An MBSE Framework to Identify Regulatory Gaps for Electrified Transport Aircraft

Stephen Glinski*, Bijan Fazal†, Evan D. Harrison‡, Mayank V. Bendarkar§, Taylor Fields¶, Elena Garcia‖, and Dimitri N. Mavris**
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, USA 30332
Email: *sglinski3@gatech.edu, †bfazal3@gatech.edu, ‡evan.harrison@asdl.gatech.edu, §mayank.bendarkar@asdl.gatech.edu, ¶tfields6@gatech.edu, ‖elena.garcia@ae.gatech.edu, **dimitri.mavris@aerospace.gatech.edu

***Abstract*—A typical aircraft certification process consists of obtaining a type, production, airworthiness, and continued airworthiness certificates. 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. Earlier work by the authors demonstrated a model-based framework for the management of these certification artifacts for normal category airplanes. Presently, it is expanded and adapted to consider certification for transport category airplanes regulated under 14 CFR Part 25, providing clear transparency and traceability between the text of the regulations and imposed requirements, contextual information, and specified test activities. In particular, a capability to identify potential gaps in the applicability of regulations for novel architectures such as electrified aircraft is proposed. This capability, based on mismatches between the functional intent and the corresponding prescribed physical implementation, is developed. A sample implementation of the proposed capability is presented for a notional electrified powertrain aircraft architecture.**

***Index Terms*—Model-based Systems Engineering (MBSE), Certification, Electrified Propulsion, Regulatory Gap Analysis**

I. Introduction and Background

Modern aircraft are complex machines that are subject to government-mandated safety rules to ensure they pose minimal risk to crew, passengers, as well as the people and property around them. An aircraft is 'certified' when it complies with such regulations, which apply as the aircraft is designed, manufactured, and operated over its life. In the United States, the Federal Aviation Administration (FAA) oversees the Type Certification (TC) process among others, which involves the creation of a Certification Plan (CP) by the FAA and the TC applicant. The CP includes the intended regulatory operating environment, the proposed certification basis, a description of how compliance will be shown, and a list of documentation showing compliance findings [1]. All of the information required for a CP can be summarily combined in a Type Certificate Compliance Checklist that includes the certification basis, the applicable Means of Compliance (MoC), and the method of compliance.

This work was supported by the Systems Analysis Support for the Electrified Powertrain Flight Demonstration Program of NASA/NIA.

At its core, the aircraft type certification is a prescribed systems engineering process involving identification of core requirements, selection of means to verify compliance, and generation of sufficient evidence for verification. Under traditional approaches, systems engineers manually produce documents, tables, figures, and flowcharts where consistency and content of the data is managed manually across documents and databases. Table I shows an example spreadsheet model of 14 CFR §25.1070 takeoff speeds along with cross-references to different sections.

TABLE I
Document-based approach to model 14 CFR Part 25 with cross-referencing

Regulation			Text	Reference
25.107 - Takeoff Speeds	c		V_2, in terms of calibrated airspeed, must be selected by the applicant to provide at least the gradient of climb required by §25.121(b) but may not be less than -	25.121(b)
		1	V_{2MIN}	
		2	V_R plus the speed increment attained (in accordance with §25.111(c)(2)) before reaching a height of 35 feet above the takeoff surface; and	25.111(c)(2)

It is important to reiterate the following observations pertinent to the document-based paradigm [2], [3]: (i) Relevant guidelines from within the 14 CFR Part 25 document have to be mapped manually to the relevant cross-references within the regulations resulting in intractable documents, (ii) The document-centric process is susceptible to human errors, with any correction or change becoming costly to rectify later, and (iii) Identifying any gaps in the applicability of the regulations to novel aircraft concepts in such a paradigm is time consuming for subject matter experts

Model-based Systems Engineering (MBSE) is an emerging discipline that leverages models, rather than documents, for systems engineering exercises. Under an MBSE paradigm, systems engineers produce a single system model. Any reports, flowcharts, and other documentation are compiled by exposing portions of the common system model, while modeling languages enable consistency in the system model data [4], [5]. Compared to a document-based approach, a model-based approach guarantees completeness and consistency when tracking requirements and verification artifacts from multiple sources. It does this by providing formalized modeling techniques leading to a coherent system model incorporating up-to-date requirements and analysis [6].

