

A Model-Based Aircraft Certification Framework for Normal Category Airplanes

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A typical aircraft certification process consists of obtaining a type, production, airworthiness, and continued airworthiness certificate. During this process, a type certification plan is created that includes the intended regulatory operating environment, the proposed certification basis, means of compliance, and a list of documentation to show compliance. This paper extends previous work to demonstrate a model-based framework for the management of these certification artifacts for normal category airplanes. The developed framework integrates the regulatory rules and approved means of compliance in a single model while using best-practices found in Model-Based Systems Engineering (MBSE) literature. This framework, developed using SysML in MagicDraw captures not just the textual requirements and verification artifacts, but also their relationships and any inherent meta-data properties via custom defined stereotype profiles. Additionally, a simulation capability that automates the extraction and export of the applicable rules (certification basis) and corresponding means of compliance for any aircraft under consideration at the click of a button has been developed. The framework also provides numerous additional benefits to different stakeholders that have been described in detail with examples where necessary.

I. Introduction

Modern aircraft are subject to government mandated safety rules to ensure these complex machines pose minimal risk to crew, passengers, as well as the people and property around them. These rules apply in different stages that describe the certification process as the aircraft is designed, manufactured, and operated over its life. “Certification” refers to some accepted form of proof that these rules have been followed. In the United States, the Federal Aviation Administration (FAA) oversees the four main types of certification for aircraft and aircraft operations as follows: (i) A type certificate (TC) ensures that an aircraft design conforms to the appropriate airworthiness rules. (ii) A production certificate approves the manufacturing process to produce an aircraft as per the approved design. (iii) An airworthiness certificate is required to ensure the aircraft enters service, and (iv) a continued airworthiness certification to ensure that the aircraft can be operated throughout its life.

The focus of the present work is the TC process for General Aviation (GA) aircraft that account for more than 90% of the roughly 220,000 civil aircraft registered in the US [1]. While the TC process is costly, time consuming, and subject to a lot of uncertainty in its own right, these problems are compounded with the advent of novel concepts of operation and novel architectures or technologies like *e*-VTOL and hybrid-electric propulsion, especially since these have not been previously type-certified. The limitations and other operational considerations generally tested during certification programs may not yet be developed, or sufficiently mature for new technologies. This can considerably affect the adoption of new technologies since the knowledge required to certify these products is unavailable due to the lack of operational experience. To compound the problem, certification rules for new technologies can take years to move through Federal rule-making processes.

In order to ensure the GA fleet and operations remain safe in a rapidly evolving new paradigm, the FAA implemented a new set of performance-based certification rules for Normal Category Aircraft in Title 14 of the Code of Federal Regulations (CFR), Part 23, Amendment 64 [2]. These updated performance-based requirements replace the earlier prescriptive design requirements. They are intended to maintain the same level of safety associated with 14 CFR Part 23

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Amendment 63, while establishing a higher level of safety for loss of control and icing [2]. The changes to 14 CFR Part 23 in Amendment 64 are extensive, with the content, structure, and even section numbers of the rules having changed significantly. Prescriptive means of compliance language that used to be contained within the rules and associated guidance material (Advisory Circulars) are now being ported over to a number of different consensus standards from the aviation community [3]. This new approach leverages the idea that the means of compliance (MoCs) developed from consensus standards organizations can be more agile than federal rule-making, thus enabling faster adoption of new technologies for these aircraft [4].

While the amendment enables the desired outcome of allowing new technologies to be introduced to a certification program in a more expedient fashion, experience with this new format has shown that it can be cumbersome and confusing to new and experienced applicants alike. Furthermore, the expansion of acceptable means of compliance to include numerous, changing consensus standards has introduced new complexities for management of a certification plan. These issues are compounded by the document-centric nature of the certification process – the rules, requirements, and means of compliance are contained within documents that must be extracted by the reader and manually adapted into a document-based certification plan.

The research objective of this paper is to extend previous work by the authors [4] to develop a model-based aircraft certification framework for the management of certification plan and related artifacts. The present work also looks at standardizing the process of developing a model based certification framework using best practices borrowed from model-based systems engineering (MBSE). The remainder of this paper is organized as follows: Section II summarizes the type certification process in relation to the creation of a certification plan, and a notional document based approach, and a model-based approach used for certification planning; Section III introduces and describes the model-based certification framework for certification plan management; Section IV presents the results generated by using the developed framework, along with any potential benefits of the proposed MBSE approach; Section V identifies avenues for future research on the developed framework that are currently being explored.

II. Background

This section briefly introduces the type certification process, a baseline document based approach, and the proposed model-based approach that can be used to manage the different certification artifacts generated. While certain information is repeated here for completeness, readers are directed to previous work [4] for additional details.

A. The Certification Plan

The current Type Certification (TC) process relies on the creation of a Certification Plan (CP) by the FAA and the TC applicant. The CP includes [5]:

- 1) The intended regulatory operating environment
- 2) The proposed certification basis
- 3) A description of how compliance will be shown
- 4) A list of documentation showing compliance with the certification basis, and how compliance findings have been made (Compliance Checklist)

The present work incorporates the rules and associated compliance information for Subpart B and Subpart E of 14 CFR Part 23 Amendment 64 as the intended operating environment. The FAA along with the applicant establishes the certification basis based on mutual understanding of the design features of the aircraft under consideration. Broadly speaking, the certification basis defines the specific rules and amendment levels in addition to any applicable noise, fuel venting, and exhaust emission requirements that the TC applicant must comply with [5]. Once a certification basis is established, a description of how compliance will be shown is created. A pre-approved Means of Compliance (MoCs) can be used for this purpose. This paper focuses on the ASTM consensus standards developed by ASTM Committee F44 that form an accepted MoC for 14 CFR Part 23-64 [3, 6]. Additionally, the CP requires a list of all documentation that will be submitted to show compliance with the certification basis, and details on how the applicant will ensure compliance showings have been made [5]. Compliance showings are generally made by Flight Tests (FT), Ground Tests (GT), Analysis (AN), Design (DE), by showing Similarity (SI), by showing an Equivalent Level of Safety Finding (ELOS), or by a Petition for Exemption. All of this information required for a CP can be summarily combined in a Type Certificate Compliance Checklist that includes the certification basis, the applicable MoC, and the method of compliance.

FAR Part 23			MOC - ASTM Standard				
Section	Title	Text	1 st reference	Text	2 nd reference	Section	Text
23.21	Weight and center of gravity	(c) The condition of the airplane at the time of determining its empty weight and center of gravity must be well defined and easily repeatable.	F3264-18 Section 5.1.1	F3082/F3082 M - 17 Standard Specification for Weights and Centers of Gravity of Aircraft	F3082/F3082M 4. General	4.4	Empty Weight and Corresponding Center of Gravity:
						4.4.1	The empty weight and corresponding center of gravity shall be determined by weighing the aeroplane with: 4.4.1.1 Fixed ballast, 4.4.1.2 Unusable fuel determined under Specification F3063/F3063M, and 4.4.1.3 Full operating fluids including: (1) Oil, (2) Hydraulic fluid, and (3) Other fluids required for normal operation of aeroplane systems, except potable water, lavatory precharge water, and water intended for injection in the engines.
						4.4.2	The condition of the aeroplane at the time of determining empty weight shall be one that is well defined and can be easily repeated.
						5.10	Unusable Fuel Supply:
						5.10.1	The unusable fuel supply for each tank must be established as not less than that quantity at which the first evidence of malfunctioning occurs under the most adverse fuel feed condition occurring under each intended operation and flight maneuver involving that tank. Fuel system component failures need not be considered.

Fig. 1 Document-based Approach at Mapping FAR 23.2100(c) to ASTM MoC [4]

B. Document-based Certification Plan Management

One way to manage a certification plan is to generate documents that map the regulatory requirements to the approved consensus standards. FAA has published a notice of applicability to map the various ASTM standards that serve as accepted MoC to the regulatory rules [3, 5, 7]. This mapping can be extracted in a manually generated spreadsheet that links each requirement to the relevant ASTM standards, and serves as a baseline attempt to simplify the process of generating a compliance checklist for the present work. Figure 1 shows such a baseline spreadsheet model of the regulations and corresponding means of compliance. It is evident that finding relevant information from these standards is not a trivial task because (i) The MoC are spread across multiple documents, and the process of mapping them to 14 CFR Part 23 is not straightforward, and (ii) These documents cross-reference each other, making it time consuming and difficult to sift through them manually

Additionally, it is important to reiterate the following observations made in previous work [4] – (i) Relevant guidelines from within the MoC document have to be mapped manually to the relevant regulatory subsections; A process that requires inputs from subject-matter-experts (SMEs), (ii) Cross-referencing within the MoC standards limits the effective amount of information that can be conveyed at once in a spreadsheet, (iii) An attempt to create a comprehensive mapping along with cross-references results in the spreadsheet becoming intractably large, (iv) The process is susceptible to human errors, which can be difficult to spot and correct later, and (v) Updating such a spreadsheet with any changes to either the rules or accepted MoC documents is a costly proposition. A model-based framework that addresses these problems and provides numerous additional benefits is presented in the next section.

