

A STUDY OF THE AIR FORCE AIRWORTHINESS ASSESSMENT PROCESS WITH RECOMMENDATIONS FOR REUSABLE LAUNCH VEHICLES

THESIS

Austin A. Troya, Captain, USAF

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AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Austin A. Troya, BS

Captain, USAF

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Austin A. Troya, BS

Captain, USAF

Committee Membership:

Lt Col L. O. Mailloux, PhD
Chair

Dr. J. O. Miller
Member

Mr. R. A. FitzHarris
Member

Mr. M. D. Mueller
Member

Abstract

Flight safety is a critical design and engineering consideration within the United States Department of Defense (DoD) and particularly the United States Air Force (USAF). This study conducts an independent evaluation of the airworthiness assessment process used by the United States Air Force's Engineering Directorate through modeling and simulation. The airworthiness process is examined for its ability to effectively verify sound engineering design and efficiency with respect to the implementation of new software-based assessment tools and its impact on timeliness of reviews and resource utilization. Simulation results guide recommendations for reducing non-value-added activities and strategic leveling of resource demands to increase efficiency and decrease processing time. Lastly, from observation and detailed study of the aircraft airworthiness process, recommendations are made for the space domain toward the development of a re-qualification process for reusable launch vehicles, as this is a growing area of interest for the space community.

Acknowledgments

I would like to thank my advisor, Lt Col Logan Mailloux, first and foremost, for his continued guidance on this thesis, and for keeping my shiny object syndrome in check. Thank you to Dr. J.O. Miller for his assistance in developing my model and recommendations for analyzing and presenting statistical analysis. Also, thank you to Mr. Bob FitzHarris and Mr. Mark Mueller in the airworthiness office for their expertise and time spent assisting with the development and validation of my model and artifacts.

Austin A. Troya

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A STUDY OF THE AIR FORCE AIRWORTHINESS ASSESSMENT PROCESS WITH RECOMMENDATIONS FOR REUSABLE LAUNCH VEHICLES

I. Introduction

Flight safety has been the burden of air travel since its inception, with monumental advancements occurring over the past century. Ensuring the continued safety and reliability of aircraft is an active and specialized discipline, and a critical field of study. Sound technical design, safety-conscious operating parameters, quality of parts and manufacturing, and proper maintenance are important factors and considerations for a holistic airworthiness perspective.

Problem Statement

A robust airworthiness assessment program is essential to the continuation and enhancement of aircraft safety, however, inefficient practices, long lead times, and non-standardized data contribute to errors and rushed efforts. Studying, standardizing, and improving this process can help to ensure airworthiness assessments are accurate, reliable, and faster. The area under study (or scope) for this research is the airworthiness technical assessment process, owned and executed by the Air Force Life Cycle Management Center's (AFLCMC) airworthiness office (AFLCMC/EZSA).

AFLCMC's airworthiness certification process underwent significant revision in 2010 to more closely align with civil aviation practices, but EZSA is uncertain of how efficient the new process is or where improvements should be made to reduce chokepoints and waste. In accordance with DoDD 5010.42 (2008)—implemented via AFI 38-401 (2016)—Continuous Process Improvement (CPI) and lean methodology should be employed continuously to streamline processes and identify non-value-added activities and wasteful efforts. However, in the domain of airworthiness, solutions must ensure the safety and security of critical warfighting capabilities are not compromised in the interest of time savings.

Significance of the Study

Airworthiness certifications sought by program offices are of critical importance, time-sensitive in nature, and have the potential to delay program milestones. Moreover, certification is required prior to starting Operational Test and Evaluation (OT&E), and as such, there is significant pressure to complete airworthiness assessments in a timely manner without sacrificing quality or safety. The Air Force airworthiness assessment process must be robust, structured, timely, and consistent to ensure aircraft and aircrew safety. However, by leveraging civil aviation standards and practices, as well as modern CPI concepts, the Air Force airworthiness certification process can be streamlined, ensuring critical objectives are met while limiting extraneous activities.

It is expected that this study will result in reduced cost and man-hours for those involved in the certification process with downstream savings for user commands in the form of more rapid fielding of new capabilities from more efficient assessments. This study provides strategic, analysis-based recommendations to increase efficiency without sacrificing quality, and more importantly, safety.

Research Objectives

The primary objective of this study is to provide an independent assessment of the Air Force airworthiness process as defined by AFLCMC/EZSA. The assessment consists of studying, modeling, and validating the existing documented and observed process. The model will be used to quantify the value of each step and associated artifacts, and discovering where efficiencies and information automation can be leveraged with the greatest benefit.

The secondary objective is to tailor the airworthiness assessment process and offer recommendations for the re-qualification assessment of Reusable Launch Vehicles (RLVs)—that is, assessing a rocket booster's capability to be re-used for subsequent space launches (i.e. after each flight, the RLV must be re-assessed and meet or exceed flight re-qualification standards). The development of these standards, and the underlying qualification process is of interest to the Space and Missiles Systems Center (SMC) Advanced Systems and Development Directorate (SMC/AD) and Launch Enterprise Directorate (SMC/LE), the latter of which is responsible for launch mission assurance practices.

Research Questions

A number of goals are developed in the form of research questions to ensure the assessment performed for EZSA satisfies the desires of the customer as well as thesis requirements.

1. How can the AFLCMC/EZSA airworthiness process be defined, to include quantitative and qualitative characteristics?
2. How can the airworthiness process be modeled?
    a. What are the value-added activities and artifacts in the process?
    b. Identify existing chokepoints/inefficiencies and measures that have been implemented previously to improve process flow.
    c. How can the airworthiness office and program offices capitalize on detailed process models (short term and long term) to aid in their understanding of the airworthiness assessment process?
3. How can the airworthiness process be applied to other domains such as reusable launch vehicles?

Research Approach

The basis for improving any process is understanding the process under inspection and its intricacies. Initial efforts are toward studying the existing documentation available on the airworthiness assessment process, combined with observing the process and interviewing Subject Matter Experts (SMEs). A conceptual process model was developed based on the most up-to-date and accurate information.

First, a model of the current process was created using Simio, which allows the relationships between the key steps in the airworthiness assessment process, the development of artifacts, and resource utilization to be studied (Simio LLC, 2018). Upon completion of an initial model, the model was then validated by SMEs in AFLCMC/EZSA and assessed for the potential to reduce cost, time, and waste, and improve quality through process changes which in turn inform the recommendations of this thesis.

Scope of Research

As stated, this research is focused on the technical airworthiness assessments conducted by AFLCMC/EZSA and will not explore operational testing or assessments. Additionally, airworthiness can be analyzed from strategic, operational, and tactical levels. The first level, strategic, represents doctrine and regulations regarding airworthiness. The second, operational, is the focus of this effort, looking at the process of certifying aircraft in accordance with strategic doctrine. Lastly, tactical represents the individual program offices; this area of study is very large with limited data available. Being able to standardize practices across every program office would be extremely beneficial, but a complicated endeavor that greatly exceeds the bounds of this research effort. By performing an analysis on and identifying areas of improvement for AFLCMC's operational-level process, these recommendations will directly impact the tactical-level processes.

Assumptions/Limitations

1. AFLCMC/EZSA is responsible for the technical airworthiness assessment, not operational airworthiness; Thus, this research is centered on studying the airworthiness certification and assessment process, not the physical design or characteristics of specific aircraft.
2. Limited access to SMEs and data is mitigated through regular communication with experts, primarily from AFLCMC/EZSA.
3. Accurate documentation is assumed; however, observations are used to validate the quality of existing documentation. Part of the research effort is to validate and document the airworthiness process.

This effort is bounded by the thesis submission and graduation timeline for AFIT graduate programs. Findings from this research are presented with recommendations for future study in Chapters 4 and 6, respectively.

Implications

A model of the airworthiness assessment process will foremost benefit AFLMC/EZSA in two ways: the model will aid in identifying wasteful or inefficient practices, and will further aid in formalizing process documentation for standardization and training. As the Army and Navy transition to objective airworthiness assessments—discussed in *Military-Industrial Synchronization* (p. 27)—data from this research benefits their efforts as well.

Lastly, this research aims to study the degree to which the aircraft airworthiness assessment process can be applied to RLVs for use in flight re-qualification. The RLV field is a new domain for the Air Force and, if there is substantial overlap from aircraft airworthiness, there exists the potential for substantial cost and time savings by tailoring existing processes and practices, rather than creating a new framework.

Chapter Summary

In Chapter II, a literature review is presented with information on the history of aviation and airworthiness practices. This extends to the development of modern military airworthiness processes and organizational structure. Chapter III details the methodology used for the modeling and simulation effort, including design decisions and an outline for the Design of Experiments (DoE) conducted as the key research effort. Results from simulation are presented and examined in Chapter IV, in the form of a journal article submitted to the Journal of Defense Modeling and Simulation. An in-depth comparison of airworthiness and space mission assurance practices is presented in Chapter V in the form of a conference paper with recommendations for a robust, yet efficient RLV re-qualification process. The results of Chapter IV and V inform a number of recommendations offered in Chapter VI, which also presents the conclusions of the research effort and areas of future study.

II. Literature Review

Chapter Overview

This chapter serves to provide a background on airworthiness and build an understanding for the analysis that follows in later chapters. Existing information is presented across three facets of airworthiness: history, policy, and effectiveness. A history is collected primarily through online and print literature, and centered on understanding the history behind what is now the Federal Aviation Administration (FAA), international partnerships, and how airworthiness practices have evolved over the past century with the development of a civil air industry and military aviation. Policy documents were acquired through publicly-available Department of Defense (DoD) websites and coordination with AFLCMC/EZSA, the customer for this study.

Available literature on the effectiveness of the airworthiness process/methods is somewhat limited, with very little information available on military airworthiness (Purton & Kourousis, 2014). With such little documentation on airworthiness practices and their impacts, it is difficult to draw conclusions on the effectiveness of changes and best practices, which will be discussed throughout this chapter.

This chapter is organized by topic, based on the three focus areas previously mentioned. Further, the policy documents in *Levels of Governance* (p. 15), are displayed in a hierarchical order, with the highest-level of governance (DoD) first.

Definition of Key Terms.

Airworthiness is defined by the DoD as, "The property of an air system configuration to safely attain, sustain, and terminate flight in accordance with approved usage and limits" (2013, p. 10). This verbiage is very common among government doctrinal and regulatory publications, with the exception being that some publications replace the word "property" with "verified and documented capability" (U.S. Air Force, 2010b, p. 5). In the general sense, the term airworthiness is the capacity for an aircraft to fly in a manner that assures the integrity of the vessel and safety of those traveling within the aircraft (Tye, 1956).

Type is a term used when referencing aircraft ratings or certifications. A type certificate is used to describe the certification of an aircraft in a specific configuration, with a specified mission and operational environment. Any aircraft that matches the parameters of the certified type may operate under that certification, until such a time that modifications or expiration of service life necessitate recertification.

A *prime manufacturer* is the entity that enters into a contract with the Air Force—a hired entity in the general sense—to deliver a product/system. In many cases, manufacturers will sub-contract components of the end system, whether due to cost, manufacturing capability, or other reasons. The prime manufacturer, synonymous with manufacturer for the purpose of this report, maintains ultimate responsibility for the end item being delivered.

Airworthiness as a System

History of Airworthiness.

The origins of airworthiness are inherently tied to that of the airplane. As noted in the definition of airworthiness, its main reason for existence is safety. Although airworthiness, as a process, was not formally established until the 1920s (Federal Aviation Administration, 2017), safety was certainly a concern for the first flyers, including the Wright brothers, while they were designing and building the early airplanes. For example, it is intuitive to position the pilot (and passengers) in such a way that they are isolated from the aircraft's moving parts to the maximum extent possible to avoid injury. Figure 1 illustrates key milestones achieved from airworthiness and safety of flight points of view; it also includes the inception of various aviation organizations.

Throughout World War I (WWI)—and post-WWI—aviation was fraught with danger. Standards had not been developed and with few navigational aids beyond a compass, flying in poor weather conditions or landing at night made flying even more perilous. The 1920s brought about the predecessor to today's Air Traffic Controller (ATC) system: flagmen who would use signals to communicate with aircraft from the ground (Federal Aviation Administration, 2017). In 1926, an American aircraft received an airworthiness inspection for the first time, with formal regulations being developed in the early 1930s (Federal Aviation Administration, 1996). Since these initial years, the substantial increase in aircraft and a number of high-profile aviation incidents have largely shaped airworthiness into its current form.

Figure 1 also shows a number of military airworthiness milestones. While these are discussed further in *Military-Industrial Synchronization* (p. 27), the most consequential result of reform in the 1990s was the development of more objective airworthiness standards and assessments. Practices continue to evolve today, with important changes occurring as recently as 2010 with the creation of an independent certifying authority.

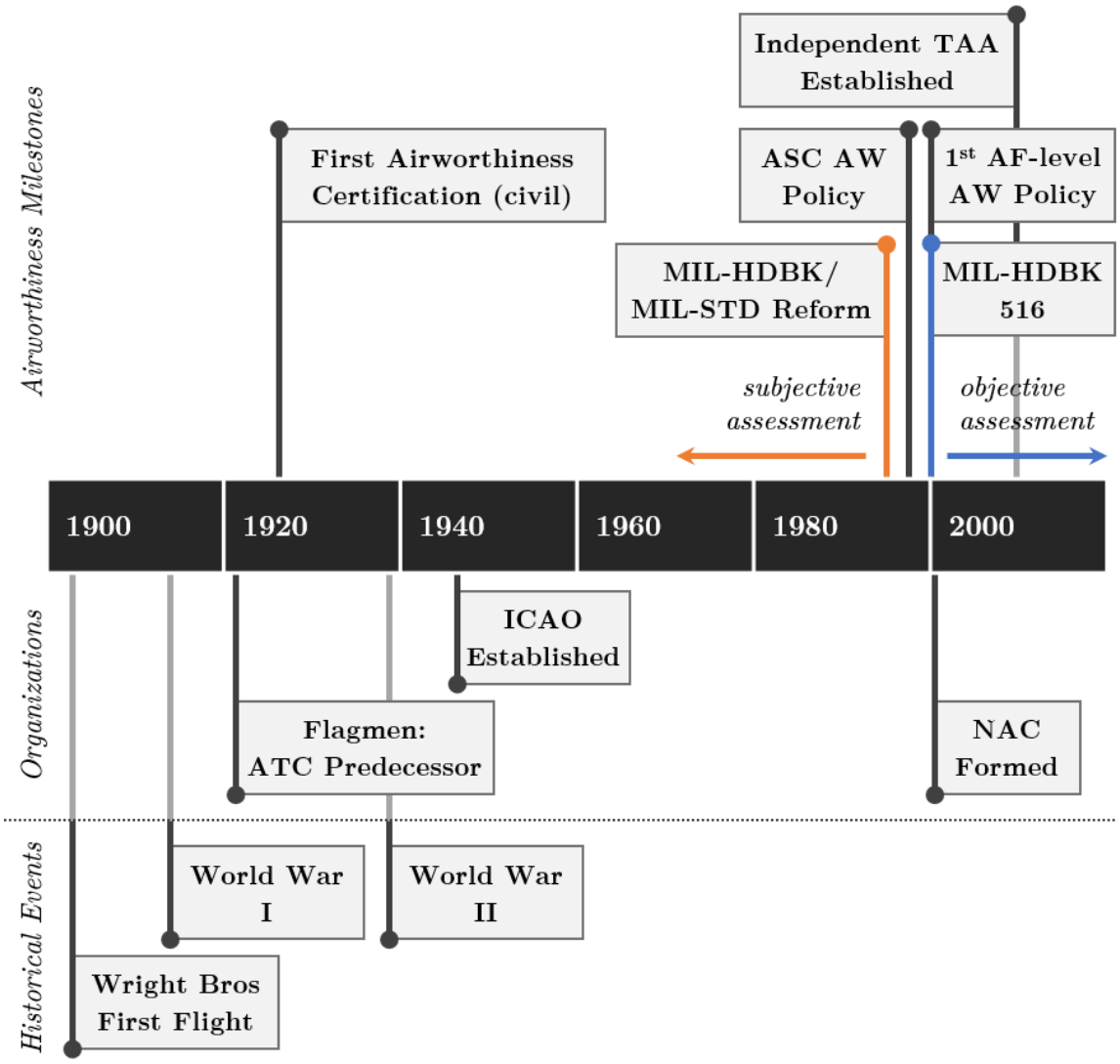


Figure 1. History of airworthiness and safety of flight milestones, including military airworthiness reform.

The formalization of aviation practices and a domestic aviation industry have allowed for data to be collected since the late 1930s (FAA U.S. Civil Airmen Statistics, 2011). This includes information on the number of aircraft and hours flown, as well as accidents and fatalities. In studying this data, trends can be observed with respect to the safety in design and operation of modern aircraft. Figure 2 shows that as the number of aircraft certificates (active aircraft) and flight hours have increased, the rate of accidents has decreased. The chart also shows that the number of aircraft and flight hours have largely leveled off since the year 2000.

It is possible that the significant reduction in incidents since the 1960s correlates with the institutionalization of commercial aviation regulations and a robust ATC network, however, no research was available to support this hypothesis. There are many factors involved in assessing airworthiness, some of which can be difficult to quantify. It is worth noting, however, that there were significant improvements to aircraft during the period of interest. In 1964, second generation aircraft were introduced with advanced auto pilot; in 1980, third generation aircraft included electronic displays and flight management systems; and in 1988, third generation aircraft introduced fly-by-wire and flight envelope protection—artificial limits on aircraft hardware which prevent the pilot from producing commands which exceed the aircraft's aerodynamic or structural limits (Airbus S.A.S., 2015). With regard to these generational improvements, steep changes would likely not be observable on Figure 2 because newer aircraft are introduced over a long period of time and not in a single year; other improvements to FAA regulations, ATC or any number of other factors would also influence the trend.

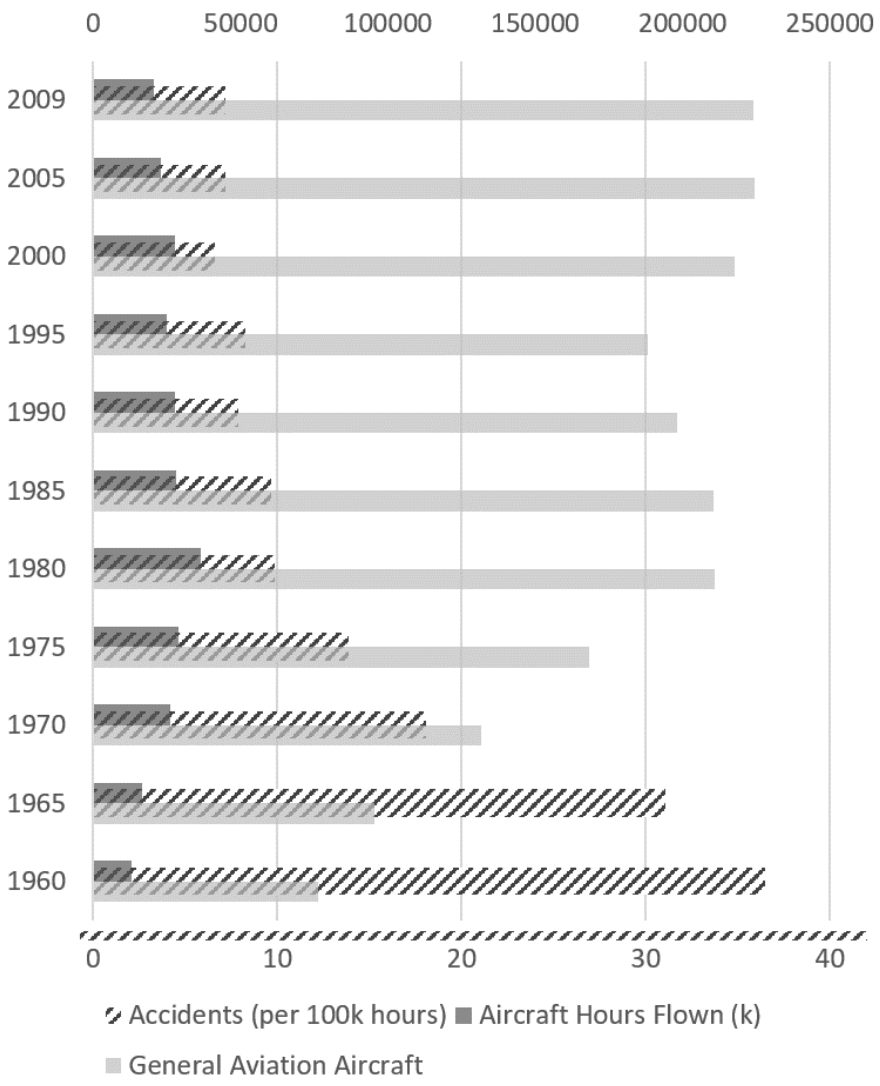


Figure 2. U.S. general aviation aircraft and accident statistics. Data from "National Transportation Statistics," by United States Department of Transportation, 2017, and "U.S. General Aviation Accidents, Fatalities, and Rates – 1938-2010," FAA U.S. Civil Airmen Statistics, 2011.

Today, the number of aircraft certified by the FAA has largely leveled off around 200,000[1] with greater than 20 million flight hours flown in 2015 (Federal Aviation Administration, 2015). Furthermore, those aircraft vary widely by type, ranging from rotorcraft, to turbojets, and lighter-than-air vehicles; thus, the regulations developed and enforced by the FAA must account for a large amount of variation. In addition to the relatively young and quickly growing drone and commercial space fields, regulations are updated and adapted as knowledge of aviation engineering and safety evolve. For instance, a recent change to 14 CFR Part 23 replaced detailed design requirements with performance-based requirements to better align with international standards (Federal Aviation Administration, 2016).

The public-facing landscape of United States military airworthiness has seen limited change in the past two decades; drastic policy changes which occurred in the 1990s shaped the field into what it is today (Perry, 1994; Shertzer, 1998). By no means does this suggest that the landscape is stagnant; it continues to evolve and adapt to the current needs of military aviation. Much of this advancement is centered on process improvement rather than technology or policy changes, highlighted by this focused study on the Air Force's airworthiness process.

[1] Includes all aircraft including, but not limited to, fixed wing, rotorcraft, gliders, and experimental aircraft.

Levels of Governance.

Ultimately, the authority on airworthiness is delegated to AFLCMC through a series of Air Force and DoD policies (Air Force Materiel Command, 2016). Doctrine which supports DoD airworthiness governance and regulations is provided in Figure 3. The primary regulatory policy and handbooks used as guidance for standards during the certification process are also shown (in darker color to differentiate them from policy documents).

At the highest level, DoD Directive (DoDD) 5030.61 (2013) directs the Military Departments (i.e. Army, Navy, and Air Force) to develop and maintain an airworthiness certification and assurance process. It further describes the requirements for the airworthiness authority—the certifying official for each service—and directs the use of MIL-HDBK-516 C (Airworthiness Certification Criteria) and MIL-STD-882 D (Standard Practice for System Safety), as shown in Figure 3 (Department of Defense, 2013). Finally, DoDD 5030.61 permits the adoption of certifications from the FAA, other Military Departments, and foreign military, provided the aircraft is to be used for the mission and in the environment as approved on the existing certification (Department of Defense, 2013). Foreign military airworthiness programs must also be assessed and determined to meet the appropriate level of rigor to be approved for reciprocity.

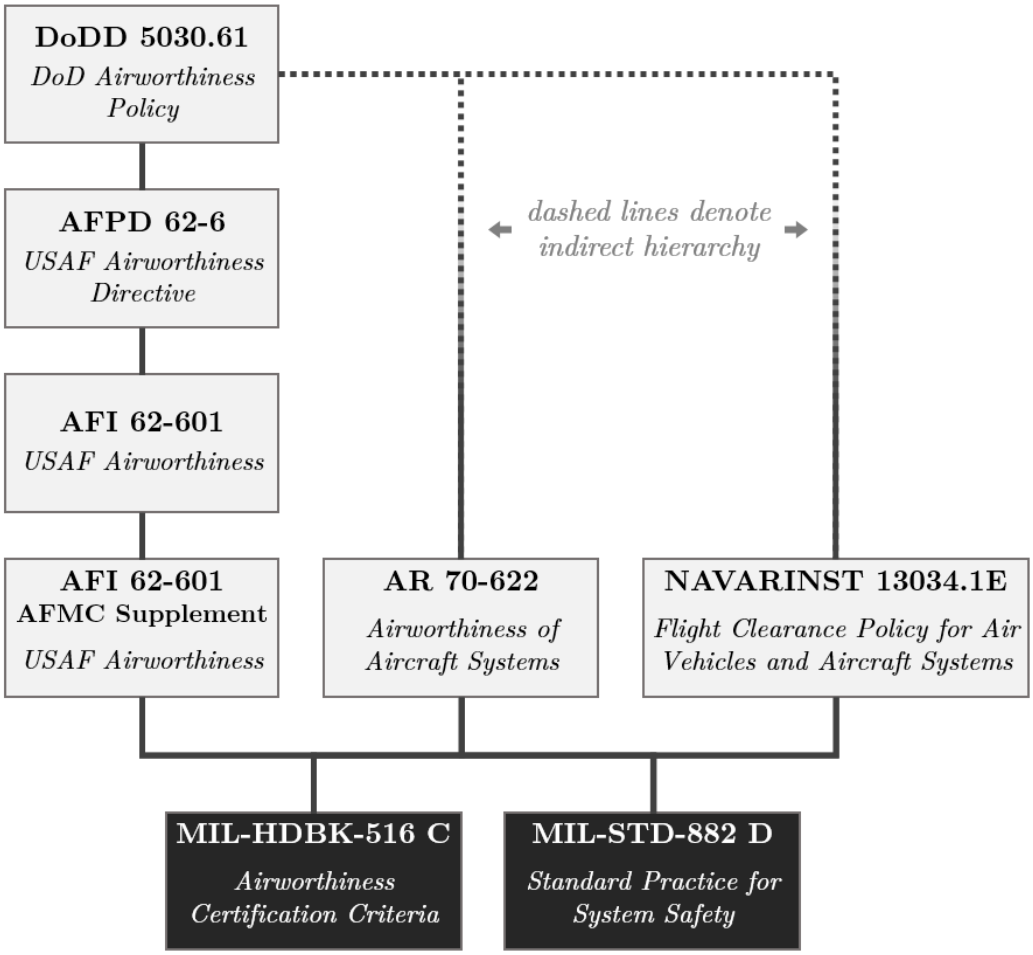


Figure 3. Hierarchy of DoD airworthiness governance by military branch and regulations.

