase IV - FAA.

The audit documentation includes the following key elements:

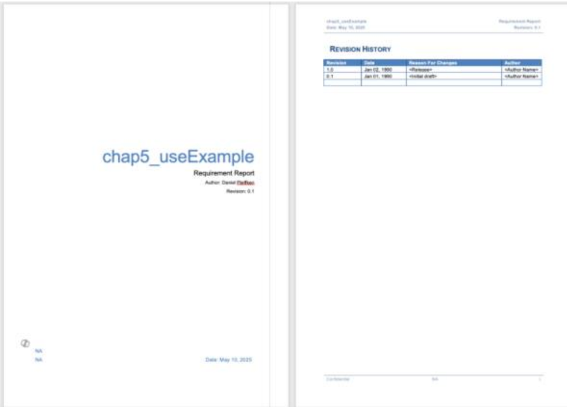
Compliance Matrix: Mapping each regulatory requirement to its respective MoC and verification evidence, ensuring comprehensive coverage of all regulatory items.

Traceability Report: Detailing the linkage between requirements, MoCs, and evidence, establishing a clear audit trail and identifying any gaps in the verification chain.

Verification Summary: Summarizing the verification outcomes, including the status of each requirement (e.g., passed, failed, pending), and identifying any open items or pending validations.

Automated Report Generation

The model-based approach enables the automated generation of audit documents, consolidating traceability data from system conception to final verification, as illustrated in Figure 5.13. This automated process ensures consistency and reduces the likelihood of human error.



chap5_useExample

Requirement Report

Author: Daniel [illegible]

Revision: 0.1

NA

NA

Date: May 10, 2025

REVISION HISTORY

Revision	Date	Reason For Changes	Author
1.0	Jan 02, 1990	<Release>	<Author Name>
0.1	Jan 01, 1990	<Initial draft>	<Author Name>

Figure 5.13 – Automated Compliance and Traceability Report Generation.

5.1.7 Evaluate Compliance and Issue Type Certificate

This phase represents the culmination of the certification process, where all compliance evidence is reviewed, and final assessments are conducted to determine conformity with regulatory requirements. The objective is to resolve any remaining nonconformities, validate the traceability structure, and issue the Type Certificate upon successful completion. This stage corresponds to Phases IV and V – FAA.

The evaluation process includes:

Review of Compliance Matrix: Ensures that all regulatory requirements have been addressed, and corresponding MoCs are substantiated with evidence.

Traceability Links: Confirms that each requirement is traceable to its respective verification activity and evidence source.

Resolution of Nonconformities: Identifies and addresses any open items or discrepancies prior to final certification.

Upon successful completion of the evaluation phase, the System Digital Twin is considered a certified model, serving as a comprehensive digital representation of the certified eVTOL. This certified digital twin establishes a baseline for continued and continuing airworthiness assessments, as further detailed in Section 5.2.2.

Automated Compliance Reporting:

The model-based approach enables the automated generation of final certification documents, consolidating traceability data from system conception to the issuance of the Type Certificate. Figure 5.14 illustrates the structure of the final certification report, encompassing all regulatory requirements, MoCs, and associated evidence.

Figure 5.14 – Automated Compliance Reporting and Type Certification.

5.1.8 Update Post-Certificate and Continued Airworthiness

Following the issuance of the Type Certificate, the certification process transitions to the post-certification phase, focusing on continued airworthiness and ongoing regulatory compliance. The objective is to maintain the integrity of the certification baseline, manage updates, and address any emerging compliance issues. This stage corresponds to Phase V – FAA.

The post-certification phase involves:

Monitoring Compliance: Ongoing verification of operational data to detect potential safety issues or regulatory nonconformities.

Updating the Model: Incorporating updates based on new regulatory guidelines, service bulletins, or field reports to ensure continued alignment with the certification baseline.

Managing Configuration Control: Ensuring that any modifications to the system or its components are properly documented and revalidated as necessary, preserving the integrity of the certified configuration.

The post-certification phase introduces a paradigm shift in managing regulatory traceability and configuration control by positioning the certified model as the primary source of truth. Unlike traditional document-centric approaches, where updates require manual transformation of documents into model elements, the proposed process enables direct updates within the digital model itself. This approach allows for the automatic generation of documentation based on model changes, ensuring alignment between the regulatory baseline and subsequent modifications, as illustrated in Figure 5.15. This transition not only enhances traceability but also mitigates risks associated with version control and documentation inconsistencies, fostering a continuous feedback loop between the physical system, its digital representation, and regulatory compliance artifacts.