The focus of the present work lies in expanding the previous model-based certification framework [2], [3] to transport category airplanes regulated under 14 CFR Part 25. In particular, this work seeks to standardize the process of developing a model-based regulatory framework for certification of electrified aircraft considering best practices in MBSE. For novel electrified aircraft propulsion architectures, the framework focuses on the identification of gaps – prescriptive regulations that assume a fixed conventional physical implementation and therefore cannot be directly applied to novel aircraft subsystems performing the same functions.

II. The MBSE Regulatory Framework

A model-based framework for regulatory analysis which adequately captures various regulatory artifacts is defined.

A. Model Structure

A review of 14 CFR Part 25 was performed to characterize the categories of statements contained within 14 CFR Part 25. This review resulted in three main categories of regulatory statements. First, many paragraphs within 14 CFR Part 25 contained direct regulatory statements wherein a requirement is imposed on either the applicant, the aircraft, or some system or component of the aircraft. Characteristically speaking, these regulatory requirements are often identified within 14 CFR Part 25 as ”must” statements, as seen in 14 CFR §25.305(a) [7]:

> The structure must be able to support limit loads without detrimental permanent deformation. At any load up to limit loads, the deformation may not interfere with safe operation.

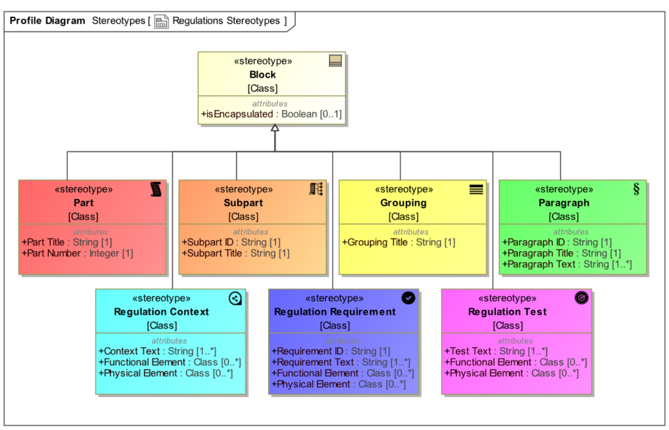

Fig. 1. Refined Regulatory Model SysML Stereotype

The second category consists of statements which provide additional context within the regulatory framework. At times these contextual statements provide general context that is utilized by several regulatory statements, such as specifications of categories or definitions, as in 14 CFR §25.301(a) [7] which specifies:

> Strength requirements are specified in terms of limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety). Unless otherwise provided, prescribed loads are limit loads.

The third category include statements of tests. These tests are specific verification activities which must be undertaken by the applicant in order to demonstrate compliance with an existent regulatory requirement. For example, 14 CFR §25.307(a) states:

> Compliance with the strength and deformation requirements of this subpart must be shown for each critical loading condition. Structural analysis may be used only if the structure conforms to that for which experience has shown this method to be reliable. In other cases, substantiating tests must be made to load levels that are sufficient to verify structural behavior up to loads specified in § 25.305.

The regulatory modeling framework begins with the definition of an underlying stereotype specification. A diagram of this refined stereotype profile is provided as Fig. 1. Namely, explicit definition of regulatory structural elements is defined, including representations of FAA regulation parts, sub-parts, groupings, and paragraphs. At each of these structural levels a small set of properties are preserved in order to capture key identifying information.

B. Model Implementation

The regulatory modeling framework becomes useful when constructing parts from 14 CFR. However, it is a daunting task to manually represent each part, sub-part, grouping, and paragraph within the Systems Modeling Language (SysML) model given the lengthy nature of 14 CFR parts. To provide a quicker solution, an automated process (see Fig. 2) was implemented to import regulatory xml files into the SysML model as part, sub-part, grouping, and paragraph elements.

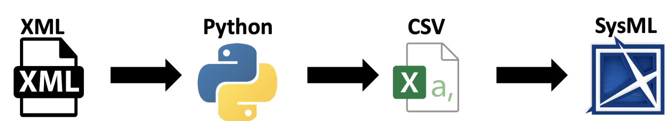

Fig. 2. Process chart for translating regulatory xml files to a SysML model

The process involves converting the data (identifications, titles, text, etc.) in xml files to a predetermined organized csv file. The csv file is then imported into the SysML model by matching the titles of the column names of the csv file and the pre-constructed table within SysML. This quickly and automatically creates and identifies the associated model elements for each part, sub-part, grouping, and paragraph. Once elements are identified they can be assembled within the model, providing a model representation which reflects the underlying structure of the regulations and provides a platform for further enrichment. Fig. 3 provides a sample of the constructed model, displaying a subset of the total synthesized part, subpart, grouping, and paragraph elements.