C. The Model-Based Approach

A model-based approach intends to streamline the certification planning process by taking advantage of Model-Based Systems Engineering (MBSE) techniques. For document-based systems engineering, systems engineers produce documents, tables, figures, and flowcharts. Under such an approach, consistency and content of the data must be managed manually across documents and databases. MBSE is an emerging discipline that leverages models, rather than documents, for systems engineering exercises. Under a MBSE paradigm, systems engineers produce a single system model. Any reports, flowcharts, and other documentation must be generated from the common system model. Reports are compiled by exposing portions of the system model, while modeling languages enable consistency in the system model data [8, 9]. This means that the traditional engineering products like geometry, equational models, behavior description, requirements, and other documentation are described via a language in a system model. A system model contains all information and relationships between operational concept, requirements, and other information. Reports and tables are generated according to this information. The systems modeling language (SysML) is general purpose architecture modeling language, and supports the specification, analysis, design, verification, and validation in systems engineering applications. SysML is graphical and uses multiple types of standardized model elements and diagrams.

The representations of given systems and the relationships that exist among them are done through the selection of model elements. These representations have standardized meanings and thus make the communication from one modeler to another much easier [10, 11].

For the present study, the model-based approach includes modeling of the regulatory requirements and verification procedures, and linking the two. At the core of the model-based approach, the aircraft type certification is a prescribed systems engineering process – identification of core requirements, selection of means to verify compliance, and generation of evidence sufficient for verification [4]. Comparing with the document-based approach described in Sec. II.B, the model-based approach guarantees the completeness and consistency when tracking requirements and verification artifacts from multiple sources by providing formalized modeling techniques leading to a coherent system model incorporating up-to-date requirements and analysis [10]. A long term goal of transitioning to a model-based paradigm is to integrate the Model-Based Certification Framework with various analysis tools and safety methods [12–17] in order to shift certification and safety considerations earlier into the design phases and streamline the aircraft conceptual design process.

III. The Model-Based Certification Framework

A SysML model representing the certification regulations and consensus standards forms the core of the framework. To extend previous work, MagicDraw continues to be the chosen tool for the development of the SysML model. Readers are referred to previous work for background and details regarding the MBSE process applied to the current context, and justification for the use of MagicDraw [4]. The model has been organized into logical groupings using ‘package elements’ within MagicDraw. The three top-level packages/groupings are shown in Figure 2 and are described below.

- The type certification profile (see Sec. III.A)
- The type certification package (see Sec. III.B)
- The simulation package (see Sec. III.C)

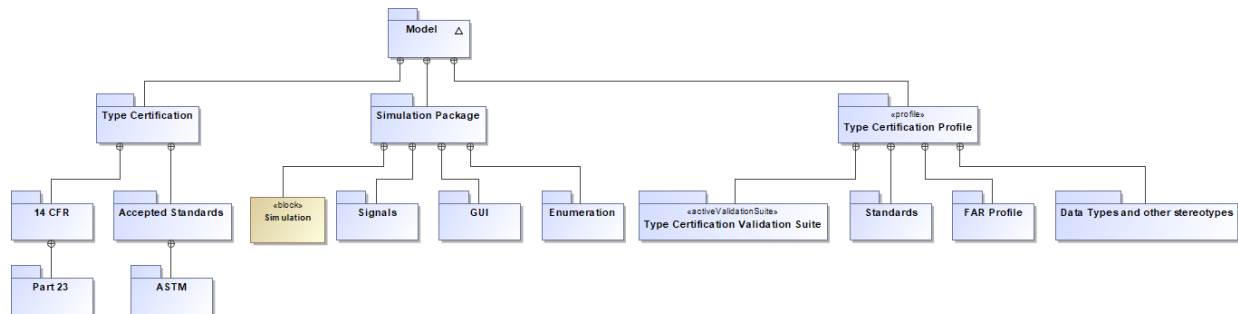


Fig. 2 Model-Based Certification Framework Package Structure

A. The Type Certification Profile

The TC profile is a first step in solving the issues presented in Sec. II by establishing a complete representation of the regulatory rules and corresponding ASTM standards. The TC profile includes shared packages used in SysML to contain model elements that are reusable [10]. In SysML, blocks are the fundamental modular units for describing a system structure [10], and are therefore extended to fit the current context. This profile allows utilization of SysML extension mechanisms called stereotypes that can be used to store additional properties, constraints, or meta-data. These properties can be used in the model-based framework not only as classification objects, but also as a template to inform best practices while setting these standards (see Sec. IV.A.2). Readers are directed to previous work [4] for additional context and explanation for the creation of customized stereotypes as against using requirement elements in SysML.

The previous work which focused solely on 14 CFR Part 23 Subpart B has been updated in the present work to include both Subpart B (Flight) and Subpart E (Powerplant), with plans of adding additional subparts in the near future. While 14 CFR Part 23 Subpart B rules and associated means of compliance (MoCs) impose more system level and performance based requirements on the aircraft under consideration, the MoCs associated with Subpart E incorporate many component oriented requirements. These prescriptive component-based requirements assume that an aircraft architecture will incorporate those components, and makes it difficult to certify novel technologies and configurations

Table 1 Representative components in different ASTM accepted MoC for 14 CFR Part 23 Subpart E [3, 21–23]

F3062 - Powerplant Installation	F3063 - Fuel Storage and Delivery	F3064 - Powerplant Control, Operation, and Indication
Air induction system	Fuel tanks	Powerplant controls
Cabin pressurization system	Fuel jettisoning system	Fuel tank indicator
Liquid cooling system	Fuel vents, drains	Fuel flowmeter
Oil system	Filler connections	Automatic power reserve

that may not incorporate the prescribed components.

Additionally, modeling the accepted MoC ASTM standards for 14 CFR Part 23 Subpart E results in challenges while standardizing the stereotype profile due to the sheer number of component specific requirements prescribed, as well as their dissimilarity with the ASTM standards that correspond to Subpart B. Table 1 shows a representative example of the diversity of components to which requirements are assigned within the different ASTM standards that form the accepted MoC for Subpart E.

To aid the generalization of the model-based framework, an ontological approach is used to update the type certification profile, including the stereotypes and relationships [18–20]. An ontology can be defined as a specification of a representational vocabulary for a shared domain of discourse [18]. These may include the definitions of classes, relations, functions, and other objects. It is also worth remembering that the design space of complex system can always be represented through functional/physical decomposition which incorporates system functions, system components, and design alternatives [20]. These ideas form the cornerstone of the new type certification profile.

A two-pronged approach is thus used to generalize the profile. First, the stereotypes used in previous work are replaced by a multi-level stereotype defined to allow every standards subcommittee (responsible for individual standards) to come up with their own ontology, while borrowing the system level ontology set by a higher committee. Such an approach that treats SysML stereotypes as a hierarchy of classes is explained in detail in the following sections. The second part of the proposed solution stems from the question – *When can a classification object be elevated to a stereotype property in this model-based certification framework?* The present work proposes five classifications that may be elevated to a stereotype property –

- 1) Configuration settings – e.g. Flaps extended , Landing gear retracted etc.
- 2) Capability – Aerobatic, Amphibious etc.
- 3) Design – Engines (number/type), Landing gear configuration (tricycle/retractable) etc.
- 4) Physical components – Fuel tanks, Air induction ducts etc.
- 5) Functional decomposition – Aircraft and sub-system level functions of components

For Subpart E, requirements that are prescriptive in nature and specify components have been assigned a ‘*function*’ and a ‘*sub-function*’ property within their individual stereotype to capture the system level functions, and the supporting sub-functions (if any) that are satisfied by the specified components. This allows the model to map the MoC requirements to system and subsystem level functions, and has numerous potential benefits (See Sec. V.B). The idea behind generalizing the TC profile is to observe trends in the kinds of information and classification objects that can be stored as meta-data, and to utilize those to infer best practices for standard setting bodies when transitioning to a model-based certification approach. Section IV.A.2 continues this discussion towards a standard of standards, which is an effort to identify best practices to transition standard setting to a model-based paradigm.

