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

A Model-Based System Engineering Approach to Normal Category Airplane Airworthiness Certification

Marc-Henri Bleu-Laine*, Mayank V. Bendarkar†, Jiacheng Xie‡, Simon Briceno§, and Dimitri N. Mavris¶
Aerospace Systems Design Laboratory, School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, Georgia, 30332

Airworthiness certification is to ensure the safety of aircraft. With the surge in novel general aviation aircraft configurations and technologies, the Federal Aviation Administration replaced prescriptive design requirements with performance-based airworthiness standards in Federal Aviation Regulations Part 23 that governs the airworthiness of normal category airplane. The amendment ported over the accepted means of compliance (MoC) from prescriptive advisory circulars to a number of consensus standards from aviation community. Because these MoCs are scattered in multiple documents and cross-reference one another, the certification practice with this new format may be cumbersome and time-consuming.This paper proposes a Model-Based System Engineering (MBSE) approach that is envisioned to parametrically transform the document-centric exercise to a model-based process. The approach helps collect the FAR-23 regulations and the associated MoC in an integrated system model along with the relevant mappings between them. This allows users to automatically generate a compliance checklist for any specific certification requirement. Other benefits of the MBSE approach include circular referencing check, automatically propagating any future changes to the FARs or MoC standards through the model, and potential incorporation with early aircraft design.

I. Introduction

Modern aircraft are complex machines with numerous interacting systems that are used to transport goods or passengers over great distances at high speeds. Improper design or operation of an aircraft may pose a safety risk to crew and passengers onboard the machine, as well as people and property near the aircraft operation. Given these potential risks, most aircraft are subject to government-mandated safety rules that apply to the airworthiness of the design, the production processes used to make these machines, and the operation and maintenance of individual aircraft. "Certification" refers to some accepted form of proof that these rules have been followed. In the United States, the Federal Aviation Administration (FAA) oversees many different types of certification for aircraft and aircraft operations. Type Certification (TC) ensures that a particular product (aircraft, engine, or propeller) design conforms to the appropriate airworthiness rules.

Of particular interest in this paper 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. An estimated 65% of GA flights annually are for business or other purposes that cannot be served by commercial flights [1]. This segment is slated to receive a big boost with the advent of novel concepts of operation such as Urban-Air Mobility (UAM) and novel architectures or technologies like $e-$VTOL and hybrid-electric propulsion. The TC process can be one of the most challenging activities for developing these new aircraft designs, particularly if the design uses technologies that have not previously been used on other type-certified products. 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 slow adoption of new technologies; the knowledge that is required to certify these products may not be available without the benefit of operational experience, and yet that operational experience may not be possible to obtain without operating the aircraft as a certified product. Furthermore, even with this experience, prescriptive 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 this 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

*Graduate Researcher, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Student Member
†Senior Graduate Researcher, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Student Member
‡Graduate Researcher, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Student Member
§Senior Research Engineer, ASDL, School of Aerospace Engineering, Georgia Tech, Senior AIAA Member
¶S.P. Langley Distinguished Regents Professor and Director of ASDL, Georgia Tech, AIAA Fellow

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 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 MoC developed from consensus standards organizations can be more agile than Federal rulemaking, thus enabling faster adoption of new technologies for these aircraft.

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 propose a Model-Based Systems Engineering approach for the management of certification plan and related artifacts. The reminder 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 used for certification planning; Section III introduces the model-based certification planning approach and describes the development of system model for certification plan management; Section IV presents the potential benefits of the proposed MBSE approach; Section V concludes the present work and identifies avenues for future research in the area.

II. Background

A. The Type Certification Process

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 the following [4]:

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

The current paper focuses on 14 CFR Part 23-64 as the intended operating environment. The proposed certification basis is established by the FAA and agreed upon by the applicant based on mutual understanding of the design features of the aircraft being considered for the TC process. Broadly speaking, the certification basis defines the specific regulation parts and amendment levels in addition to any applicable noise, fuel venting, and exhaust emission requirements that the TC applicant must comply with [4]. Once the certification basis has been established, a description of how compliance will be shown is created. A pre-approved MoC can be used for this purpose. This paper will focus on the ASTM consensus standards developed by ASTM Committee F44 that form an accepted MoC for 14 CFR Part 23-64 [3, 5]. 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 [4]. 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.

B. Document-based Certification Plan Management

As discussed in Sec. II.A, ASTM consensus standards form an accepted Means of Compliance (MoC) for the new FAR 23 requirements. Currently, ASTM F3264-17 serves to map the ASTM standards applicable to normal category airplane certification that serve as MoC [3, 6]. For this paper, a manually generated spreadsheet that maps each FAR 23 requirement to the relevant sections of relevant ASTM documents serves as a baseline attempt to simplify the

FAR Part 23			MOC - ASTM Standard				
Section	Title	Text	1st reference	Text	2nd 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.
					F3063/F3063M (ref) 5. Fuel Tanks	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

process of generating a Compliance Checklist. While creating such a baseline spreadsheet model of the regulations and corresponding means of compliance, it was observed 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 FAR 23 is not straightforward, and (ii) These documents cross-reference each other, making it time consuming and difficult to sift through them manually

Figure 1 shows an example of one such spreadsheet that was created to map FAR 23.2100 - Weight and Center of Gravity requirements to the relevant sections of ASTM F3082/F3082M-17 [7]. This example was chosen because it represents a section of FAR 23 that is relatively simple to map to the the ASTM MoC manually. Even then, it can be seen that Figure 1 only contains subsection 'c' of FAR 23.2100. In that light, it is important to note the following observations – (i) Relevant guidelines from within the MoC document have to be mapped manually to the relevant FAR 23 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 FARs or MoC documents is a costly proposition. A proposed approach to address these problems is presented in the next section.

III. Model-Based Approach

A. Model-based Certification Plan Management

The model-based certification plan management is an approach to streamline the the certification planning process by taking advantage of Model-Based Systems Engineering (MBSE) techniques. MBSE is an emerging discipline that leverages models, rather than documents, for systems engineering exercises. This includes developing models that represent requirements, and linking these models to other models of verification procedures. Defining requirements and associated verification artifacts in models rather than documents opens up a variety of new database-driven approaches to streamline generation of systems engineering workflows. 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. Comparing with the document-based approach described in Sec. II.B, the model-base approach guarantees the completeness and consistency when tracking requirements from multiple sources (i.e. certification regulations, advisory circulars, pre-approved means of compliance) by providing formalized modeling techniques leading to a coherent system model incorporating up-to-date requirements and analysis [8].