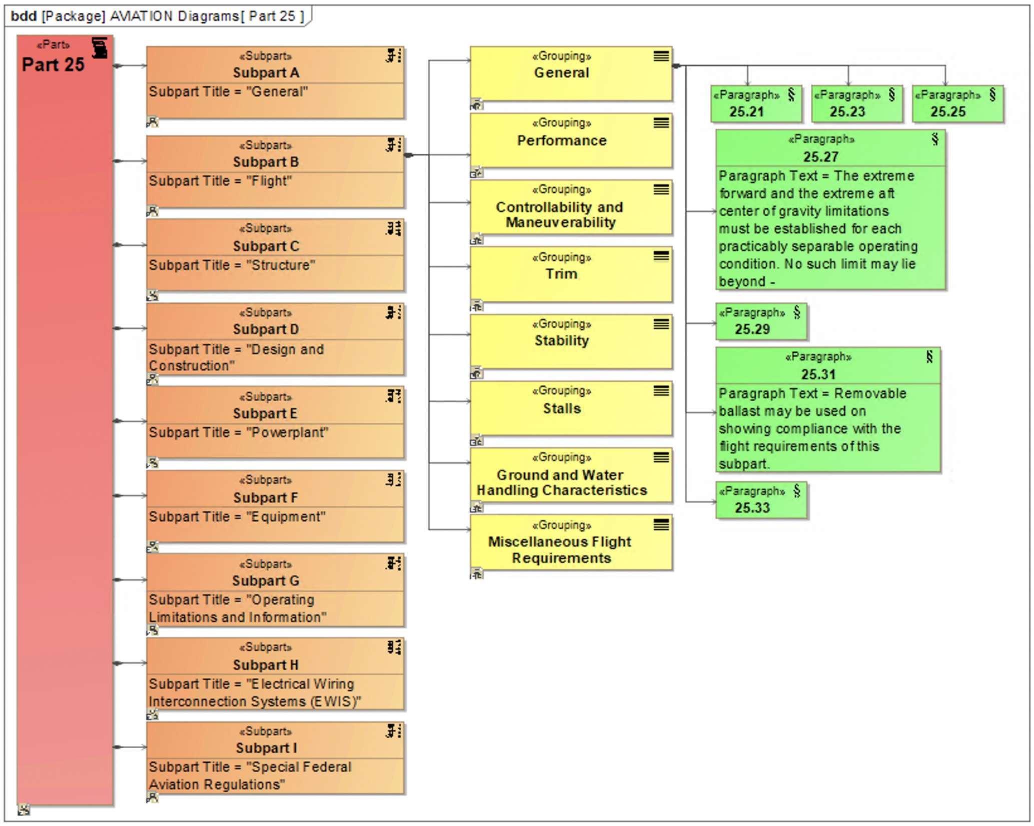

Fig. 3. Model Representation of Part 25 Regulatory Elements

III. Identification of Regulatory Gaps

As new technology-infused architectures are investigated, serious consideration must be given to their compatibility with existing airworthiness regulations. Regulations such as those within 14 CFR Part 25 present particular challenges whereby existing regulations may be incompatible with novel aircraft architectures. Gaps are likely to emerge when one seeks to apply existing regulatory requirements, which are based on traditional architectures, to unconventional vehicles with unique architectures that depart from traditional implementations. These portions of the regulations represent costly challenges and roadblocks to the certification of innovative aircraft. Thus the systematic identification of these gaps is paramount to the continued development of novel, technology-infused aircraft.

Within the overall regulatory process for aircraft airworthiness, regulatory requirements are imposed on vehicles which meet some set of criteria. Many requirements are deemed to be applicable to a given vehicle based upon some inherent attribute of the system, such as its classification as a transport category aircraft or the intended number of passengers, and as such tend to be broadly applicable for a wide spectrum of vehicles and vehicle architectures. Other regulatory requirements are more narrowly applicable to particular aircraft types or aircraft architectures. For instance, consider the regulatory statement of 14 CFR Part 25.951 (a) [8]:

> Each fuel system must be constructed and arranged to ensure a flow of fuel at a rate and pressure established for proper engine and auxiliary power unit functioning under each likely operating condition, including any maneuver for which certification is requested and during which the engine or auxiliary power unit is permitted to be in operation.