Each Military Department is organized in a different way, which necessitates delegating responsibilities to lower levels. In the case of the Air Force, Air Force Policy Directive (AFPD) 62-6 (2010b) establishes the role of the Technical Airworthiness Authority (TAA)—the individual responsible for approving the flight operation of each system configuration and the environment in which the system may operate. To avoid the possibility of the TAA being influenced by program cost or schedule pressures, this individual no longer resides in the acquisition chain of command for the system. This

change occurred in the 2010 airworthiness process revision, prior to which the Program Manager (PM) for the aircraft was the airworthiness authority; the individual with arguably the most pressure to meet cost and schedule demands. AFPD 62-6 (2010b) also assigns the responsibilities of key stakeholders in the Air Force airworthiness process, including the PM, Air Force Material Command (AFMC), and the Major Commands (MAJCOMs).

The lowest echelon of doctrine for the Air Force, Air Force Instruction (AFI) 62-601 (2010a), elaborates on the responsibilities of the TAA and details the requirements for a system to receive certification. The ultimate certification that an Air Force air vehicle attains is the Military Type Certificate (MTC). After receiving an MTC, any individual aircraft—referenced by tail number—that is of the same *type* (i.e., configuration, mission, and environment) can receive a Military Certificate of Airworthiness (MCA), issued by the PM for that platform (U.S. Air Force, 2010a).

There are a number of special certifications including experimental certifications that can be issued when an MTC is not possible or appropriate. This is because MTCs can only be issued when a system reaches full compliance with airworthiness regulations—the highest level possible—with varying levels of risk acceptance. Ultimately, the TAA has the authority to grant flight approval with exemptions for non-compliant designs in two ways: a Military Experimental Flight Release (MEFR) for systems undergoing developmental flight test or a Military Restricted Flight Release (MRFR) may be issued for aircraft that meet significant noncompliance criteria (U.S. Air Force, 2010b). Both of these exemptions expire after a designated period and are meant to be temporary certifications.

Finally, the Air Force Materiel Command (AFMC) supplement to AFI 62-601 (2016) designates the director of the AFLCMC Engineering Directorate (AFLCMC/EN-EZ) as the TAA for the Air Force. AFLCMC/EZSA fills the role of assessing the technical aspects of airworthiness and is responsible for reviewing applications, and providing recommendations to the TAA, while operational assessments are conducted at the MAJCOM level. More specifically, AFLCMC/EZSA performs technical airworthiness assessments, ensuring that aircraft have sound engineering design and test flight data meets expectations and requirements for the design.

Manufacturing Oversight.

The evolution of airworthiness certification and assessment practices has been motivated by the significant growth of the aviation industry since the 1960s. The increase in aircraft and certificates being granted has forced change upon inspection practices for aircraft manufacturers and parts suppliers. Whereas it was feasible in the early days of flight for a government entity to inspect each part coming off an assembly line, modern aircraft—each generation more complex than the previous—and an increasing number of parts from overseas manufacturers means it is no longer practical to inspect or visit each manufacturer (Department of Transportation, 2008). Instead, manufacturing practices have become the focus of audits; ensuring quality and safety of in-house and imported parts are carefully monitored and documented by the prime manufacturer.

Despite these complexities, modern aircraft designs are vastly safer than those developed half a century ago because of safety advancements including carefully designed aerodynamic bodies, redundant systems, the introduction of computer-controlled

stabilization, and passenger restraints (Airbus S.A.S., 2015). Airbus conducted an examination of aircraft incident data from 1958-2014 using a ten-year moving average—long-term trends provide more reliable and valuable insight than year-to-year data—and found that third and fourth generation aircraft introduced in the 1980s, which brought about improvements including flight management systems and fly-by-wire technology, correlated with a dramatic decrease in the number of aircraft accidents per flight hour (Airbus S.A.S., 2015).

As design enhancements have improved the inherent safety of aircraft, the reliability of aircraft safety further depends on components performing as designed; thus, placing greater responsibility on manufacturers and suppliers (Airbus S.A.S., 2015; Song, Li, Song, & Zhang, 2014). This increased responsibility calls for manufacturers to maintain a higher level of control and awareness over their suppliers and sub-tier suppliers. The prime manufacturer is the ultimate responsible party for the component which they have paid to deliver, regardless of any other companies the prime manufacturer contracts with that may have contributed to the end item.

An incident involving the Boeing 787 Dreamliner in 2013 reinforces the importance of supplier control and comprehensive auditing practices. A battery used in the avionics system was sourced from a sub-tier supplier (two levels down from the prime manufacturer) and did not undergo integration testing with the production-standard battery charger. Undoubtedly, this lack of oversight resulted in the batteries overheating and smoking or catching fire (Song et al., 2014). Further, it is not uncommon for entire fuselage sections to be delivered to the manufacturer from suppliers with wiring already

completed, in a plug-and-play fashion (Department of Transportation, 2008); this distributed method of development necessitates more robust integration testing and oversight of suppliers at every level.

Subcontracting aircraft components is not inherently bad, as it allows manufacturers to reduce the number of disciplines being executed in-house and takes advantage of equipment and processes that are already in place by first-or-second-tier suppliers. Ideally, this results in reduced risk, cost savings for the prime manufacturer, and encourages small business growth. When subcontracting safety-critical items, however, it is imperative that manufacturers complete a holistic vetting process of potential suppliers, to include an examination of past performance, business approach, process quality, and documentation standards (Song et al., 2014). Boeing, in the case of the 787 Dreamliner, did not execute this level of scrutiny over suppliers or sub-tier suppliers (Song et al., 2014).

The number of suppliers in today's aviation industry is striking; one major manufacturer reviewed as part of the assessment had more than 4,000 supplier facilities in Fiscal Year (FY) 2008 (Department of Transportation, 2008). In 2008, the Department of Transportation's (DOT) Office of the Inspector General for Aviation Audits released a report detailing their findings of the FAA's oversight program for aircraft manufacturers and suppliers (Department of Transportation, 2008), which revealed that the:

1) FAA was not evaluating the quality or frequency of manufacturer oversight/audits of suppliers;

2) FAA was not executing sufficient audits of suppliers to evaluate manufacturer quality assurance programs;

> 3) FAA and manufacturers, together, were not doing enough to ensure suppliers were meeting standards and providing appropriate training.
>
> (2008, p. 5)

Regarding these findings, the inadequate monitoring practices and accountability of manufacturers put aircraft and lives at risk. As stated earlier, the technical design of aircraft is much safer today than even a few decades prior, but an aircraft is only as reliable as its weakest link. A critical component to aviation safety and airworthiness is the holistic system perspective, which includes verifying the quality—with respect to sourcing and manufacturing (including tools)—and interoperability of parts being installed.

It would be unreasonable and inefficient for the FAA to evaluate and monitor the manufacturer's oversight over each supplier facility (i.e., the FAA visiting each of these facilities in person to conduct audits). On average, the DOT assessment found that the FAA only inspected 0.01-1% of supplier facilities for the 5 major manufacturers studied during the period FY 2003-2006, where the manufacturer with more than 4,000 suppliers never had more than seven suppliers audited by the FAA (Department of Transportation, 2008).

Moreover, FAA inspectors are not provided access to the findings from supplier audits conducted by manufacturers (Department of Transportation, 2008). The ability to review these findings—with the added benefit of being able to study the manufacturer's audit and oversight process—would provide inspectors with a much larger dataset and allow inspectors to target their audits toward suppliers with a history of deficient performance and maintain a prioritized list of high-to-low-risk suppliers.

The report states:

> In assessing risks and determining how to target their inspection resources, inspectors do not consider the number of suppliers that manufacturers use and the level of responsibility suppliers have assumed. For example, at the time of our review, FAA had never inspected one critical parts supplier of major structural components, such as landing gear. Additionally, FAA does not maintain a complete universe of manufacturers' foreign, domestic, and sub-tier suppliers to identify inspection priorities.
> (Department of Transportation, 2008)

Information on the status of remediation strategies resulting from the 2008 report was not available, however, these findings highlight a critical flaw in aircraft safety and oversight at the lowest levels.

Oversight in Government Contracting.

Aircraft development is a very costly endeavor, so if a commercial aircraft will meet the needs of the military's intended mission, the DoD will use Commercial Derivative Aircraft (CDA) rather than paying to develop a new aircraft. In these cases, the aircraft may be used in its original civil purpose as certified by the FAA (e.g., a passenger jet), or may require modifications to suit the Military Department's mission and operating environment (e.g., retrofitting a Boeing 767 for use as a refueling tanker aircraft). As with the FAA's inspection program for civil aviation, the Department of Defense has implemented mechanisms for contractor oversight via the Defense Contract Management Agency (DCMA) (Defense Contract Management Agency, 2017a). The authority for DCMA personnel is delegated from the Federal Acquisition Regulation (FAR), which details Contract Administration Services (CAS) responsibilities.

FAR (2005) Subpart 42.302 (a) states the following:

> (38) Ensure contractor compliance with contractual quality assurance requirements.
> (39) Ensure contractor compliance with contractual safety requirements.
> (Department of Defense, 2005)

One of the major deficiencies noted in 2008 DOT report on FAA inspection practices was that inspections were not prioritized based on performance or known problem areas. DCMA-INST 8210.2 (2017a) Section 3.4.1 mandates monthly inspection audits of contractors, and allows more frequent audits in areas of poor performance. DCMA also has a dedicated office for the development and implementation of standards for inspection practices, ensuring consistency in inspections over time. In this aspect, DCMA appears to have a more efficient and rigorous inspection practice than the FAA.

When discussing Safety of Flight (SOF), or components critical to the integrity of the aircraft and passenger safety, sound manufacturing processes are imperative. As with the FAA inspections, it is not possible to maintain persistent surveillance over every supplier. DCMA has adapted and shifted focus from individual product inspection—with a previous requirement of 100% inspection—to inspecting the manufacturing processes, risk management program, and holding contractors to a higher level of accountability (Defense Contract Management Agency, 2017b). In terms of root cause analysis, a defect in a part is not caused by itself, but rather some action upstream in the process.

Thus, the goal of DCMA analysis is to find and correct steps in the manufacturing process that could jeopardize passenger safety; and to prevent defects from the outset. The Air Force Airworthiness Office has access to information published by DCMA to vet unknown or less-familiar suppliers. This system allows the Air Force to consider other

options if a potential supplier has serious open deficiencies, at least until corrective action is taken. The importance of supplier and manufacturing quality, and its influence on aircraft safety, cannot be understated, and the Air Force—in partnership with DCMA—has proven through its actions that it understands the criticality in performing due diligence in assessing and monitoring contractors and subcontractors.

Global Synchronization

The late 1940s signaled a shift to unify operations among international partners, enabling greater standardization of products and practices—and thereby, increasing efficiency (Provisional International Civil Aviation Organization, 1946). The largest such body, International Organization of Standards (ISO), was established in 1946 as a partnership of European organizations, and later expanded to become a global leader for standards across all industries. Since 1947, with the ratification of the International Civil Aviation Organization (ICAO), the members of the United Nations (UN) have worked together to develop aviation standards that reach across borders (International Civil Aviation Organization, n.d.). ICAO set forth regulations for and began issuing international airworthiness ratings in 1951, requiring passenger-carrying aircraft to comply in a unified fashion (Provisional International Civil Aviation Organization, 1946). This global partnership has allowed regional coalitions including the European Aviation Safety Agency (EASA), the FAA, and others to collaborate in pursuit of safer civil aviation; ICAO regulations, however, do not have authority over military aviation (Purton & Kourousis, 2014). Figure 4 illustrates the relationships between international and domestic entities, detailed further in the proceeding paragraphs.

Figure 4 serves in part to convey the complexities associated with the numerous international partnerships and organizations. In addition to ICAO, the United States is party to a number of additional international aviation councils and organizations, including most notably: the North Atlantic Treaty Organization (NATO) Airworthiness Working Group (AwWG), which includes all NATO member states; and the Air and Space Interoperability Council (ASIC) focused on interoperability between the United States and four of its closest allies (i.e. United Kingdom, Australia, New Zealand, and Canada) (Air and Space Interoperability Council, n.d.).

The European Defence Agency (EDA) Military Airworthiness Authorities (MAWA) Forum is another large organization, and although the United States is not a member, it bears mentioning (the United Kingdom, is the only member from ASIC which is also part of MAWA). Collectively, MAWA, ICAO, and NATO AwWG form a trifecta of sorts for international airworthiness standards—from the perspective of the United States and its Western allies (Purton & Kourousis, 2014). The three operate in harmony, with the adoption of standards from one another and the pursuit of enabling mutual recognition (reciprocity of airworthiness certifications from another organization). For example, NATO AwWG and ASIC are focused on developing standards while EDA's MAWA is focused on policy and regulation.

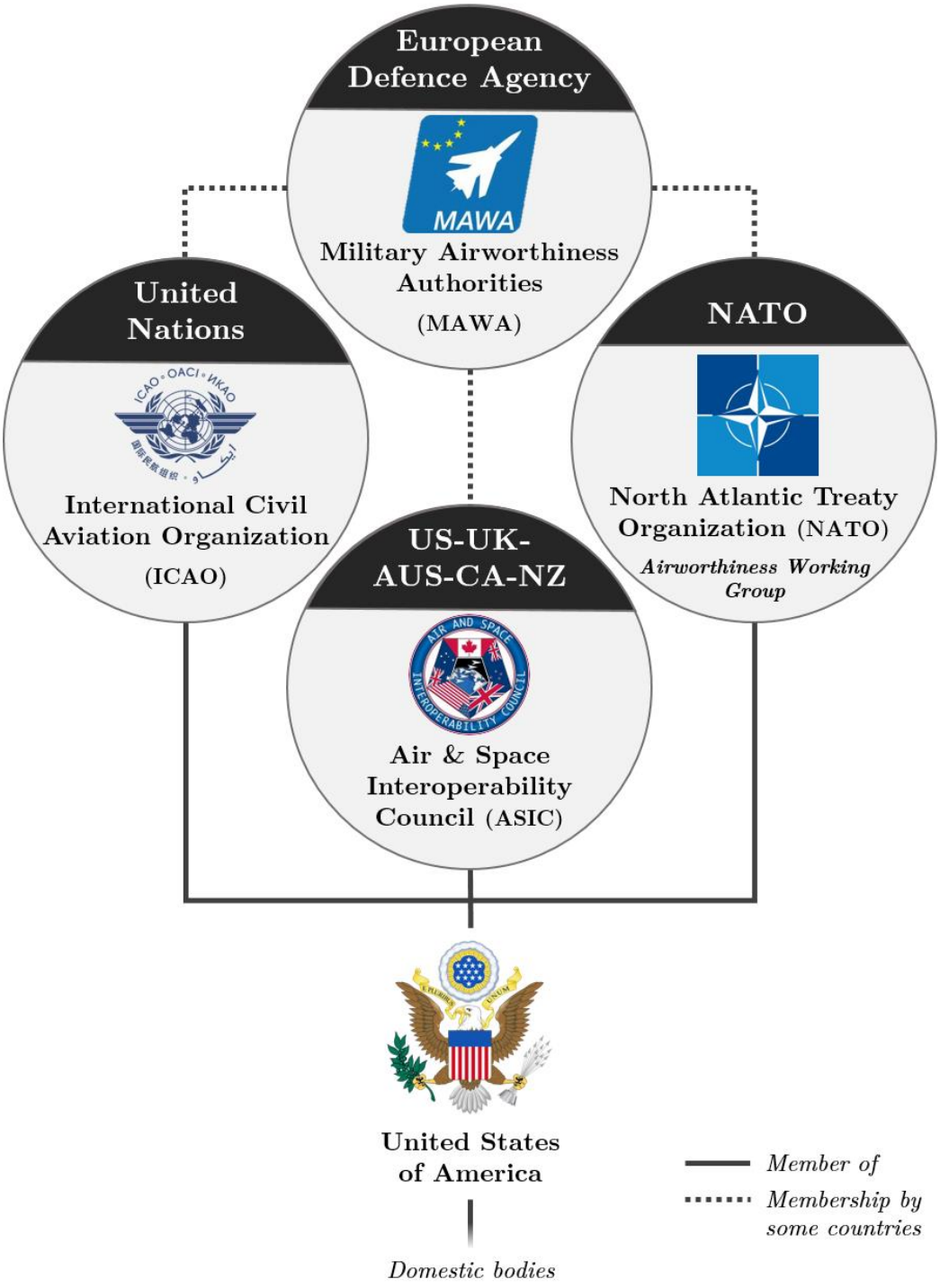


Figure 4. Organization and membership of United States with international bodies on airworthiness standards.

Military-Industrial Synchronization.

In the decades after WWII, the United States military focused more on quality, and operated under the assumption that commercial products were not good enough; many components including common hand tools were made specifically, and unnecessarily for military purposes (Shertzer, 1998). The 1990s ushered in a new approach to airworthiness for the Military Departments, continuing into the 2000s. Industry observed and struggled with over-constrained military specifications (MIL-SPEC) being applied across the board unnecessarily, rather than performance-based requirements on specific programs. Then Secretary of Defense, William J. Perry (1994) wrote a memo to the Military Department chiefs and DoD leadership, directing the use of commercial aviation standards, where applicable, rather than the numerous military handbooks and standards that had accumulated. Perry, recognizing the unique mission sets of the military, directed that military specifications were only to be developed as a last resort to fill gaps where commercial standards did not exist (Perry, 1994).

This paradigm shift had two immediate effects: a) it introduced confusion initially as the overly restrictive MIL-SPECs were cancelled altogether, rather than being loosened, requiring unprecedented cooperation between aircraft manufacturers and the military; and b) program offices had to select individual performance requirements for their system rather than directing the contractor to reference a handbook (Shertzer, 1998). The removal of existing MIL-SPECs took with it engineering data that had commonly been used—without replacement guidance indicated, military programs had to quickly find other sources for standards and best practices to develop contract requirements. Although this

acquisition reform occurred suddenly with the release of Secretary Perry's memo, it should not have come as a shock to the military. Other directives had been previously released dating back to 1984 mandating the use of commercial products when possible, as well as the use of commercial standards over military-specific standards and specifications where duplication existed (Shertzer, 1998).

Since the 1994 mandate, the Air Force has worked to align more closely with civil aviation (FAA) airworthiness standards over DoD components, citing such an alignment is the standard for military aviation worldwide (Purton & Kourousis, 2014). Most recently, the Air Force overhauled their airworthiness assessment process in 2010 and modeled it after the FAA, with one major change being the implementation of a program-independent TAA. Additionally, DoD quality control standards have shifted from in-house programs to the acceptance of international standards such as ISO-9000 series (a collection of quality management standards) and NATO standardization agreements, the latter of which are military standardization treaties (Shertzer, 1998). The implementation of ISO standards, specifically, took place to eliminate redundancy within government and industry standards, synchronize government and commercial practices, and most importantly, provide a renewed focus on quality assurance within the DoD (Beckerdite, 1992).

As with international organizations, maintaining synchronization between the civil and defense-focused entities within the United States is important. An independent charter of aviation leaders was established to facilitate such a relationship in the early 2000s. As shown in Figure 5, the National Airworthiness Council (NAC) is composed of the three Military Departments, the United States Coast Guard, the FAA, and the National

Aeronautics and Space Administration (NASA) (Joint Aeronautical Commanders Group, 2014). The core principles of NAC—which meets on a monthly basis—include reducing rework (or duplicative processes) in airworthiness certification, identifying and sharing commonalities, and working together to develop new policies for emerging technologies (Joint Aeronautical Commanders Group, 2014).



Figure 5. Organization of domestic bodies on airworthiness standards.

The other Military Departments follow a similar format to the Air Force's airworthiness policy. One key similarity is the independence of the airworthiness authority from the programmatic chain of command (e.g., PM) (Merkel, 2017). As mentioned earlier, this is important in ensuring certification is not influenced by program cost or schedule overruns. Variants exist, however, such as the Air Force mandating the use of MIL-HDBK-516 C for developing airworthiness criteria (Department of Defense, 2013); the Army and Navy regulations—AR 70-62 (2016) and NAVAIRINST 13034.1F (2016), respectively—are less specific and define the requirements as military, commercial, and company specifications and standards, and military handbooks.

Lack of a definitive criterion source leaves much to the interpretation of the certifying official or SME responsible for reviewing a particular aircraft section (e.g., engine, wheels, safety equipment). Furthermore, a non-standards-based approach results in inconsistency and a lack of continuity; the departure of a SME could result in their work being challenged if documentation is insufficient, or leave others unsure of how to proceed for a work in progress. Individuals from AFLCMC/EZSA were instrumental in the writing of the first iteration of MIL-HDBK-516, which was published in 2002, and was an evolution of existing Air Force documents used to assess aircraft compliance for flight releases. Initially, MIL-HDBK-516 was simple and consisted only of a list of criteria. In the revisions since, and including the current iteration 516 C, every service has been heavily involved in the writing of a more robust handbook which has three main components: criterion, standards, and

methods of compliance, the latter of which is a critical addition and provides solutions for ensuring component compliance (R. FitzHarris, personal communication, Aug 2, 2017)[2].

Although the Air Force initiated the movement to, and is the first to fully adopt, use of objective airworthiness standards, the other military departments have also encouraged less-subjective assessments and are beginning to use MIL-HDBK-516 C. To further encourage this unification, there are numerous sections which have different criterion, standards, or methods for each service—for cases where a consensus cannot be reached on a common standard. The implementation of these standards still requires assessments from a SME, but seeks to reduce subjectivity by providing a more systematic, checklist-type approach, enabling better continuity and a more confident airworthiness assessment.

The movement to institutionalize and create a consistent and robust airworthiness certification process is characterized by a global synchronization of standards and methods for aviation, both civil and military.

Airworthiness Moving Forward

New research in the field of airworthiness is sparse. Much of the literature found is published from China and focuses on their civil/military aviation programs (Jilian, Kangming, & Lintong, 2011; Kun & Cunxi, 2011; Shijun, 2014; Tan, Li, Miao, & Lv, 2014). Parallels can be drawn, although the applicability of these publications to the US military is limited due to differences in business and operational environments, systems,

[2] Robert FitzHarris is the Non-DoD Military Aircraft Lead for AFLCMC/EZSA and a subject matter expert in the field of airworthiness. His work extends to the development of MIL-HDBK-516 and other airworthiness practices since the 1990s.

and standards. Searches for domestic aviation research (excluding technical aircraft design) most often produced results related to air traffic control reform or safety, generally related to manufacturing or maintenance (Department of Transportation, 2008; Golaszewski, 2002; United States Government Accountatbility Office, 2016). Prior discussion has shown that safe manufacturing practices clearly have an impact on airworthiness and passenger safety, and will likely remain at the forefront of airworthiness process improvement in the future.

The need for a military airworthiness system stems from risk-based assessment. Military aviation accepts greater risk than civil aviation, which requires different rules. One potential risk is a lack of standardized processes. Purton and Kourousis state, "Inconsistent US Service policies have resulted in confusion," (2014, p. 564). As discussed in the section Military-Industrial Synchronization, the services have worked toward unifying frameworks and using common standards in their airworthiness assessments. In part, this shift is based on the understanding that, in the past, the airworthiness field was very subjective and that a more objective assessment method should be developed. As the field of airworthiness continues to evolve, standardization and more robust risk management principles are key toward ensuring the safety of aircraft and aircrew.

Summary

The idea of airworthiness and ensuring aircraft and passenger safety stretches from the inception of aviation and continues to progress today. The DoD continues to push fiscal responsibility and a standards-based approach to acquisition programs with revised policies governing the use of military handbooks and standards. The Air Force has helped lead the effort of reducing subjectivity in airworthiness assessments, resulting in more robust, efficient, and confident airworthiness certifications of military aircraft.