1. Regulatory Profile

The regulatory profile is a subclass of the block classifier and is currently used to model 14 CFR Part 23 Subpart B and E. While previous work reported by the authors mentions certain properties for this custom stereotype [4], the present work extends these to include additional properties that are used by the framework in a variety of ways. The profile of regulatory stereotype is shown in Figure 3. As can be seen, a multilevel stereotype is utilized to model Subpart B and E, with a few top level properties that are inherited by both. The idea here is to allow each unique working group to be given the flexibility to define their own profile, while adhering to certain commonalities. The entire list of properties, including those previously defined within [4] are enumerated below:

- *Section*: Every rule within 14 CFR Part 23 has a unique section number. To streamline the creation and maintenance of regulatory elements, this property follows a specific numbering scheme as explained in previous work [4].
- *Amendment*: The amendment number of the regulations
- *Text*: The actual text of the requirement is stored as a string here. Just like the previous two, this is a top level property that will be inherited by every subpart.

Properties specific to 14 CFR Part 23 Subpart B (Flight) include (see Fig. 3):

- *Certification Level*: This property is used to describe what certification level the rule applies to and is defined according to maximum number of passengers the aircraft is certified for as given in 14 CFR Part 23.2005
- *Performance Level*: This property is used to define the performance level the rule applies to, and is defined in 14 CFR Part 23.2005
- *Propulsion*: This property is used to describe whether the relevant rule applies to single engine or multi-engine aircraft
- *Aerobatic*: Describes whether the rule applies to aerobatic aircraft
- *Icing*: Describes whether the rule applies to icing conditions
- *Landing Gear*: Describes whether the rule applies to a retractable landing gear
- *Wing Flaps*: Describes whether the rule applies to wing flaps configuration
- *Altitude Limit*: This property is used to extract any altitude limitations applicable to any regulation.

Properties unique to 14 CFR Part 23 Subpart E (Powerplant) include (see Fig. 3):

- *Component*: This property is used to specify the component to which a requirement applies to
- *Function*: Describes the aircraft level function that the specified component helps perform
- *Sub-function*: Describes a sub-system level function performed by the component that supports the main function

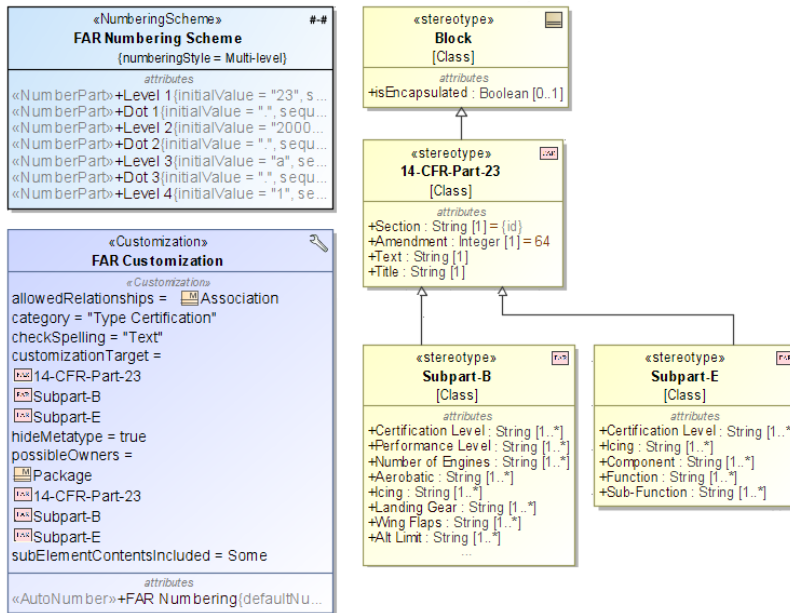


Fig. 3 FAA Regulation SysML Stereotype Profile

2. The Standards' (ASTM) Profile

The ASTM profile is defined as a multi-level stereotype similar to its regulatory counterpart with a few differences. Currently the ASTM standards that serve as a MoC for Subpart B have properties based on item numbers 1-3 mentioned in Sec III.A. This is because the Subpart B MoCs are more at the system level and are performance based, with little or no emphasis on prescribing component level requirements. For the MoCs for subpart E, the stereotype properties currently focus on item numbers 2-5 mentioned in Sec. III.A, since these standards prescribe component level requirements. While work to have properties of all MoCs reflect the five classifications mentioned in Sec. III.A will continue in the future, the current work is based on the ASTM stereotype as shown in Figure 4. It is also anticipated that as additional

standards are modeled, additional properties will be defined for the ASTM profile. A list of top level properties for the ASTM MoCs is given below:

- *Approval and Published Date*: The day the standard was approved and the day it was published
- *Designation*: Equivalent to the section number in the regulatory profile, the numbering system here is unique to each individual ASTM standard. An automatic numbering system is established in the model [4]
- *Text*: This property stores the text contained in the ASTM standard
- *Change Description*: Stores details of any changes made to the requirements
- *Reason or Rational for Change*: Stores the rational for the above change

Properties specific to ASTM MoCs for 14 CFR Part 23 Subpart B (Flight) include (see Fig. 4):

- *Certification Level*: Similar to the regulatory profile
- *Performance Level*: Similar to the regulatory profile
- *Propulsion*: Similar to the regulatory profile
- *Engine Type*: Stores whether the MoC standard specification applies to turbine or propeller engine
- V_{S0} : Stores whether the standard requires a particular stalling speed constraint
- *Seaplane/Amphibian*: Stores whether the suggested MoC applies to a seaplane or amphibian
- *Aerobatic*: Similar to the regulatory profile
- *Landing Gear*: Similar to the regulatory profile
- *Wing Flaps*: Similar to the regulatory profile
- *Aileron*: Stores whether the MoC standard specification applies to normal aileron configuration
- *Rudder*: Stores whether the MoC standard specification applies to normal rudder configuration
- *Simplified Lateral Control*: Stores whether the MoC standard specification applies to an aircraft with simplified lateral control or not
- *Elevator*: Stores whether the MoC standard specification applies to normal elevator configuration
- *Horizontal Stabilizer*: Stores whether the MoC standard specification applies to normal horizontal stabilizer configuration
- *Ramp Weight*: Stores the ramp weight the MoC standard applies to
- *Altitude Limit*: Stores the altitude limit of the airplane the MoC standard applies to
- M_D : Stores the design dive mach number the MoC standard applies to

Properties unique to ASTM MoCs for 14 CFR Part 23 Subpart E (Powerplant) include (see Fig. 4):

- *Component*: Similar to the regulatory profile
- *Function*: Similar to the regulatory profile
- *Sub-function*: Similar to the regulatory profile

3. Reference

The reference stereotype is defined under the data types and other stereotypes package as a subclass of the association relationship, which represents the semantic relationship between two or more classifiers [4, 10]. Although no meta-data or properties are assigned to this stereotype, it is meant to represent the reference relationship that exists between the rules and accepted MoCs as given in the notice of applicability [5]. It is used in the present work to map the rules under 14 CFR Part 23 Subpart B and associated MoCs, with extensions to Subpart E and other subparts in the near future.

4. The Validation Suite

The details of this sub-package are provided under the results section (see Sec. IV) where the benefits of this modeling framework are discussed in detail.

B. Type Certification Package

The TC package is where the regulations and ASTM consensus standards are modeled using elements defined in the type certification profile (Sec. III.A). Individual regulatory rules and consensus standards are modeled in a hierarchical view, while the reference relationships that map the rules to the accepted MoC are modeled using a referential view in MagicDraw. These two views have been updated from previous work and are included here for completeness [4]. It is important to note that these views are not just visual representations, and are used to develop the model relationships and hierarchies that provide numerous benefits as will be seen in Sec. IV.