One may observe that this regulatory requirement is more narrowly scoped to aircraft whose physical architectures include a fuel system. Furthermore, it may be contextually observed that the fuel systems of interest for §25.951 are those which provide fuel to engines or auxiliary power units. Together, it is noted that the criteria for the applicability of the requirements of § 25.951 are posed with respect to the physical and functional architecture of some vehicle of interest. Should a vehicle exhibit this physical component (i.e. a fuel system) intended to perform this system function (i.e. provide energy to engines or APUs), then the requirement in question is applicable.

These means of identifying applicable regulations are characteristic of the airworthiness regulations found within 14 CFR Part 25. In addition, physical and functional applicability criteria have historically been well suited to traditional aircraft architectures, due in part to the evolution of airworthiness regulations which encompass growth and change in the aviation industry. However, this specification of an applicability

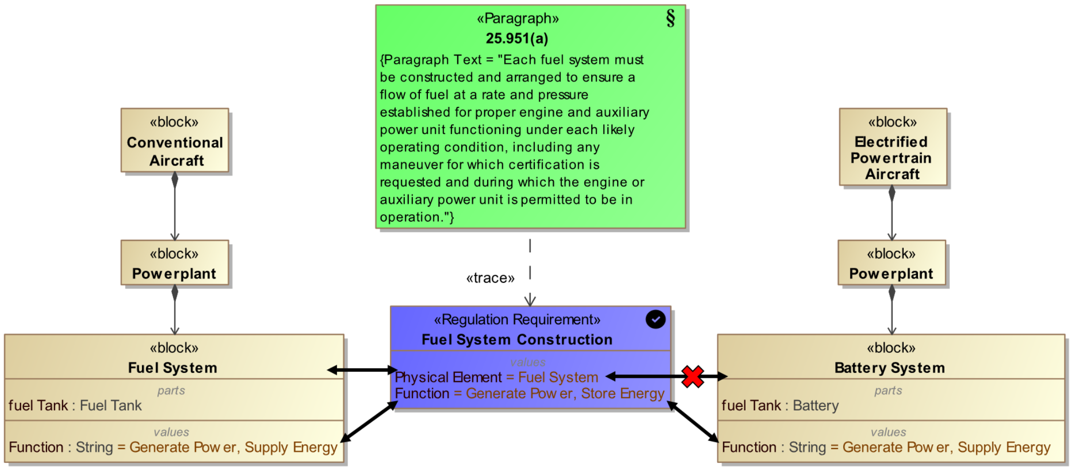

Fig. 4. Utilizing physical and functional decomposition for identifying potential gaps

criterion is inherently brittle with respect to the ability to extend existing regulatory statements to novel aircraft architectures, such as aircraft architectures which include electrified powertrains.

As new technology is developed and integrated into aircraft systems fundamental changes are made to the underlying vehicle architecture. Commonly the introduction of a new technology may manifest as a new element within the aircraft's physical architecture which performs some number of existing system or vehicle level functions. For example, the transition from piston-driven engines to turbine-driven engines may be represented as a transition between different physical architectures wherein the underlying allocation of system and vehicle-level functions is largely unchanged. The incorporation of new technology may also manifest as a re-allocation of system or vehicle level functions to new or existing physical elements. A recent experimental aircraft program, the X-57 Maxwell, serves as an example of such a technological change. The introduction of electric distributed propulsion manifested as an architecture which leveraged several inboard propellers as high-lift devices [9], thereby allowing for a reallocation of vehicle functions typically accomplished by mechanical flaps or slats.

This dual view of the physical and functional elements, which are used as applicability criteria for regulatory requirements on one hand and defined by system architects for novel aircraft system on the other, provides a pathway towards identifying key regulatory gaps. Furthermore, the model-based regulatory framework presented in Section II provides a platform within which both regulatory requirements and vehicle architectures may be consistently expressed and leveraged to facilitate the systematic identification of regulatory gaps.