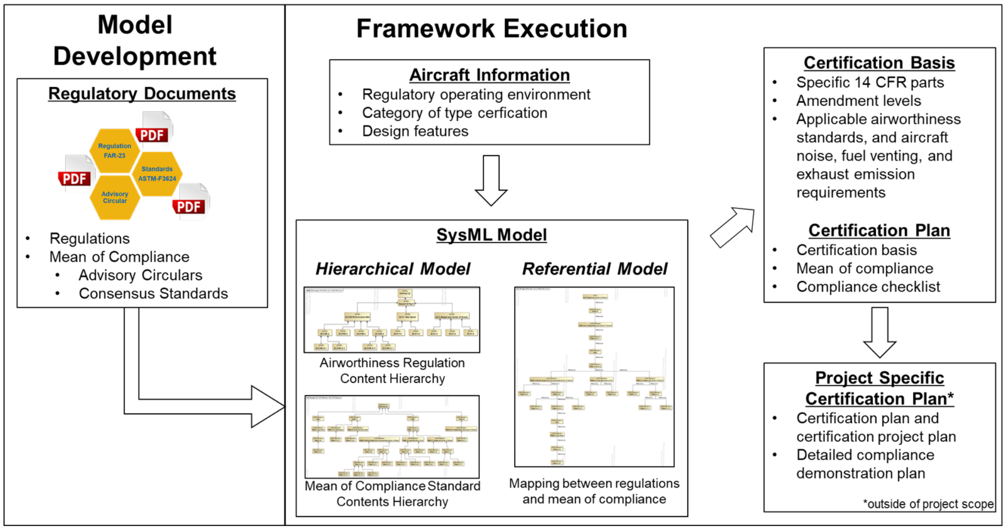

Fig. 2 Overall Process of Model-Based Certification Plan Management

The transition from document-based approach to model-based approach is enabled by the Systems Modeling Language (SysML) [8]. SysML is a general-purpose architecture modeling language for System Engineering applications. It supports the specification, analysis, design, verification, and validation of systems, which may include hardware, software, data, personnel, procedures, and facilities [9]. The modeling language 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.

The MBSE certification framework is shown in Figure 2. The core of the framework is a SysML model representing the certification regulations and consensus standards. To generate the certification plan, an aircraft model containing information on design features (e.g. maximum takeoff gross weight, number of passengers, engine category, number of engines, etc.) and operating conditions (e.g. regulatory operational environment, flight envelope, etc.) is specified and provided as input to the SysML model. The first step of making a certification plan is to determine the certification basis, in which the SysML model will automatically determine the airplane certification and performance levels based on input aircraft model information, and choose the specific certification rules applied to the aircraft from 14 CFR Part 23. Once the certification basis is determined, the MBSE framework will automatically capture the verification evidence (means of compliance) corresponding to certification rules and select the means of compliance for the input aircraft by tracing the SysML representative model of regulations and consensus standards. Finally, a compliance checklist will be generated from the SysML model associated with the certification basis and certification plan, which further facilitates the creation of the project specific certification plan for the aircraft.

B. SysML Model Development

The development of a SysML model is performed in MagicDraw. MagicDraw is chosen because of its capability to connect to an external tool and its document generation and scripting engine to retrieve, modify, and manipulate data from the model [10]. The created SysML model aims to store documentation relevant to the certification of airplanes. The model will include the FARs, the MoC, in particular the ASTM standards, and the relationships between these regulatory documents. Two views are created and used in the model. The sections that follows will expand on the construction of the views and their goals.

1. Implementation of the MBSE Method For Type Certification

The SysML model was built using the MBSE methodology. Three steps highlighted in Figure 3, that the MBSE methodology proposes, were implemented (the others were not necessary to achieve the goals of the present work). It is important however, to note that the steps omitted in this paper would need to be implemented when developing a full model that includes more than just documentation.

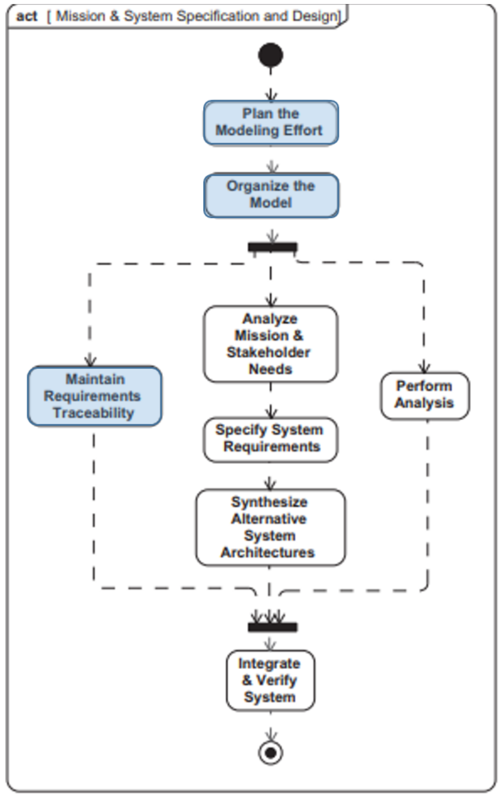

Fig. 3 Simplified MBSE Methodology

Planning The Modeling Effort The overall objective of the model is to establish a new modeling approach to facilitate the certification process for regulators and aircraft manufacturers. This implies that regulatory entities should be able to easily depict regulations and their changes inside the model. Manufacturers should also be able to navigate easily through regulations and select the ones that pertain to them. This leads to the selection of appropriate modeling artifacts that are presented in Sec. III.B.4.

Organizing The Model In MagicDraw, package elements can be used to organize the model in logical groupings. For this project, higher level logical groups were:

- The type certification package containing model elements used to describe the FARs and the standards.
- The model library package further described in Sec. III.B.4
- The simulation package presented in Sec. III.B.5

The package structure created is shown Figure 4. The structure of the type certification package mimics the hierarchy of the regulations defined by the FAA [11]. For instance, the package contains another package entitled CFR title 14 which contains additional packages that correspond to the different sections of the FARs. Only one package representing FAR Part 23 is currently modeled as a proof of concept. However, more packages could be created to represent the other parts. A sub-package inside part 23 is used to show Subpart B Flight, which was chosen to be the lowest package level. This package contains multiple lower FAR's sections such as performance and flight characteristics, which are modeled using FAR elements.