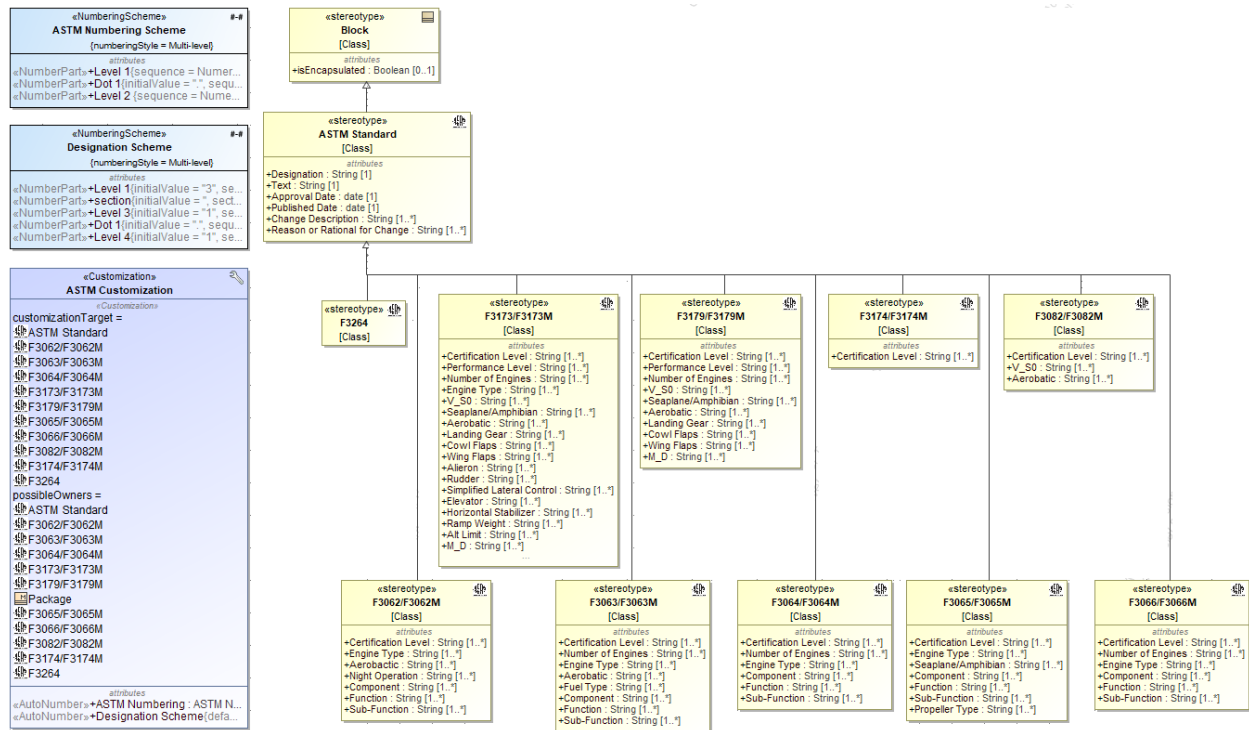


Fig. 4 ASTM Standard SysML Stereotype Profile

1. The Hierarchical View

A block definition diagram (BDD) provides a visual representation of the underlying SysML elements and their inter-relationships. It is created manually once and has a high degree of reusability and adaptability. A large BDD can be sliced to include the same model information in multiple BDDs without loss of any information, thus making visualization and modeling easier. This is used especially to model the ASTM standards when a single standard is visualized and modeled using multiple BDDs in the present work.

The FAR hierarchical view is a BDD that represents the relationships between the regulatory sections and subsections and is visualized as seen in Figure 5. Tree structures representing the entire hierarchy of 14 CFR Part 23 Subpart B and E have been created in the present work, with scope for expansion into other subparts as this work proceeds.

Similarly, the ASTM hierarchical view represents the information and relationships within ASTM standards, with an example shown in Figure 6. ASTM MoCs for subpart B and E [3] have been modeled completely in the present work, with scope for expansion to other standards in the future.

While creating the hierarchical views of both rules and standards, each custom stereotype is assigned properties defined in Sec. III.A. The validation suite helps ensure no regulatory or ASTM element is incomplete in terms of its meta-data properties when created.

2. The Referential View

The referential view in the present work has been updated to model the FAA’s notice of applicability that establishes the accepted means of compliance for different regulatory requirements. This is again accomplished using a BDD to map the top level 14 CFR Part 23 requirements to the top level ASTM standards. This BDD however, utilizes the custom defined ‘reference’ relationship defined earlier instead of the ‘allocate’ relationship found in the hierarchical views. Figure 7 illustrates an example of this referential view.

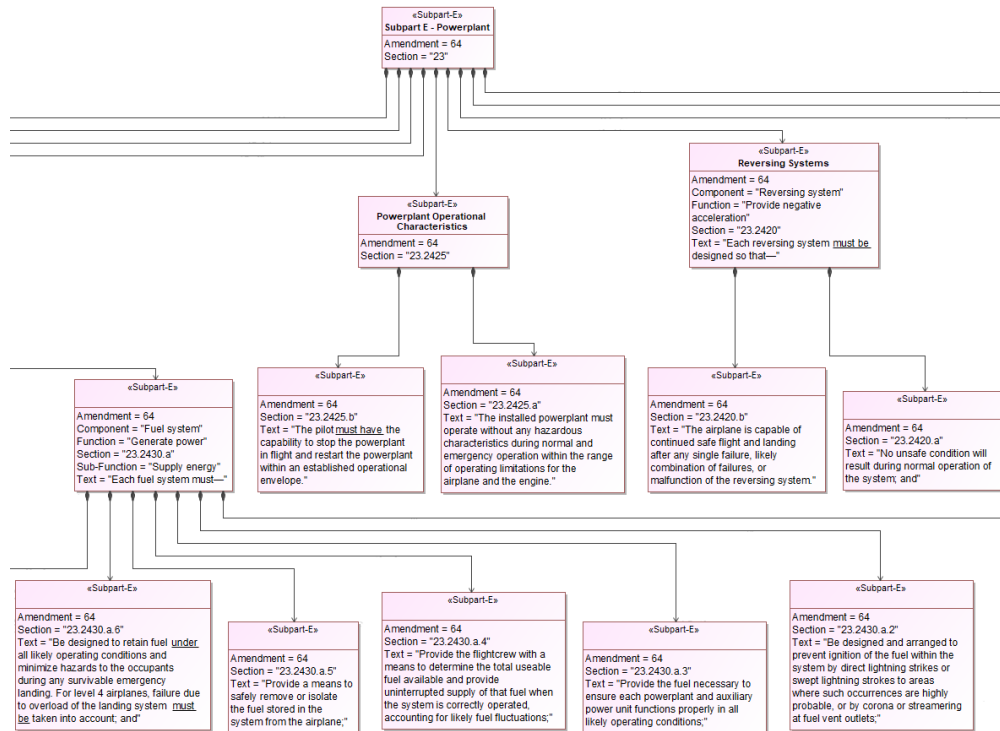


Fig. 5 14 CFR Part 23 Subpart E Hierarchical View (Partial)

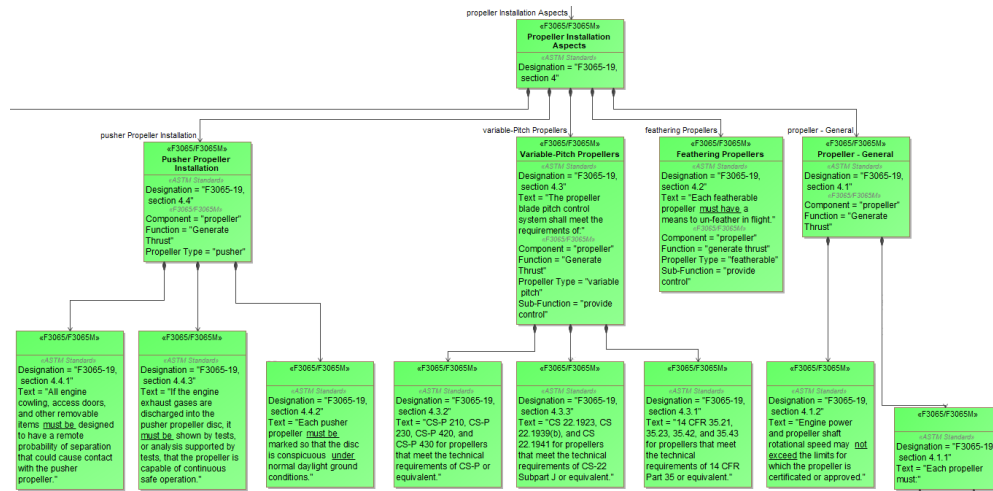


Fig. 6 ASTM F44 Standards Hierarchical View (Partial)