III. Methodology

Chapter Overview

The primary focus of this research effort is to provide an independent look at the airworthiness assessment process to identify inefficiencies and opportunities for improvement. This chapter explains the steps required to complete the research effort and satisfy the objective of developing and validating a process model which can answer the research questions presented in Chapter I. This chapter also provides background on process modeling and simulation studies, including best practices.

Process Modeling Background

It is important to understand that the goal of a model is to mimic or represent, but not replicate, reality. George E. P. Box (1976) wrote, "all models are wrong, but some are useful." As a model becomes more representative of reality, its complexity also increases significantly. The goal then, is to create a model that is useful to the customer in both detail and simplicity. It is important to integrate feedback iterations into the modeling effort as well (Rosemann, 2006). Regular conversation and progress checks with the customer help the designer understand if they are meeting the customer's needs and expectations.

A model can be used for improving a process, but also to illustrate an existing process. For example, a model can be especially useful when a new employee is learning a process, (Nolte, Bernhard, Recker, Pittke, & Mendling, 2016). The challenge then becomes to ensure that the model stays up-to-date and associated documentation always reflects the

current state of the process. Thus, the process models developed for this research are used for analytical-based CPI and to fill a documentation gap for EZSA and will enable faster and more informative training for new employees (i.e., those not familiar with the airworthiness assessment process).

This study has a shared goal with EZSA as they seek to minimize subjectivity in their assessments. In order to provide an objective assessment, quantitative data is used as much as possible. A formal process methodology is followed to ensure rigorous modeling and complete analysis are accomplished.

Process Methodology

The basic sequence for a modeling and simulation effort is well-defined, and follows the Systems Engineering (SE) process flow (commonly represented as the SE 'V'), which decomposes the problem into component pieces and reconstructs it through verification, validation, and analysis to confirm results (Buede & Miller, 2016, p. 10). Figure 6 depicts the notional steps with normal and feedback paths indicated, which has been tailored from Banks, Carson, Nelson, and Nicol (2010) for this research effort.

This methodology can be broken down into 10 steps: 1, Problem Formulation; 2, Defining Objectives; 3, Data Collection; 4, Model Conceptualization; 5, Model Translation; 6, Verification; 7, Validation; 8, Experimental Design; 9, Analysis; and 10, Documentation and Implementation. Steps 1 and 2 are primarily conducted through the execution of Chapters I and II, this chapter describes the activities in steps 3–5, Chapter IV presents the execution of steps 6-9, and Chapter VI offers recommendations for implementation (step 10). Each process step, as illustrated, is described in further detail.

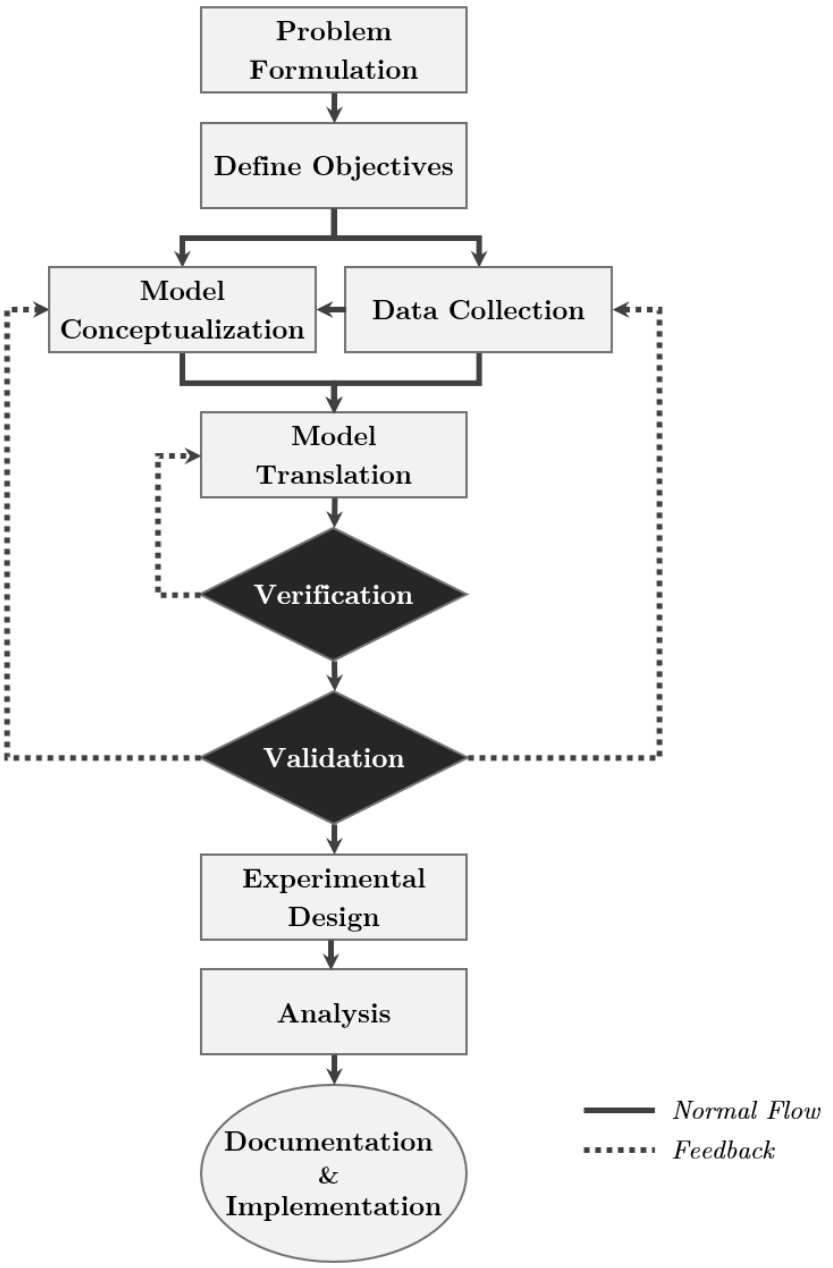


Figure 6. Modeling and simulation notional process flow diagram. Adapted from "Steps in a simulation study," by Banks, Carson, Nelson, & Nicol (2010), p. 17.

Step 1 – Problem Formulation.

The *problem formulation* step is that which is detailed in Chapter I: understanding the context of the issue at hand and defining boundaries for the research effort. In this case, the research effort is aimed towards formalizing and improving the airworthiness assessment process. Specifically, this applies to the technical airworthiness assessment conducted by AFLCMC/EZSA. This step is critical to avoiding what is known as 'Type III Error,' studying the wrong problem.

Step 2 – Defining Objectives.

Defining objectives takes place in Chapter I. Research goals—the primary being an independent assessment of the airworthiness assessment process to provide insight on efficiency—are used to motivate research questions. Answering these questions is key to knowing when the goal of the research effort has been achieved.

Step 3 – Data Collection.

Data collection should begin as early as possible once the problem and objectives have been defined. A useful model cannot exist or be developed without supporting information such as process documentation or recorded metrics and data. This information can take many forms and may be quantitative or qualitative, and collected through various means. Once the model is built, the data will help in developing distributions for process times, resource availability, and error rates.

The data for the existing airworthiness assessment process can be broken down into two main categories: process flow information and process data. The former came from two sources: recording the observed process and existing documentation. The information

from these two sources is evaluated to develop the most accurate and complete model. Process data consists of existing EZSA data recorded for process times, resource quantities, and artifact attributes. When a large amount of data is presented, it must be limited to items critical to understanding the process to ensure the model reflects an appropriate level of depth such that it is detailed enough to be useful, but also at a high-enough level that it is usable (Nolte et al., 2016). In this case, limited data is available, and standard project tracking timelines are used as a primary input. The Simio model has a physical construct and a logical construct. These metrics play a vital role in the latter, when assigning numerical values to the duration of each step.

It is imperative that process flow information be analyzed from several perspectives. There is qualitative vs. quantitative, as well as communication flow vs. activity flow (as described in Process Modeling Background). An ideal model would be based purely on quantitative information, if available, because there is no room for subjectivity. In this study, because limited quantitative information is available, it is not enough to construct a complete model. Qualitative input, mostly from SME interaction, supplements the quantitative data.

First, existing documentation is collected from AFLCMC/EZSA and studied. A preliminary block diagram process is developed with a list of associated artifacts resulting from each step. This first diagram is completed using pen and paper to facilitate quicker editing and brainstorming for process flow, and is shown in Figure 7. Every discrete step in the airworthiness assessment process should result in the creation of some artifact or information that feeds into a future step. If this is not the case, that is a key indicator

that there is likely waste or a non-value-added interaction in the system (Morgan & Liker, 2006, p. 74).

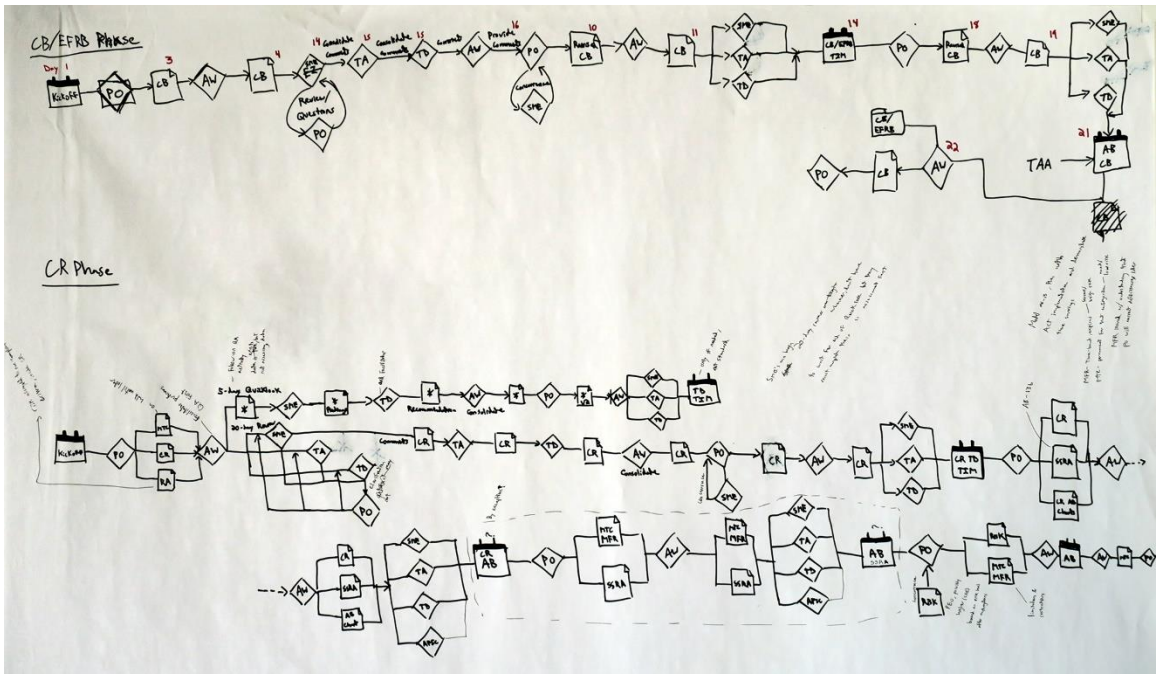


Figure 7. Hand-drawn sketch of airworthiness phases 2 and 3 based off of existing documentation with notes from EZSA expert input.

Step 4 – Model Conceptualization.

The goal of the *model conceptualization* effort is to gain a holistic understanding of the process being modeled and to develop a plan for the technical modeling effort in Step 5. Note that in Figure 6, an arrow is indicated from data collection to model conceptualization; as more data is collected, the conceptual model continues to evolve.

Model conceptualization is an iterative process. It begins early in the overall effort, especially in tandem with data and information collection. The conceptual model is the

perceived understanding of the process from the perspective of the researcher, and is constantly evolving as more information becomes available; it may be a hand-drawn sketch, computerized drawing, or remain unwritten. For speed and ease of use, it is usually beneficial to develop an initial 'sketch' of the system of interest outside of the primary modeling program, which can be used to more quickly build a more detailed model in Step 5 with reduced risk of re-work.

Developing a plan for the design and implementation of a model is a critical activity; doing so results in time savings and reduced rework later in the process. A useful way to visualize the model construct is through the use of Unified Modeling Language (UML) diagrams. UML standards provide the foundation for numerous 'views' which aid in planning or presenting a process. This a common way of illustrating a process, and represents the steps required to complete such a process. Kock, Verville, Danesh-Pajou, and DeLuca (2009) cite the importance of incorporating communication flow in addition to activity flow. For example, knowing how many times a document changes hands, and if any of the individuals who 'touch' the document actually *do* anything with it, is critical to identifying wasteful interactions. Part of the lean methodology is minimizing unnecessary movement and over-processing, ensuring each activity and interaction has a purpose (Liker, 2004).

The modeling conceptualization for this research effort consists of combing the following: an activity diagram, showing the basic steps in the airworthiness assessment process, and a communication flow diagram, to understand how information is passed between steps. A modified activity diagram allows for this mapping, showing how an

output from one step can feed the input of the next step. See Chapter IV for detailed descriptions and figures of the process model.

Step 5 – Model Translation.

Model translation is the act of using the conceptual model, which evolves as it is informed with more data, to build the simulation model (i.e., used for experimentation). If the conceptual model is accurate, the model translation effort should be significantly less challenging. With a sufficiently detailed and correct model conceptualization, the key building blocks for the model are already identified, including their relationships to one another. In essence, the model conceptualization is defining the physical, front-end design of the model, while the model translation implements that design in a chosen software tool and incorporates logical, back-end elements. In this case, the modeling tool is Simio, with logical elements being the addition of resource constraints and variable process times, as described in *Simio* Simulation (p. 43).

Steps 6 & 7 – Verification and Validation.

The *verification* and *validation* steps are highly interconnected. Although they are two distinct events, these critical steps ensure, respectively: the model operates as intended by the designer, and the model reflects the existing real-life process. The feedback loops on Figure 6 indicate where verification and validation (V&V for short) activities link to earlier steps. Verification involves primarily the model designer, examining the model and verifying that it runs as expected. Validation involves going back to the customer and asking if the model matches how the process occurs. Corrections or adjustments are then made to the model, and the V&V cycle repeats as necessary until the designer and

customer are both satisfied. Completion of V&V activities sets the baseline configuration of the model.

Step 8 – Experimental Design.

Once the model has been built to a sufficient level of fidelity and validated by the customer, *experimental design* begins. This step is the setup for analysis conducted in Step 9, and includes identifying the objective of the simulation effort and understanding what model outputs are of interest. Described in more detail in *Experiments* (p. 48), this step is where decisions are made for the variables to be used in the simulation and which responses will be recorded for analysis.

Step 9 – Analysis.

In *analysis*, changes to inputs or activities in the process model are studied based on their impact to the result and how new results compare to the baseline configuration. This is the essence of the simulation effort. The key question during this phase is, "Can the process being modeled be improved without hampering technical rigor?"—which serves to answer the research objectives and questions identified in Chapter I. The analysis phase may involve a great deal of deliberate and calculated trialing through DoE.

Step 10 – Documentation and Implementation.

The final step is *documentation and implementation*. The results of the analytical phase are organized and documented, and recommendations are presented for the real-life process. Due to the short timeline for this thesis, recommendations are presented and implementation will take place independent from the research effort at a future time.

Simio Simulation

The key activity for this research effort is based in simulation: varying inputs and process variables of the model to study their effects on the output. Simio is selected as the simulation software for two main reasons: first, familiarity for the research team; two, capabilities focused toward process flow design and modeling.

Familiarity is gained through OPER561, Discrete Event Simulation, and personal knowledge through use of the program, as well as the Simio Reference Guide (2018) and Rapid Modeling Solutions: Introduction to Simulation and Simio (Pegden & Sturrock, 2014). Next, important Simio terminology is introduced.

Entity: Represents an object or person that move through the model system, in this case artifacts (i.e., AWP, AB, and CR), which are created and destroyed inside the model. Entities can belong to a parent; the model first creates a Project entity, which carries each artifact through their respective phase.

Resource: Represents an object or person who is required for processing at a server. Resources can be assigned work schedules, though this is not used for this model. A resource type (e.g., Facilitator, SME, TA, TD) has multiple units; for example, there are 49 SMEs, meaning 49 resource units available.

Property: A value, generally used as an input parameter, that can be changed for individual runs or experiments. These represent the variables for scenarios and are the factors for our DoE.

Server: Where a process takes place within the system, each server representing a discrete step in the overarching process. Servers are assigned a processing time and

can require a number of resources to process the entity as it enters the server. Servers can have add-on processes, which allow for advanced logic to be used for processing inside a server.

Queue: When a server has already reached its processing capacity, entities wait in a queue until room is available in the server for the next entity.

Path: Connects servers and can move an entity instantaneously or over a set amount of time. Paths are used to represent program office processing time for this model.

Run: Running the simulation in the facility view is a way of viewing the model running with graphics enabled to verify that entities are flowing as desired. Properties can be adjusted and random number seed manually selected to troubleshoot issues that may be encountered during an experiment. This view also displays a trace of every action taken by each entity in the system.

Experiment: The heart of the simulation effort. Experiments run without any graphical display for efficiency of computing resources. Users assign values to properties and choose which output values they are interested in recording.

Scenario: Within an experiment, users may create multiple scenarios. Each scenario can have independent property values, allowing for a design of experiments to compare how changing an input value affects the output.

Replication: Each scenario may have multiple replications (this model uses 30), with each replication using a different random number seed. The proceeding section, Random Number Generation, provides an explanation for the way random numbers are used across scenarios and replications.

Random Number Generation.

A pseudorandom number, as calculated by modern computers, is simply a mathematical formula and is based on a pre-programmed seed number. This means every time the simulation is run, the formula starts with the same number and, as long as no parameters are changed, the same results will be produced on every time (also known as synchronization) (Banks et al., 2010). Random number streams can be assigned wherever a random number is generated (from a distribution) in order to maintain repeatability in simulation runs but create variability between steps, allowing the user to see whether changes to the model have an impact on the results without worrying about variations in the random number. Random number *streams* allow you to choose a different seed for different processes or steps in your model to maintain independence. Simio (2016), in particular, employs a Mersenne Twister pseudorandom number generator, the most common algorithm employed and today's industry standard (Marsland, 2011).

The importance of this idea with respect to the model in this study is in the experiments. As the researcher performs various experiments and changes parameters, consistency in the random numbers across experiments is critical to understand how the model is impacted by input variability. For example, replications one through 'n' in scenarios one and two will always have the same random number seed to provide random variation within scenarios (internal) but maintain consistency of randomness across scenarios (external).

Selecting Distributions.

The only metric data available for model development is the project tracker, which provided notional times for each step in the process. This provided the mode value but no other information for the development of a distribution. With limited data availability, a triangular distribution is used with project tracker data for the mode and a 10-percent width on each side. If more data had been available, the metrics from the existing process would be aggregated and fitted to a hypothetical distribution with accompanying parameters (i.e., mean and standard deviation). For the arrival rate of projects into the system, an exponential distribution is chosen, as it most-closely approximates arrival rates in many systems.

Model Translation Detail.

The first step in building the Simio model is translating each step in the process model diagrams to a server in Simio and creating paths between them to represent time spent at the program office. In Simio, the entities—items that move through the system—must be created and destroyed through the use of a source and sink. As mentioned, a parent project entity can flow through the entire system and pick up member entities, in this case each artifact is carried through its respective phase. For example, this action through phase one is shown in Figure 8; the Project and AWP entities are both created and enter a combiner, where the project entity becomes the parent of the AWP entity. This new, combined entity moves through phase one and then enters a separator. At the output of the separator, the AWP entity is destroyed, its data is recorded, and the project entity moves to phase two to be combined with an AB entity, and later phase three where the CR entity is created.

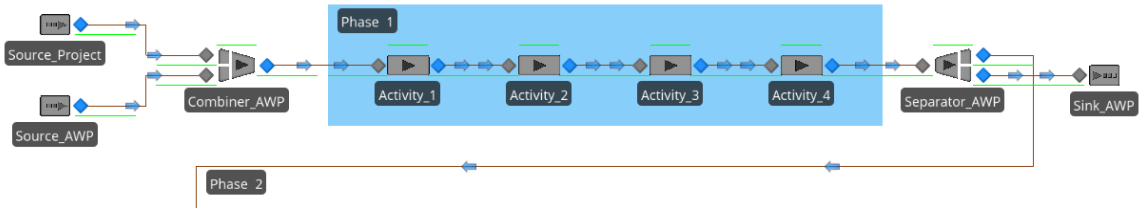


Figure 8. Illustration of entity flow through Phase 1 of the model.

After phase two, a flight test activity (server) is created. Although this time is not part of our scope of interest, this server is used with a wide triangular distribution to vary the rate at which entities move from phase two into phase three; this is representative of programs that can take anywhere from a few months to years to gather the necessary flight test data between phases two and three.

Next, resources are created to represent each of the key actors in the system. These resources are introduced in Chapter IV, but each one is required at various servers in the system. Several of the steps in the process flow diagram show sub-processes. These are implemented through add-on processes in Simio to model individuals passing an artifact to each other within a single step. For these instances, resources are not seized for the entire processing time of the server, but only for the sub-steps for which they are required, implemented through logic in the add-on process.

Rather than assigning process times to each server directly, properties are used to allow for changing process times in the experiment. This is important for testing ACT implementation and seeing how removing now-unnecessary interactions would affect model

performance. The number of units assigned to each resource is also assigned this way, to allow resource sensitivity analysis to be conducted through experimentation.

Experiments.

In Simio, an experiment allows the user to create numerous scenarios—use cases with varying parameters—to study how the outputs of each scenario differ or exhibit similarities as variables change. These variables can range from changing the arrival rate, processing times, or adding or removing workers, to name a few. As previously mentioned, the focus of the results is on comparing results between various experiments rather than the raw values produced by the simulation. A DoE approach will be used to vary a number of factors.

With a large number of variables available from the model, factors are carefully chosen to best study process time and resource sensitivity. The two main experiments are studying arrival rate and resource utilization, both before and after ACT implementation. Within each experiment are a number of treatments—known as scenarios within Simio—where the project arrival rate or resource availability is modified to monitor output response. The full experimental design is presented in Table 1. Lists of items in brackets indicate multiple treatments but have been grouped by experiment type on the same row for ease of understanding (e.g., For row two: 12-day arrival rate for the current process, 12-day arrival rate for the ACT process, 14-day arrival rate for the current process, and so on).

Table 1. Treatments (Scenarios) used for model experimentation.

Factors / Treatment	Facilitator [%]	PO [%]	SME [%]
Baseline Configuration (Control)	Current Process	14 Days	Standard
Varied Arrival Rate	[Current, ACT] Process	[12, 14, 16, 18] Days	Standard
Individual Resource Reduction	[Current, ACT] Process	14 Days	80% Availability [Facilitator, SME, TA, TD]
Individual Resource Increase	[Current, ACT] Process	14 Days	120% Availability [Facilitator, SME, TA, TD]
Global Resource Increase	[Current, ACT] Process	14 Days	120% Availability All Resources

The development of scenarios in Simio is also part of the experimental design process, as outlined earlier in Step 8 of the methodology. A total of 27 scenarios are presented Table 1. Each scenario is run for 30 replications each. Recall that each replication in Simio uses a different random number seed. This is akin to a Monte Carlo simulation for each scenario and provides randomness within the results to better understand system performance, but also ensures enough replications for the mean to converge with reduced standard errors. Each replication begins with a 30-week warm-up period to allow projects and resources to be evenly distributed throughout the system. After the warm-up period, each replication runs for 260 weeks (5 years).

The first treatment in Table 1 is the baseline configuration or control scenario, that which all other treatments are measured against when analyzing results. In Chapter IV, the baseline configuration is run and results are assessed and presented to the customer,

AFLCMC/EZSA, for validation. This ensures that the model is operating as expected before any experimental analysis is conducted. Once the control is validated, the remainder of the experiments are run.

Analysis of each set of experiments includes studying the results graphically and using statistical methods. Standard error is calculated to validate results within treatments and ensure sufficient replications are run to obtain a statistically significant result. Additionally, between treatments, t-tests are conducted to determine whether the difference between treatments is statistically significant. This analysis is critical to informing recommendations for the customer—ensuring recommendations are well-founded and supported by reliable data.

Summary

This research effort progressed through a number of iterations to develop a sound and validated model from which experiments are performed and conclusions could be drawn from the process of interest. Initial sketches fed a detailed process model, which is instrumental in the development of the physical and logical constructs of the simulation model. With a model built and a baseline configuration validated, a DoE is executed to determine how process inputs varied model responses for the current process as well as a future-state ACT process. These results fed recommendations for improved process flow and resource utilization, as well as enhancements to ACT.

IV. Model and Simulation-based Recommendations to Improve the Air Force Airworthiness Process with Considerations for Reusable Launch Vehicles

Introduction

Since the inception of flight, safety has been paramount. Ensuring the continued safety and reliability of aircraft is an active practice and a critical field of study known as airworthiness. Over the past century, robust airworthiness assessments and certification programs have been developed to verify the sound technical design—and thereby safety—of aircraft prior to fielding. For example, in the United States, the Federal Aviation Administration (FAA) is responsible for overseeing the certification and operation of civil aircraft and associated activities (e.g., airport operations, air traffic control, and mishap investigation) (Federal Aviation Administration, 2017). Likewise, the Department of Defense certifies its aircraft (independently from the FAA) due to the unique nature of military airworthiness requirements and mission sets (Department of Defense, 2013). An airworthiness approval—there are multiple types which are discussed in detail later—is required prior to an aircraft's flight, even prior to flight test. As such, there is significant pressure to complete airworthiness assessments in a timely manner without sacrificing quality or safety.