Maintaining Requirements Traceability The first step towards solving the issues presented in Sec. II is to establish complete representations of the FARs and the ASTM standards. The identification of the regulations and the standard structures is performed by initially reviewing the documentation and looking at every section, subsection and lower level divisions. This task is fairly easy but requires some time in making sure that all the breakdowns of these large documents are covered such that the structure that is to be modeled is a perfect one-to-one representation. A hierarchical view is then created to represent the structure of the FARs and the ASTM standards. The model element selected for

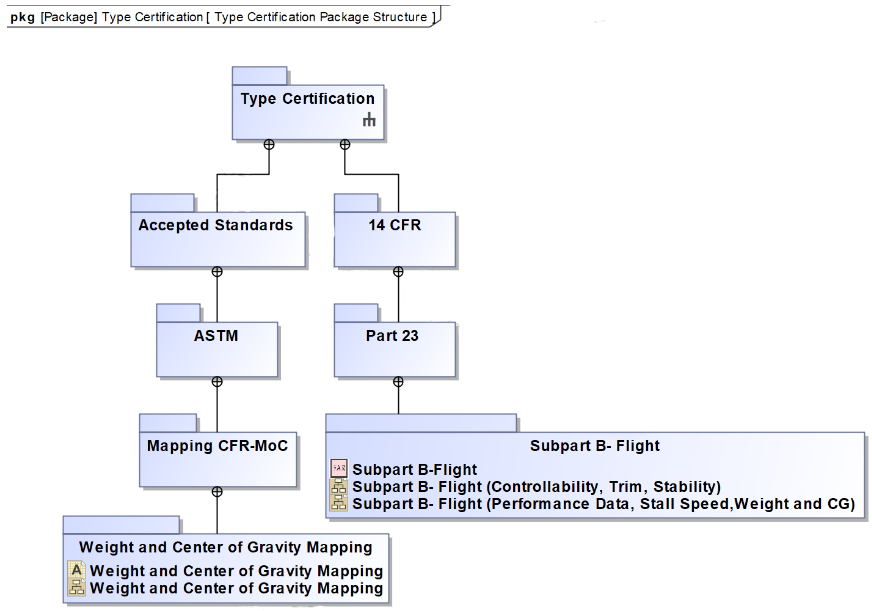

Fig. 4 High-Level Package Structure

their representation is a block. In SysML, blocks are the fundamental modular units for describing a system structure [8] hence their selection. Requirement elements were not used to model FARs and ASTM standards for multiple reasons:

- The first and most important reason is due to the code that was developed by the authors to traverse trees created in MagicDraw. The code relies on the association relationship elements to traverse a given tree structure. Requirement elements cannot be related using such relationships, which makes the developed code unable to traverse a tree made from requirement elements
- In SysML the semantic is important, and requirement elements do not have relationships that invoke a reference meaning [12]. Using blocks, associations with this meaning can be used [8] and are therefore more helpful to describe the relationship between FARs and ASTM standards, which reference each other
- The FARs and ASTMs can be thought of as requirements because they contain constraints that need to be met by the vehicle being developed. However, the aim of the model was to capture their structure as documents in addition to their textual content
- The customization abilities of MagicDraw enabled the creation of new elements (FARs and ASTM), which are sub-classes of blocks. They are given more properties than a regular block, and some of them are copied from relevant properties from requirement elements

2. The Hierarchical View

The hierarchical view is a BDD that shows how the sections and subsections of the FAR are broken down as seen in Figure 5. A tree structure represents the hierarchy of the regulation with the root of this tree being the Subpart B Flight. A subsection of this node is Subpart B Flight which itself has multiple subsections. The convention that is followed when creating an FAR element is to provide the element with a name attribute that corresponds to the title of the section or subsection that is given by the FAA. For subsections that only contained the textual requirement, the name attribute was omitted. There is no benefit or drawback from choosing this convention, it can therefore be changed by the user. For instance, one might decide to use the section or subsection number in the name attribute instead of of leaving it blank. A similar breakdown is created for the ASTM standards as shown in Figure 6. The standards are divided into multiple subsections with unique designation. Name attributes are omitted on certain standards for the same reason as for FARs. An anticipated benefit of this implementation is the visual breakdown of the regulations alongside essential source of information such as the textual requirements, the section number, the category of the FAR or ASTM, and other properties that are specific to these novel model elements. Once the structure of both the FARs and the ASTM standards is constructed and relevant additional information is added to the model element representing them, the next view can then be created.