The identification of potential regulatory gaps is proposed as an extended view of the applicability process for regulatory requirements. Consider the diagram pictured in Fig. 4, which shows an example scenario of the proposed process. First, any specific physical and functional elements inherent to a given regulatory requirement are identified. These physical and functional elements are later compared to a given aircraft architecture in order to identify if the requirement is applicable to the vehicle in question. For a conventional aircraft architecture, both the physical components and functions allocated to them match with their applicable regulatory counterparts. However, a conflict over applicability of regulations occurs when a novel architecture only partially matches the regulation in question. In many instances, a novel architecture may exhibit functional elements which match those in a given requirement, but differ in terms of physical components, resulting in a gap caused by this physical conflict. Likewise, a gap may arise from a functional conflict between the vehicle architecture and the regulation requirement, wherein a matching physical element differs in its allocated system function. In Fig. 4, the requirement prescribes a 'fuel system' (component) to satisfy an aircraft level function of 'supplying energy', which is a typical configuration present within traditional vehicle architectures. However, in aircraft with electrified powertrains, the same system functions may be satisfied by a different physical component - the battery system. In such a scenario, the physical conflict between the requirements and the architecture under consideration can be identified as a potential regulatory gap.

Within the regulatory model framework presented in Sec. II, additional "regulation requirement" elements are defined to refine the regulatory paragraphs with properties that help determine their applicability to an architecture of interest. For example, these properties specify architecture characteristics like the number of engines, the engine type (turbojet vs. reciprocating), etc. to which a regulatory paragraph applies. If the regulatory paragraph prescribes a particular physical implementation or a component, the corresponding model refinement element is annotated with the component and the function it satisfies as additional properties. These elements can then be leveraged to conduct a systematic comparison of the regulatory requirements and a given vehicle architecture as exemplified in the next section.

IV. Sample Implementation

The regulations of 14 CFR Part 25 are modeled in MagicDraw per the generalized implementation described. Fig. 5 provides a breakdown of Part 25 Subpart E requirements by aircraft subsystem and discipline. The majority of the regulations in this subpart are observed to be prescriptive in nature. Since these are also directly affected due to the transition towards an electrified powertrain, they form the bulk of the observed gaps and are of interest in this section.

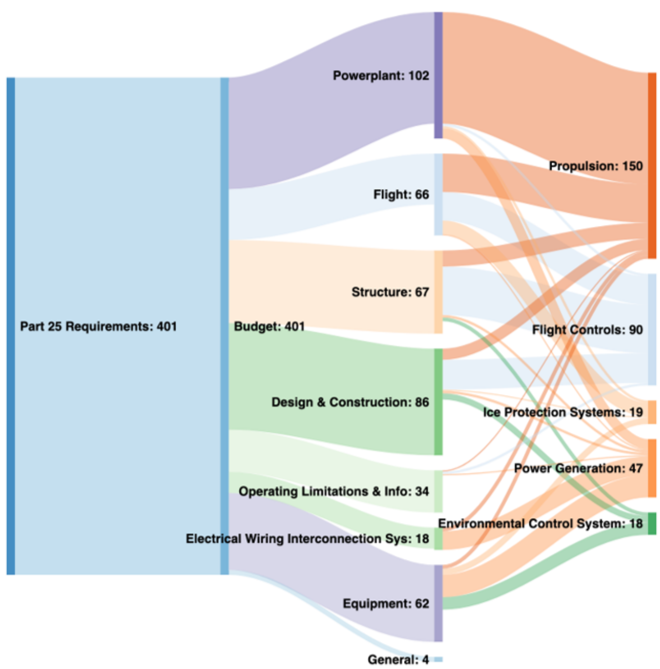

Fig. 5. Breakdown of 14 CFR Part 25 Subpart E Regulations

A SysML activity diagram with Cameo Simulation Toolkit (CST) is used to implement the gap analysis capability. The activity diagram takes an aircraft architecture of interest as an input. It then reads the entire Part 25 model using a pre-order depth first tree search algorithm to determine the applicability of every requirement. An applicability property defined for every regulation requirement block takes three values that are modified by the activity diagram – a value of 1 denotes an applicable requirement, a value of 0 denotes an inapplicable requirement, and a value of 2 denotes a potential gap. A potential gap is identified when the prescribed physical implementation of a function in a regulation requirement does not match the physical implementation in the aircraft architecture.