This paper models and studies the USAF airworthiness assessment process executed by the Air Force Lifecycle Management Center Engineering Directorate's (AFLCMC/EN-EZ) Airworthiness Office (AFLCMC/EZSA) (Air Force Materiel Command, 2016). In particular, this study is focused on understanding the efficiencies gained through a

Continuous Process Improvement (CPI) effort by implementing software automation. More specifically, AFLCMC/EZSA is seeking to understand the reduction in time and resource utilization when incorporating an information-sharing software tool—the Airworthiness Certification Tool (ACT)—to replace spreadsheets and email communication with a unified database solution that allows for simultaneous inputs by users. This study provides an independent assessment of ACT implementation by modeling and comparing the current "as-is" process with the proposed ACT "to-be" process. As an appendix, examining the shift in aircraft safety management practices from component-to-process inspection and leveraging insights gained in this study guide recommendations towards a re-qualification process for Reusable Launch Vehicles (RLVs), presented as an Appendix.

This paper begins with a brief discussion of airworthiness history and a detailed explanation of the USAF's airworthiness process. Next, the process is modeled and analyzed in both its current form and using automation (i.e., ACT) to increase timeliness and improve workforce resource utilization. Lastly, recommendations are presented in an Appendix for a DoD-focused RLV re-qualification process.

Background

Safety has always been at the forefront of aviation, although airworthiness as a practice was not formally established until the 1930s (Federal Aviation Administration, 1996, 2017). A number of milestones including the inception of the FAA and Air Traffic Control (ATC) system, and significant technological advancements, have re-shaped the aviation landscape over the past 80 years (Airbus S.A.S., 2015; Federal Aviation Administration, 1996).

Major organizational changes include revolutionary domestic and global synchronization of aviation and airworthiness practices for both military and civil aviation authorities—one of which is the International Civil Aviation Organization (ICAO) (International Civil Aviation Organization, n.d.). Another such organization is the National Airworthiness Council (NAC), which provides a forum for discussion and commonality between the FAA, U.S. military services, and other domestic entities. This international harmonization has contributed to increased safety through the use of common rules across organizations and nations; it has also facilitated easier sale of aircraft to foreign entities (Purton & Kourousis, 2014). Figure 9 illustrates major milestones in airworthiness practices.

The public-facing landscape of United States military airworthiness has seen limited change in the past two decades; drastic policy changes in the 1990s shaped the field into what it is today (Perry, 1994; Shertzer, 1998). The 1990s ushered in a new approach to airworthiness for the Military Departments, as industry observed and struggled with over-constrained military specifications (MIL-SPEC). Then Secretary of Defense, William J.

Perry (1994) wrote a memo to the Military Department chiefs and DoD leadership, directing the use of commercial aviation standards rather than the numerous military handbooks and standards that had accumulated. Perry, recognizing the unique mission sets of the military, directed that military specifications were only to be developed as a last resort to fill gaps where commercial standards did not exist (Perry, 1994). This resulted in the removal of many existing documents and the strategic development of new airworthiness doctrine. In fact, for first Aeronautical Systems Center (ASC), the predecessor to AFLCMC, the first airworthiness policy was created as a result of the reform in the 1990s, and Air Force-level guidance was not developed until 2000.

The responsibilities for each military branch with respect to airworthiness are the same, mandated by DoD Directive 5030.61, which directs the implementation of an airworthiness assurance system and provides for the adoption of FAA standards (Department of Defense, 2013). Responsibilities for individual branches diverge from there, with the Air Force following Air Force Policy Directive 62-6, which defines the types of airworthiness certificates that can be granted (detailed further in the Phase 3 section) (U.S. Air Force, 2010b). Further guidance is delegated to Air Force Instruction 62-601, which provides process information at a high level and indicates which types of modifications require an airworthiness assessment as well as decomposing the responsibilities of Technical Airworthiness Authority (TAA), the ultimate decision-maker for the Air Force (U.S. Air Force, 2010a).

A critical development from the 1990s reform—and depicted in Figure 9—was the introduction of Military Handbook (MIL-HDBK)-516. Currently on the fourth version, MIL-HDBK-516 C is used as the rule of measure for aircraft technical qualities and operation (Department of Defense, 2013). This handbook is comprised of 960 criteria, with a standard, and method of compliance for each criterion (Department of Defense, 2014). The criteria are items to be assessed (e.g., failure conditions, navigation systems, repeated loads, flying qualities in icing conditions, passenger restraints). Standards are the required specifications that a criterion must meet, oftentimes referencing a military standard (MILSTD) publication. The method of compliance is the way in which the aircraft/modification in question will meet the standard, including any tailoring to the standard. For example, if testing is required for the method of compliance but is only available to a certain level, simulation may be used in lieu of further testing to show compliance. In other cases, criteria, standards, and methods are written with multiple military services in mind and must be tailored to the Air Force's practices.

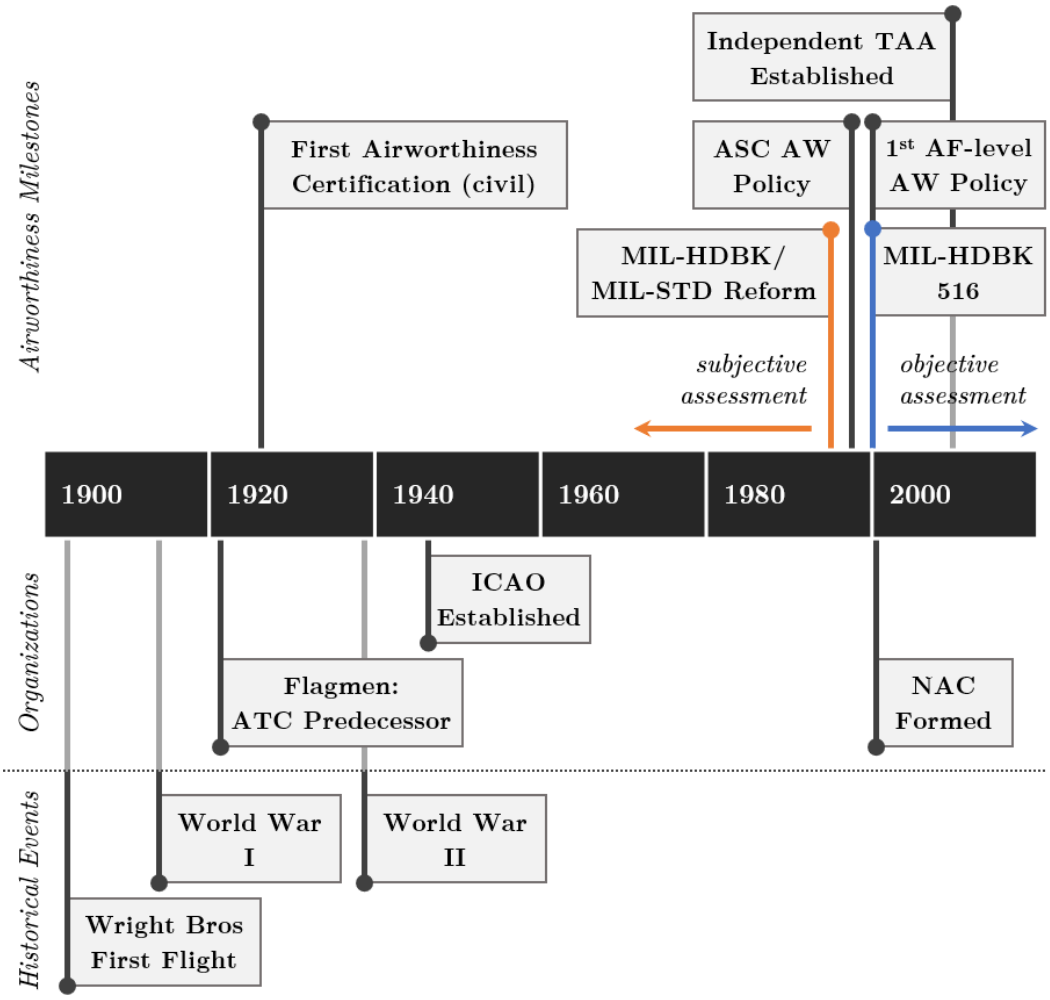


Figure 9. History of airworthiness and safety of flight milestones, including military airworthiness reform.

Another more recent development is the inception of an independent authorizing official, known as the TAA. This individual, responsible for the airworthiness certification of USAF assets, is the director of AFLCMC/EN-EZ and is independent from the development of any USAF Program. Prior to 2010, Program Managers (PMs) were the technical airworthiness authority for their program, which could be seen as a potential

conflict of interest; PMs are under significant pressure to keep their program on schedule. This format, with an authorizing official independent from the programmatic chain of command, was one of several changes modeled after the FAA airworthiness process in 2010.

Process Model

The modeling and simulation methodology used is an adaptation from Banks, Carson, Nelson, and Nicol (2010), presented in Figure 10 in a format that more closely resembles the steps taken in this study. It is a method of decomposing the problem at hand and reconstructing it through verification, validation, and analysis to confirm results.

The particular methodology varies from Banks et al. in several ways. First, an information flow path is drawn from Data Collection to Model Conceptualization, because the latter activity, while relying heavily on the objectives, changes as data becomes available. Second, to convey more information about the types of information, different lines are used to represent different types of flow. Solid lines indicate normal flow path while dashed lines indicate feedback to an earlier step for the verification and validation activities, seeking more information or making corrections to the model or assumptions, with the main point being that this type of feedback takes time. Finally, for this study, the documentation and implementation steps are one; the findings of the research are implemented by providing the airworthiness office with a number of recommendations.

The introduction and background present the motivation for this study and cover the objectives of the modeling and simulation effort. Data is initially collected via documented and observed processes. As documentation and data becomes available, process information is translated from spreadsheets and static artifacts into an initial process flow diagram. Through iteration, and verified by EZSA, the process diagrams in the following section are developed as a foundation for the study. The diagrams inform the design of the simulation environment, as well as the inputs and outputs from each activity. As with the process flow diagrams, results from the simulation are validated by EZSA to ensure the outcome is logical and a good representation of system behavior. Finally, the baseline model is modified to reflect the future state with the implementation of ACT, as well as to understand system sensitivity to various environmental changes (i.e., resource availability and processing time). This process guides the research effort and outlines each of the following subsections.

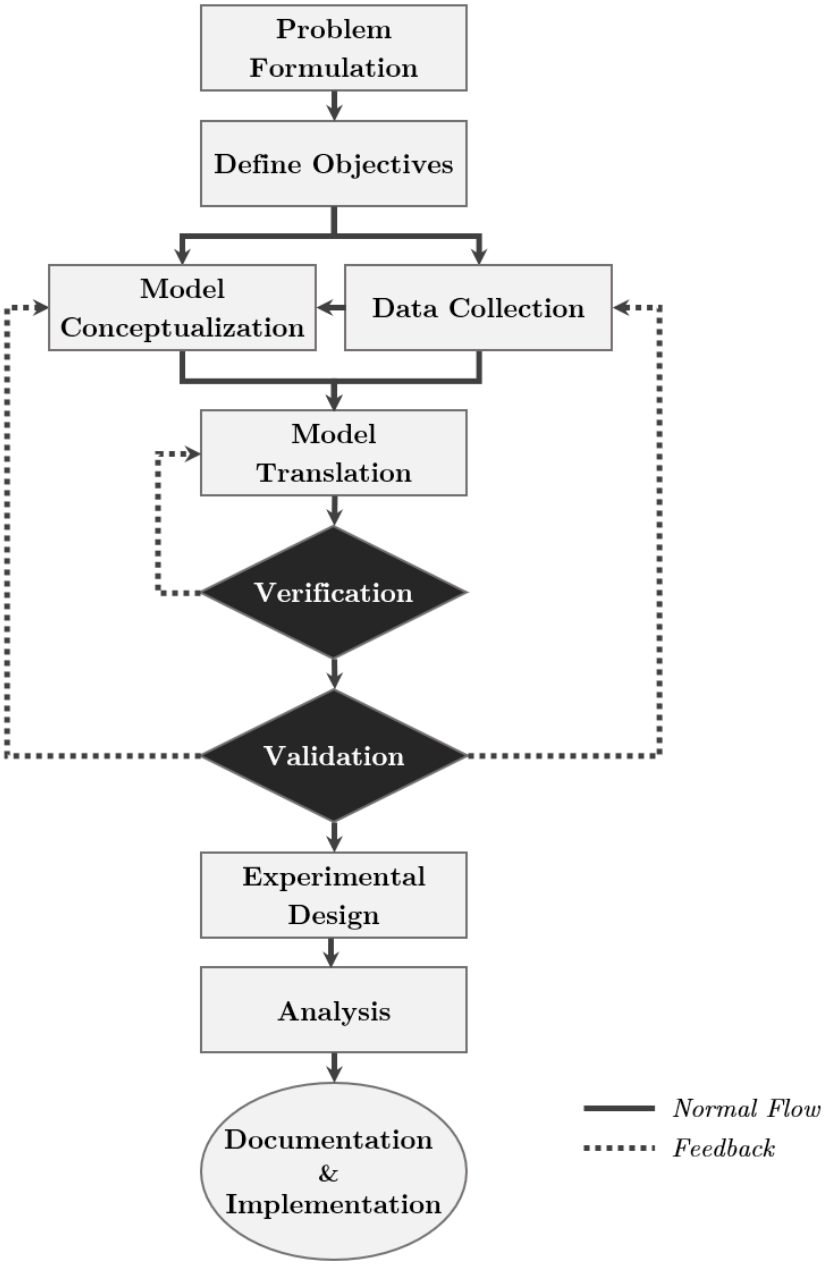


Figure 10. Modeling and simulation notional process flow diagram. Adapted from "Steps in a simulation study," by Banks, Carson, Nelson, & Nicol, 2010, p. 17.

Additionally, the model consists of both physical and logical constructs. The key data source for the airworthiness assessment process is the project tracking timeline that details each step in the process and the allotted time for each step. Modeling each step linearly would be cumbersome and make for confusing (and impractical) process diagrams.

To create a systematic process model, first a number of key activities are identified for each phase; this represents the physical construct of the model. To account for each step on the project tracker, activities are composed of sub-processes, which form the logical component of the model. This deconstruction transforms the linear tracker information by logically binning process-related steps to form a more-organized process flow model that allows for rapid recognition of key activities that take place in the assessment process.

The Airworthiness Process.

For the scope of this research effort, we studied cases when a full airworthiness assessment is required—there are circumstances in which modifications to aircraft do not warrant this assessment. Before an airworthiness assessment is started, an Airworthiness Determination Form (ADF) is completed. For new aircraft, an airworthiness assessment is always required. Modifications, however, are evaluated to determine if there is an impact to airworthiness. If the answer is yes, there are two categories of modifications which impact airworthiness: reportable and non-reportable. Reportable modifications—approximately 10 percent of all modifications—are the only type to undergo a full airworthiness assessment by AFLCMC/EZSA and the TAA. For non-reportable modifications, the System Program Office (SPO) maintains paperwork showing that they performed the steps necessary to assess airworthiness impacts of the aircraft modification.

For reportable modifications, the ADF becomes an Airworthiness Plan (AWP) and the assessment process begins.

In order to develop an accurate view of the process, data collected from AFLCMC/EZSA is used to create a series of process flow diagrams. Designed primarily with a Unified Modeling Language (UML)-style activity diagram in mind, further details are added to denote notional timelines and create unique identifiers for each activity to maintain traceability with the eventual process model and simulation. The process models are created with UML principles in mind but tailored to our application domain. These diagrams also show detail inside each activity to understand the communication flow and touches that occur by various individuals. Knowing how many times a document changes hands, and if any of the individuals who 'touch' the document actually *do* anything with it, is critical to identifying wasteful interactions (Kock et al., 2009). Fundamental to CPI is minimizing unnecessary movement and over-processing, ensuring each interaction has a purpose (Liker, 2004).

Figure 11 illustrates a high-level view of the airworthiness assessment process, comprised of three main phases: Planning, which produces an AWP; Assessment Basis (AB); and Compliance Report (CR). These represent the core activities executed by AFLCMC/EZSA. The data gathering phase for the program office (known as the flight test phase), while important from a modeling standpoint, is a 'black box' activity that can take anywhere from months to years to complete. That time is outside of the control of the airworthiness office but it is included in the model to ensure more-accurate flow. That is, as a project finishes the AB, its arrival to the CR phase should be delayed and

randomized since the time in flight test can vary greatly. Each of the three phases of interest for the airworthiness assessment process are decomposed in the following sections and subsections.

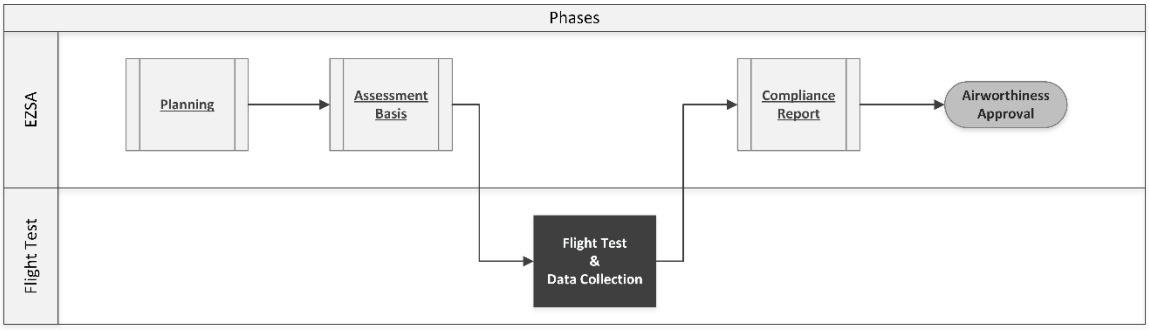


Figure 11. Airworthiness assessment process overview.

It is also important to introduce the various actors—or participants—who are involved in the airworthiness assessment process. Figure 12 depicts the types of actors involved in the process. The facilitator is the individual in AFLCMC/EZSA responsible for managing an airworthiness project, ensuring each step is completed in order, enforcing timelines, and passing artifacts and documents between other actors. The SPO is the team responsible for the acquisition, maintenance, and upkeep of an aircraft, weapon system, or other Air Force asset; they are the ones trying to obtain and maintain an airworthiness approval.

Level three Subject Matter Experts (SMEs) are individuals (primarily engineers) dispersed throughout program offices and accredited by the TAA for their expertise in one or more criteria from MIL-HDBK-516—there are 960 criteria across 16 sections. When a new airworthiness assessment is conducted, the artifacts are sent to SMEs for review. Due

to the large number of level three SMEs, this group is referred to simply as "SMEs." Level two SMEs, referred to as Technical Advisors (TAs), review the work of assigned groups of level three SMEs. TAs are responsible for reviewing all applicable criteria in one of the 16 sections in MIL-HDBK-516. At the highest level of SME review are level one SMEs, known as Technical Directors (TDs), who review the work of assigned level two TAs and level three SMEs. This tiered approach provides rigor and ensures accurate technical compliance.

The TAA, as previously mentioned, is the sole authorizing official for airworthiness certification in the USAF. His role is to ensure the approved airworthiness process is followed, the assessment is fully vetted (criteria, standards, and methods are met) and any risks and non-compliances are accepted prior to issuance of the appropriate airworthiness approval. The Air Force Safety Center reviews the CR in phase three, and are members of the airworthiness board who support the TAA in decision making. For the purpose of this model, the AF Safety Center plays a relatively minor role as they are only involved in a small number of steps in the process. The last individual is the Risk Acceptance Authority (RAA) in the program acquisition chain, represented by the Program Manager (PM), Program Executive Officer (PEO), or Service Acquisition Executive (SAE), depending on the level of risk involved. As the level of risk increases, so too must the rank of the RAA.

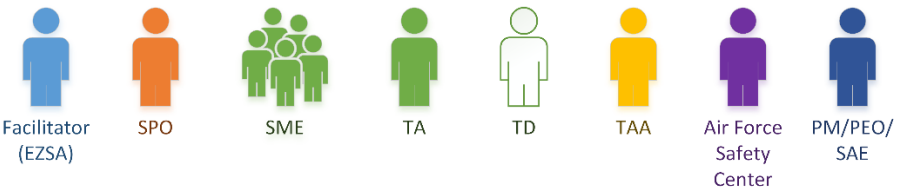


Figure 12. Actors (resources in the model) involved in the airworthiness assessment process.

For model simplicity, the assumption is made that all resource units within a single type (e.g., SME) are treated identically rather than being specialized. In reality, individuals including SMEs, TAs, and TDs are trained and accredited to review only specific criteria or sections of MIL-HDBK-516 and are therefore not necessarily replaceable. In most cases, there are backup personnel who can cover a section in the absence of the primary reviewer, but this is not guaranteed in all cases. The data to determine how many criteria from each section are required for an average assessment is not available; therefore, accurately modeling resource unit allocation and availability is not feasible.

Although it is not modeled, projects typically pass through phase two and phase three at least twice each. As is discussed in the phase three section, phase three can produce either an Military Type Certificate (MTC) or Military Flight Release (MFR), with the latter being used for testing. An MFR is, in fact, required to complete the flight test phase (between phases two and three). Thus, projects may complete an airworthiness assessment to enter flight test and a later assessment for final airworthiness approval. This involves a phase-two pass to establish an Experimental Flight Release Basis (EFRB) and a phase-three pass to be granted an MFR for flight test. For the purpose of this study and the use

of ACT, we have chosen to model the path flow without this activity as it is simply another pass through the model phases, with no unique activities.

Phase 1 – Planning.

The planning phase, shown in Figure 13, is designed primarily to provide an awareness for upcoming projects. This is important because many individuals involved in the airworthiness assessment process—SMEs, for example—may work on aircraft programs or other disciplines and airworthiness-related functions are an additional duty and a smaller percentage of their overall workload. Although SMEs are not dedicated fully to conducting airworthiness reviews, airworthiness assessment remains a high priority. As such, airworthiness projects must be scheduled to reduce overlap and ensure assessment resources are not overburdened by simultaneous projects (one of the primary goals of this study).

Each phase produces a unique artifact upon completion. For the planning phase, that artifact is the AWP, which contains information about the new aircraft or modification, the certification and flight test schedule, and information about upcoming reviews. In the first review step (S1) in Figure 13, the SPO completes the AWP and submits it to the facilitator, who performs an initial review before sending it to the TDs for further review. When the TDs have completed their review, they send it back to the facilitator, who tasks the SPO with making any necessary changes. The second review (S2) is similar but the facilitator and TDs mainly review any changes made prior to attending the Technical Interchange Meeting (TIM) to discuss the AWP (S3). If there is consensus that the AWP is satisfactory, an Airworthiness Board (AWB) is held (S4) with the TAA, who gives

approval to move forward with phase two. In many cases, this AWB is virtual, but is held in-person for high-interest projects.

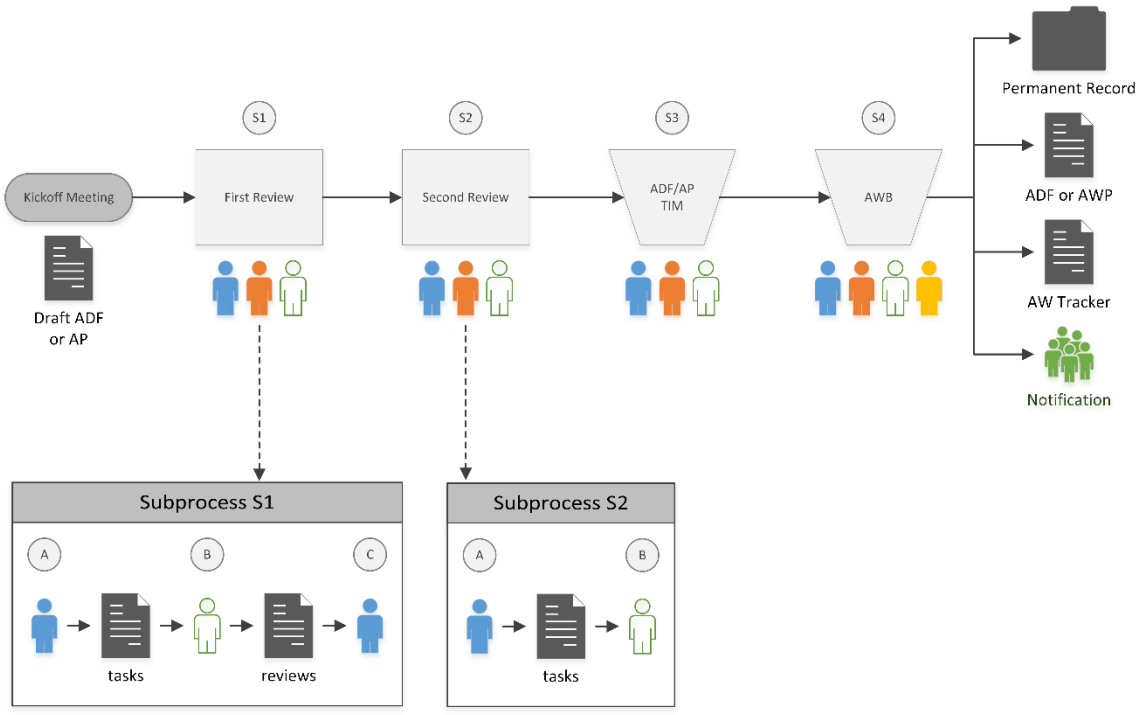


Figure 13. Phase 1 (Airworthiness Plan) process flow diagram.