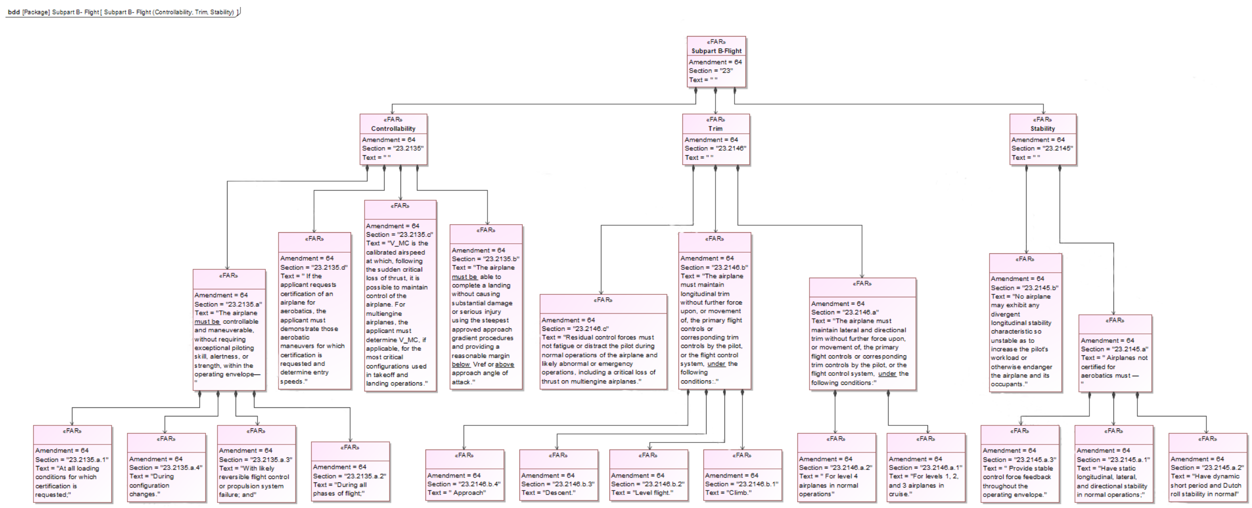

Fig. 5 Partial Subpart B-Flight Subsections Hierarchical View

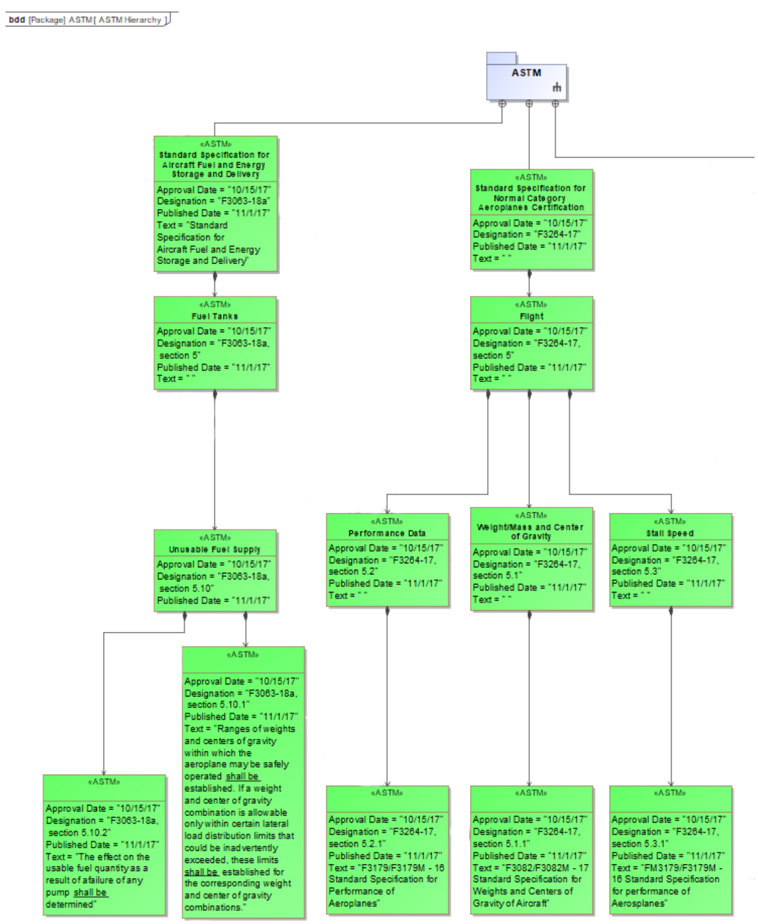

Fig. 6 Partial ASTM Standards Hierarchical View

3. The Combined Mapping Referential View

The goal of this view is to tackle the cross-referencing issue and enable an easier identification of the appropriate MoC. Building this view involves initially selecting an FAR and then using a document-based approach by reviewing standards' files and extracting relevant information that can be mapped back to the chosen regulation. The text found in the standards needs to be analyzed to determine if it provides more information on how to successfully satisfy the chosen FAR. This exercise requires an understanding of both the FARs and the standards, which makes it time consuming and non-trivial. Since this activity is a key step towards the requirements determination for a given vehicle, there is little room for error. Ideally, the mappings would be created and checked by subject-matter-experts that are familiar with the process. The mappings are only required to be accepted once and they can then be modeled using the mapping referential view in SysML. At the end of the exercise all the mappings from the FARs to ASTM standards should be established and modeled. Current work involves the development of a referential view to map the FAR 23.21-Weight and Center of Gravity to relevant standards. Figure 7 illustrates this mapping. This diagram demonstrates how easily one can visualize the connection between a regulation and the standards by following the three paths. Creating this type of view would largely reduce the amount of time spent on trying to find a document. The stereotype «Reference» is used to show that in this view the structures are not shown anymore and that the relationships are the only important information presented.

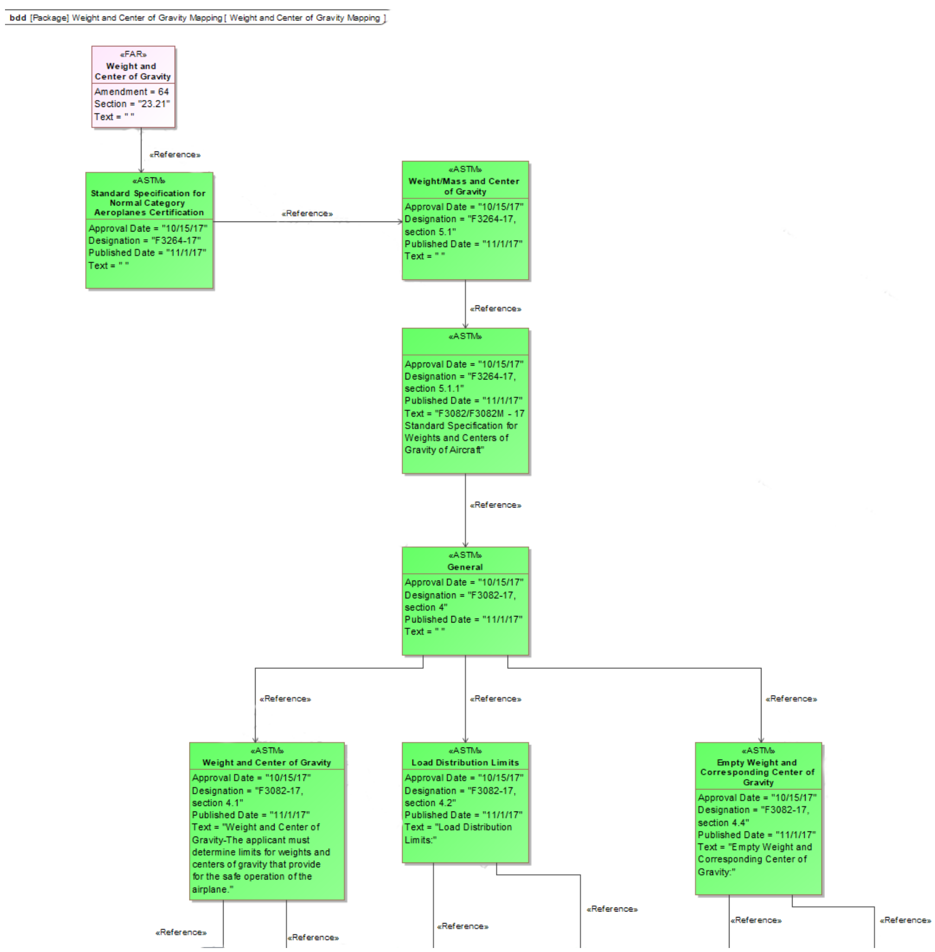

Fig. 7 Partial Combined Mapping Between FAR 23.21 and ASTM Standards

4. The Model Library

Model libraries are shared packages that are used in SysML to contain model elements that are reusable [8]. As this MBSE approach could be implemented in the future by different groups in the same organization, the need to formalize