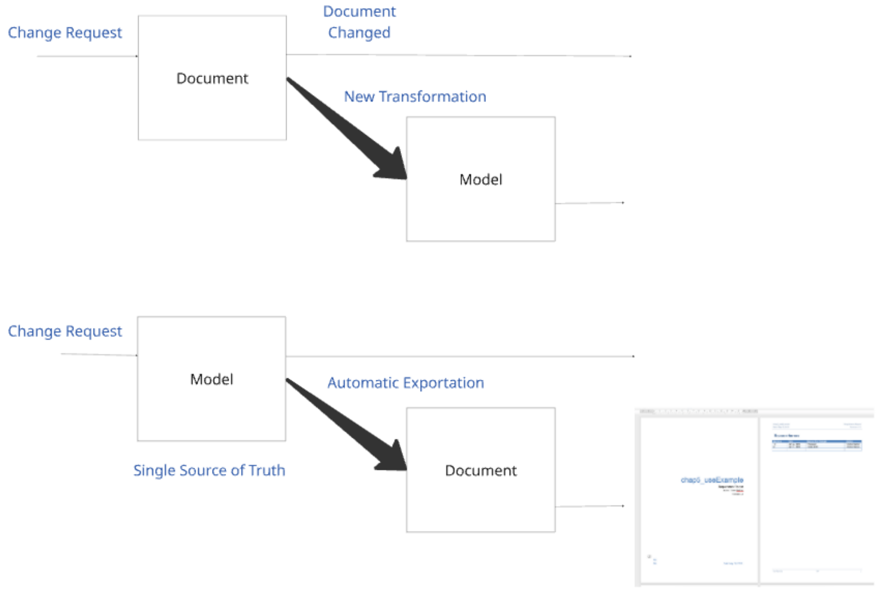


Figure 5.15 – Transition from Document-Centric to Model-Centric Configuration Control in Post-Certification Processes.

Upon completion of the post-certification phase, the System Digital Twin emerges as a certified model that continues to receive updates, integrating real-time data, operational insights, and regulatory changes. This dynamic approach establishes a continuous feedback loop between the physical system and its digital counterpart, supporting continued and continuing airworthiness assessments as detailed in Subsection 5.2.2 – Digital Twins for Continuing and Continued Airworthiness.

5.2 Scope Limitations and Expert-Based Evaluation

While the results of this research demonstrate the potential of the proposed approach to enhance regulatory traceability in aerospace projects, some limitations related to scope, and application must be acknowledged for a balanced interpretation of the findings.

The case study was developed based on a modeled certification scenario, using FAA and ASTM standards applied to a representative eVTOL project. Although the regulatory elements used are real and consistent with current certification practices, the modeling scope was limited to a specific portion of the certification process. As such, extrapolating these results to other regulatory contexts, such as military products, space systems, or multi-authority programs, should be approached with caution.

Furthermore, the framework was applied in a simulated environment, without direct involvement in an actual certification campaign under regulatory oversight. The verification structure was built using plausible compliance requirements and methods, abstracted for conceptual validation purposes.

To reinforce the technical soundness of the approach and assess its institutional applicability, a qualitative evaluation was conducted with six subject-matter experts. All participants had at least ten years of direct experience in systems engineering, aerospace certification, and regulatory compliance management.

The evaluation focused on the proposed model and its documentation and was carried out through free-form comments and structured annotations. This enabled reviewers to identify strengths, technical refinements, and methodological considerations. Overall, the feedback was positive, highlighting the consistency of the proposed framework, the clarity of traceability structures, and alignment with current practices in both civil and military contexts.

Reviewers also noted relevant institutional factors for future implementation, including the need for regulatory maturity, tool interoperability, and organizational adaptations. These aspects are further addressed in the next sections, which discuss institutional adoption challenges and enablers.

By combining a structured case study with expert validation, this research aims not only to offer a conceptual contribution, but also to provide a validated foundation for advancing model-based certification practices, with potential institutional applicability across diverse aerospace domains.

5.3 Exploratory Cases

The exploratory cases presented in this section aim to extend the applicability of the proposed Model-Based Traceability Process by incorporating emerging digital technologies that address critical gaps in regulatory traceability and compliance management. By integrating

AI-driven mechanisms for MoC recommendation and Digital Twins for lifecycle monitoring, these exploratory applications offer a conceptual basis for augmenting traceability workflows, enhancing data-driven decision-making, and reinforcing regulatory alignment throughout the certification process.

5.3.1 Experimental Integration of LLMs for MoC Recommendation

Complementing the traceability mechanisms established in previous sections, this section explores an exploratory application of LLMs to assist in the preliminary recommendation of MoCs. The objective is to address a recognized bottleneck in certification workflows: the manual effort required to analyze regulatory texts and assign technically valid MoCs, particularly in complex aerospace programs.

This component operates externally to the formal MBSE environment, serving as a supportive layer that suggests potential MoCs based on textual analysis of requirements and regulatory standards, under expert supervision. It does not replace the SysML traceability logic but aims to augment the MoC definition phase by providing preliminary, explainable suggestions, ranked by confidence scores.

As discussed in Sections 4.2 and 5.1.2, organizing requirements into structured, traceable models is essential for certification readiness, particularly in the context of SysML-based decomposition and MoC allocation. However, in large-scale programs, manual MoC assignments are time-consuming, prone to inconsistency, and highly dependent on expert knowledge. To mitigate these challenges, this thesis investigates the use of LLMs to assist engineers during the MoC definition phase, reducing ambiguity and enhancing initial verification planning.

As detailed by Moreira et al. (2024), a prototype was developed using a GPT-3.5-turbo model, fine-tuned with a domain-specific dataset of 2,790 annotated requirement-MoC pairs for aerospace defense systems. The dataset, labeled by certification specialists, was structured to ensure consistency and generalization across regulatory domains. The development process included preprocessing, dataset upload, model fine-tuning, validation, and testing using structured aerospace requirements data. The resulting model demonstrated 80.72% accuracy on the validation set and 80.18% on the test set, indicating stable performance across MoC classes.