Fig. 6 shows an example electrified powertrain aircraft architecture on which the gap analysis capability is tested. An example identified gap, 14 CFR Part 25.951 (b) [8], is used here for further discussion:

> Each fuel system must be arranged so that any air which is introduced into the system will not result

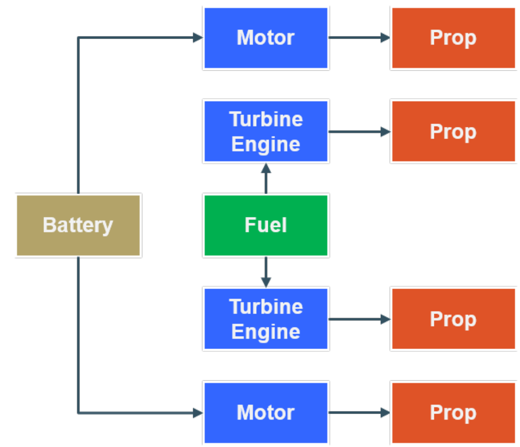

Fig. 6. Simplified example hybrid-electric aircraft powertrain

> in -
> (1) Power interruption for more than 20 seconds for reciprocating engines; or
> (2) Flameout for turbine engines.

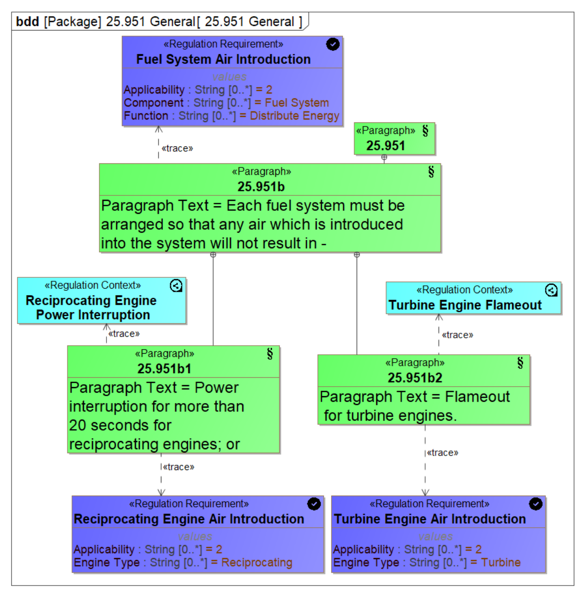

Fig. 7. SysML implementation of 14 CFR 25.951(b)

This regulation refers to a requirement applicable to the fuel system of an aircraft. Additionally, the requirement differs when the aircraft is powered by a turbine or a reciprocating engine. The aircraft function of interest here is “distributing energy”, conventionally fulfilled by a fuel system. For an electrified propulsion aircraft, this function may be provided by an electrical power system and its components. While the functional intent of the requirement may still be applicable, the prescriptive statement about the physical implementation is not. This requirement can therefore be classified as a gap, warranting further scrutiny by subject matter experts. The SysML implementation of this requirement paragraph, its refinement through properties, and applicability assigned

Applicability Legend: Applicability=0 (NA) Applicability=1 (applicable) Applicability=2 (gap)

#	Paragraph	Paragraph Text	Applicability/Gap
1	§ 25.107b	V2MIN, in terms of calibrated airspeed, may not be less than -	Applicability : String = 1
2	§ 25.107b2	1.08 VSR for -	Applicability : String = 1
3	§ 25.107b2i	Turbopropeller and reciprocating engine powered airplanes with more than three engines	Applicability : String = 1
4	§ 25.107b2ii	Turbojet powered airplanes with provisions for obtaining a significant reduction in the one-engine-inoperative power-on stall speed	Applicability : String = 0
5	§ 25.951a	Each fuel system must be constructed and arranged to ensure a flow of fuel at a rate and pressure established for proper engine and auxiliary power unit functioning under each likely operating condition, including any maneuver for which certification is requested and during which the engine or auxiliary power unit is permitted to be in operation.	Applicability : String = 2
6	§ 25.951b	Each fuel system must be arranged so that any air which is introduced into the system will not result in -	Applicability : String = 2
7	§ 25.951b1	Power interruption for more than 20 seconds for reciprocating engines; or	Applicability : String = 2
8	§ 25.951b2	Flameout for turbine engines.	Applicability : String = 2
9	§ 25.951c	Each fuel system for a turbine engine must be capable of sustained operation throughout its flow and pressure range with fuel initially saturated with water at 80 °F and having 0.75cc of free water per gallon added and cooled to the most critical condition for icing likely to be encountered in operation.	Applicability : String = 2
10	§ 25.951d	Each fuel system for a turbine engine powered airplane must meet the applicable fuel venting requirements of part 34 of this chapter.	Applicability : String = 2

Fig. 8. Aggregate of requirement applicability and gap analysis for sample electrified powetrain aircraft

through the activity diagram are shown in Fig. 7. Note the value of 2 assigned by the simulation code to the applicability property, recommending the regulation be considered as a gap.