Table 1 List of Stereotypes for The Model

«Stereotype Name»	Model Element
«FAR»	Block
«ASTM»	Block
«Reference»	Association

Table 2 Implemented Numbering Schemes for FARs

Numbering Level	Numbering Format	Examples
0^{th}	<number>	"23"
1^{st}	<number> <separator> <number>	"23.21" "23.2135"
2^{nd}	<number> <separator> <number> <separator> <character>	"23.21.a" "23.2135.b"
3^{rd} and higher	<number> <separator> <number> <separator> <character> <separator> <number>	"23.21.a.1" "23.2135.b.2"

the modeling scheme becomes important. The current model library's main purpose is to store stereotypes which are SysML extension mechanisms that allow additional properties and constraints to be created. Stereotype examples for the blocks and the relationships are listed in Table 1.

FAR Element The FAR element is a subclass of the block classifier and it contains new additional properties which are:

- *Amendment*: The amendment Level of the FAR was defined as an integer in SysML
- *Category*: It is a helpful additional property meant to help distinguish between FARs that are definitions, flight test conditions, performance data, and design constraints. It was defined as an enumeration in SysML
- *Section*: It is the unique number of the section of the given FAR defined as a string in SysML. The section follows a specific numbering scheme, presented in Table 2, so that when any new FAR is created and contained in another one, it will automatically be given a section number that implies that the new FAR is a lower level section. For example starting with the performance data §23.2105, FAR elements created and contained by 23.2105 will be given section numbers 23.2105.a, 23.2105.b, etc. This section level is characterized by a character similarly to how the FAA divides sections. Section numbers lower than this level will be characterized by numeric values, 23.2105.a will contain a FAR with section 23.2105.a.1. An "Element Numbering" function allows modelers to recursively change the section number for the lower level sections, which saves time by avoiding manual renumbering of every single FAR
- *Text*: It is where the textual requirement obtained from the FAR will be inserted. It was defined given string as a type in SysML

Table 3 Implemented Numbering Schemes for ASTM Standards

Numbering Level	Numbering Format	Examples
0^{th}	<Fnumber-number>	"F3063-18a" "F3264-17"
1^{st}	<Fnumber-number> <separator> <number>	"F3063-18a, section 1" "F3264-17, section 5"
2^{nd} and higher	<Fnumber-number> <separator> <number> <separator> <number>	"F3063-18a, section 1.1" "F3264-17, section 5.2"

ASTM Element Similar to the FAR element, the ASTM one is also a subclass of a block. However, different properties are given:

- *Approval and Published Date*: The day the standard was approved and the day it was published
- *Category*: Similar to the categories for the FARs
- *Designation*: It is the equivalent of a section for the ASTM standards, and is unique to each individual ASTM standard. It was given a string type in SysML and new ASTM element contained in a higher level one will automatically be given a lower level designation following a numbering scheme that was established in the model. The designation for ASTM standards start with the letter “F” and are follow by a numeric value corresponding to a standard. For instance, F3284-18 is the standard designation corresponding to the weight/mass and center of gravity standard. Furthermore, standards contained in F3284-18 will be given designations of “F3284-18, section 1,” “F3284-18, section 2,” etc. Creating lower levels from this point will add numerical values to the section number and these values will be separated by dots. “F3284-18, section 1” will have lower levels such as “F3284-18, section 1.1,” “F3284-18, section 1.2,” and so on. The numbering scheme for ASTM is presented in Table 3. Similar to the section property for the FAR, the designation property can also be renumbered recursively
- *Text*: It is the text contained in the ASTM standard. It was modeled as a string in SysML

Reference The reference stereotype is a subclass of the association relationship, which represents the semantic relationship between two or more classifiers [8]. No properties added to the element using the stereotype, but its semantic is meant to reflect the idea that FARs and ASTM standards reference each other.

5. The Simulation Package

This package contains the modeling artifacts required to create a user interface, along with other artifacts used to create a simulation using Cameo Simulation Toolkit (CST), an additional plugin in MagicDraw. The simulation leverages MagicDraw’s scripting engine and uses an in-house developed Python code to traverse trees created in the hierarchical and combined mapping views. When a tree is traversed the section or designation and the text of each node along a given path are saved to be displayed in the MagicDraw’s console and also written in a text file found in the software’s installation folder. For the combined mapping views, this means that it is possible to obtain the MoC for the FAR in the view. The package is composed of:

- Signal and UI elements packages
- The MoC Block

Signal and UI elements packages The UI elements package contains the necessary setup for creating the user interface including the physical and logical aspects. In MagicDraw the user interface is built using User Interface Modeling Diagrams, which allows for drag and drop of elements to create the physical aspect. The logical aspect is created by specifying attributes to these elements. For example, the text field created for this work is linked to the ID property of the MOC block. The user interface requires the user to type in the element identifier in the text field, and select or unselect the reference only box as can be seen in Figure 8. The two buttons RUN MOC and STOP are meant to start the CST simulation once the inputs have been entered and stop it when the user is done. User interface was set up by following the Cameo Simulation Toolkit's user guide [13]. The signal package contains the RUN MOC and the STOP signals, and could contain more signals as the model is further developed.