Figure 5.16 illustrates the structured workflow for developing the LLM-assisted classifier, encompassing preprocessing, dataset upload, fine-tuning, parameter setup, validation, and testing. Output was exported in machine-readable formats (XML and JSON), enabling integration with MBSE tools while preserving traceability attributes. Despite its experimental nature, the LLM-assisted classifier, as validated in paper entitled 'Using LLMs to Automate Means of Conformity Assignment in Aerospace Defense Systems, provided initial MoC suggestions that supported consistency and reduced ambiguity during requirements screening, demonstrating potential for optimizing conformity verification in both civil and defense aerospace projects.

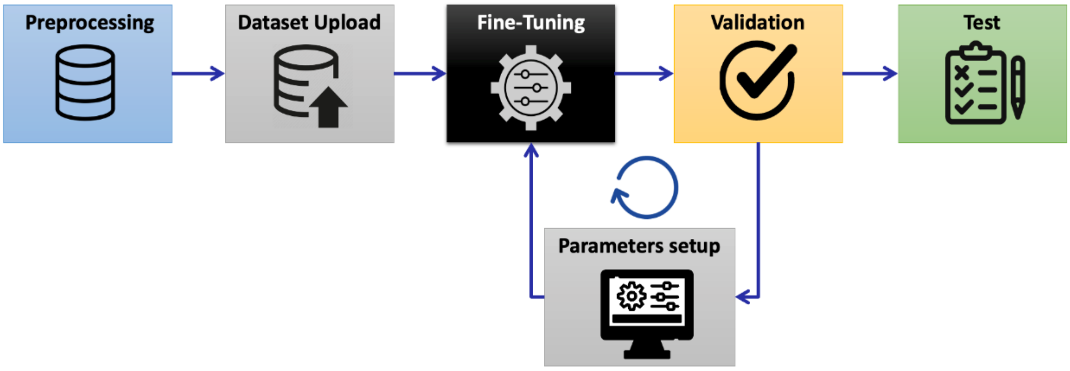


Figure 5.16 – Workflow for LLM-Assisted MoC Recommendation (Adapted Moreira et al., 2024).

However, as discussed in that paper, limitations were identified, including class imbalance, security restrictions, and potential overfitting, particularly in the context of defense aerospace systems where sensitive data could not be included in the training dataset. Recommendations include expanding the dataset, integrating additional regulatory sources, and developing a SysML assistant module to streamline MoC assignment and verification within the MBSE process.

5.3.2 Digital Twins for Continuing and Continued Airworthiness

The concept of Digital Twins has emerged as a transformative technology in aerospace certification, particularly in the context of continuing and continued airworthiness. By creating a digital replica of physical assets, Digital Twins enable real-time monitoring, predictive analysis, and lifecycle management of certified aircraft components.

In the process of continuing airworthiness, Digital Twins provide a comprehensive, continuously updated model that reflects the current operational status of critical systems, structures, and components. This allows regulatory authorities and operators to assess compliance dynamically, identifying potential discrepancies and anticipating maintenance needs before they escalate into safety-critical failures.

For continued airworthiness, the integration of Digital Twins facilitates proactive management of aging aircraft, tracking the cumulative effects of operational stress, environmental exposure, and maintenance actions. By consolidating data from in-service operations, maintenance records, and sensor feedback, the Digital Twin framework can predict failure modes, optimize maintenance schedules, and support evidence-based modifications to TCDS or other documents related with aircraft design.

To implement this approach, a structured methodology is proposed that includes the following key elements:

1. Data Acquisition and Integration: Collect operational and maintenance data through sensors, flight logs, and maintenance management systems, ensuring that data streams are synchronized with the Digital Twin model.
2. Model Validation and Synchronization: Continuously validate the Digital Twin against physical inspections and operational benchmarks, ensuring data fidelity and regulatory compliance.
3. Predictive Analysis and Maintenance Optimization: Apply predictive algorithms to assess the impact of cumulative stress and wear on critical components, providing actionable insights for preventive maintenance.
4. Compliance Reporting and Traceability: Generate automated reports that align with regulatory requirements, ensuring that all Digital Twin data is traceable to specific regulatory clauses and verification artifacts.
5. Adaptive Certification and Configuration Management: Update the Digital Twin model to reflect any changes to the aircraft configuration, including modifications, repairs, and new certification directives.

To further illustrate the application of Digital Twins in the context of regulatory traceability and certification, Figure 5.17 presents the Boeing Digital Thread framework. This model emphasizes the integration of modeling, simulation, and operational data throughout the product lifecycle, demonstrating how a certified Digital Twin can streamline project updates and enhance traceability, as highlighted in Section 2.1.3. By aligning digital and physical systems, the Digital Twin framework has substantial potential in failure prediction, preventive maintenance, and continued airworthiness management, fostering proactive risk mitigation and regulatory compliance.