Phase 2 – Assessment Basis (AB).

Figure 14 illustrates the process flow for the AB phase. The SPO begins by using a spreadsheet containing each of the criterion in MIL-HDBK-516 C and determining which are impacted by the project in question. For each impacted criterion, a standard and method of compliance must also be identified. Once complete, the draft AB is forwarded to the facilitator for review (S1). As discussed, each SME is certified to review a number of criteria. Once the facilitator receives the spreadsheet for review, he or she forwards it

to the SMEs, who each review their assigned criteria to verify that all applicable criteria are addressed, and standards and the planned methods of compliance for each criterion are acceptable. This artifact is then sent to the respective TA and TD whom assure proper process and content. Upon completion, the draft basis is returned to the facilitator who passes any resulting comments back to the SPO. The SPO reviews these changes and corrections are made.

The second review (S2) is similar to the first and, like the planning phase, the second review provides the necessary parties—in this case SMEs, TAs, and TDs—with an awareness of any issues before they meet for the AB TD TIM (S3). This meeting is an opportunity for all parties to discuss perceived issues before the SPO makes final adjustments and submits the AB for final review (S4). If the reviewing entities believe the AB has satisfied all requirements, the AWB is held (S5) for TAA approval. Prior to flight testing, aircraft require a condensed airworthiness assessment, and use an EFRB instead of an AB. In many cases, the EFRB becomes the AB for the second, post-flight test assessment.

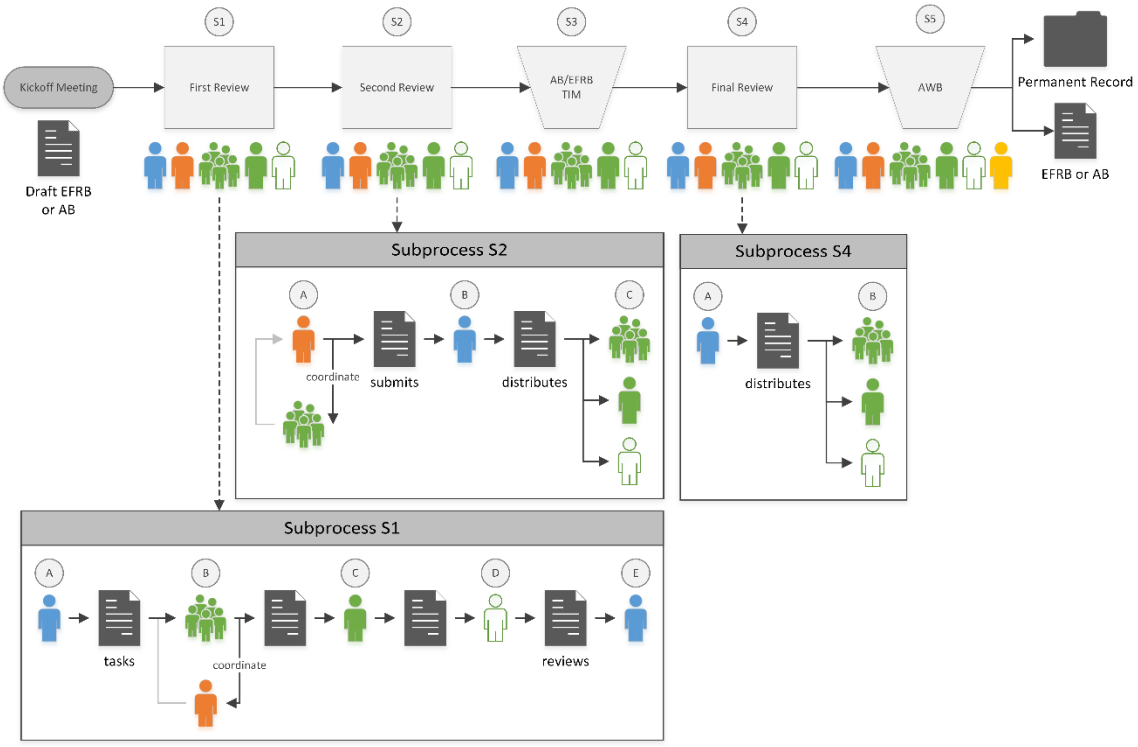


Figure 14. Phase 2 (Assessment Basis) process flow diagram.

Phase 3 – Compliance Report (CR).

The final and most time-consuming phase, the CR phase, is shown in Figure 15 and takes place after flight testing (the data gathering phase) to enable the SPO to show compliance with each AB criterion. The CR verifies that each of the applicable criteria in the second phase meet the standards required using data from analysis, flight testing, or other activities identified in the method of compliance. The CR is a way of documenting traceability of airworthiness criteria with supporting artifacts which show that standards have been met, as well as related risks and mitigations. This phase begins with a cursory review of the artifacts, performed primarily by the facilitator (S1).

The proceeding steps, (S2) and (S3), together, form the in-depth assessment of artifacts known as the 20-day review. The 5-day quicklook in step (S2) is a review conducted in the first five days of the 20-day review in which each SME verifies that all necessary artifacts are present and complete, prior to actually conducting their assessment. A consensus among all SMEs that the necessary information is available reduces the chance of discovering something is missing after many man-hours have been spent reviewing artifacts only to find that data is missing and the process must start over. In step (S2), SMEs have five days to complete this quicklook and report any issues. Once they have completed their individual quicklook, SMEs may immediately begin their full assessment. (S3), the full assessment, serves to ensure all standards have been met and that the tailored method of compliance is sufficient and acceptable. This review is known as "making a finding of compliance."

The second review (S4) is similar to those of phase one and two and serves primarily to inform individuals of any changes prior to entering a CR TIM (S5). The purpose of this meeting is to verify the status of the program in relation to where it should be for the requested airworthiness approval to be awarded, and it is the first inclusion of the Air Force Safety Center. Based on the quality of artifacts and proceedings of the TIM, a determination will be made on whether or not the project is ready for the final AWB. The artifact review (S6), like (S4), is an information dissemination activity rather than a formal review.

Next, the risk acceptance step (S7) ensures that the appropriate authority is aware of the program risks, related limitations and constraints, and accepts the risk. Further, the hazards and mitigations presented for each risk are evaluated for sufficiency in reducing the risk to an acceptable level. The RAA varies depending on risk level: low and medium risks are accepted by the PM; serious risk is accepted by the PEO; and high risk requires SAE (a pentagon-level signatory) acceptance. The latter two are rare and require additional documentation known as a System Safety Risk Assessment (SSRA), which has not been modeled due to low frequency of occurrence and minimal perceived impact to timelines.

Once all airworthiness risks have been appropriately accounted for and accepted, the certifying AWB is held. In this meeting, all of the stakeholders brief the TAA on the assessment results and any outstanding issues. Based on prior meetings, status updates, and briefings given during the AWB, the TAA may grant an airworthiness approval for the system. Most frequently, a Military Flight Release (MFR) is issued. The MFR is a temporary airworthiness approval which expires after a designated period of time or upon specific conditions, and is granted for flight testing or pending further risk-mitigation efforts. The alternate, and preferred, airworthiness approval is a Military Type Certificate (MTC), which is a permanent certificate until such a time that modifications or expiration of service life necessitate recertification.

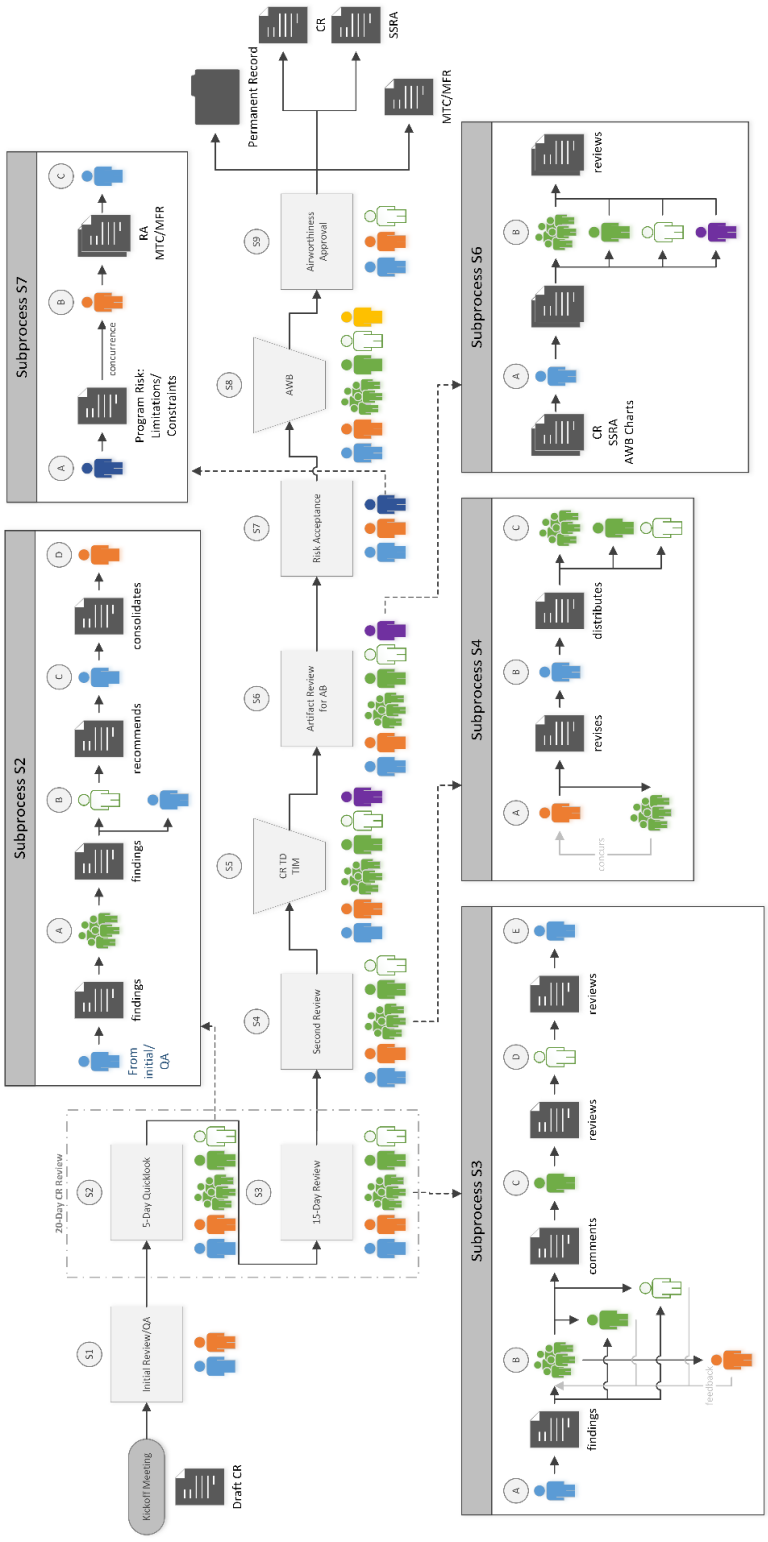


Figure 15. Phase 3 (Compliance Report) process flow diagram.

Simio Model and Experiment.

A Simio model is developed from the process flow diagrams in Figure 13, Figure 14, and Figure 15 (Simio LLC, 2018). Changes made throughout the research effort are propagated across both the flow diagrams and simulation model simultaneously to ensure the integrity of the model design. The model is composed of the three assessment phases—including steps within each phase—and a flight test phase as previously described in Figure 11.

Process times are translated from the AFLCMC/EZSA Project Tracker, which contains default timeline used for any new project. With a scarcity of process time information (a single data point) and the sole source of metrics being the project tracker, a triangular distribution was selected for processing times; standard process times serve as the mode for the triangular distribution. A 20% distribution width (10% on each side of the mode) is applied to form a triangular distribution for server and path times. Servers refer to actions that take place within the AFLCMC/EZSA office. Paths between servers represent tasks completed by the SPO, in many cases making modifications to artifacts based on feedback from AFLCMC/EZSA reviewers; paths have time values and are part of the model flow. Furthermore, data is presented in a 'number of days to complete' fashion, rather than the number of man-hours a particular task takes to complete. As such, the model runs continuously and worker schedules are not implemented. This also means process times are a big-picture estimation and do not accurately reflect the amount of time taken by an individual to complete a task. For this reason, in the results section discussion

focuses on changes in model behavior across treatments rather than the discrete values which are observed.

The entities (or items moving through the system) are the key artifacts used in each phase (i.e., AWP, AB, CR). An overall project entity picks up each artifact for its respective phase and is separated at the end if its phase. The actors introduced earlier are the resources in the simulation. The number of resources is representative of reality using data from AFLCMC/EZSA; standard experiment values are as follows: 3 Facilitators, 49 SMEs, 15 TAs, 3 TDs, and 5 SPO resources.

Each experiment consists of a number of scenarios, representing treatments in the context of design of experiments. Within each scenario, any number of properties (or factors) is changed to see how scenarios compare to each other and the control scenario, the latter of which uses standard values for all factors. Additionally, each scenario is run 30 times (known as replications), using a different random number seed at the beginning of each replication to generate values from specified distributions. 30 replications provides a good estimate of system performance for each scenario or design point with a significantly small standard error to capture statistically significance of the difference between scenarios. Finally, each run is 260 weeks long (approximately 5 years) after a 30-week warm-up period. The warm-up period ensures data is only collected while the system is in normal operating condition—that is, projects and resources are appropriately distributed across all three phases—and eliminates potential bias which would occur during ramp-up prior to normal operation. As a note, the total quantity of projects in the system at a

given time is not of concern, as AFLCMC/EZSA states they anticipate being able to support any number of projects at a given time.

In order to provide a comprehensive comparison of simulation runs in both the pre- and post-ACT configuration, results for all experiments are presented side-by-side after the ACT implementation is introduced.

Airworthiness Certification Tool (ACT) Implementation

AFLCMC/EZSA is currently transitioning to use SharePoint-based ACT in favor of email-based documentation and reviewing methods. The tool is composed of a front-end SharePoint site where edits are made by users that propagates changes to a back-end database. By accessing and changing artifacts online, multiple individuals can make edits in real time without waiting for the previous editor to disseminate a new version via email. These changes are initiated with time-savings in mind; EZSA is interested in how much time could be saved and will use results to influence a new project tracking timeline. The consequences of this are: a) reduced time spent waiting for documents, thus reducing the overall timeline; and b) elimination of re-work and errors caused by poor version control.

The existing "as-is" process (referred to as the current process) model is adapted to reflect anticipated changes and time-saving strategies from using ACT, the "to-be" model. This consists primarily of reducing the number of 'touches' by the AFLCMC/EZSA facilitator—who is responsible for emailing artifacts to other individuals—and, secondly, shortening timelines of steps that require back-and-forth communication. These types of interactions are an example of unnecessary movement and over-processing, commonly

found when conducting lean process analysis (Liker, 2004). For example, a number of actions performed by the facilitator consist simply of emailing an artifact to the next reviewer. ACT eliminates the need for this action and eight one-day steps are migrated to a zero-day processing time in the new model.

Moreover, there are four 'back-and-forth,' or collaborative, steps in the assessment process—for example, see step B in "S3 Subprocesses" on Figure 15. ACT moves these steps from a strict serial architecture to one that allows for more flexibility and parallel interactions. To account for the reduction in time waiting for individuals to email artifacts back and forth (with the potential for man-in-the-middle emailing), these steps—ranging in length from five to 15 days in the pre-ACT model—are assessed to have a 25% reduction in processing time. 25 percent is selected as a conservative estimate based on the serial-to-parallel improvement and automatic notification of users with ACT.

It is important to note that while some aspects of ACT have already been implemented, the ACT model includes additional features which are not currently implemented. As such, the model is a projected 'to-be' state and results must be treated as such. The following analysis serves to study potential time savings that could be realized if ACT is extended to the suggested modeled state.

Results

A number of experimental scenarios are simulated to evaluate the performance of the model with varying inputs, namely time and resource factors, as noted previously. The primary interest through the analysis effort is to observe changes between treatments; comparison rather than looking at discrete values. Statistical significance of results within scenarios is validated through the calculation of standard error across replications, and improvements between treatments are validated through the use of two-sample t-tests assuming equal variances. The one-sided t-test results are presented in Table 3

Table 3 (arrival rate) and Table 4 (resource sensitivity) with the point estimate mean difference and a 95-percent confidence interval.

First and foremost, the baseline model is examined to verify that it operates as expected and results are valid with respect to the real-life process times. Table 2 shows the comparison of the input (process times from EZSA documentation) versus simulation output process times—mean values with standard error—for each phase. The variability between the actual and simulated process times can be explained by two main influences. First, the distribution widths of each property in the simulation (i.e., process times) is 20 percent (10 percent on each side) and produces varied results across replications. However, this is why 30 replications are run, with the goal that the mean will converge on a value that is representative of true system performance. We can observe from standard error values that the samples are relatively well distributed and, statistically, the baseline configuration is acceptable in this regard.

The second, and crucial, reason for a disparity between actual and simulated times is the type of data available for this study. The simulation uses times from a process tracker, which is based on the number of days a particular individual is allotted to complete a task,

and is not representative of how long a task actually takes to complete. This means the tracker allots time to account for resource unavailability. When simulated however, we start with the process time (which already accounts for resource loads) and place additional resource constraints by seizing limited resources to complete tasks. As such, we expect simulation results to present longer project times due to the "doubling" of resource accountability; the consistency of the difference between actual and simulated time across all four phases (as projects wait for resources to become available) helps to verify this concept and validate model operation. Having validated the baseline configuration, further experimentation and analysis is conducted.

Table 2. Validation of model performance through comparison of documented process times and simulation results. Simulated time is reported as the mean value plus/minus standard error.

	AWP (Phase 1)	AB (Phase 2)	CR (Phase 3)
Current Process Time [days]	27	29	62
Simulated Time [days]	30.58 ± 0.22	33.22 ± 0.28	67.12 ± 0.31
Deviation from Actual [%]	13.26	14.55	8.25

Arrival Sensitivity.

The arrival rate of projects into the airworthiness process is calculated from an estimated 25 airworthiness assessments completed each year. This results in an arrival rate

of one project every 14 days, which is used as the control scenario. Although the airworthiness office has no control over arrival rates, since the value used is derived from an estimate, sensitivity analysis is conducted to verify that, should the true arrival rate be slower or faster, the difference between scenarios will largely remain the same and conclusions drawn from results will remain valid.

To present the findings of the sensitivity analysis, a box and whisker plot is used to show how variability between replications changes significantly with different arrival rates. In the following figures, beginning with Figure 16, the "x" represents the mean value and the mid-line inside the "box" represents the median. The data is then separated into quartiles (25 percent of the data, or approximately 7 replications per quartile) with the first quartile being the lower whisker, second and third quartiles being the bottom and top halves of the box, and fourth quartile being the top whisker; some outlying points may not be captured by the whiskers.

Airworthiness Plan.

Although AWPs are not currently integrated into ACT, efficiencies are added to this phase as well for future consideration. This is done, in part, to see if it is worth the effort to add functionality for AWPs to the SharePoint platform. Figure 16 shows the arrival rate sensitivity of phase one for the current process and ACT future-state process. Remembering that 14 days is the control scenario arrival rate, the frequency of new projects is increased and decreased. Increasing the frequency of arrivals to every 12 days shows a 2.76-day lengthening of project duration, as well as much more variability across replications. With outlying values as high as 47 days, the 12-day arrival rate is highly

sensitive to input variability and resources allocated to servers in other phases. A 10-day arrival scenario is run but does not offer statistical interest and increases the project time enough to make all other scenarios illegible; for this reason, 10-day arrival data is excluded from the figures. Further, although fewer arrivals with the 16- and 18-day scenarios resulted in decreased processing time (.88 and 1.63 days shorter, respectively), it also means fewer projects completed by EZSA; a fact that should be kept in mind throughout this analysis. All scenarios displayed a large amount of variability, as evidenced by elongated outer quartiles, likely due to the availability of limited resources and time spent waiting for resources to become available for processing.

Looking at the ACT model results for phase one, with the control 14-day arrival rate, there is just under one day of time savings (.86 days on average). This correlates closely with the changes made to the process model: the removal of a one-day facilitator interaction. These results, confirmed with the two-sample t-test suggest that there is statistically significant improvement—albeit less than a day—from our model with the implementation of ACT in phase one.

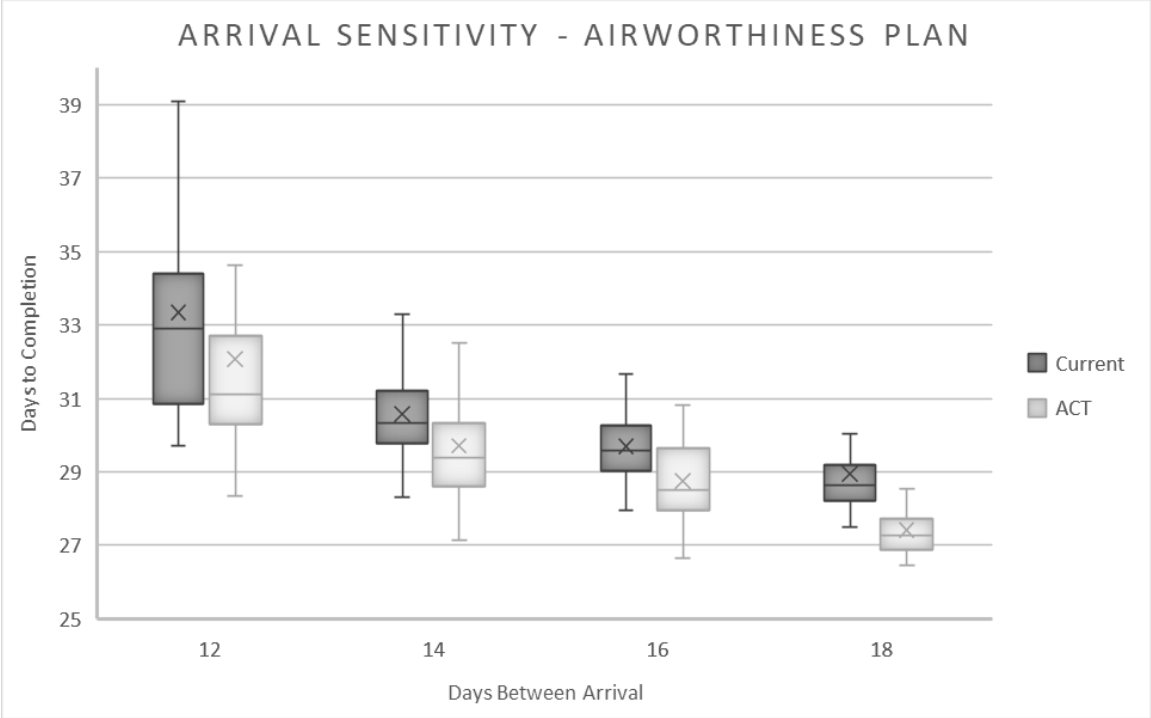


Figure 16. Arrival sensitivity analysis of Phase 1 - Airworthiness Plan, using box and whisker plots.

Assessment Basis.

In phase two, as with phase one, there is minimal improvement from the standard 14-day scenario with a slower arrival rate. The 16- and 18-day scenarios result in a savings of 1.02 and 1.85 days, respectively. The increased arrival rate (12 days), again, exhibits a high level of variability with outlying data points elongating the upper quartile of the 12-day plot.

Observing the ACT results, there is marked improvement over the current process (5.60 days in the control scenario). The improved phase two process flow eliminates three facilitator interactions and minimizes the timeline of two collaborative steps. For phase

two, the estimated savings from ACT implementation is 6.75 days, a result which shows statistically significant improvement over the control scenario. When accounting for resource dependencies, 5.6 days is still a practically significant improvement in processing time. In fact, the control scenario shows the most conservative amount of time savings from ACT implementation. Both increased and decreased arrival rates result in greater than 6 days of time savings, closer to the estimation.