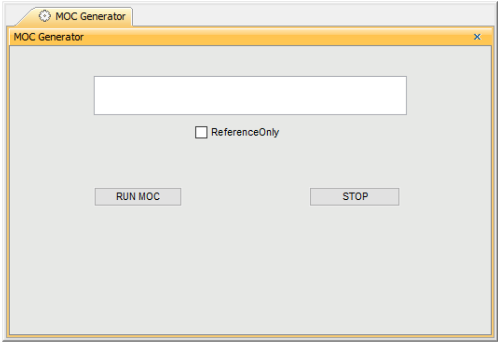

Fig. 8 MOC Generator User Interface

The MoC Block is a SysML block that has two properties. One of them is of type string and is named ID while the other one is a Boolean named ReferenceOnly. These properties are meant to be specified in a user interface that appears when running CST. The ID corresponds to the element identifier of the chosen root element. For a given combined mapping view, it will correspond to the FAR. Every model element in MagicDraw has a unique identifier, hence its selection for the user interface. Further development will allow the user to select just the FAR of interest instead of having to enter the identifier. The ReferenceOnly Boolean is set to true when the user wants to traverse a tree depicted in a combined mapping view, otherwise it set to false and the algorithm will traverse the hierarchical structure of the selected element. The MoC block is also the owner of a state machine behavior, which starts executing when the owner gets instantiated and is used in MagicDraw to describe how the states of objects change over time [8, 10]. As seen on Figure 9, the state machine begins in an idle state, in which nothing happens. When the RUN MOC signal is sent by the user through the user interface, the state shifts to GENERATE MOC which contains an activity behavior called a MOC activity that is run upon entering this state. Having these two states allows the user to change inputs and run simulations without having to reinitialized the MOC block every time. The MOC activity seen in Figure 10 is required to handle the

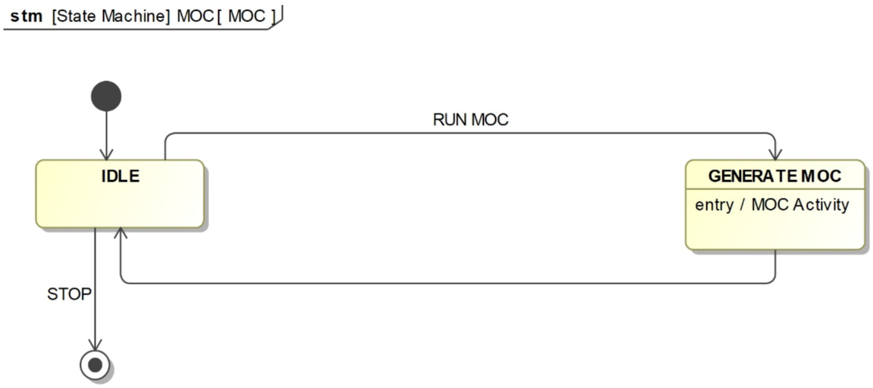

Fig. 9 MoC Block State Machine Diagram

inputs from the user interface, which are routed to the written script script. The created activity is a combination of FUML actions and an opaque action that has a body and language attribute containing the Python code to traverse the tree. Once this activity is run the certification basis is created and the state machine goes by the idle state. In order to shutdown the state machine, the user has to send the STOP signal via the user interface.

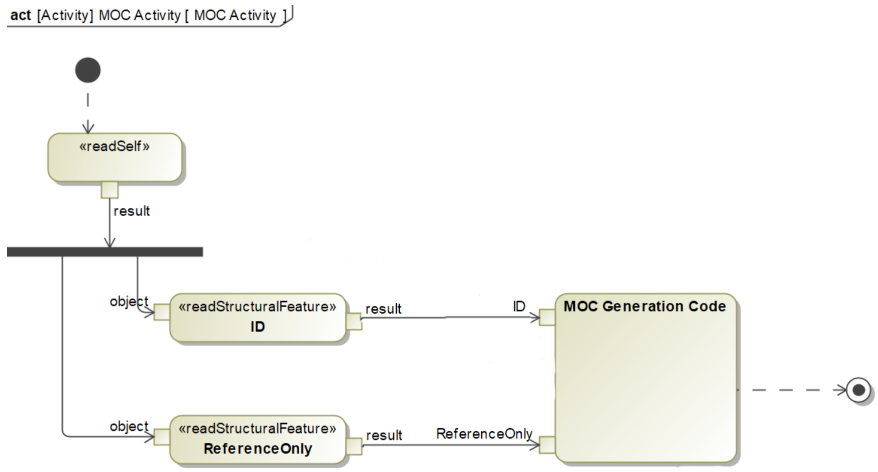

Fig. 10 MOC Activity Diagram

IV. Summary of the Expected Benefits

A. Benefits for Regulators

1. Auto-Updating and Synergy For Changes

Amendments are sometimes made to FARs and/or standards. In a document-based approach, the amendments have to manually change and update in every single regulatory document, which may take time and man power. However, the model-based approach is able to automate the process of updating amendments and avoid the need to make manual changes in each document. This approach allows for changes in one part of the model to be propagated to others. Figure 11 shows an example in which a change was made to correct the section number of "Weight and Center of Gravity" in the FAR. The wrong section number "23.201 - Weight and Center of Gravity" was corrected in the FAR hierarchical view to the right version of "23.21 - Weight and Center of Gravity". As shown in Figure 11, this change is conducted in a short time and the update is immediately propagated to other views and models as soon as the change is performed. In this case, we can see that the combined-mapping view also has the newer block name. This update propagation through the different views are inherent to SysML and are useful to maintain a consistent model. However if the change was to intentional, it is possible to automatically propagate it down the hierarchical tree nodes using the "Element Numbering" function in MagicDraw. In addition, the MagicDraw's scripting engine can help ensure that the model does not have circular referencing. A code can be written to check paths created in the referential view and determine if an infinite referencing loop was created.

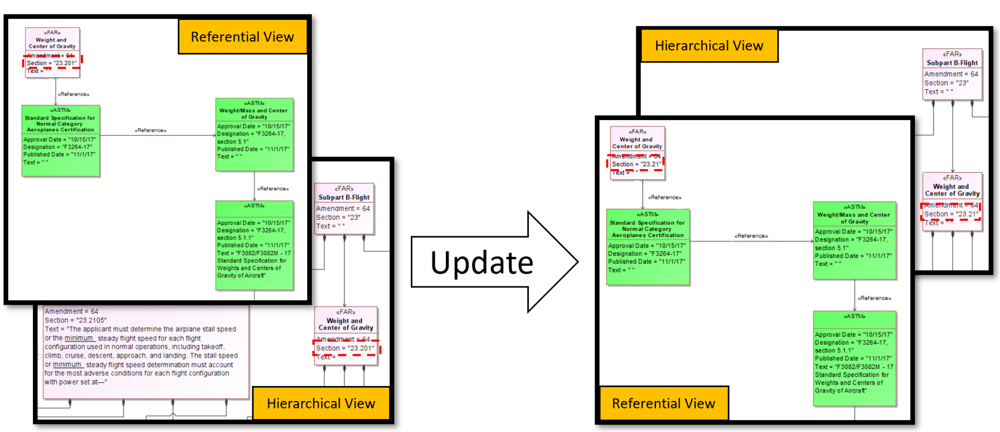

Fig. 11 Updates Visibility in Multiple Views

Additionally, validation constraints are created to help modelers keep track of changed section names. As shown in Figure 12, MagicDraw automatically checks 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. These validation rules were created for the FAR section numbers and the ASTM standard designations. 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.