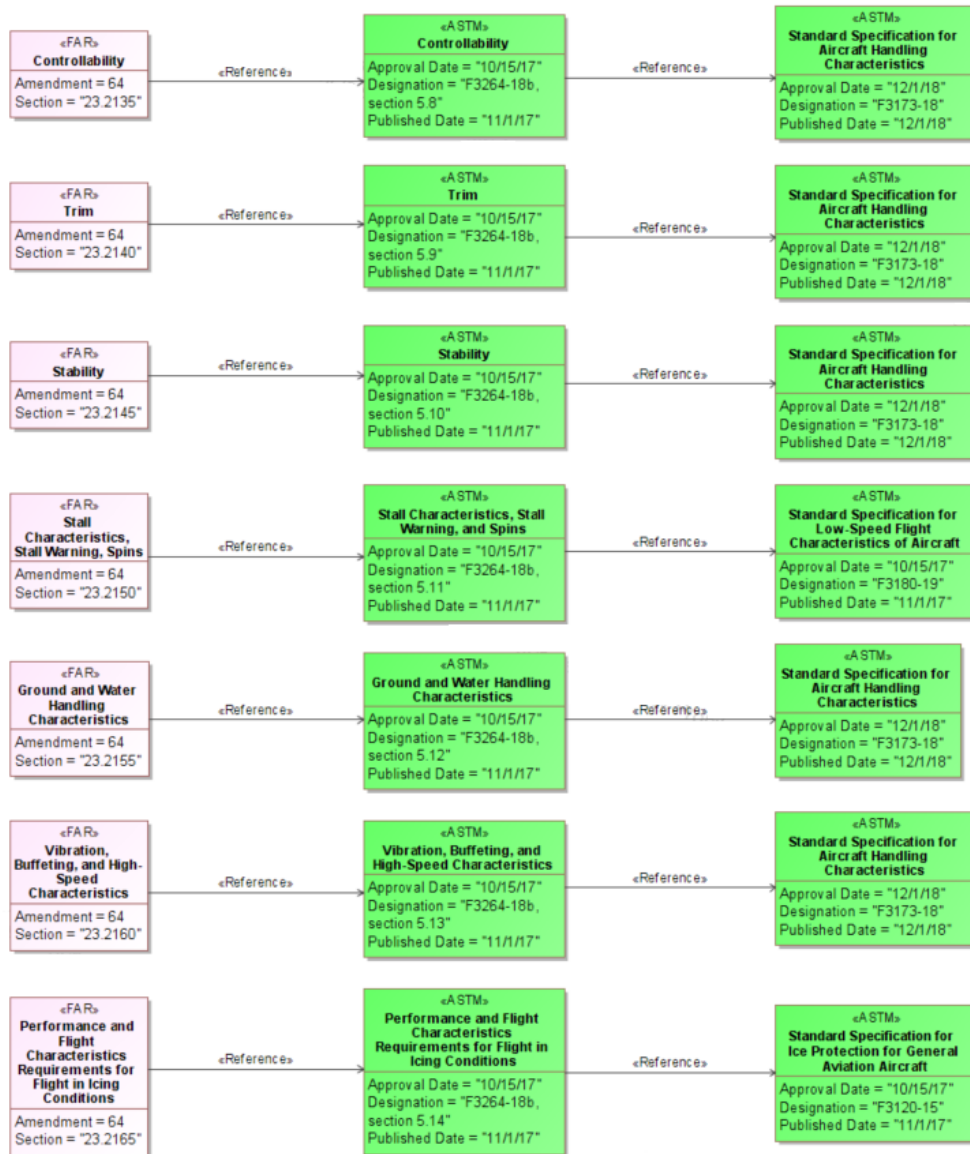


Fig. 7 Regulation-Standard Referential View

C. The Simulation Package

This package contains modeling artifacts for the automatic generation of certification basis, compliance checklist, and means of compliance. These modeling artifacts include elements used to create a Graphical User Interface (GUI) for aircraft design specifications collection, a state machine diagram used to process the signal from the GUI, and activity diagrams used to process the inputs from GUI and to execute the in-house developed Python code for the generation of certification documents. Execution of the in-house Python code is enabled by the MagicDraw Cameo Simulation Toolkit and performed in a block called "Simulation" as shown in Figure 2. For the current work, automatic generation of certification documents is implemented for 14 CFR Part 23 Subpart B and partially for Subpart E.

1. Graphical User Interface

The GUI shown in Figure 8 is used to collect the input aircraft design features pertinent to Subpart B. These design features are used to filter the applicable regulations and means of compliance for the input aircraft, which will be explained in following sections. The required input aircraft design features included in "Aircraft Specifications" part indicate the minimum amount of design knowledge necessary to generate certification basis, compliance checklist, and means of compliance for Subpart B. Aircraft design information like the maximum takeoff weight (MTOW), number of passengers, stall speed, etc. can be input using text boxes provided in the GUI. These are used to determine the performance level and certification level of the input aircraft. The spin buttons allow the user to determine the input aircraft configuration layouts based on pre-defined options (e.g. engine features, control surfaces, etc.), which are enabled by the "enumerate" element of SysML. The scroll-down menus in "Certification Basis" and "Means of Compliance" allow the user to select appropriate certification basis (e.g. FAA 14 CFR Part 23 Amend. 64, EASA CS-23 Amend. 5 etc.) and corresponding means of compliance (e.g. ASTM F44 F3264-18b, EASA CS-23 Amend. 4, EASA CS-VLA Amend. 1, etc.) for the input aircraft. All these inputs included in the GUI are defined as 'value properties' in the "Simulation" block.

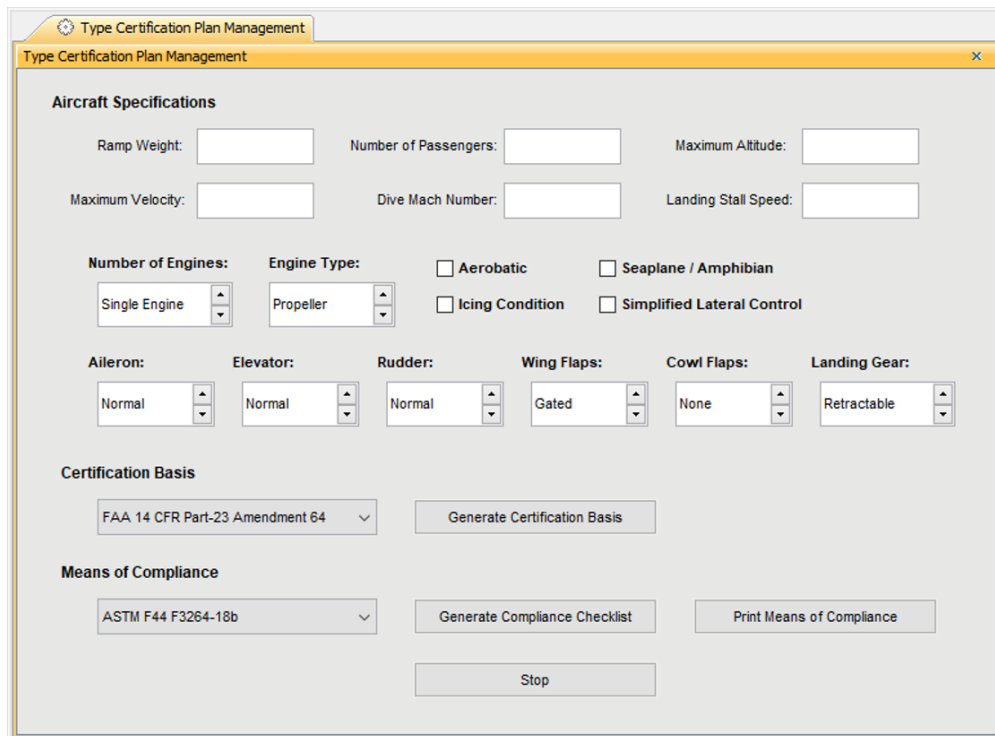


Fig. 8 Graphical User Interface

2. State Machine Diagram

A state machine diagram describes how the states of objects change over time during a simulation. As shown in Figure 9, once the simulation starts, the developed state machine will hold in the "Idle" state. A change of state is informed by the signals from the buttons of GUI. For example, if the user clicks on "Generate Certification Basis" button, the state machine enters the "Generate Certification Basis" state to activate the "CertBasis Activity".