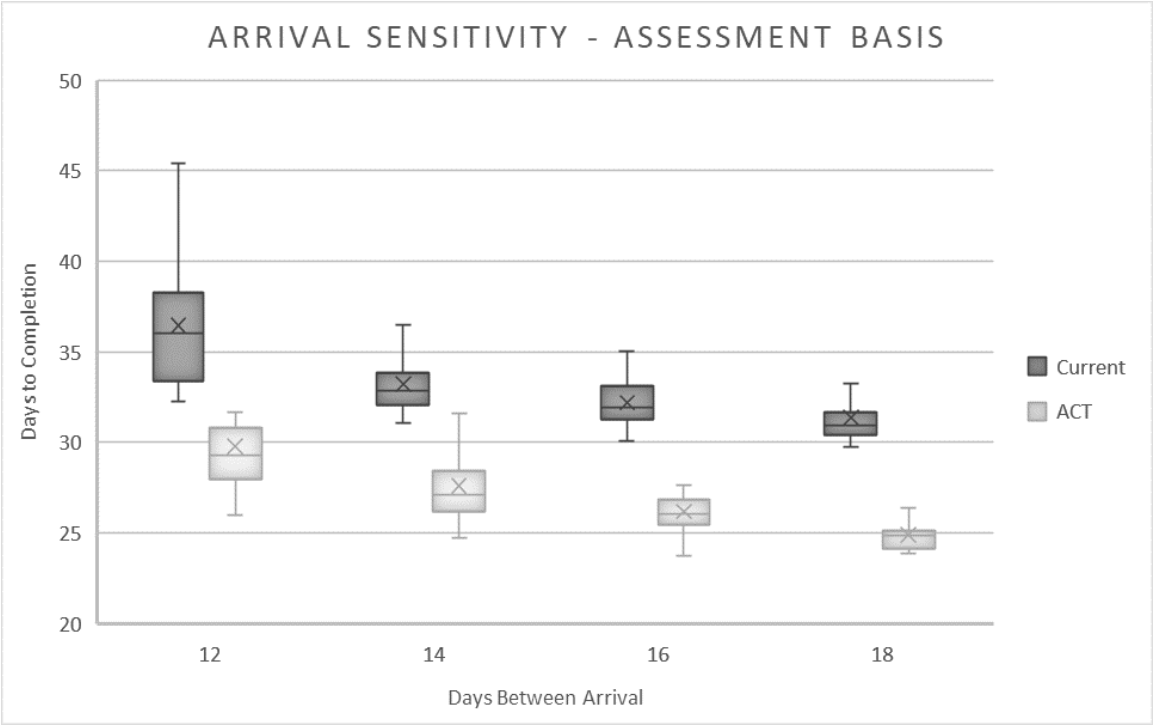


Figure 17. Arrival sensitivity analysis of Phase 2 - Assessment Basis, using box and whisker plots.

Compliance Report.

Being the longest and most resource-intensive phase, we expected phase three to show more variability than the previous two phases. We observe up to 3.7 percent time-savings on the 16- and 18-day arrival scenarios, and a 5.7 percent increase from the 12-day scenario. However, the 12-day scenario exhibits significant variability with multiple outlying replications as high as 17 percent away from the mean.

Consideration of ACT (pre-simulation) results in an estimated savings of 8.75 days—by removing four facilitator touches and shortening the duration of two collaborative steps. Of the latter, one step is a significant portion of the 20-day CR review. This being one of the most time-intensive steps of the airworthiness assessment, it is also one of the key advantages of ACT: collaborating in real time and minimizing delays due to data transfer. Model performance results in 8.73 days of time savings, conservative gains on the 14-day scenario. Both the shortened and lengthened arrival rates show even higher levels of improvement, all above 9.1 days. Across all scenarios, the implementation of ACT resulted in a statistically significant 14–17 percent improvement over the current process, confirmed through the use of a t-test. These results, when assessed with those from the previous two phases, suggest that overall the implementation of ACT results in significant improvement over the current process.

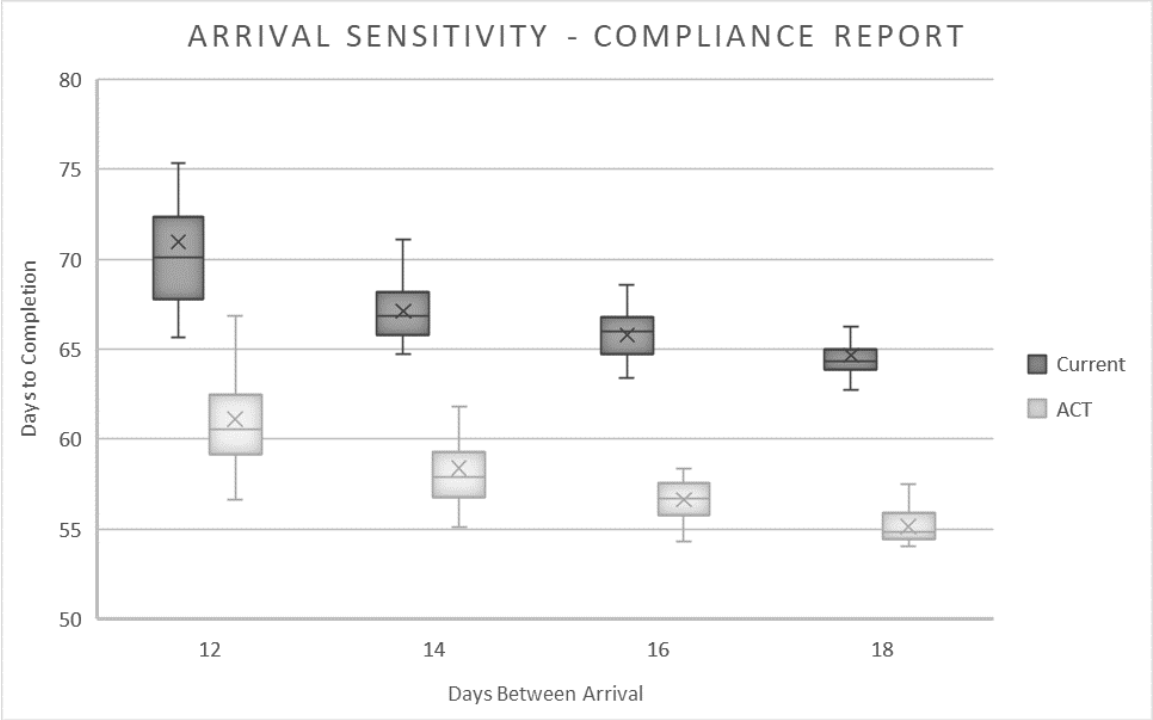


Figure 18. Arrival sensitivity analysis of Phase 3 - Compliance Report, using box and whisker plots.

Summary of Results.

Table 3 shows the results of the arrival sensitivity analysis for all three phases as well as overall project timeline (excluding flight test). As with Table 2, process times are taken from the project tracker, and simulation times are displayed as a mean value plus or minus standard error. Across all scenarios, we observe approximately the same amount of time savings through ACT implementation in the simulation as is expected from the process tracker. The difference between process and simulation time savings are .14 days, 1.15 days, and .01 days for the AWP, AB, and CR, respectively. The CR simulation response is less than one percent different from the expected time savings, which is significant given

the variability due to resource availability in the model. Furthermore, the results of each phase are studied using a t-test and ACT is found to have significant impact in all cases. Overall, we see 15.2 days of estimated savings from the implementation of current and anticipated features for ACT. The most significant impact is to phase two, which exhibits an approximately 17-percent improvement. This is a substantial amount without any changes to resource availability, which is studied next.

Table 3. Results of arrival sensitivity analysis and improvement shown through the implementation of ACT.

	AWP (Phase 1)	AB (Phase 2)	CR (Phase 3)	Total
Current Process Time [days]	27	29	62	118
Simulated Time [days]	30.58 ± 0.22	33.22 ± 0.28	67.12 ± 0.31	130.93
ACT Process Time [days]	26	22.25	53.25	101.50
ACT Simulated Time [days]	29.71 ± 0.37	27.62 ± 0.42	58.38 ± 0.45	115.73
ACT Improvement with 95% CI [days]	0.862 ± 0.526	5.601 ± 0.613	8.738 ± 0.669	15.20
ACT Improvement [%]	2.8	16.9	13.0	11.6

Resource Sensitivity.

Next, sensitivity of resource utilization based on changes to the availability of resources is conducted. Second-order effects on project completion times are also studied. In this portion of the analysis, we chose to study the four actors under control of the airworthiness office: EZSA Facilitators; SMEs; TAs; and TDs. Figure 19 shows resource utilization for all resources in the 14-day control scenario over a 30-week section of the simulation. From this figure, it is apparent which resources have the highest utilization and, with further analysis, helps to identify potential chokepoints in the model. We see the most important resources of interest are the TD, Facilitator, and SME, which are studied individually.

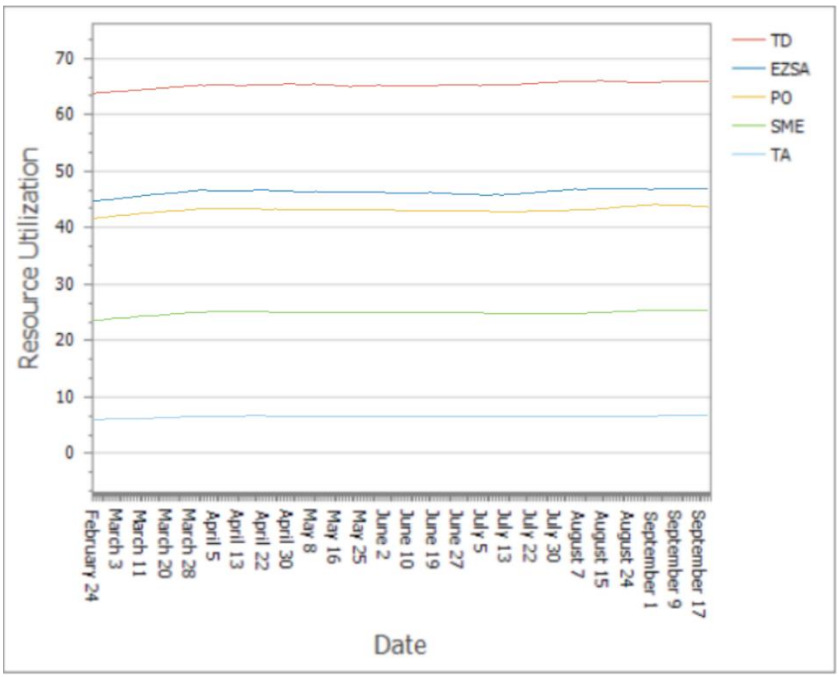


Figure 19. Screenshot from Simio runtime environment displaying resource utilization vs. simulation time in normal operation over a period of 30 weeks.

In the case of each resource, resource utilization is evaluated across four scenarios in both the current and ACT configuration: standard resource availability (control), 120-percent availability (20-percent increase) for the resource of interest, 80 percent availability (20-percent decrease) for the resource of interest, and 120-percent availability (20-percent increase) for all resources. The last scenario is chosen to see if changes to a single resource provide significant improvement when compared to changes to multiple resources. This helps to identify potential chokepoints, where improving availability to one resource has the potential to have global impact. Resource utilization results for the current and ACT processes are presented as bar graphs in the following figures. Additionally, resource changes are evaluated against project completion times for phases two and three (phase one is not currently part of ACT) as a reference tool. These results are shown as lines (dashed for AB and solid for CR) on the same figures as resource utilization. Finally, results of comparisons are presented in Table 4 at the end of this section. To reiterate, our interest is not in the raw numbers, which do not accurately reflect reality and have not been modeled with that intention, but to study the changes to results based on input variation.

Technical Director (TD) Resource.

We first study the TD resource, which exhibited the highest utilization rate, as shown in Figure 19—40 percent higher than the next-closest resource (Facilitator) in the control scenario. Figure 20 shows a control utilization rate of 61 percent for the current process and ACT. ACT enhancements impact primarily the SPO, Facilitator, and SMEs. As such,

we anticipate minimal impact (whether it be improvement or degradation) associated with the TD from ACT implementation. The increase in utilization for the TD in the control scenario is likely as a result of relief on other resources (i.e. Facilitator, SME) creating more strain for the TD. Interestingly, studying the 120-percent TD resource scenario shows very similar results to 120 percent for all resources (less than one percent difference for both AB and CR). T-tests confirmed statistically significant changes between the control scenario and other treatments with the exception of ACT implementation, which did not result in a statistically significant difference. Overall, results indicate that adding one more TD resource—120 percent of three original units, rounded to four—is nearly equivalent to adding more than 12 additional units across various resources.

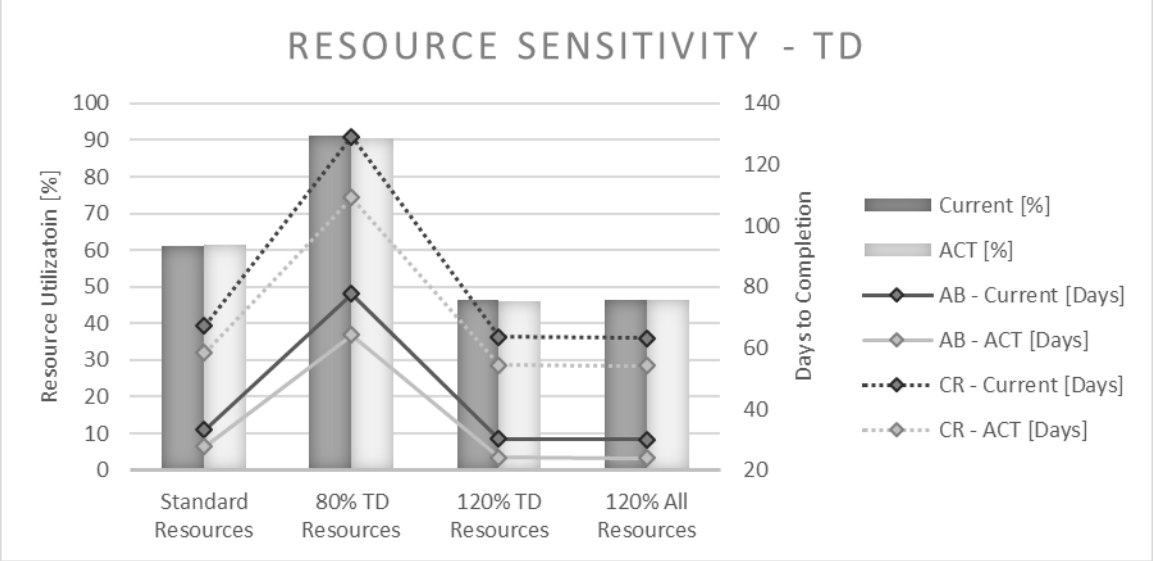


Figure 20. Resource sensitivity of TDs using a 14-day arrival rates comparing resource utilization of the two models as well as impact on project completion times.

Facilitator Resource.

The Facilitator is often the only active resource in steps where it is used—as opposed to steps that require multiple resources simultaneously—and as such should not experience any effects from the aforementioned software limitation. In the control scenario in Figure 21 (left side), Facilitator utilization is 43 percent. 80-percent resourcing results in a substantial increase in utilization (additional 18 percent), and with 120 percent resources, utilization decreases (decrease of 10 percent).

Additional Facilitator units do not have as substantial of an impact as the TD exhibited at 120-percent availability. In fact, with 120-percent availability for the Facilitator resource, project times are largely the same as in the control scenario (improvement of less than 0.2 days). Studying utilization across treatment comparisons, the differences are statistically significant and show improvement in all but the 80-percent availability, which results in system degradation. When studying the impacts to project times, increased facilitator resources reduces times by less than 1 percent and is not a statistically significant improvement. This suggests that the facilitator resource is not as much of a chokepoint as the TD resource and alleviating strain on just the facilitator does not have significant global impact to resource utilization and project times, as seen with the TD.

Evaluating the ACT improvements, reductions in utilization track closely across scenarios, with improvements ranging from 18 to 25 percent. With regard to timeliness, the ACT completion times do not show as much variation with fewer resources as the current process, due to the reduction in Facilitator touches and interactions with ACT.

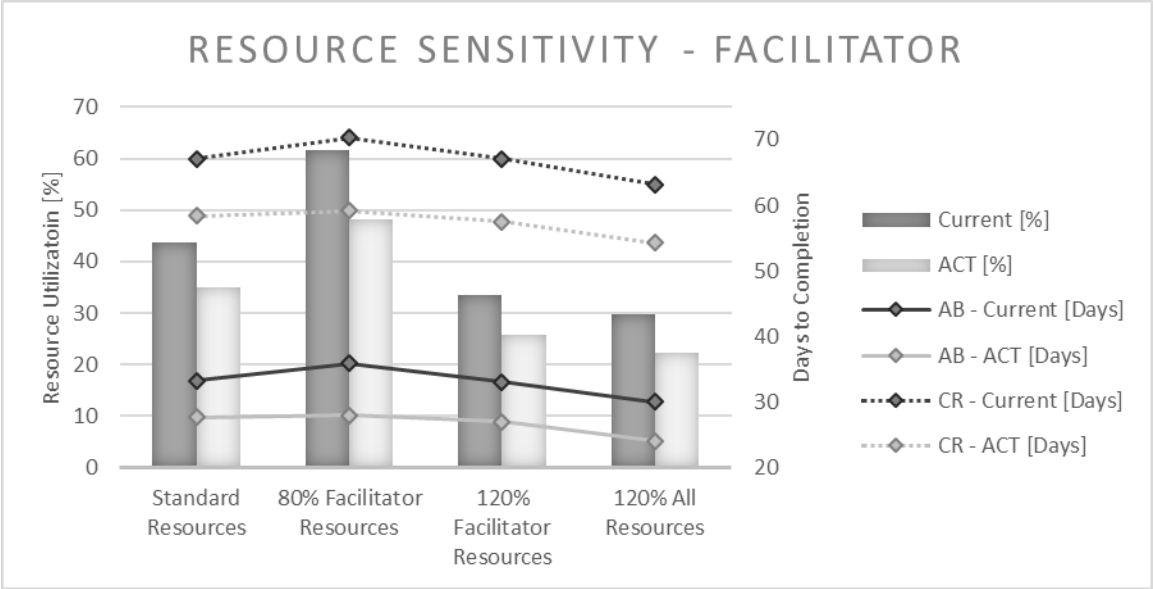


Figure 21. Resource sensitivity of Facilitators using a 14-day arrival rate comparing resource utilization of the two models as well as impact on project completion times.

Subject Matter Expert (SME) Resource.

With limited data availability, accounting for the utilization of the 49 total SMEs required assumptions to be made; one being the aforementioned modeling of resources as identical and replaceable. With each SME responsible for a number of criteria and the possibility of multiple SMEs' criteria not being applicable to a particular project, it did not make sense to require all SMEs for each project. This would also make simulation much more difficult. As such, generally five SMEs are seized for a particular step such as a smaller review or TIM. Larger reviews including the 20-day review seize 10 SMEs. As a reminder, resources are seized as they become available but processing does not begin until all required resources have been seized.

The behavior across scenarios for SMEs is similar to the Facilitator resource, but with less pronounced change on the 120-percent scenarios. There is an 18-percent improvement for SMEs, whereas the Facilitator showed a 32-percent improvement. This is likely because the quantity of SMEs (49) is far greater than that of Facilitators. The Facilitator resource, with only three resource units, is highly sensitive to changes. T-test results confirmed that SME utilization shows significant improvement with 120-percent availability of SMEs, however, project times are not significantly improved. ACT implementation does not exhibit remarkable behavior and tracks closely with results from the current process.

Technical Advisor (TA) Resource.

Studying the TA resource results, the findings are more interesting. There is a noticeable lack of improvement with ACT implementation. As with the TD, there are few interactions involving the TA that change with ACT (only one interaction for the TA), whereas the SPO and SMEs are part of every ACT collaborative enhancement. As such, we expected to see less improvement for the TA resource, but find that there is a one-percent degradation with ACT implementation, although t-tests indicate that this finding is too small to be statistically significant. This degradation is likely because relief is being placed on other resources, which in turn places more strain on the TA. Although one percent isn't very significant degradation and the results aren't significant, the key finding is that current ACT process enhancements do not benefit TA utilization.

The TA resource also exhibits one of the lowest utilization rates overall. Assuming the model sufficiently represents resource involvement in the process flow (based off EZSA documentation), the TA resource may be under-utilized and there may be potential for

improvement by shifting resource units to another position. A t-test conducted against the control and 80-percent availability scenarios does not indicate significance in resource utilization, further informing that reducing TA resources is not significant and the resource may be under-utilized.

Finally, ACT implementation has noticeably more-pronounced effects on completion time for both phases two and three as resource availability decreases for each resource. This is because as resources are reduced, their availability is more sensitive to other changes in the model. For example, with only two facilitators in the 80-percent scenario, removing numerous Facilitator resource interactions has a profound effect on overall utilization compared to when there are three Facilitator units.

Summary of Results.

Table 4 summarizes the results of the sensitivity analysis for the four actors of interest. In each case, a treatment is assessed against the control scenario. First, ACT implementation results in the removal of several unnecessary interactions. Second, resource availability for the resource of interest is decreased (fewer resources) by 20 percent. In this case, we observe negative differences for all resources, indicating that the applied treatment results in degradation from the control scenario. Third, resource availability for the resource of interest is increased (additional resources) by 20 percent. Finally, resource availability for all resources is increased by 20 percent. The result of each comparison is presented with the difference between treatment means and a 95-percent confidence interval.

Table 4. Results of resource sensitivity analysis and improvement shown through the implementation of ACT. Comparisons are shown with point estimate and 95-percent confidence interval.

	Facilitator	SME	TA	TD
ACT Implementation vs. Control [%]	8.511 ± 1.40	3.466 ± 0.739	-0.273 ± 1.486	1.103 ± 0.462
80% Availability vs. Control [%]	-18.04 ± 1.886	-5.936 ± 0.746	-30.0 ± 1.886	-0.405 ± 0.462
120% Availability vs. Control [%]	10.04 ± 1.352	4.073 ± 0.643	14.55 ± 1.328	1.048 ± 0.254
120% Availability (global) vs. Control [%]	3.908 ± 1.082	1.411 ± 0.523	0.042 ± 1.156	0.942 ± 0.191

Findings and Recommendations.

A combination of observations, the process model diagrams, simulation results—and analyses thereof—were used to derive a series of recommendations. As part of the analysis, two-sample t-tests were conducted to ensure recommendations were based on sensible model data and validate the statistical significance of results being presented to stakeholders. These recommendations include applications for both pre- and post-ACT implementation and serve as a culmination of an independent assessment of the EZSA process workflow. Again, the ACT model is representative of a 'to-be' state which includes improvements that are not yet included in ACT software and results should not be used to drive official changes to timelines without additional examination.

During this study, it was observed that not all steps documented on the assessment process tracking timeline were necessary or used for all projects. Although a single, linear process timeline lends itself to simplicity and is easy to follow, we recommend the use of gates or decision points to explicitly state that some steps are required only by exception. This ensures individuals are still following the tracker as required and avoids the perception of steps being skipped by making it clear that all steps have been evaluated but not all are unnecessary.

The current process is very rigid and necessitates that preceding steps must be fully completed prior to beginning the next step. There may be opportunities in the timeline to begin subsequent steps as information becomes available from preceding steps rather than waiting for full completion. For example, analyzing artifacts as they become available against the compliance report requirements. Some artifacts are completed early in the program and have a very low probability of ever changing. By reviewing and processing these artifacts earlier, resource utilization can be leveled—SMEs can review artifacts over a greater period of time rather than all at once when flight test is complete—and the process timeline could be condensed. This would make the most sense for documents such as systems engineering documentation, which has a low risk of changing later in the program schedule. Further, this action is not designed to reduce the timeline (the 20-day review would still take place), but to alleviate burden on resources by leveling the workflow.

To fully leverage the advantages that come with live collaboration, we strongly recommend ACT notify appropriate users when updates have been made to a project. Known as workflow integration in SharePoint terms, this is a key efficiency to the process by reducing waiting time and providing for automated, instantaneous feedback when changes are made. This feature also allows for escalation to a higher tier if individuals are not timely in responding to updates.

During simulation, it was noted that TA utilization is quite low. One possible explanation is the model assumptions that were used; TAs can often fill in to complete work for SMEs in their absence, which is not modeled. The fidelity of the model is not high enough to present definitive recommendations and results were not statistically significant, however, we suggest a further study into TA utilization to determine if resources can be assigned to a different role.

Finally, we recommend TD resources be carefully studied. Assuming model validity, this resource is under considerable strain when compared with other resources. Simulation showed that adding just one more TD resource to the current process could provide efficiencies that paralleled drastic changes to all resources. The addition of one more, strategically placed TD has the potential for significant gains in the assessment process.

Conclusions and Future Work

This study served primarily to provide AFLCMC/EZSA with an independent evaluation of the airworthiness assessment process. Further, EZSA sought recommendations for increasing the efficiency and effectiveness of their process through reduced project times and improve resource utilization. Through a modeling and simulation effort, a number of scenarios were generated to compare the current process with a proposed future-state, portions of which have already been implemented by EZSA through ACT. Recommendations based on statistical analysis were made toward continued development of ACT and the implementation of additional features, to include automated notifications. Resource sensitivity analysis also showed where resource allocation should be evaluated to increase productivity and reduce strain on particular resources. Finally, the analysis from these experiments provided EZSA with a notional future-state timeline for projects, provided recommended enhancements are implemented.