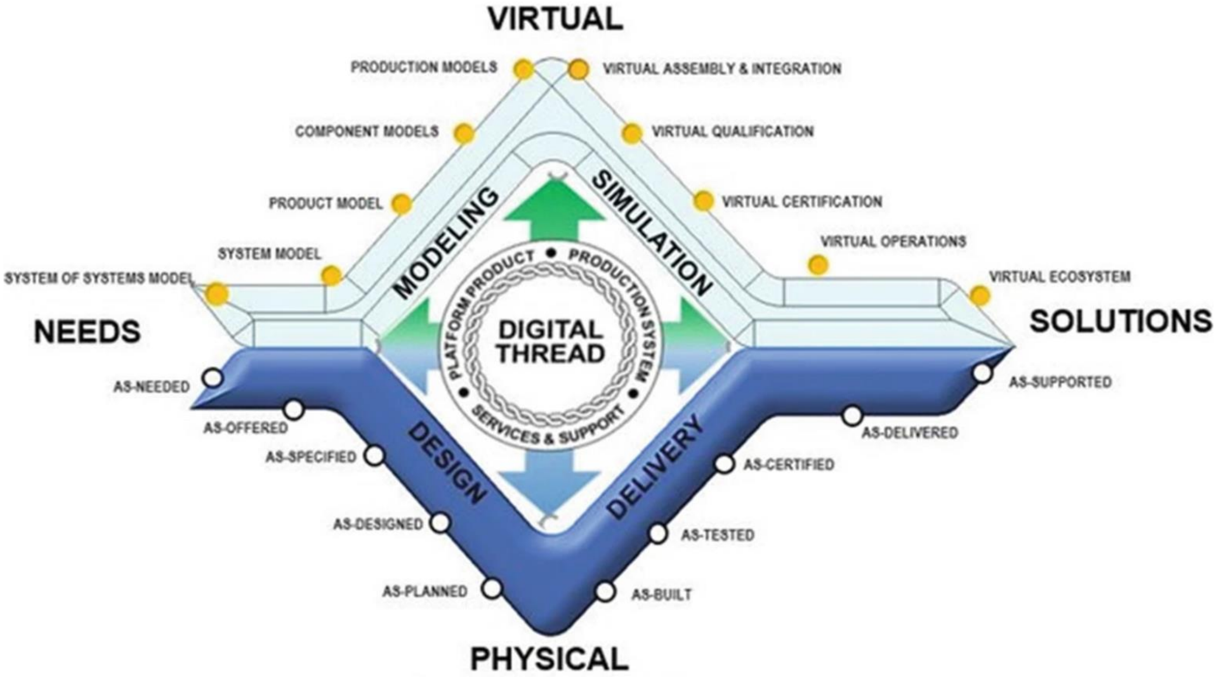


Figure 5.17 – Boeing Digital Thread Framework (Boeing, 2018).

By integrating Digital Twins into the proposed Model-Based Traceability Process, aerospace manufacturers and regulatory authorities can achieve a continuous feedback loop that enhances compliance oversight, reduces operational risks, and extends the operational life of certified aircraft systems. This approach aligns with the broader industry trend toward digital transformation and regulatory harmonization, as outlined in Sections 2.1.3 and 5.1.8.

Explorations with LLMs and Digital Twins demonstrate that the framework can incorporate emerging mechanisms to support compliance, going beyond document traceability and promoting an integrated vision of the lifecycle. However, these initiatives also show that the full application of MBSE to certification requires more than advanced tools. It involves adapting organizational practices, digital infrastructure and, above all, a cultural change that allows requirements, evidence and regulatory decisions to be treated as modelable and auditable entities. Thus, although the process has the potential to transform certification flows, its large-scale adoption will depend on the ability of the ecosystem to evolve together with the technologies that support it.

5.4 Challenges and Migration Strategies

The simulation conducted in the certification scenario of an eVTOL aircraft demonstrated that the proposed process is capable of structuring regulatory content, supporting the preliminary allocation of MoCs, and organizing verification evidence in a cohesive manner. As part of the ex post evaluation phase of the Design Science Research cycle, the transition from a simulated environment to real-world applications revealed practical challenges that directly impact the traceability, repeatability, and reliability of certification artifacts. This section discusses the main obstacles identified and presents strategies for progressive adoption, highlighting that the effective incorporation of MBSE requires transformations that go beyond the model itself, encompassing organizational, cultural, and regulatory aspects.

Organizational Resistance and Capability Gaps

A significant portion of aerospace organizations continue to operate using document-centric processes, with limited exposure to MBSE methodologies. These adoption delays are often associated with limited availability of trained personnel, unfamiliarity with formal modeling practices, and perceived risks associated with transitioning to a new compliance paradigm.

To address these barriers, a phased adoption strategy is recommended. The initial deployment phase should target non-critical systems or subsystems with clearly defined regulatory scopes. Pilot projects can serve as controlled environments to demonstrate tangible outcomes, foster internal alignment, and provide practical training grounds for engineering and certification teams. Concurrently, targeted capacity-building initiatives and structured change management processes are essential to align stakeholders, mitigate resistance, and build technical competencies in MBSE and digital traceability.

Coexistence with Legacy Systems

Complete replacement of legacy infrastructure is typically unfeasible due to cost, risk, and the necessity to preserve historical certification records. Therefore, the process is designed to accommodate hybrid implementations, allowing MBSE models in SysML to coexist with legacy documentation and artifacts.