A more aggregate view of the gap analysis exercise is shown in Fig. 8. The systematic identification of applicable requirements and those which may present regulatory gaps enabled by the MBSE framework provides an automated platform for assessing numerous regulations for a given vehicle concept. For instance, §25.107(b)(2)(i) is applicable to the example notional architecture, while §25.107(b)(2)(ii) is not because it pertains to turbojet aircraft. Regulations in the §25.951 paragraph broadly talk about a fuel system, which may have a conflict with the electrical system implementation in the example. These are still applicable to the same function and are identified as gaps.

V. Conclusions

Ongoing research continues to increase the technical feasibility of novel aircraft architectures like those with electrified powertrains. As technical challenges for these concepts are overcome, greater attention is given to issues which may emerge in order to fully realize these vehicle concepts as aircraft in operation. Chief among these concerns is the airworthiness certification process. The proposed approach of this work provides a model-based perspective to the identification of regulatory gaps that enables a systematic, transparent, and coherent vantage point on potential regulatory challenges.

One category of gaps not covered by the functional-physical mismatch utilized in this work relates to definitions of certain operating conditions. An example is the "critical engine inoperative" condition, which in traditional transport aircraft with two or more engines generally refers to having the biggest and most-outboard engine inoperative. For novel aircraft concepts with fully or partially electrified powertrains, this definition needs to be revisited. A potential solution for future work may lie in incorporating an aircraft performance driven risk assessment alongside an MBSE certification capability [10]. The current framework nonetheless provides a first step in systematically identifying potential regulatory gaps for novel aircraft architectures, thus enabling additional work in this area.

Acknowledgment

The authors would like to thank Herb Schlickenmaier and Vincent Schultz for their feedback and help.

References

[1] "Order 8110.4C - Type Certification - With Change 6," Federal Aviation Administration (FAA), U.S. Department of Transportation, 2017. [Online]. Available: https://www.faa.gov/documentLibrary/media/Order/FAA_Order_8110_4C_Chg_6.pdf

[2] M.-H. Bleu-Laine, M. V. Bendarkar, J. Xie, S. I. Briceno, and D. N. Mavris, "A model-based system engineering approach to normal category airplane airworthiness certification," in *AIAA Aviation 2019 Forum*, 2019. [Online]. Available: https://doi.org/10.2514/6.2019-3344

[3] M. V. Bendarkar, J. Xie, S. Briceno, E. D. Harrison, and D. N. Mavris, "A model-based aircraft certification framework for normal category airplanes," in *AIAA Aviation Forum*, VIRTUAL EVENT, June 2020. [Online]. Available: https://doi.org/10.2514/6.2020-3096

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

[5] J. N. Martin, *Systems engineering guidebook: A process for developing systems and products*. CRC press, 1996, vol. 10.

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

[7] "Federal Aviation Regulations (FAR) Part 25 - Airworthiness Standards: Transport Category Airplanes," Federal Aviation Administration (FAA), U.S. Department of Transportation, 2021. [Online]. Available: http://www.ecfr.gov/

[8] "Federal Aviation Regulations (FAR) Part 25, Subpart E - Fuel System § 25.951 General." Federal Aviation Administration (FAA), U.S. Department of Transportation, 2021. [Online]. Available: http://www.ecfr.gov/

[9] N. K. Borer and M. D. Patterson, "X-57 high-lift propeller control schedule development," in *AIAA AVIATION 2020 FORUM*, 2020, p. 3091.

[10] S. Datta, R. Roy, M. V. Bendarkar, E. Harrison, and D. N. Mavris, "MBSE-Enabled Risk Reduction for Certification of Novel Aircraft Configurations," in *AIAA SCITECH 2022 Forum*, 2022. [Online]. Available: https://doi.org/10.2514/6.2022-1189