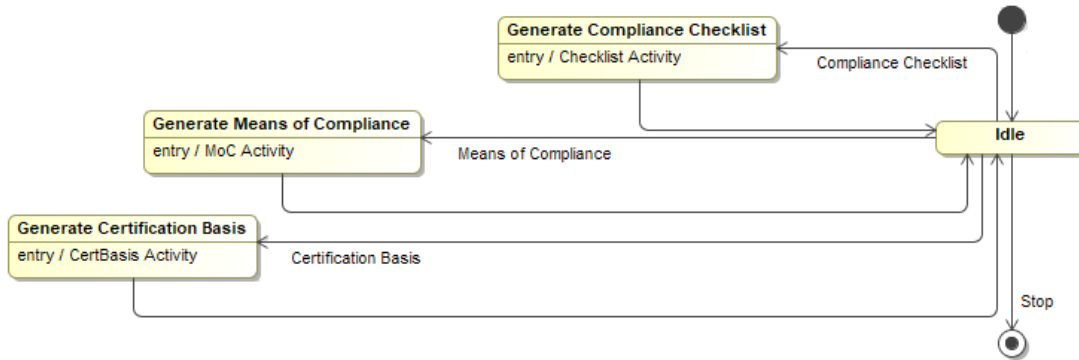


Fig. 9 State Machine Diagram

3. Activity Diagram

Activity diagrams are used to process input value properties from the GUI and to generate certification artifacts for the input aircraft. Figure 10 shows the activity diagram for generating compliance checklist ("Checklist Activity"). Four actions are included in this activity. The "readSelf" action is to process the "Simulation" block on which the simulation is executed. The "readStructuralFeature" action is to identify the value properties assigned to the "Simulation" block and the associated values input from the GUI. The values properties are then sent to the opaque action (":Checklist Code" in Fig. 10) in the format of input variables. The opaque action contains the in-house developed python scripts which go through the hierarchical and referential model of regulations and consensus standards to filter the applicable rules and means of compliance for the input aircraft. This filtering process is performed by comparing the meta-data pre-assigned to the regulation or standard element to the input aircraft values from the GUI. The IDs of the SysML elements of applicable regulations and standards are transferred to the opaque action of "Print Checklist Code" which prints out the compliance checklist as text files. The activity diagrams for certification basis generation ("CertBasis Activity") and means of compliance generation ("MoC Activity") follow a similar logic.

IV. Results

The developed model-based framework provides numerous benefits to a variety of stakeholders. This section focuses on potential benefits to the standards bodies who develop the consensus means of compliance standards, and stakeholders in the aerospace industry who will benefit from a more streamlined approach to generating a certification plan. The present work expands on some of the potential benefits enumerated previously [4].

A. Benefits for Regulatory Bodies

1. Benefits of a Model-Based Approach

This model-based approach to certification plan management provides certain benefits to the standards setting bodies while creating, updating, and maintaining their standards. Since these standards are stored in a model as against documents, they are easier to update, can provide cross-referencing with higher fidelity, and can have inbuilt automatic validation functions to ensure consistency and completeness according to pre-defined conventions.

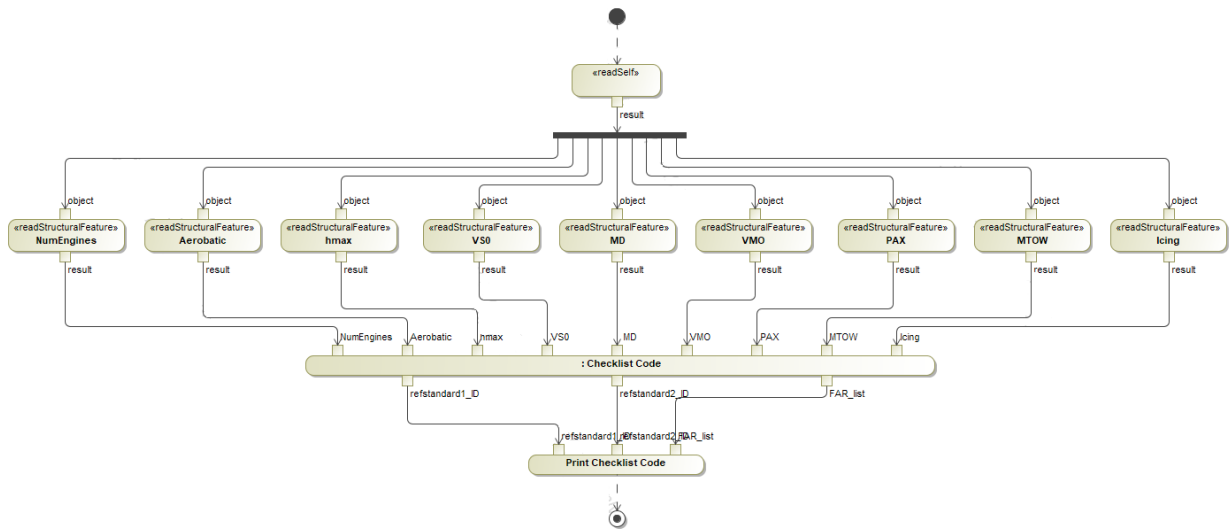


Fig. 10 Activity Diagram for Generating Preliminary Compliance Checklist

Auto-Updating and Synergy For Changes The present framework requires manual input to create models of the regulatory requirements and standards while including their relationships and any annotations with meta-data properties. However, this task needs to be completed once, after which the modeling framework provides great flexibility and adaptability for any updates or changes. While amendments are made infrequently to rules, the standards go through revisions sometimes twice in a year. In a traditional document-based approach, these changes have to be made manually in multiple documents that may cross reference a proposed change. The model-based framework on the other hand allows authors of the model to make any update in a single place once while ensuring all relationships and cross-references synergize automatically, thus saving time and effort while minimizing the scope for making any errors [4]. In other words, changes made in one part of the model are automatically propagated to all related model elements. Such a capability allows the authors of the model-based framework to maintain a consistent model. As an additional benefit, this framework utilizes MagicDraw’s scripting engine to ensure that the model does not have circular referencing by check paths created in the referential view to determine if an infinite referencing loop has been created.

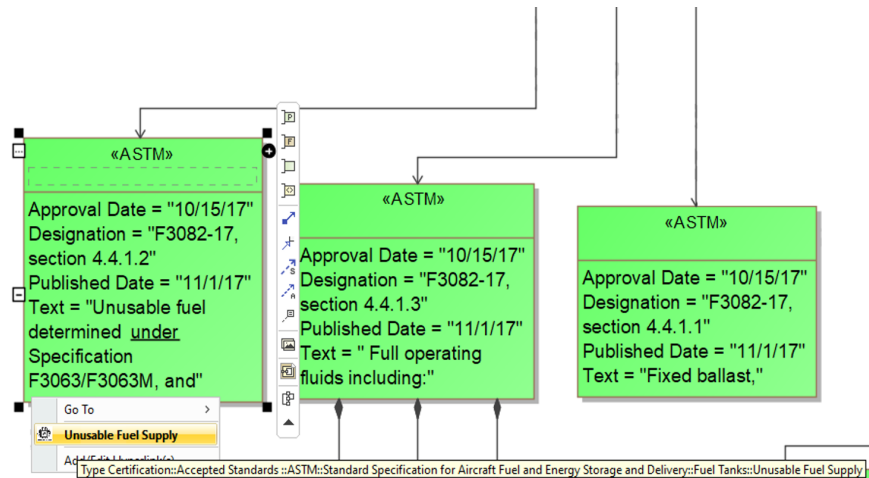


Fig. 11 Standards Cross-Reference Modeling Example

SME defined Cross-Referencing While cross-references in the consensus standards are defined at the top level in terms of names of a referenced standard, the current model allows subject matter experts (SMEs) to define such

cross-references at the lowest possible level. This provides greater resolution to users in terms of the appropriate section or subsection within a standard that has to be cross-referenced by any model element. Figure 11 provides an example of how the present framework allows this cross-referencing via adding hyperlinks in the MagicDraw model. While the standard document for F3082 - Weight and Center of Gravity references to F3063 to define "unusable fuel supply", the model based framework can directly refer "Section 5.10: Unusable fuel supply" defined within F3063 - Fuel Storage and Delivery standard, thus providing a far greater resolution [22, 24].

Model Validation Constraints Validation constraints in MagicDraw help modelers automatically validate their models. In the current work, validation constraints can be used to ensure every element created is assigned a minimum necessary set of meta-data properties defined in Sec. III.A. As an example, Figure 12 shows how the present model utilizes this capability to automatically check if the section names are coherent. Whenever there is an inconsistency between higher and lower level section numbers, the elements of interest are highlighted in red and a custom error message is shown. As mentioned in previous work [4], it is important to note that the directed composite relationships used to create the hierarchical views are enablers for these validation rules verifying the consistencies among the sections and the designations.