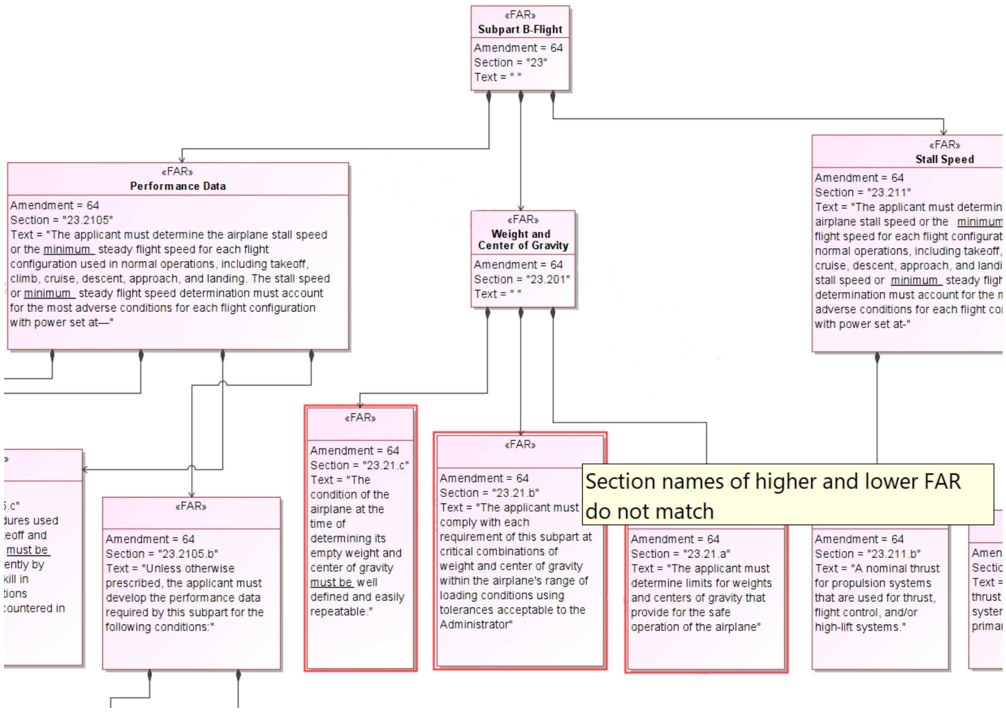

Fig. 12 Validation of Section Names

2. The Hierarchical View

Additional properties can be given to the FARs and ASTM standards, and any number of them can be displayed by the modelers in the hierarchical views. This can allow for summary of the properties of interest to be easily displayed, making the view a useful source of information. This view provides an additional benefit by making the most relevant piece of information accessible at the leaves of the tree. Lastly with this view, the structure of the FAR can be changed with minimal effort.

3. Expansion to Other MoC

The model-based approach is not limited to ASTM standards. If new consensus standards from the aviation community are approved as additional means of compliance by the FAA, similar implementations can be done such that the end user will be able to use a mapping of choice to relate an FAR to a selected standard. The process of creating the combined-mapping referential view will be the same as the one used for the ASTM standards. A combined-mapping referential view was created for the FAR 23.21 for the proof of concept, but more mappings can be completed following the same way if necessary.

B. Benefits for Aircraft Manufacturers

1. Compliance Checklist

The compliance checklist is a document ... As previously mentioned, the leaves of the tree in the diagrams contain the most relevant information for a given FAR, though previous nodes in the tree are helpful to understand the context. Once a FAR is selected, a compliance checklist can be generated by using the combined-mapping view of this FAR and the documentation associated with the standards presented in the view. There will be no need to go through multiple documents to obtain a checklist required for certification. On the one hand, it is possible to create organized Word or Excel templates from model elements using the MagicDraw document generation engine and Velocity Template Language (VLT). This is an easy and fast way of retrieving requested information for communication purposes. On the other hand, the selected scripting engine can be used to print the compliance checklist directly into MagicDraw through its console or through the created user interface. This approach is more friendly to the users who are not familiar with the MBSE software. An additional capability of this option is to write the checklist into a text file.

An example of the generated MoC is given in Figure 13. Each path of the tree created in the referential view is shown in the generated MoC. As seen on the generated MoC under each path, the textual information that was contained in each node of the path is also displayed.

```
_________________All Paths (Root to Leaf)_________________
Weight and Center of Gravity (23.21)--->Standard Specification for Normal Category Aeroplanes Certification (F3264-17)--->Weight/Mass and Center of
Gravity (F3264-17, section 5.1)--->F3264-17, section 5.1.1--->General (F3082-17, section 4)--->Load Distribution Limits (F3082-17, section 4.2)---
>F3082-17, section 4.2.1


F3082/F3082M - 17
Standard Specification for Weights and Centers of Gravity of Aircraft

Load Distribution Limits:
Ranges of weights and centers of gravity within which the aeroplane may be safely operated shall be established. If a weight and center of gravity
combination is allowable only within certain lateral load distribution limits that could be inadvertently exceeded, these limits shall be established
for the corresponding weight and center of gravity combinations.
___________
Weight and Center of Gravity (23.21)--->Standard Specification for Normal Category Aeroplanes Certification (F3264-17)--->Weight/Mass and Center of
Gravity (F3264-17, section 5.1)--->F3264-17, section 5.1.1--->General (F3082-17, section 4)--->Load Distribution Limits (F3082-17, section 4.2)---
>F3082-17, section 4.2.2


F3082/F3082M - 17
Standard Specification for Weights and Centers of Gravity of Aircraft

Load Distribution Limits:
The load distribution limits shall not exceed any of the following:
___________
Weight and Center of Gravity (23.21)--->Standard Specification for Normal Category Aeroplanes Certification (F3264-17)--->Weight/Mass and Center of
Gravity (F3264-17, section 5.1)--->F3264-17, section 5.1.1--->General (F3082-17, section 4)--->Weight and Center of Gravity (F3082-17, section
4.1)--->F3082-17, section 4.1.2


F3082/F3082M - 17
Standard Specification for Weights and Centers of Gravity of Aircraft

Weight and Center of Gravity-The applicant must
determine limits for weights and centers of gravity that provide
for the safe operation of the airplane.
Ranges of weights and centers of gravity within which the aeroplane may be safely operated shall be established. If a weight and center of gravity
combination is allowable only within certain lateral load distribution limits that could be inadvertently exceeded, these limits shall be established
for the corresponding weight and center of gravity combinations
```