To enable effective interoperability, data transformation mechanisms are essential. These mechanisms may include custom scripts (e.g., Python, M2Doc), standardized data formats (e.g., JSON, CSV), and Open Services for Lifecycle Collaboration (OSLC) APIs. Such connectors facilitate incremental construction of traceability layers, ensuring consistency between existing compliance documentation and newly generated MBSE artifacts.

It is worth noting that the bidirectional traceability built into the simulated model, connecting regulatory requirements to the respective MoCs and verification artifacts, depends on the consistency of the modeled elements, the use of standardized semantics, and the disciplined application of systems engineering practices. However, in operational environments, this consistency is often affected by heterogeneous workflows, tool-specific constraints, and the lack of standardized modeling conventions among the various stakeholders involved. These factors reduce the robustness of compliance chains and can generate gaps or overlaps in certification documentation.

Toolchain Heterogeneity and Data Interoperability

Certification processes often involve multiple stakeholders, including OEMs, subsystem suppliers, and regulatory authorities, each operating with different modeling tools and data formats. This heterogeneity complicates traceability, version control, and multi-stakeholder compliance alignment.

To address these challenges, the process advocates for the adoption of open standards, such as OSLC and XML Metadata Interchange (XMI), which enable model exchange, change tracking, and semantic consistency. Future work should explore toolchain orchestration strategies that support automated validation, compliance reporting, and lifecycle traceability across distributed systems and model repositories.

Regulatory Acceptance of LLM-Based Automation

The exploratory use of LLMs in this thesis demonstrated potential efficiency gains in MoC assignment; however, regulatory acceptance remains a significant barrier. Authorities are justifiably cautious regarding AI-generated outputs, especially in safety-critical contexts, due to concerns about explainability, repeatability, and verification mechanisms.

To align with regulatory expectations, LLM integration should adhere to a human-in-the-loop paradigm, with outputs treated strictly as decision-support suggestions rather than final authoritative recommendations. All model-generated recommendations must include:

- Traceable rationale.
- Confidence scores or probability thresholds.
- Version-controlled logs.

- Verifiability and consistency check within the MBSE model.

In summary, although the process has demonstrated technical potential in organizing certification artifacts and supporting regulatory logic, its practical application depends on the maturity of the ecosystem. This includes not only the tools and data infrastructure, but also the degree of alignment between the actors involved, the adequacy of institutional processes, and the cultural willingness to adopt a model-driven approach. The simulation performed allowed us to validate central aspects of the proposal, but also highlighted weak points, especially in the sections where it was necessary to improvise solutions for interoperability and regulatory uncertainties.

5.5 Practical Implications

The application of the process in a representative eVTOL certification scenario provided evidence of its utility in consolidating regulatory content, MoCs, and verification artifacts into a cohesive model structure. By integrating regulatory requirements into SysML, the process enabled systematic modeling of certification processes, enhancing the traceability of compliance evidence across the lifecycle stages defined in the eVTOL certification case study. The structured approach provided a clear mechanism to trace regulatory requirements to their respective MoCs, verification methods, and evidentiary artifacts, as emphasized in Section 5.1.

Enhancements to Engineering and Certification Practice

The process demonstrated tangible benefits, such as improved organization of compliance documentation and reduced ambiguity in MoC allocation and facilitating bidirectional traceability between requirements and verification artifacts. The use of SysML as a modeling environment allowed for the establishment of hierarchical decomposition structures, aligning regulatory requirements with system components and verification pathways. This structuring approach was exemplified in the eVTOL case study, where the integration of MoCs and verification artifacts into a single model environment reduced ambiguity and reinforced regulatory alignment.

Lessons from Subject-Matter Expert Feedback

Feedback from subject-matter experts highlighted the potential for the process to reduce verification effort by clarifying evidence structures and enabling better requirement interpretation, although these gains were not quantitatively assessed in this study. The experts noted that the MBSE-driven approach facilitated more coherent requirement interpretation and improved the management of traceability artifacts, particularly in complex certification scenarios involving multiple regulatory processes. However, quantitative metrics to substantiate these observations were not formally established and remain an area for future empirical validation.

Potential Implications for Continued Airworthiness

The structured integration of regulatory content within the model environment suggests a pathway for extending the process to post-certification and continued airworthiness activities. This extension would involve the integration of service bulletins, airworthiness directives, and other regulatory updates, maintaining traceability across the entire lifecycle as outlined in Section 5.1.8.

Institutional Impact and Future Directions

The findings indicate a pathway toward more integrated certification ecosystems, where digital models serve as persistent regulatory artifacts, maintaining traceability even as requirements evolve. Future work could be explored:

- The extension of the process to military and space certification contexts.
- The incorporation of digital twins to support ongoing compliance verification, particularly in the context of continued and continuing airworthiness.
- The development of structured compliance threads that link regulatory updates to specific model artifacts, reinforcing the alignment between operational data and regulatory criteria.