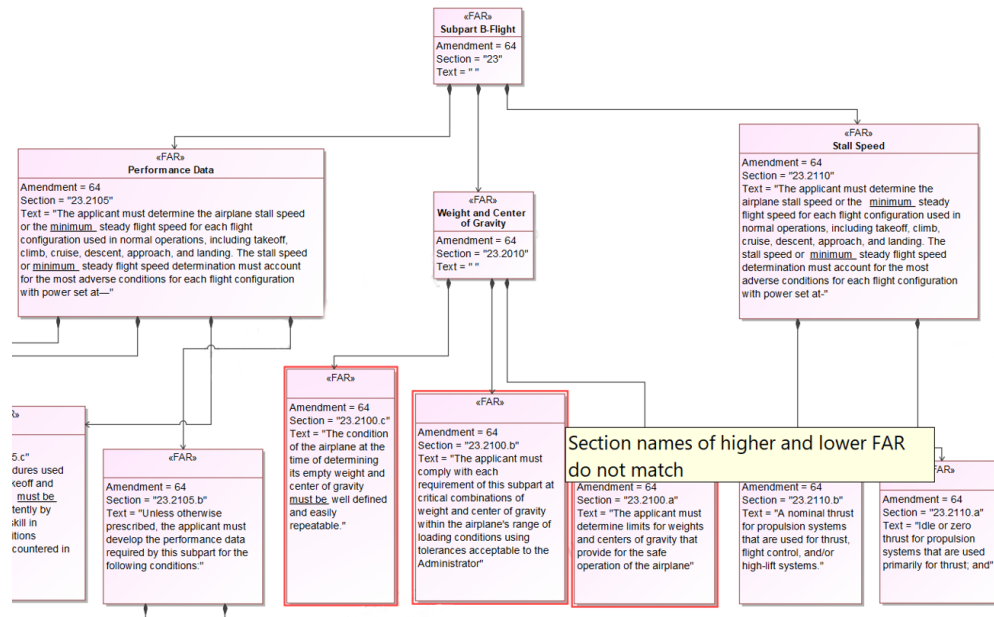


Fig. 12 Automatic Model Validation Example

2. Towards a Standard of Standards

One of the main challenges in applying MBSE to complex systems on a larger scale is determining how the information required can be structured and organized into an efficient, scalable model library of “stereotypes”. A first-look at these efforts is visible in the form of the type certification profile (see Sec. III.A). It shows how, in a model-based framework, the textual information can be converted into meta-data by defining custom properties. SMEs can assign or define properties to categorize all textual information as per the aircraft characteristics like configuration, performance, etc. By defining a common vocabulary across multiple standards committees, this model-based framework can drive information consistency and reduce errors that occur due to misinterpretation of common vernacular by [20].

- Providing a common structure of information
- Enabling reuse and analysis of knowledge
- Making assumptions explicit

Within this approach, the properties of different regulatory and standards blocks in MagicDraw can be represented as a “hierarchy” of classes, with rules set for inheritance from top level to bottom. Standards bodies can determine what

meta-data properties and data types need to be defined for every verification artifact they define to ensure completeness of the generated standards and models.

B. Benefits for Aircraft Manufacturers

The primary benefit of this model-based framework to stakeholders like the airplane manufacturers or OEMs is anticipated to be the automatic generation of certification artifacts that help create the certification plan. The current model, in particular can automatically export the relevant certification basis, means of verification (accepted MoCs), and a preliminary compliance checklist for all of 14 CFR Part 23 Subpart B and Subpart E (limited) by utilizing the simulation capability (see Sec. III.C). To evaluate the capability, this paper performed a case study of generating certification artifacts using the model-based framework on a notional input aircraft model developed based on Cessna-402C. The design specifications of the input aircraft model are included in the Appendix (See Table 2).

With the certification basis (FAA 14 CFR Part 23 Amendment 64) and means of compliance (ASTM F44 F3264-18b) selected, the inputs are sent to the activities of "CertBasis Activity", "Checklist Activity", and "MoC Activity" following the signals from GUI buttons and the state machine diagram shown in Figure 9. Once these activities are activated, the in-house developed python scripts stored in the opaque actions will go through the hierarchical and referential models of selected regulations and standards to filter the applicable certification rules and means of compliance for the input aircraft. Filtering mechanism is performed based on the meta-data assigned to the blocks of regulations and standards. For example, 14 CFR §23.2115 (c) poses a requirement for level 1, 2, and 3 high speed multiengine airplanes and level 4 multiengine airplanes, which is not applicable to the level 3 low-speed input aircraft used in this case study. By comparing the meta-data assigned to the block of 23.2115 (c) and the input aircraft data, the python script will automatically filter out 14 CFR §23.2115 (c) in the output certification basis. Similar logic also applies to consensus standards when generating the means of compliance. The compliance checklist is established based on the referential mapping between regulations and standards. A partial example certification basis, compliance checklist, and means of compliance printed out from the model-based framework are shown in the Appendix (see Fig. 15a, 14b, and 14c).

V. Conclusions and Future Work

The present work extends a model-based certification framework reported previously by the authors [4]. Certification rules for normal category airplanes in 14 CFR Part 23 Subparts B (Flight) and E (Powerplant), and their accepted MoCs given by ASTM standards were used as the proof of concept for the developed framework. Some salient features of the model-based framework are a new type certification profile that seeks to extract different types of certification information as data objects that can be used to inform the applicability as well as the functional decomposition of the associated requirements. It is envisioned that in the future, this will lead to the development of a standard of standards, that will provide best practices and guidance to standards bodies to transition to a model-based approach effectively. A hierarchical view allows easy representation, cross-referencing, and management of rules and standards, while a referential view allows the mapping of regulatory rules to accepted MoCs. The inbuilt model validation constraints within SysML can be utilized to check the model for consistency and correctness on the go. The implemented simulation functionality allows end users to filter and extract relevant requirements, saving time and effort.

In addition to the implemented functionality, the model has been developed with an eye on certain future applications. A few of these are currently in the works, and have been mentioned below to provide a glimpse into the future areas of research.

A. Input Aircraft Model

Sec. IV shows an example of automatic generation of the certification basis and means of compliance for a reference aircraft using the GUI introduced in Sec.III. However, such an aircraft input processing approach may not be suitable when moving from Subpart-B to Subpart-E. As mentioned above, Subpart-B relevant rules and standards are mostly system-level, performance-based requirements, while Subpart-E relevant rules and standards are more component-oriented. While the developed GUI can take inputs that include system level aircraft characteristics, it is relatively difficult and cumbersome for a GUI to represent each component and specify physical decomposition of novel architectures. To maintain the capability of automatic generation of certification artifacts, one potential solution is to utilize an aircraft system model created using SysML elements to represent the input aircraft instead of the GUI. Figure 13 shows an example of an aircraft SysML representative model developed using SysML blocks. The hierarchy of the aircraft SysML model follows the physical breakdown of the aircraft system, and each block represent a subsystem

or component of the aircraft. The function of a subsystem/component or any other qualitative/quantitative characteristic of a subsystem/component could also be assigned to the aircraft system model as value properties to the specific block. Compared with the GUI, utilizing an aircraft SysML model is expected to improve the flexibility of processing input aircraft characteristics while allowing specification of functional and physical decomposition. The capability of automatic generation of certification artifacts can be facilitated by the interaction between aircraft SysML model and model-based certification framework. Enabled by the state machine and activity diagrams, the framework can directly extract data from aircraft system model while the in-house developed Jython code can be used to compare the aircraft physical components and their functions, thus allowing filtering of the applicable certification basis and means of compliance as well as potentially identifying regulatory gaps for the “input” aircraft system.

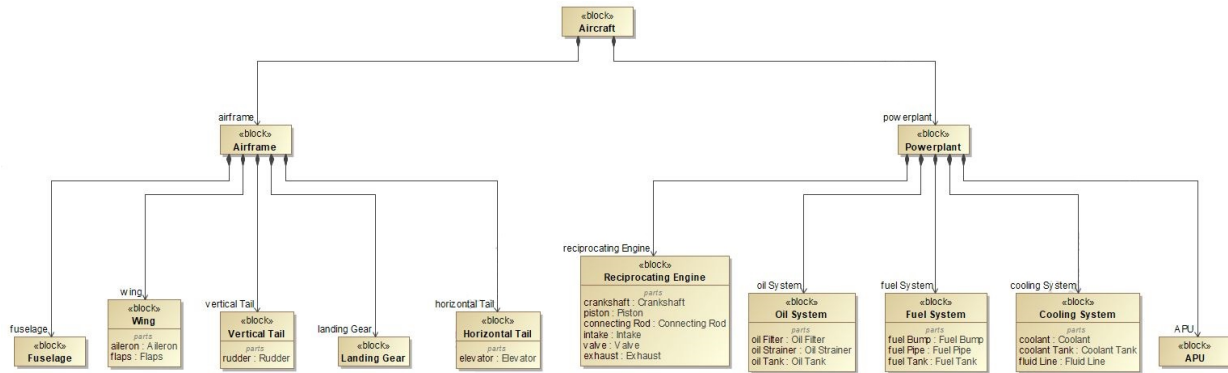


Fig. 13 A representative aircraft model - component breakdown

B. Gap Analysis for Future Technologies and Configurations

For novel aircraft configurations and technologies, presently accepted MoC standards may not be sufficient, or may be inapplicable all together. This is especially true for the accepted MoCs for Subpart E, since these are component specific and prescriptive in nature (see Table 1). While the goal of the present work is not to suggest which standards' requirements will be applicable or not for these novel technologies, it is understood that providing decision makers with information about requirements imposed on functionally 'similar' components may be useful to determine gaps and equivalent levels of safety required. With that goal in mind, the type certification profile for Subpart E and corresponding ASTM standards was provided a 'function' and a 'sub-function' property (see Sec. III.A). If the aircraft model used as an input does not contain the traditional components prescribed under currently accepted MoCs, the framework's simulation capability will extract requirements based on functional similarity with a caution to alert the users about potential gaps.