Application and Recommendation for Reusable Launch Vehicles (RLVs)

An average of 1,700 planes took off from Los Angeles International Airport on a daily basis in 2017 (Los Angeles World Airports, 2017). By contrast, there were only 90 space launches globally in 2017, with 29 of those taking place in the United States (Spaceflight101, 2017). Between the 1960s and the 1990s, the commercial aviation industry saw an exponential surge in aircraft production and use. The rapid growth meant that methods of quality assurance which had been used in the past were no longer adequate. The current method of operation was inspecting each part off the line, thereby ensuring

flawed components did not make their way into an aircraft; this also allowed for full quality control over the production line. When production more than tripled in a matter of years, this practice was no longer feasible when also keeping a tight production timeline. As such, the manufacturing and quality control practices were monitored, rather than inspecting individual parts (Department of Transportation, 2008).

Space technology is nearing a similar tipping point with regards to mission assurance, with a 30% increase in space launches since 2015 (Spaceflight101, 2015). Further, SpaceX has set a goal of a 24-hour turnaround for a Falcon 9 rocket by the end of 2018 (Etherington, 2017). Historically, the U.S. Air Force has used very rigorous checklists prior to a rocket launch to check each minute detail and ensure a successful launch. While this is productive from a mission assurance standpoint, with the introduction of reusable rocket boosters, completing such an extensive pre-launch checklist does not lend itself to a quick turnaround time for subsequent launches. In fact, the Air Force's mission assurance stance of all but eliminating risk is mutually exclusive with a rapid launch schedule, especially when reusing components from a previous launch. As FAA inspection practices for aircraft manufacturing changed significantly in the 1960s-1970s, so too must the approaches for mission assurance for RLVs in order to decrease launch turnaround times.

RLV Process Flow.

In order to shorten timelines, RLV mission assurance practices need to embrace the abundance of data available after flights and leverage that information for booster re-qualification. In the aircraft realm, critical items and component-systems are still tested, but as noted above, there has been a paradigm shift from part inspection to inspection

and monitoring of practices. Translating this to RLVs would take the form of inspecting flight-critical areas and structures, but using data to verify nominal flight patterns and only performing full inspections on equipment that experienced non-normal activity or failures prior to the next launch. This idea is illustrated with a flow diagram in Figure 22.

The top portion of the figure is the initial booster qualification, taking place prior to the first launch. This qualification would be a full assessment of the booster and each of its mission-critical functions, similar to or the same as current mission assurance assessments. Under current Air Force business rules, this lengthy assessment, as denoted by the dashed outline, would be conducted prior to each launch. The first new step is to take the existing MIL-HDBK-516 and modify the document's 960 criteria to remove items that are not applicable to RLVs as well as add items that pertain to the space launch domain which are not already covered. This new "MIL-HDBK-516 for Space Applications" would be down-selected for each booster type, thereby creating a template of criteria appropriate for each launch vehicle. Further, for each booster, thresholds would be set for normal operation for various data parameters (e.g., force, acceleration, temperatures, current).

The lower portion of Figure 22 depicts the new proposed process flow for subsequent launches. After a launch, the data is recovered from the launch vehicle—it's quite possible this would occur in real-time during flight. The aforementioned criteria template, which is already geared toward a particular booster, would be tailored (if necessary) for a particular mission, similarly to the EZSA assessment process. The vast amount of data recorded during flight would then be filtered based on the applicable criteria and what information

is necessary to complete the assessment. The key to this new assessment method is the tiered approach to the assessment. A list of pre-selected 'critical criteria' (i.e., structural inspection) always receive a full assessment, akin to the current-day method of re-qualification. Criticality could also encompass inspection intervals such as a mechanical system that requires inspection for every 100 flight hours. For non-critical items, however, the depth of the assessment is then based on recorded data. Systems which recorded nominal operation throughout the duration of the flight (e.g., impact force, acceleration, temperature, current) would receive no further inspection. If the system/equipment records a value outside of the preset threshold or encounters a failure, the full assessment is conducted on that item.

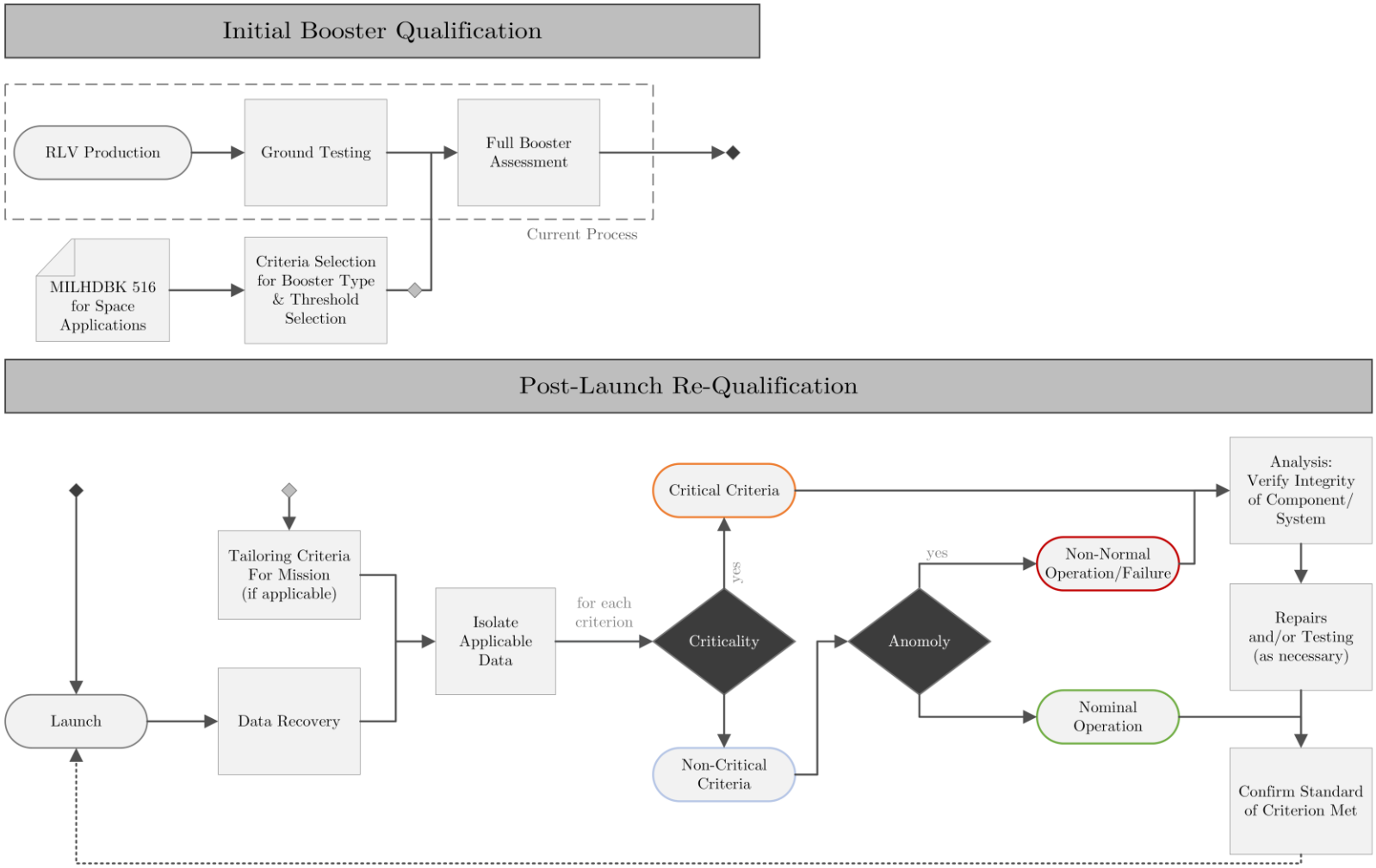


Figure 22. Proposed RLV re-qualification process model for initial launch and a condensed assessment for subsequent launches.

This approach presents three key advantages: a) leveraging existing data and taking advantage of opportunities for automation; b) reducing the number of items which require in-depth inspection expedites completion of the re-qualification assessment; and c) this process maintains the objectivity of an RLV re-qualification assessment by evaluating the launch vehicle against preset criteria and thresholds, thereby maximizing operational safety.

There is a case to be made for strict mission assurance and low risk tolerance, with payloads worth upwards of one billion dollars and taking enormous amounts of man-hours to construct. Further, there are operational differences between aircraft and spacecraft/space launch vehicles. With a deliberate risk-mitigated approach, however, inspection practices can evolve to facilitate expedited launch turnaround times without sacrificing safety or the mission.

RLV Recommendations.

A few recommendations resulted from the work done in studying RLV re-qualification. First, access to documentation from RLV manufacturers (i.e., SpaceX) on their re-qualification process would be beneficial, however, is not an all-encompassing solution. As mentioned, the Air Force has a very low tolerance for risk, which needs to be factored into the development of any re-qualification process. This, in conjunction with Air Force mission assurance practices, would provide a solid foundation for developing a robust and risk-sensitive approach to qualifying RLVs for future launches.

Second, a proactive approach to the development of a RLV re-qualification process begins with identifying criteria which need to be assessed. In this regard, we recommend

pursuing the development of a list of criteria in the format of MIL-HDBK-516 for space launch vehicle applications. This document would be expanded to include upper and lower thresholds for a semi-autonomous evaluation of non-critical criteria, as well as the identification of critical criteria and component service intervals.

Conclusion.

Having completed a thorough study on the airworthiness assessment, the secondary goal was to provide recommendations toward the creation of an RLV re-qualification process. A tiered approach to re-qualification was developed, translating the use of criterion for airworthiness to space vehicles. The recommended process allows for thorough analysis of critical systems while using a monitoring approach for less-critical systems. Recommendations were developed in pursuit of reduced launch turn-around times while maintaining the Air Force's mission assurance posture of minimal risk acceptance.

V. A Study of Cross-Domain Process Adaptation Applied to Reusable Launch Vehicle Re-Qualification

Introduction

The United States Air Force (USAF) has an increasingly urgent need to identify and develop technologies to provide persistent access to space. This is because increases in commercialized space vehicle development around the globe has reignited competition in the space domain, which has ultimately threatened the Air Force's space dominance (Air University, 2017). For example, in 2017, projected Department of Defense (DoD) space launches accounted for only 20 percent of the total planned launches executed by the USAF 45th Space Wing (Gebhardt, 2017). With plans to increase launches by nearly 40 percent in the coming years (Gebhardt, 2017), there is growing interest in Ultra Low-cost Access to Space (ULCATS) efforts, with Reusable Launch Vehicles (RLVs) being the most-promising current technology (Air University, 2017). However, the Air Force's current position of extremely low risk tolerance in current mission assurance practices is in conflict with the goals of rapid launch turnaround and decreased mission cost. In order to achieve productive gains in mission assurance efficiency, a give-and-take mindset must be used to shorten process times while still remaining informed and risk-conscious.

The Air Force Airworthiness Office within the Air Force Lifecycle Management Center's Engineering Directorate (AFLCMC/EN–EZ) is responsible for the technical airworthiness of USAF assets defined as 'The property of an air system configuration to safely attain, sustain, and terminate flight in accordance with approved usage and limits'

(Department of Defense, 2013, p. 10). This assessment process is a structured methodology of identifying all facets of the aircraft and flight systems which have the potential to impact airworthiness, and verifying full compliance of systems with prescribed standards (in some cases, non-compliance is accepted with risk mitigation). A comparison between airworthiness and mission assurance definitions allude to the parallels between the two domains. Mission assurance—referred to in the context of space throughout this paper—is defined as 'a structured, disciplined, and layered verification process that requires rigorous analysis by subject-matter experts on every aspect of a mission to ensure all risks are known' (Pawlikowski, 2008, p. 6). This paper explores the history and applicability of the Air Force airworthiness assessment process towards space mission practices for RLVs, where both practices serve to provide an objective assessment, ensure safety, and minimize risk.

Background

Department of Defense Acquisition Reform.

The parallels between DoD airworthiness practices and mission assurance trace back to extensive acquisition reform during the 1990s. The development and approval of over-constraining military specifications and standards (MIL-SPEC, MIL-STD) in prior decades foreshadowed a paradigm shift in the execution of acquisition programs, with increased pressure to use more-appropriate commercial standards (Shertzer, 1998). Post-World War II and through the Cold War, the assumption that commercial standards were not sufficient for military assets—as a matter of national security—led to unnecessary financial

burden for the government and frustration for manufacturers who had difficulty maintaining compliance with numerous of MIL-SPEC and MIL-STD regulations (Shertzer, 1998). In 1994, then Secretary of Defense, William Perry, wrote a memo (Perry, 1994) directing the heads of the military departments to use commercial specifications in all cases except where military-specific needs compelled the creation of regulations. By requiring military specifications and standards to be authorized prior to use, significant focus was placed on appropriately scoping and identifying requirements for acquisition programs.

As a result of Secretary Perry's memo, many specifications containing essential technical information were cancelled under the new business rules, causing confusion among program offices and manufacturers alike (Shertzer, 1998). Cancelling the majority of DoD standards and specifications had substantial impact to both airworthiness and mission assurance practices that relied heavily on the use of MIL-SPEC and MIL-STD regulations. This widespread acquisition reform forced the development of new, targeted standards and practices across airworthiness and mission assurance domains.

For airworthiness, it came at a time when national and international synchronization was occurring (Joint Aeronautical Commanders Group, 2014) and Air Force airworthiness policy became more defined. Simultaneously, subjective airworthiness assessments progressed into more rigorous, confident, and objective assessments (Department of Defense, 2014). In the case of mission assurance, however, new practices which aimed to reduce cost resulted in an increase in launch failures, including a number of high-profile failures (Pawlikowski, 2008). One critical change found to contribute significantly to the

increase in failures was the elimination of independent, pre-launch reviews (Freitag & Higuera, 2007; Pawlikowski, 2008). In 2001, independent reviews were reintroduced for the USAF Space and Missiles Center (SMC) with an increased focus on continuity throughout launch programs—prior to acquisition reform, review teams were large with no permanent membership (Freitag & Higuera, 2007). It was evident that despite the financial cost, independent reviews were a critical component to effective mission assurance. Because they were eliminated, in part, due to the high cost of training new individuals, emphasis on maintaining long-term relationships and enabling continuity between the Air Force and commercial entities allowed lean review teams and reduced financial burden moving forward.

The reinstatement of an independent review program also resulted in the introduction of an independent certifying official—the SMC commander became the individual outside the program office responsible for granting space flight worthiness certificates prior to each launch (U.S. Air Force, 2005).

Likewise, the Air Force airworthiness office, in an effort to synchronize assessment efforts with the Federal Aviation Administration (FAA), similarly introduced an independent Technical Airworthiness Authority (TAA). As the director of AFLCMC's Engineering Directorate (AFLCMC/EN–EZ), the TAA is separated from the programmatic chain of command (Department of Defense, 2013; U.S. Air Force, 2010b). Prior to the introduction of an independent TAA, the program manager—who is under considerable pressure to meet cost and schedule constraints—was the airworthiness approval authority, creating the potential for a conflict of interest.

In addition to the development of independent approval authorities, 1990s acquisition reform drove a parallel progression of the mission assurance and airworthiness fields with the development of objective standards-based assessments. These assessment practices, and understanding by what means similarities between the two domains enable process adaptation, are the focus of this study. In addition, as each field continues to develop, drawing on the best practices of each will ensure continued efficiency and maturation of assessment practices.

Air Force Interest in Reusable Launch Vehicles.

The Air Force's interest in efficiencies gained by RLVs are at odds with the existing mission assurance mindset; a report published by Air Force Air University (AU) highlighted this issue by stating:

> Holding Launch and Flight Readiness Reviews days before launch (a launch-by-launch certification process) is a visible sign of an outmoded set of methods that must be replaced. While needed for previous and existing systems that lack proof of dependable operations, the serial flight-by-flight process is incompatible with the system characteristics required of a responsive military capability and a thriving space economy.
> (Air University, 2017, p. 22)

As the RLV development efforts of commercial entities continues to progress, the durability and repeatability of their process does as well, which should encourage Air Force leaders to rethink the way risk is viewed in this context. The AU report goes on to explain, 'Leadership needs to understand there will almost certainly be high-profile failures during the development process. (Air University, 2017, p. 21)' The intent to protect costly and valuable assets during launch must be balanced with an appropriate level of risk tolerance

as government investment is made in the RLV and ULCATS field. Already, RLV manufacturers recognize the reduced risk-tolerance of government and DoD entities, and have implemented higher safety margins and redundant systems to create products that aim to satisfy strict requirements (Hill, 2009).

In order to form recommendations on the development of strategic, efficient re-qualification processes, the airworthiness assessment process is first introduced. Portions of the existing air-domain process can then be adapted toward use for space-domain applications—in this case RLVs.

Airworthiness Assessment Process.

A shown in Figure 23, the Air Force airworthiness assessment process—as defined by AFLCMC/EN–EZ—consists of three phases: airworthiness plan, assessment basis, and compliance report—this paper focuses on the latter two. At the heart of the process is MIL-HDBK-516 C, which is composed of 960 criteria across 16 sections (Department of Defense, 2014); where less than 300 criteria are typically used for any single assessment. For each criterion, there is an associated standard and method of compliance. The former is the level to which the criterion must perform, and the latter defines what type of documentation, artifact, or other evidence is required to prove compliance (e.g. flight test article or model performance results). For every airworthiness project, the assessment basis for a project—whether it be a new aircraft or modification to an existing aircraft—is developed by the program office, to include selection of criteria, and tailoring of standards and methods of compliance.

The assessment basis is reviewed by a progression of Subject Matter Experts (SMEs) from the airworthiness office, separated into three tiers: level one SMEs, known simply as SMEs; level two SMEs, known as Technical Advisors (TAs); and level three SMEs, known as Technical Directors (TDs). Each level one SME is accredited to review a number of criteria (averaging five to six) from MIL-HDBK-516 (U.S. Air Force, 2010a). TAs are tasked with reviewing the work of a group of level one SMEs from one of the 16 sections. The TDs—of which there are three—review the work of several TAs.

Once the assessment basis is complete and approved by the program office, airworthiness office, and TAA, the program undergoes flight testing to collect results which, in addition to program documentation, produce artifacts that prove it meets the standards for each criterion. Upon completion of flight test activities, the program office sends all pertinent artifacts to the airworthiness SMEs for review. They, in turn, ensure each applicable criterion is accounted for, and that the standard is met and supported by an appropriate method of compliance. Provided the compliance report satisfies all criteria, standards, and methods of compliance, and all program risks, limitations, and constraints are accepted, the TAA validates the compliance report and grants an airworthiness approval in the form of a Military Type Certificate (permanent) or Military Flight Release (temporary for flight test purposes or until higher-risk items can be mitigated).

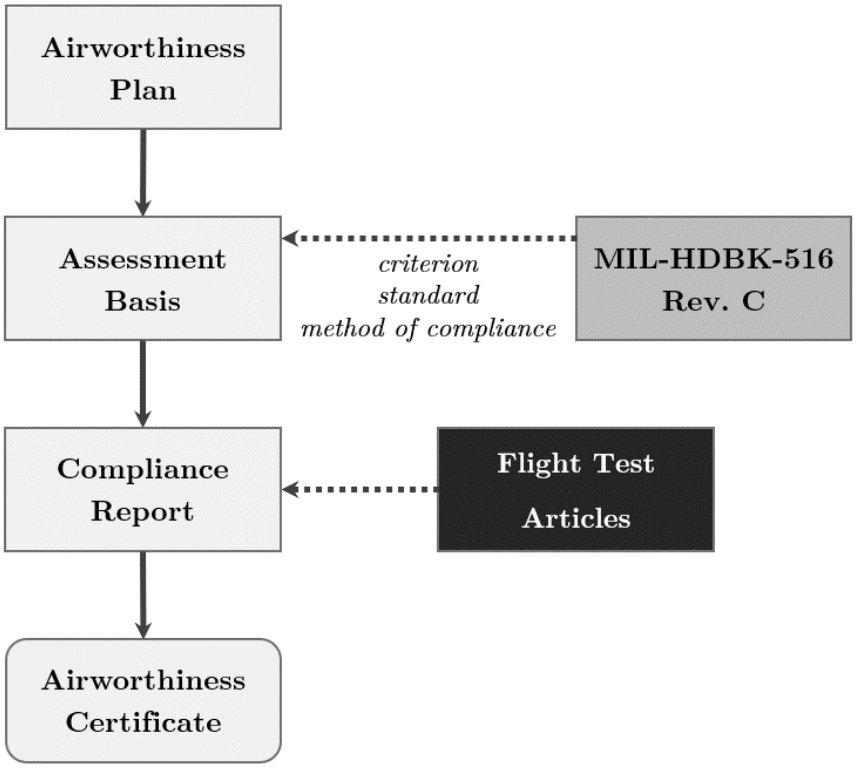


Figure 23. Overview of the airworthiness assessment process phases and inputs.

Reusable Launch Vehicle Process Model

Between the 1960s and the 1990s, the commercial aviation industry saw an exponential surge in aircraft production and use. Now, an average of 1,700 planes take off from Los Angeles International Airport each day (Los Angeles World Airports, 2017). This rapid growth meant that past methods of quality assurance were no longer adequate. The accepted method of assurance was inspecting each part off the line, thereby ensuring flawed components did not make their way into an aircraft; this also allowed for full quality control over the production line. However, when production more-than-tripled in a matter

of years, this practice was no longer feasible. As such, the manufacturing and quality control practices were migrated toward monitoring and auditing processes, rather than inspecting individual parts (Department of Transportation, 2008).

Space launch is poised for a similar evolution with mission assurance practices, supported by a 30% increase in space launches since 2015 (Spaceflight101, 2015), with 90 space launches globally in 2017 (29 of which were in the United States) (Spaceflight101, 2017). Further, SpaceX has set a goal of a 24-hour turnaround for a Falcon 9 rocket by the end of 2018 (Etherington, 2017). This rapid growth (both operationally and developmentally) must leverage autonomy in order to achieve their intended goals. As FAA inspection practices for aircraft manufacturing evolved significantly in the 1960s-1970s, so too must the approaches for mission assurance for RLVs in order to decrease launch turnaround times.

Adaptation of Airworthiness Assessments.

When the Atlas V and Delta IV rockets were new (in the mid-2000s), lessons learned from previous, more mature platforms informed the development of a new baseline for technical risk assessment (Freitag & Higuera, 2007); a similar approach needs to be accepted and applied to RLV re-qualification. In a telling example, autonomy has already been embraced from a launch perspective with the introduction of Autonomous Flight Termination System (AFTS) (Gebhardt, 2017). AFTS uses Global Positioning System (GPS) and Inertial Measurement Unit (IMU) processing to make autonomous decisions regarding flight termination and eliminates the person-in-the-loop operation. This single change reduced launch-day operational requirements by 60%, which translates to a 96-

person reduction on launch day (Gebhardt, 2017). This adoption of automated processing and decision-making shows promise towards other aspects of space launch, such as RLV re-qualification.

The introduction of RLVs and pursuit of ULCATS necessitates rigorous assessments prior to first flight and strategic, reduced assessments thereafter, where the abundance of available data from launch makes a condensed assessment possible with minimal impact to risk.

Currently, the airworthiness process relies on this data in the form of program documentation or flight test articles and uses SMEs to validate compliance of each criterion from the assessment basis. There is an equivalent group of individuals for space launch, known as the Independent Readiness Review Team. This team has a similar mandate to identify and mitigate technical risks, examine compliance documentation, and is comprised of levels of SMEs: level one SMEs, known as system leaders, and level two SMEs, known as panel leaders. Thus, a well-qualified personnel hierarchy with an elaborate existing data infrastructure is in place to support informed assessments with the aid of data-driven automation.

While the long-term goal is to develop launch vehicles with agile operation and sufficient self-monitoring to eliminate or reduce inspections between flights, a paradigm shift in the approach to launch vehicle development will need to take place. The AU report notes:

> True reusability leads to much higher levels of reliability, which leads to a transformation [where] expensive tests, maintenance and inspections are no longer required between every airplane flight. Instead, we have automated health maintenance systems that watch many indicators for signs of wear and tear. (Air University, 2017, p. A-4)

True reusability will require time and must be deliberately designed in to future launch vehicles, not adapted from existing assets. In the short term, the Air Force needs to take steps towards the development of a substantial, yet strategic, evolution in the way RLV assessments occur.

With the goal being a condensed, post-flight analysis and assessment, there is increased pressure to perform a rigorous testing and initial assessments on launch vehicles to avoid integration and interoperability failures (Song et al., 2014). Using modern aircraft as an example, major aircraft manufacturers have more than 4,000 suppliers (Department of Transportation, 2008), with one high-visibility case highlighting the criticality of thorough integration testing. In the case of the Boeing 787 Dreamliner, a battery (sourced from supplier A) was not tested with the intended charger (sourced from supplier B), resulting in the integrated product system overheating and catching fire (Song et al., 2014). While subsystem failure on a large aircraft is not desirable, during space vehicle launch, aborting mid-flight and safely returning to the ground in the event of an emergency is not as simple as an aircraft. Such a scenario places greater importance on conducting thorough and exhaustive testing for components prior to launch, especially for manned missions. As a result of the need for rigorous initial assessments, there is less potential for improvement on timeliness of initial qualification than for post-flight re-qualification.