Furthermore, institutions such as the Industrial Development and Coordination (IFI), responsible for the certification of military and space products in Brazil, could play a strategic role in the practical validation of the proposed process. The adoption of pilot projects, in partnership with engineering centers and manufacturers, would allow the model’s applicability to be assessed in real compliance scenarios, especially in the context of emerging military systems that require greater traceability and digital integration. This gradual approach, with a controlled scope, would enable technical and organizational gains, while strengthening the IFI’s institutional capacity to prototype and validate model-based certification processes, particularly in defense and space domains.

6 Conclusion and Future Work

This chapter consolidates the findings and contributions of this doctoral research, aligning them with the objectives and hypothesis initially defined in Chapter 1. The purpose is to provide a structured reflection on the methodological advancements and practical implications of the Model-Based Regulatory Traceability Process developed through a model-based approach and evaluated through a simulated regulatory scenario serving as a proof of concept within the DSR framework.

The chapter is organized into four sections: the first revisits the research problem, hypothesis, and objectives, confirming their alignment with the achieved outcomes; the second addresses the scientific relevance, originality, and utility of the proposed process in the context of aerospace certification; the third discusses the identified limitations, clearly defining the boundaries of the current implementation and outlining potential directions for future work; and the fourth section summarizes the primary scientific and industrial contributions, emphasizing the impact of model-based regulatory traceability within safety-critical engineering domains.

6.1 Research Problem, Hypothesis, and Objectives

This doctoral research addressed the central problem presented in Chapter 1: the absence of structured, model-based traceability mechanisms within aerospace certification processes. This deficiency compromises transparency, consistency, and auditability in compliance workflows across regulatory domains. The analysis developed throughout Chapters 3 and 4 emphasized how current practices, still predominantly document-centric, are insufficient for managing traceable and scalable certification logic, particularly in high-complexity and cross-jurisdictional scenarios. In response, the study investigated whether a MBSE process could be developed to enhance regulatory traceability and compliance verification without undermining the integrity of certification processes.

The research hypothesis, also formulated in Chapter 1, proposed that a structured MBSE-based framework, combining regulatory structures modeled in SysML with systematic mappings of MoCs would improve lifecycle traceability, enable more robust verification paths, and support digital auditability of aeronautical systems.

To examine this hypothesis, the research established the following general objective:

- To develop a model-based traceability process for aerospace certification.

This objective was pursued through three specific objectives, each addressed in detail throughout the thesis:

To analyze the certification process and propose a regulatory mapping to support traceability and interoperability.

– This objective was fulfilled in Chapters 3 and 4 through the construction of a comparative regulatory model, formalized using SysML, which enabled harmonized interpretation of certification structures across FAA and EASA. This modeling effort supported both document-level and process-level traceability.

To develop a structured compliance process that integrates regulatory requirements, MoCs, supporting documentation, and verification activities in a model-based environment.

– This was implemented in Chapter 4, where a SysML-based metamodel was developed to establish bidirectional traceability between regulatory clauses, verification methods, technical documentation, and system elements. This structure provides a foundation for both manual assessment and potential automation of compliance reasoning.

To demonstrate the proposed traceability process through a simulated regulatory scenario in the eVTOL domain.

– This demonstration was conducted in Chapter 5, using a representative use case focused on bird strike protection for eVTOL aircraft. The case illustrated how the modeled certification framework could integrate applicable regulatory sources (e.g., FAA Part 23, ASTM F330-21), associate them with MoCs, and generate traceable certification artifacts. Although not intended as empirical validation, the scenario served as a practical testbed to reveal both the potential and challenges of adopting model-based certification artifacts.

The research hypothesis was ultimately supported by the conceptual consistency of the framework, the structural coherence of the SysML metamodel, and the practical outcomes of the simulated implementation. In addition, an expert-based review presented in Chapter 5 confirmed the technical clarity, regulatory relevance, and institutional applicability of the proposed approach. The research problem introduced in Chapter 1 was thus systematically addressed, and all research objectives were achieved.

6.2 Relevance, Originality, and Utility of the Results

The proposed Model-Based Regulatory Traceability Process constitutes a significant methodological contribution to the aerospace certification domain. It addresses persistent deficiencies in traceability, verification logic, and regulatory auditability by integrating principles of MBSE with formalized regulatory structures modeled in SysML. These contributions respond directly to the challenges identified in Chapters 2 and 3, particularly the fragmentation of compliance information and the limitations of document-centric processes in managing complex certification workflows.

From an epistemological standpoint, this work is positioned as a design-oriented research endeavor, grounded in the DSR paradigm as outlined in Chapter 1. Following DSR principles, the research cycle was structured around a well-defined problem (the absence of integrated traceability mechanisms), the design of an innovative artifact (the SysML-based regulatory traceability framework), and a demonstration of its utility through a controlled case study. The process iteratively refined its modeling approach based on theoretical grounding and empirical simulation, thereby satisfying the DSR criteria of relevance, rigor, and artifact evaluation.

The originality of the proposed process lies in its capacity to consolidate regulatory criteria, compliance rationale, and verification artifacts into a cohesive model-driven structure. Unlike conventional certification methods, which are highly dependent on fragmented documents, manual interpretation, and loosely linked verification plans, the model developed in this research enables structured, bidirectional traceability between regulatory clauses, selected MoCs, system components, and verification methods. This is not merely a digitization of existing workflows, but a formal transformation of the regulatory reasoning process into a computationally traceable model, as emphasized in Chapter 3.