Fig. 13 Generated Means of Compliance Example

2. Incorporation of Certification Requirements to Conceptual Design

Recently, with the surge of interest in transformational aviation concepts, many new aircraft manufacturers are getting involved in the general aviation market. However, for these new manufacturers that have limited certification experience or historical data, the certification process can be expensive and time-consuming. Moreover, unconventional configurations, such as e-VTOL, pose to incorporate a multitude of novel technologies that are not previously seen in traditional FAR-23 type of aircraft. The scarcity of knowledge on new configurations and technologies poses a high risk and uncertainty type-certifying these vehicles. Failure to meet certification requirements may force modification and redesign, which could potentially bring long delays and cost overruns to aircraft manufacturers. Therefore, in order to reduce the cost and uncertainties associated with the certification process, there is a need to incorporate certification considerations earlier in aircraft design.

One way to incorporate certification considerations into the design process is to transform the requirements from regulations and standards to mathematical constraint functions and develop a certification analysis capability for early aircraft design and optimization [14]. Such a method can be supported by the MBSE approach. Firstly, the structured SysML model helps the designer to identify the design requirements from regulations and standards that need to be mathematically modelled, and provides the designer a clear view of the how regulatory requirements and standards are correlated. Secondly, the mathematical modelling of regulatory requirements and the development of certification analyses can be integrated into the SysML model by using the SysML constraint blocks. The constraint blocks are the primary elements to support parametric models construction, which are composed of sets of parameters and their associated constraints [8]. The constrained parameters can be the metrics identified from the compliance checklist mentioned above. Once the metrics are assigned to constraint blocks, the physics-based certification analysis can be either coded within the parametric diagram or established externally and integrated by the Phoenix Integration Model Center. The goal of supporting certification analysis and creating a capability in SysML is the long-term vision of a model-based aircraft certification approach and the general process is presented in Figure 14.

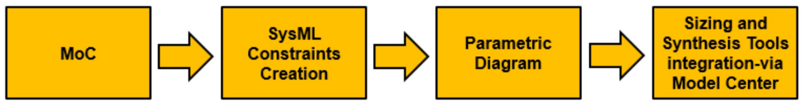

Fig. 14 Long Term Vision of The Model-Based Approach

V. Conclusion

This paper presents a model-based certification planning approach to facilitate the type certification process of normal category airplanes and overcome shortcomings of document-based approach. In particular, the regulation 14 CFR Part 23 and ASTM standards, that are used to comply with it, were used as the proof of concept. A model-based systems engineering approach for normal category airplane type certification was developed, and part of it was implemented. The execution of the plan requires obtaining information about certification regulations, advisory circulars, pre-approved means of compliance, as well as the relationship between regulatory documents. The information is then used to create a SysML model in MagicDraw. The hierarchical view of the SysML model provides a clear view of the structure of regulations of standards and enables a straight-forward access to the content and relevant data included in the regulatory requirements. The referential view allows the mapping between FARs and pre-approved means of compliance, as well as the mapping within regulations or standards. From this mapping a certification plan and a compliance checklist are generated leveraging MagicDraw's scripting engine. The model-based approach provides multiple benefits to stakeholders such as regulatory agencies and aircraft manufacturers and streamlines the certification process for all parties.

References

[1] AOPA, "Aircraft Owners and Pilots Association - What is General Aviation?" Online: `https://www.aopa.org/-/media/files/aopa/home/advocacy/what_ga.pdf`, Accessed May 3, 2019.

[2] FAA, "Revision of Airworthiness Standards for Normal, Utility, Acrobatic, and Commuter Category Airplanes," Federal Register, online: `https://www.federalregister.gov/documents/2016/12/30/2016-30246/revision-of-airworthiness-standards-for-normal-utility-acrobatic-and-commuter-category-airplanes`, 2017.

[3] FAA, "83 FR 21850 - Accepted Means of Compliance; Airworthiness Standards: Normal Category Airplanes," Federal Register, online: `https://www.govinfo.gov/app/details/FR-2018-05-11/2018-09990`, 2018.

[4] FAA, "Order 8110.4C - Type Certification - With Change 6," online: `https://www.faa.gov/regulations_policies/orders_notices/index.cfm/go/document.information/documentID/15172`, 2017.

[5] ASTM, "Committee F44 on General Aviation Aircraft," online: `https://www.astm.org/COMMITTEE/F44.htm`, accessed May 3, 2019.

[6] ASTM, "ASTM F3264-18 Standard Specification for Normal Category Airplanes Certification," Standard, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-0259, United States, Mar. 2018. doi:10.1520/F3264-18.

[7] ASTM, "ASTM F3082M/F3082M-17 Standard Specification for Weights and Centers of Gravity of Aircraft," Standard, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-0259, United States, Oct. 2017. doi:10.1520/F3082_F3082M-17.

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

[9] Friedenthal, S., Moore, A., and Steiner, R., "OMG Systems Modeling Language (OMG SysML) Tutorial," INCOSE and affiliated Societies, online: http://www.omgsysml.org/INCOSE-OMGSysML-Tutorial-Final-090901.pdf, 2009.

[10] No-Magic-Inc., "MagicDraw User Manual," online: https://www.nomagic.com/support/documentation, Accessed Nov 4, 2018.

[11] "Federal Aviation Regulations (FAR) Part 23 - Airworthiness Standards: Transport Category Airplanes," Federal Aviation Administration (FAA), U.S. Department of Transportation, online: http://www.ecfr.gov/, 2018. URL http://www.ecfr.gov/.

[12] Armonas, A., "Requirements Writing in SysML," online: https://www.nomagic.com/mbse/images/whitepapers/Requirements_Writing_in_SysML.pdf, Access May 10, 2019.

[13] No-Magic-Inc., "CAMEO SIMULATION TOOLKIT user guide," , 2015.

[14] Xie, J., Chakraborty, I., Briceno, S., and Mavris, D., "Development of A Certification Module for Early Aircraft Design," *2019 AIAA Aviation Technology, Integration, and Operations Conference*, American Institute of Aeronautics and Astronautics, 2019.