The foremost activity in developing a new, faster, yet thorough, process is recognizing and using the vast amount of data produced and recorded by each RLV. Leveraging data which is already being collected and using intelligent automation to inform assessment decisions is necessary for shortened turnaround times.

Process Model Development.

Figure 24 presents a notional process model for RLV re-qualification, divided into two distinct sections: Initial booster qualification (prior to first launch), and post-launch re-qualification (for all subsequent launches). There is limited change to the initial qualification from current mission assurance practices except for the addition of criteria selection from a MIL-HDBK-516-like document, which is yet to be developed. We will refer to this as MIL-HDBK-X, which is key to the proposed process and comprised of a list of criteria, standards, and methods of compliance adapted for space launch applications. Additionally, safe thresholds for nominal operating ranges and criticality ratings are applied to each criterion. Threshold information should be readily available as current post-flight analysis is conducted to examine anomalies (Pawlikowski, 2008), which requires defined limits for normal and non-normal operation. The criticality rating, discussed further in the following paragraphs, is an indication for a full inspection regardless of normal operation.

Recall that less than one third of the criteria are generally used for an airworthiness assessment. As such, first an activity similar to the assessment basis must be conducted to select the applicable criteria for each booster. This assessment basis serves as a template for all launches using that booster type and requires few, if any changes, between launches

(e.g., the addition of manned flight criteria). Adding or removing criteria and modifying standards or methods of compliance is known as tailoring, and is common activity in airworthiness assessments.

After the first flight, a tiered approach is depicted in the bottom portion of Figure 24 to assess launch vehicle health. The first step following a launch and successful recovery is to collect the necessary data for a re-qualification assessment. This data could have been recorded on-board or transmitted throughout flight to the ground station. In either case, the enormous amount of data resulting from the flight must be filtered into what is necessary to conduct the assessment. This is completed by cross-referencing the criteria selected in the assessment basis and isolating pertinent recorded data.

Once necessary data is identified and collected, the tiered assessment method begins by identifying criteria listed as critical criteria in MIL-HDBK-X. Critical criteria-components (e.g., rocket body inspection) receive a full assessment. Criticality can also encompass inspection intervals; for example, a mechanical system that requires inspection after every 100 flight hours. Non-critical items move to the next decision point in the process flow, where collected data is leveraged to semi-automate decisions in the Anomaly step. Systems that recorded nominal operation throughout the duration of the flight (e.g., impact force, acceleration, pressure, temperature, current) receive no further inspection. Systems that exhibit non-normal operation or failures receive the same full assessment as critical criteria-systems. This tiered approach to re-qualification presents three key advantages: a) leveraging existing data and taking advantage of opportunities for semi-automation; b) reducing the number of items which require in-depth inspection expedites

completion of the re-qualification assessment; and c) maintaining the objectivity of an RLV re-qualification assessment by evaluating the launch vehicle against preset criteria and thresholds, thereby maximizing operational safety.

Re-Qualification Moving Forward.

After presenting the proposed process model, the question becomes 'How does the Air Force execute this process?' The AU team proposes the development of a new organization responsible for commercial ULCATS initiatives. They outline a number of recommendations for the formation of this organization, and describe the requirement for a '"Fail-Fast, Fail-Forward" culture as opposed to the traditional operationally-focused risk-averse culture where "failure is not an option."' (Air University, 2017, p. 35). This makes sense in the short term, as the pace of DoD acquisition is slow and does not lend itself to entering the rapidly growing field of ULCATS. Of equal importance, a standalone organization should not be used as a long-term solution. The introduction of RLVs and ULCATS present an opportunity to effect change on a larger scale across the mission assurance domain and not just a small, isolated team. This new organization should, as part of its core objectives, explore and propose ways in which the Air Force at large can improve the efficiency of mission assurance practices.

Furthermore, pursuit of long-term goals including self-assessing and self-monitoring launch vehicles should remain at the forefront. True reusability is a point at which extensive inspections and tests are not essential between launches. As the technology matures toward true reusability, assessment practices must continue to adapt and leverage opportunities offered through the use of automated data processing and semi-automated assessments.

Recommendations.

Through an understanding of the parallel history and nature of airworthiness and space flight worthiness activities, a number of recommendations are presented for consideration.

First, access to documentation from RLV manufacturers (e.g., SpaceX, Blue Origin, etc.) on their re-qualification process would be beneficial, however, is not an all-encompassing solution. As mentioned, the Air Force has a very low tolerance for risk, which needs to be factored into the development of any re-qualification process. This documentation, in conjunction with Air Force mission assurance practices, would provide a solid foundation for developing a robust and risk-sensitive approach to qualifying RLVs for future launches.

Second, a proactive approach to the development of a RLV re-qualification process begins with identifying criteria which need to be assessed. In this regard, we recommend pursuing the development of a list of criteria (with standards and methods of compliance) and MIL-HDBK-X for space launch vehicle applications. This document would be expanded to include thresholds for a data-assisted evaluation of non-critical criteria, as well as the identification and tracking of critical criteria and component service intervals.

Finally, as recommended by AU, the pursuit of a rapid acquisition organization for commercial ULCATS would be beneficial in the short term. RLV manufacturers have shown great agility in their development efforts and the Air Force, intending to be a key participant in future growth, must demonstrate the ability to operate in a similarly agile fashion. This organization should also use the opportunity and increased freedom to develop recommendations toward improved mission assurance across the Air Force and DoD.

Conclusion

This study served to explore the applicability of using the existing Air Force airworthiness process toward the development of a new RLV re-qualification process. A number of parallels were drawn between the airworthiness and mission assurance domains, including similarities in the development of practices and organizational structure dating back to acquisition reform in the 1990s. A notional process model was presented with a tiered and data-driven semi-automated approach to RLV re-qualification. The recommended process allows for thorough analysis of critical systems while using a monitoring approach for lower-risk systems. Recommendations were developed in pursuit of reduced launch turnaround times and toward adapting the Air Force's mission assurance posture of low risk acceptance toward one which remains informed but is more risk-tolerant.

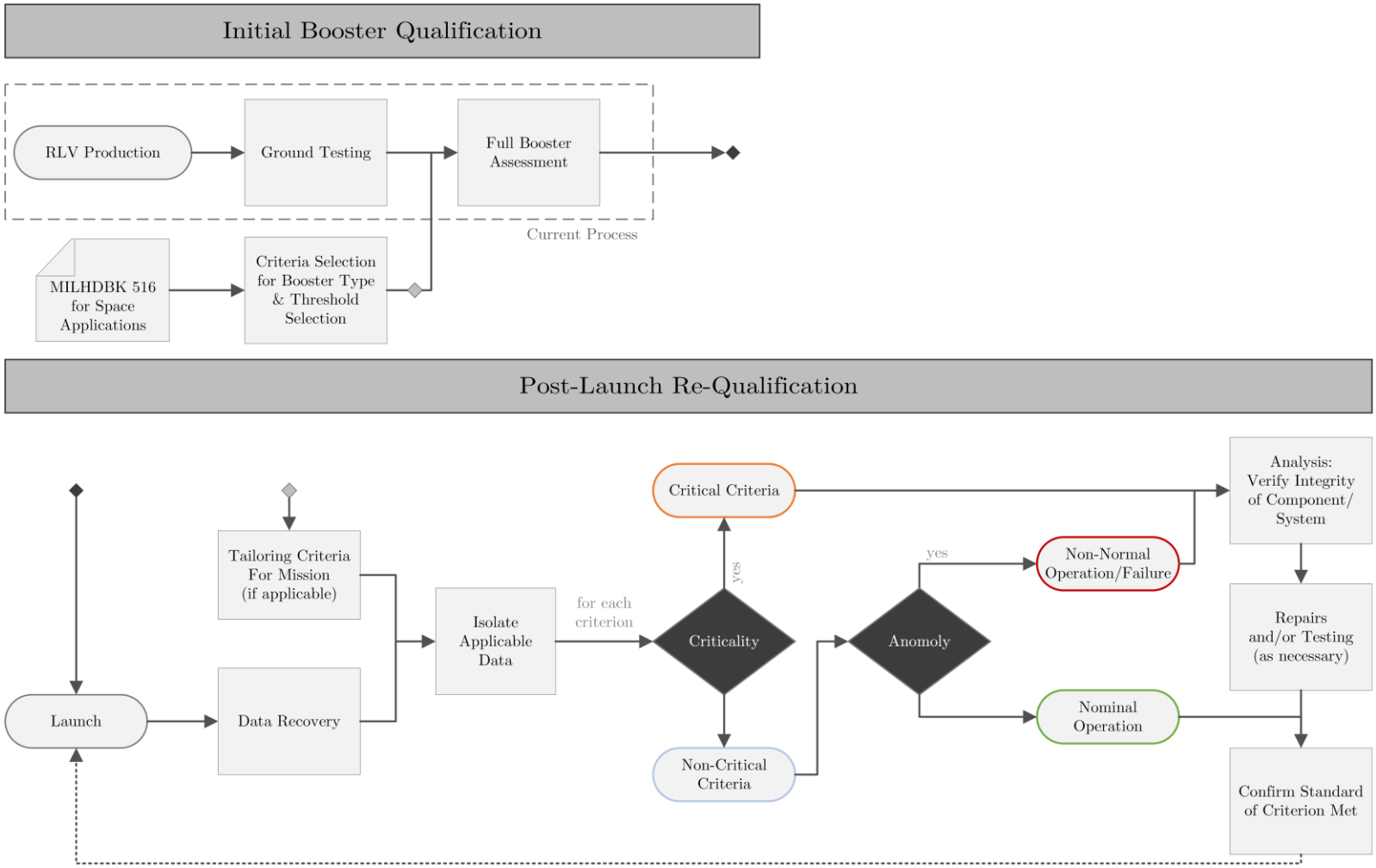


Figure 24. Notional process model for the use of data-driven semi-automated RLV re-qualification assessment.

VI. Conclusions and Recommendations

Chapter Overview

The purpose of this research effort was to use modeling and simulation to provide an independent evaluation of the airworthiness assessment process conducted by AFLCMC/EZSA. This chapter serves to summarize the study conducted and provide recommendations for EZSA as well as future research.

Conclusions

Airworthiness Assessment Process

There were a number of research questions presented in Chapter I, each of which is answered through the various activities performed in this study. First, the airworthiness assessment process was documented through the resulting process models and studied in both quantitative and qualitative aspects through the research effort. Previously undocumented components of the airworthiness process are captured in the models and associated documentation which can be used for further research or as an asset for EZSA for training purposes. The recommendation is to condense the number of publications including the AFLCMC standard process and EZSA airworthiness policy and maintain the currency and accuracy of those key documents.

Second, the airworthiness process was modeled in both a UML-style process flow diagram with activity and communication facets represented and a simulation model for thorough data analysis and experimentation. Each of these models aided in the identifying the artifacts in the process as well as value-added and non-value-added activities, before

and after the implementation of ACT. Process flow diagrams enabled a visual representation of sub-processes and steps that could be shortened or removed altogether with the addition of ACT. In total, 12 of the 40 steps identified (excluding program office touches) were removed or shortened in the ACT model, resulting in a 15-day improvement in total project time. Further, experiments on the simulation model allowed for detailed sensitivity analysis and a number of factors could be controlled to test improved process times and resource utilization. In addition to the value provided through simulation and the results of that effort, as mentioned, these models also become a valuable tool from a training standpoint and for developing accurate and detailed documentation.

In studying the current and future-state airworthiness process, a number of recommendations were developed. First, as data was gathered and through discussions with SMEs, it became apparent that not all steps on the project tracking spreadsheet were necessary for every project; however, there were no documented conditions for when certain steps were mandatory or not required. Explicitly stating entry criteria for these steps will benefit future data analysis and, moreover, ensure the process is being followed properly and as specified.

The next recommendation pertains primarily to phase three activities. Currently, approximately 80 to 90 percent of the data (or artifacts) required from test flight for a project must be received prior to beginning the thorough SME review of artifacts in order to complete the compliance report. The requirement to have a large portion of the data available before it enters review is designed to reduce re-work for EZSA staff if artifacts are changed. In reality, there are a number of artifacts that are nearly guaranteed to be

finalized earlier in the program—reviewing these documents earlier before the official start to phase three could help to level resource utilization by allowing SMEs to review artifacts over a longer period of time leading up to the larger compliance report reviews.

During the analysis conducted on the sensitivity of resources, one of the most significant findings was the high utilization of the TD. Results showed that adding one more TD unit (i.e., an individual) could significantly improve project times and reduce resource strain. It is recommended that EZSA perform further study of the TD resource to determine where an additional unit could provide the most benefit. Additionally, TA utilization was comparatively low. Reassigning a TA resource unit to a TD would be beneficial.

The final recommendations are with respect to ACT and its implementation or potential features. Currently, ACT does not have the ability to notify (or remind) individuals of items which have been edited or are awaiting their approval. This is an important feature which would leverage the automation offered by SharePoint applications and could offer substantial improvements to process times during key activities which require collaboration between multiple individuals. Additionally, the ability to use software automation to record metrics should be utilized. With the implementation of ACT, it is possible to collect metrics on the frequency of use of criteria and sections of MIL-HDBK-516 C, informing areas in which additional SME, TA, or TD resources would be best suited. ACT also tracks each interaction and update made by users. This data can be used to understand how many back-and-forth interactions occur in each step to make a more informed tracker timeline, and definitively measure time-savings as a result of ACT.

RLV Re-Qualification

The final research question asked how ideas or methods from the airworthiness assessment process could be adapted for other disciplines, namely RLVs. Information gained from the entirety of the research effort was used to develop a notional process model for RLV re-qualification. This model aims to create a tiered approach for assessing launch vehicle health for subsequent launches in an effort to reduce turnaround times while maintaining low-risk mission assurance.

Based on the RLV research performed, the primary recommendation is to pursue the development of a blended process; that is, one which incorporates components from commercial RLV re-qualification processes and existing USAF mission assurance practices. However, if the Air Force has a goal of reducing launch turnaround times, it is imperative that the assessment criteria for re-qualification be reduced to critical components or those that exhibit non-normal operation, as presented in the RLV re-qualification process model.

Significance of Research

The results of this research and the recommendations presented have the potential to provide for more efficient and effective airworthiness assessments. By implementing the aforementioned process improvements, unnecessary actions can be eliminated to reduce re-work and errors, while increasing the timeliness of assessments in order to provide more rapid fielding of new capabilities to the warfighter. Additionally, ideas toward RLV re-qualification are presented as a foundation for the development of a new process. Using airworthiness assessments as a baseline for new process development capitalizes on

existing, efficient processes, resulting in fiscal and man-hour savings. Finally, the results of the study were submitted for publication in the Journal of Defense Modeling and Simulation in order to supplement the little research that is available on airworthiness practices, and present ideas for the development and use of process models.

Recommendations for Future Research

Future study in the field of airworthiness assessments would benefit from a larger data set. With the implementation of ACT, automated metrics could more accurately define how long individual steps take and the interactions that take place. It would be beneficial to perform additional analysis with future data to determine if timelines vary greatly from project-to-project or based on the size or type of the project (e.g., new aircraft, large modification, or small modification). Process data would also enable greater precision in the development of distributions for simulation.

With respect to RLVs, the greatest asset would be existing process documentation from commercial space launch entities. Although the Air Force is new to the RLV field, they are actively being used in the commercial sector where boosters must be evaluated prior to flying on subsequent launches. Leveraging this existing process data would prove useful for the development of an Air Force-specific RLV re-qualification process; the main difference being that the Air Force has a lower tolerance for risk acceptance. Finally, further development of an adaptation of MIL-HDBK-516 for space launch vehicles would provide an objective set of criteria and thresholds for launch re-qualification.

Summary

Multiple process models were created based on the Air Force's airworthiness assessment process in order to study the efficiency of the existing process and potential benefits to be realized from software automation. Resulting information from the models fed recommendations to achieve decreased process times and improved resource utilization, based on the identification of unnecessary artifact movement and chokepoints in artifact review steps. The models also serve to better capture the airworthiness assessment process for the development of more-robust documentation and higher quality training materials.

This effort further studied the applicability of airworthiness assessment practices and principles toward RLV re-qualification. A notional process model was developed based on a risk-mitigated tiered approach to assessing RLVs with recommendations for the creation of a launch re-qualification process which would enable expedited launch turnaround times without sacrificing mission assurance or safety.

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1.

Appendix A – Simulation Results

Table 5. Arrival sensitivity of current process.

Arrival Rate	Facilitator [%]	PO [%]	SME [%]	TA [%]	TD [%]	AWP [d]	AB [d]	CR [d]
12 Day	52.399	48.471	28.873	8.204	69.938	33.340	36.473	70.958
14 Day	43.587	40.916	24.066	6.286	61.133	30.581	33.228	67.122
16 Day	39.211	37.114	21.837	5.535	56.139	29.702	32.204	65.797
18 Day	34.430	32.841	19.316	4.720	49.944	28.956	31.373	64.682

Table 6. Arrival sensitivity of ACT process.

Arrival Rate	Facilitator [%]	PO [%]	SME [%]	TA [%]	TD [%]	AWP [d]	AB [d]	CR [d]
12 Day	42.396	41.460	24.403	7.981	69.590	32.077	29.806	61.134
14 Day	35.076	35.144	20.600	6.350	61.406	29.719	27.626	58.384
16 Day	30.672	31.322	18.255	5.378	56.258	28.749	26.195	56.655
18 Day	25.796	26.933	15.698	4.407	49.019	27.420	24.892	55.165

Table 7. Resource sensitivity of current process.

Scenario	Facilitator [%]	PO [%]	SME [%]	TA [%]	TD [%]	AWP [d]	AB [d]	CR [d]
Standard Resources	43.587	24.066	40.916	6.286	61.133	30.581	33.228	67.122
80% Facilitator Resources	61.634	24.711	42.512	6.700	63.750	32.746	35.875	70.365
120% Facilitator Resources	33.549	24.178	40.789	6.374	61.016	30.488	33.068	67.048
80% SME Resources	44.352	29.992	41.580	6.482	61.973	30.779	33.519	67.536
120% SME Resources	43.587	19.993	40.916	6.286	61.133	30.581	33.228	67.122
80% TA Resources	43.587	24.066	40.916	7.858	61.133	30.581	33.228	67.122
120% TA Resources	43.587	24.066	40.916	5.239	61.133	30.581	33.228	67.122
80% TD Resources	76.948	46.934	68.921	19.848	91.136	80.484	77.787	129.149
120% TD Resources	39.166	22.338	38.298	5.160	46.582	28.019	30.254	63.542
120% All Resources	29.641	18.582	32.083	4.297	46.540	27.898	29.980	63.147

Table 8. Resource sensitivity of ACT process.

Scenario	Facilitator [%]	PO [%]	SME [%]	TA [%]	TD [%]	AWP [d]	AB [d]	CR [d]
Standard Resources	35.076	20.600	35.144	6.350	61.406	29.719	27.626	58.384
80% Facilitator Resources	48.053	20.133	34.740	6.140	61.760	30.051	27.970	59.142
120% Facilitator Resources	25.769	19.896	33.893	6.062	59.894	29.304	26.950	57.533
80% SME Resources	35.096	25.168	35.112	6.354	61.263	29.738	27.664	58.282
120% SME Resources	35.299	17.243	35.341	6.421	61.568	29.806	27.742	58.529
80% TA Resources	35.076	20.600	35.144	7.937	61.406	29.719	27.626	58.384
120% TA Resources	35.076	20.600	35.144	5.292	61.406	29.719	27.626	58.384
80% TD Resources	70.411	40.264	62.778	18.173	90.485	70.126	64.229	109.118
120% TD Resources	29.184	18.305	31.492	4.933	46.154	26.687	24.058	54.298
120% All Resources	22.343	18.544	26.594	4.193	46.482	26.702	24.032	54.242

Appendix B – Graphical Results

The following figures were omitted from the journal article for brevity but are included here to provide a graphical representation of the findings from the resource sensitivity analysis of the SME and TA resources.

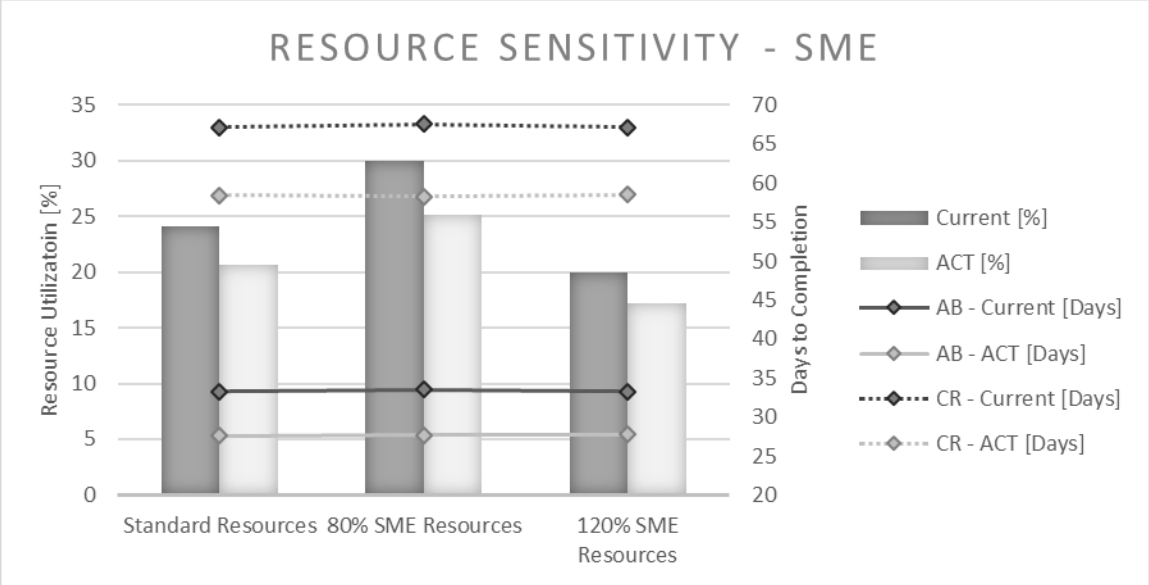


Figure 25. Resources sensitivity of SMEs using a 14-day arrival rate comparing resource utilization of the two models as well as impact on project completion times.

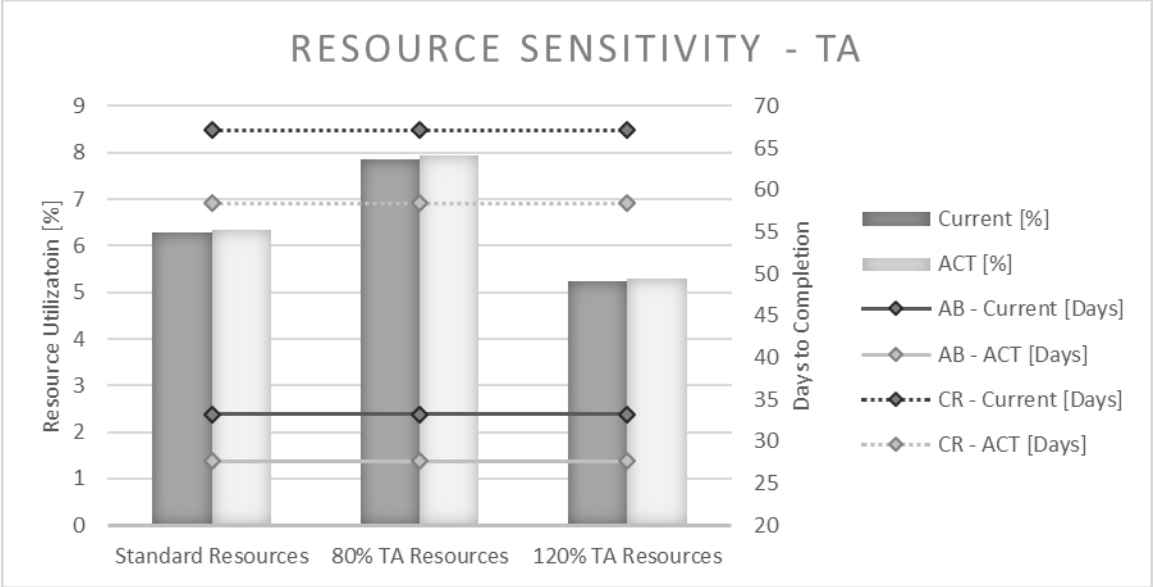


Figure 26. Resources sensitivity of TAs using a 14-day arrival rate comparing resource utilization of the two models as well as impact on project completion times.

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14. ABSTRACT
Flight safety is a critical design and engineering consideration within the United States Department of Defense (DoD) and particularly the United States Air Force (USAF). This study conducts an independent evaluation of the airworthiness assessment process used by the United States Air Force's Engineering Directorate through modeling and simulation. The airworthiness process is examined for its ability to effectively verify sound engineering design and efficiency with respect to the implementation of new software-based assessment tools and its impact on timeliness of reviews and resource utilization. Simulation results guide recommendations for reducing non-value-added activities and strategic leveling of resource demands to increase efficiency and decrease processing time. Lastly, from observation and detailed study of the aircraft airworthiness process, recommendations are made for the space domain toward the development of a re-qualification process for reusable launch vehicles, as this is a growing area of interest for the space community.

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