In terms of utility, the application of the framework to a representative eVTOL certification scenario, as developed in Chapter 5, demonstrates its feasibility in a simulated but realistic context. This case allowed for the instantiation of regulatory mappings, the association of compliance methods, and the generation of traceable verification reports, all within a unified SysML modeling environment. Although not intended as empirical validation, this implementation served as an evaluation strategy within the DSR framework, confirming that the proposed artifact effectively addresses the targeted problem and aligns with current and emerging certification practices.

Therefore, this research not only fills a methodological gap identified across civil, military, and emerging aerospace domains but also provides a foundation for future developments in digital certification, regulatory automation, and compliance reasoning, with potential to support both industry adoption and institutional transformation.

6.3 Limitations and Future Work

Limitations

Despite the structured methodology adopted in this research, certain limitations must be acknowledged to establish the scope of the proposed process and identify areas for further development:

Civil Aviation Focus: The exemplification of the process was conducted primarily in the context of civil aviation certification, specifically using an eVTOL case study aligned to FAA Part 23, EASA SC-VTOL, and ASTM standards.

Controlled Simulation Environment: The exemplification of the process was confined to a regulatory example, excluding real-world dynamics such as organizational resistance, integration with existing legacy systems, and the practical adoption of the proposed methodology.

Regulatory Generalization: While the process was mapped to FAA and EASA standards, broader deployment in other jurisdictions (e.g., ANAC, CAAC, IFI) would require further contextual adaptation, including regulatory mapping, procedural refinement, and semantic alignment.

Future Work

Building upon the identified limitations, the following future research directions are proposed to enhance the robustness and applicability of the process:

Real-World Pilot Studies: Conduct structured pilot implementations in collaboration with regulatory authorities and OEMs to assess process applicability across the certification lifecycle, capturing institutional feedback and operational dynamics.

Extension to Military and Space Domains: Develop domain-specific structured regulatory models and evaluate the process through targeted case studies in military and space certification, incorporating MIL-HDBK-516C and ECSS standards.

Expansion of Regulatory Mappings and Interoperability: Expand the structured regulatory mappings to encompass emerging process, including UAM, unmanned systems, and sustainability criteria, ensuring semantic consistency and interoperability.

Exploration of Digital Twin and Digital Thread Concepts: Further explore the integration of Digital Twin and Digital Thread concepts as future architectural layers, developing observer viewpoints and regulatory dashboards to facilitate real-time compliance monitoring and support post-certification lifecycle management.

These proposed directions aim to consolidate the methodological foundations established in this research, fostering structured academic-industry collaboration and regulatory innovation in model-based certification processes.

6.4 Contributions

The main scientific contribution of this research lies in demonstrating the feasibility and effectiveness of modeling regulatory structures within a model-based environment as a key enabler of digital transformation in aerospace certification. By replacing document-centric approaches with model-based representations of certification regulations, the proposed process facilitates structured traceability, compliance verification, and digital auditability throughout the system lifecycle.

Unlike traditional practices that rely on static documentation and fragmented traceability mechanisms, this research showed that modeling certification regulations in SysML enables more consistent, integrated, and semantically aligned compliance processes. This approach enhances the observability of regulatory logic, supports robust two-way traceability linking regulatory clauses, compliance methods, and supporting verification evidence.

From a practical standpoint, the thesis contributes to the facilitation of regulatory processes by offering a structured methodology to support the transition from document-based certification workflows to a model-centric paradigm. This shift promotes early identification of compliance gaps, reduces redundancy in verification tasks, and enables, in the medium term, the automation of regulatory audits.

Additionally, the results of this research may serve as a foundation for future initiatives at institutions such as the IFI, should there be institutional interest in exploring digital certification methodologies and regulatory modeling. The proposed process provides methodological foundations that can support the transition toward more integrated, transparent, and digitally aligned certification processes.

Collectively, these contributions represent a significant advancement in the state of the art in model-based systems engineering and regulatory science, laying the groundwork for scalable, auditable, and digitally integrated certification processes.

6.5 Publications

This section presents the publications developed during doctoral research. Only works coauthored by the doctoral candidate are listed, categorized according to their alignment with the dissertation's central themes.

6.5.1 Strongly Related Publications

PLEFFKEN, D. R.; MOREIRA, G.; BOURGUIGNON, V.; CERQUEIRA, C. S. (2024). Automating eVTOL Airworthiness Certification Using MBSE and Large Language Models: A Framework for Regulatory Alignment.

MOREIRA, G.; PLEFFKEN, D. R.; SANTOS, W. G.; CERQUEIRA, C. S.; GOTELIP, M. R. (2024). Using LLMs to Automate Means of Compliance Assignment in Aerospace Defense Systems. Accepted at Journal of Aerospace Information Systems (AIAA).

PLEFFKEN, D. R.; MOREIRA, G.; CERQUEIRA, C. S. (2023). Enhancing Spaceworthiness Process Based on Certification Procedures Applied in KC-390 and Gripen F-39. XXV SIGE, São José dos Campos, Brazil.