Figure 14 shows an example scenario to explain how the gap analysis capability is envisioned to work. Consider a conventional aircraft with a fuel system and a fuel tank. These components are mentioned by 14 CFR §23.2430, and ASTM F3063-18a, section 5.1, and can be assigned the 'generate power -> supply energy' and 'generate power -> store energy' function and sub-function properties respectively. Note that the functional decomposition for the current framework has been truncated at the sub-system level. Since the components and the function-subfunction pairs both match, the simulation capability mentioned in Sec. III.C can output the mentioned rule and standard requirement. However, in the case of a novel architecture consisting of a battery system ('generate power -> supply energy') and a battery ('generate power -> store energy'), the components do not match the ones prescribed by the rules or standards. However, the simulation capability can still filter applicable rules and MoCs based on the functional decomposition, and output 14 CFR §23.2430 and F3063-18a Sec. 5.1 as potential gaps. This information can be provided to subject matter experts to make a determination of gaps and equivalent levels of safety required, saving time and effort needed to explore gaps manually.

C. Incorporation of Certification Requirements into Conceptual Design

Type certification is an expensive process for aircraft manufacturers. Failure to meet certification requirements may force modification and redesign, which could bring unforeseen delays and cost overruns. To reduce cost and

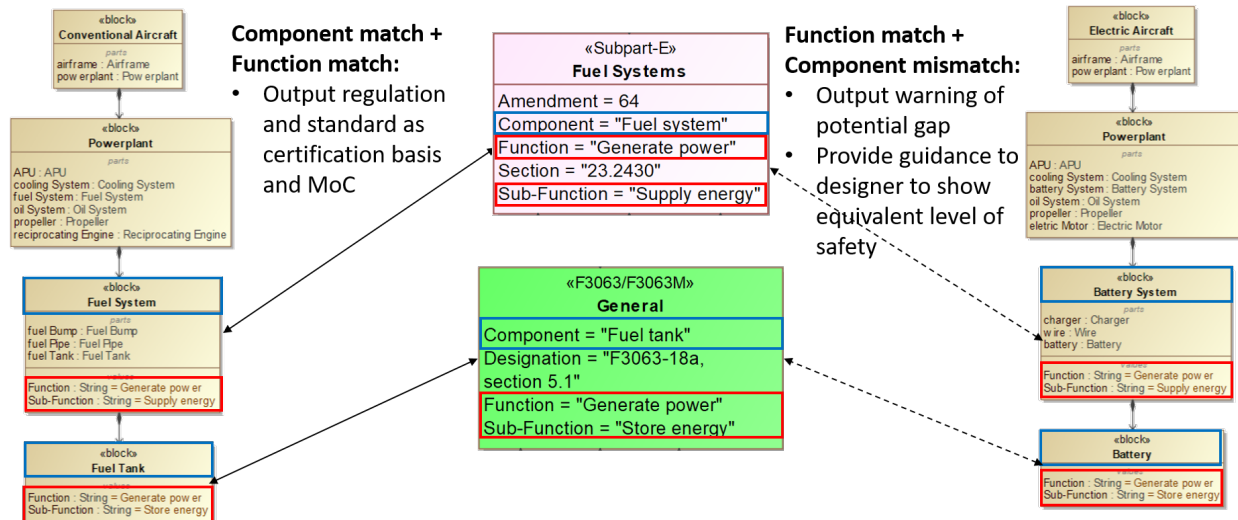


Fig. 14 Utilizing functional decomposition for identifying potential gaps

uncertainties associated with the certification process, there is a need to incorporate certification considerations in aircraft conceptual design. While several aircraft conceptual design tools exist as standalone capabilities for conducting sizing and constraint analysis, an integrated approach that combines the developed Model-Based Certification Framework with various in-house analysis tools and methods can provide a solution to shift certification and safety considerations earlier into the design phases and streamline the aircraft conceptual design process.

While the model-based framework currently automatically generates the certification basis and corresponding MoCs in a textual format, future work will look at transforming these to quantitative analysis functions to constrain the design in conceptual level sizing and optimization. Numerous options exist to implement the integration between the model-based framework and analysis tools, including (i) Wrapping aircraft design tools using SysML parametric and activity diagrams to formulate a system modeling representation for conceptual design activity, and integrating this wrapper with a Certification Module in an identical system model; (ii) Integrating aircraft design tools in a third-party integration platform, such as the Phoenix Integration Model Center, and connecting the integration platform with the Certification Module in system model using constraint blocks and diagrams; (iii) Connecting the Certification Module and aircraft design tools outside the MBSE framework via an intermediate input/output file of the appropriate format (e.g. csv, xml, etc.). These options are being researched and compared to best practices in literature. This goal of integrating the present model-based certification framework with a physics based analysis capability to augment aircraft conceptual design trades is a long-term vision of the present work.

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Appendix

Table 2 Design Specifications of Input Aircraft Model

Parameter	Value	Unit
Ramp weight	6885	lb
Number of passengers	9	-
Maximum operational altitude	30 000	ft
Maximum operational velocity	235	kts
Dive Mach number	0.5	-
Landing stall speed	50	kts
Number of engines	2	-
Engine type	Propeller	-
Aileron	Normal	-
Elevator	Normal	-
Rudder	Normal	-
Wing flaps	Gated	-
Cowl flaps	None	-
Landing gear	Retractable	-

```

=====
Subpart B - Flight
-----
23.2120 Climb Requirements
The design must comply with the following minimum climb performance out of ground
effect:
23.2120.a
With all engines operating and in the initial climb configuration -
23.2120.a.2
For levels 1 and 2 high-speed airplanes, all level 3 airplanes, and level 4 single-
engines a climb gradient after takeoff of 4 percent.
23.2120.b
After a critical loss of thrust on multiengine airplanes -
23.2120.b.2
For levels 1 and 2 high-speed airplanes, and level 3 low-speed airplanes, a 1 percent
climb gradient at 400 feet (122 meters) above the takeoff surface with the landing
gear retracted and flaps in the takeoff configuration(s); and
23.2120.c
For a balked landing, a climb gradient of 3 percent without creating undue pilot
workload with the landing gear extended and flaps in the landing configuration(s).
-----

```

(a) Example Output: Certification Basis (Partial)

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=====
Compliance Checklist
-----
23.2100 Weight and Center of Gravity----->F3264-18b, section 5.1 Weight/Mass and
Center of Gravity----->F3082-17 Standard Specification forWeights and Centers of
Gravity of Aircraft
-----
23.2105 Performance Data----->F3264-18b, section 5.2 Performance Data----->F3179-18
Standard Specification for Performance of Aircraft
-----
23.2110 Stall Speed----->F3264-18b, section 5.3 Stall Speed----->F3179-18 Standard
Specification for Performance of Aircraft
-----
23.2115 Takeoff Performance----->F3264-18b, section 5.4 Takeoff Performance-----
>F3179-18 Standard Specification for Performance of Aircraft
-----
23.2120 Climb Requirements----->F3264-18b, section 5.5 Climb Requirements-----
>F3179-18 Standard Specification for Performance of Aircraft
-----
23.2125 Climb Information----->F3264-18b, section 5.6 Climb Information----->F3179-
18 Standard Specification for Performance of Aircraft
-----

```

(b) Example Output: List of associated MoCs (partial)

```

=====
Standard Specification for Aircraft Powerplant Installation Hazard Mitigation
-----
F3066-18, section 10 Fire Extinguishing

F3066-18, section 10.1 Fire Extinguishing Systems:

F3066-18, section 10.1.1
The fire extinguishing plumbing and electrical connections must be constructed,
arranged and installed such that cross connection is not possible during normal
maintenance actions (for example, changing the fire extinguishing bottles or trouble
shooting the system).
F3066-18, section 10.1.3
If an auxiliary power unit is installed in any aeroplane certificated to this part,
that auxiliary power unit compartment must be served by a fire extinguishing system
meeting the requirements of 10.1.2.2.
F3066-18, section 10.2 Fire Extinguishing Agents:

-----

```

(c) Example Output: Means of Compliance (Partial)

Fig. 14 Automatic filtering and generation of certification artifacts

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