PLEFFKEN, D. R.; MOREIRA, G.; CERQUEIRA, C. S. (2022). Aplicando Engenharia de Sistemas Baseada em Modelos para Suportar Projetos Aeroespaciais Militares no Brasil. XXIV SIGE, São José dos Campos, Brazil.

PLEFFKEN, D. R. (2021). KC-390 Certification Process – Entry into Service (EIS). International Journal of Advanced Engineering Research and Science (IJAERS).

6.5.2 Weakly Related Publications

PLEFFKEN, D. R.; CERQUEIRA, C. S. (2024). Incorporating Military Certification Practices in the Aerospace Industry for Enhanced Safety and Compliance. Observatório de la Economía Latinoamericana. DOI: 10.55905/oelv22n7-108.

PLEFFKEN, D. R.; BOURGUIGNON, V. O.; MOREIRA, G.; CERQUEIRA, C. S. (2023). Acceptance of Residual Risk in Brazilian Military Aeronautical Design Through Methodology

Application. 33rd ESREL – European Safety and Reliability Conference, Southampton, UK. Preprint.

PLEFFKEN, D. R.; CORDERO, R. M.; HAMASAKI, P.; CARDOSO JÚNIOR, M. M. (2023). Risk Analysis for In-Flight Refueling Missions Between a Jet-Powered Aircraft and Helicopters. ESREL 2023, Southampton, UK.

PLEFFKEN, D. R.; MAXIMILIANO, M.; CERQUEIRA, C. S. (2023). A Necessidade de Padronização de Modelos de Maturidade em Projetos Aeroespaciais Brasileiros. XV ENAPID – Encontro Acadêmico de Propriedade Intelectual, Inovação e Desenvolvimento, Brazil.

PLEFFKEN, D. R.; SOUZA, M. L. O. (2021). Sumarização do Processo de Certificação de Tipo Militar no Brasil para Adaptá-lo a Produtos Espaciais. In: Capítulo de Livro.

MOREIRA, G.; PLEFFKEN, D. R.; SANTOS, W. G.; CERQUEIRA, C. S. (2024). Enhancing Brazilian Aerospace Systems Lifecycle Directive. XXVI SIGE – Simpósio de Aplicações Operacionais em Áreas de Defesa, São José dos Campos, Brazil.

MOREIRA, G.; PLEFFKEN, D. R.; SANTOS, W. G.; CERQUEIRA, C. S. (2022). STPA Analysis over the Earlier Phases of Brazilian Aerospace Products Life Cycle Using OPM. 13th ICMAE – International Conference on Mechanical and Aerospace Engineering, Bratislava, Slovakia. DOI: 10.1109/ICMAE56000.2022.9852838.

6.5.3 Remotely Related Publications

PLEFFKEN, D. R.; SOARES, C.; CERQUEIRA, C. S. (2023). Strategic Planning Development for the Inclusion of Individuals with Autism Using Value-Focused Thinking Method for Future Urban Mobility. LV SBPO – Simpósio Brasileiro de Pesquisa Operacional, Rio de Janeiro, Brazil.

PLEFFKEN, D. R.; GARCIA, S. (2022). Elaboração do Planejamento Estratégico de uma Empresa do Ramo de E-Commerce Utilizando o Método Value-Focused Thinking. LIV SBPO, Juiz de Fora, Brazil.

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5. TÍTULO E SUBTÍTULO:

A model-based traceability process for aerospace certification.

6. AUTOR(ES):

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8. PALAVRAS-CHAVE SUGERIDAS PELO AUTOR:

1. Model based Systems Engineering 2. Aerospace Certification 3. Regulatory Traceability Compliance.

9.PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO:

Administração de projetos; Certificação; Regulamentação aeronáutica; Gestão de projetos; Aeronaves de decolagem vertical; Sistemas de segurança; Industria aeroespacial; Estudos de caso; Engenharia aeroespacial.

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11. RESUMO:

The accelerated evolution of aeronautical systems, combined with regulatory fragmentation, poses significant challenges to certification processes, which demand rigorous verification and validation to ensure compliance and safety. The absence of a structured model that transparently connects regulatory requirements to compliance evidence weakens traceability, undermines standardization, and hinders the effectiveness of audits. To address these challenges, this thesis proposes a model-based regulatory traceability process, structured according to the Design Science Research (DSR) paradigm and grounded in the principles of Model-Based Systems Engineering (MBSE). A Systematic Literature Review (PRISMA) was conducted to analyze the certification process, revealing methodological gaps and a pressing need for regulatory harmonization. Based on these findings, a SysML-based traceability model was developed to integrate requirements, verification artifacts, and compliance workflows. Furthermore, the research explores the conceptual foundations of traceability, contributing to the ongoing management of certification data in digital environments. An exploratory and simulated case study involving the certification of an eVTOL aircraft was carried out, demonstrating the benefits of the proposed process in terms of conceptual clarity and alignment with structures compatible with digital verification flows. The proposed solution is potentially adaptable to multiple regulatory domains, offering manufacturers and authorities a digital traceability approach that enhances transparency in certification. Thus, this research contributes to the advancement of certification methodologies by promoting regulatory interoperability, continuous verification, and digital transformation.

12. GRAU DE SIGILO:

(X) OSTENSIVO ( ) RESERVADO ( ) SECRETO