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An Uncertainty-Driven Risk Assessment Framework for Development of Advanced Aircraft Technologies

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An Uncertainty-Driven Risk Assessment Framework for Development of Advanced Aircraft Technologies

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ABSTRACT

The task of assessing which technologies are most suitable for long-term aeronautics research investments is a matter of understanding the uncertainties and risk posed by technologies in terms of performance, maturity, and scalability into commercial production and operation. Within this study, a novel technology development risk assessment (TDRA) framework for advanced aircraft technologies is presented, where the concept of technology development risk is evaluated using the five-step Performance, Integration, Certification, Timeline, and Operation (PICTO) approach. The PICTO approach provides a TDRA framework for decision-makers that outlines uncertainty-driven qualitative and quantitative methods that can be used as early as the conceptual design phase to determine the risk levels, associated uncertainties, and commercial viability of advanced aircraft technologies within a portfolio. For performance and schedule risks, new systems-level analysis techniques are introduced within the PICTO approach that couple semi-empirical methods, aircraft sizing and performance estimation techniques, and Monte Carlo simulations within a modeling and simulation environment. Additionally, important risk factors absent from previous TDRA frameworks such as integration, certification, and operation are now formally included in this new approach to technology development risk. Finally, to demonstrate the capabilities of the new TDRA framework to early-stage risk assessment, a case study applying advanced aircraft technologies from the Advanced Air Transportation Technologies (AATT) project portfolio onto a short-haul, commuter regional turboprop studied under EPFD to obtain performance, timeline readiness, integration, certification, and operational risk assessment results.

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NOMENCLATURE

AEO = All Engines Operating

ALA = Active Load Alleviation

ARMD = Aeronautics Research Mission Directorate

AATT = Advanced Air Transportation Technologies

ASDL = Aerospace Systems and Design Laboratory

BSFC = brake-specific fuel consumption

c = chord length, ft

CEI = Critical Engine Inoperative

DAC = Damage-Arresting Stitched Composites

ρ = air density, slugs/ft^3

C_f = skin friction drag coefficient

C_d = 2D sectional/airfoil drag coefficient

C_D = 3D/wing drag coefficient

C_L = 3D/wing lift coefficient

D = drag force, lb

EPFD = Electrified Powertrain Flight Demonstration

ERA = Environmentally Responsible Aviation

FAA = Federal Aviation Administration

FAR = Federal Aviation Regulation

IASP = Integrated Aviation Systems Program

ICAO = International Civil Aviation Organization

L = lift force, lb

L/D = lift-to-drag ratio

M&S = Modeling & Simulation

n = load factor

NASA = National Aeronautics and Space Agency

nmi = nautical mile

NLF = Natural Laminar Flow

OPR = overall pressure ratio

pax = passenger

Re = Reynolds number

S = Reference area, ft^2

shp = shaft horsepower

SFD = Sustainable Flight Demonstrator

SFW = Subsonic Fixed Wing

t = airfoil thickness, ft

x_{tr} = transition location, ft

SME = Subject-Matter Expert

V_{c} = design cruise number

$(x, y, z)_{comp}$ = x, y, or z component location in the aft, right, up convention

TSFC = thrust-specific fuel consumption, lb/hr/lb

TCM = Technology Compatibility Matrix

TIR = Technology Integration Roadmap

T.O. = takeoff

W = weight

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PART I: INTRODUCTION

“What are you trying to do? Articulate your objectives using absolutely no jargon. How is it done today, and what are the limits of current practice? What is new in your approach and why do you think it will be successful? Who cares? If you are successful, what difference will it make? What are the risks? How much will it cost? How long will it take? What are the mid-term and final "exams" to check for success?” – George H. Heilmeier, 1975, *The Heilmeier Catechism*

I. INTRODUCTION

1.1 Background and Motivation

Over the past decade, sustainability and reducing energy consumption have become significant goals for the commercial aviation industry at large. According to the FAA, 97% of U.S aviation CO_2 emissions was derived from the combustion of jet fuel [1]. In 2010, ICAO introduced Resolution A37-19 to establish standards and set limits on CO_2 emissions from commercial aircraft worldwide [2]. Following this, NASA ARMD set forth a Strategic Implementation Plan in 2019 that set reduced fuel consumption, noise, and emissions as performance-based goals for future civilian aircraft development [3]. To meet the mid-term goal of 50-60% reduced aircraft fuel/energy consumption, NASA ARMD plans to fund the research and development of promising advanced aircraft concepts and technologies that lead to marginal improvements in performance areas related to aircraft propulsion, flight systems, aerodynamics, and lightweight structures [3, 4, 5]. Programs such as ERA from 2009-2015 focused on exploring and documenting the feasibility, benefits, and technical risks associated with integrating advanced technologies onto existing aircraft [6]. These efforts under ERA culminated in a flight test demonstration of the NASA/Boeing 757 ecoDemonstrator, which featured several technologies selected from ERA's portfolio that were sufficiently matured to TRL 6 [7]. During the technology selection process for the ecoDemonstrator, stakeholders recognized the complexity of evaluating which technologies were cost-effective and practical for demonstration, which necessitated deep understanding of their expected performance impact, current level of maturity, integration difficulty, and commercial viability [8]. With on-going NASA ARMD projects preceding ERA such as EPFD, SFD, and AATT that focus on the selection of technologies for development and demonstration of sustainable aviation concepts, the need to develop a structured approach to assessing advanced aircraft technologies remains outstanding in the present day.

1.2 Introduction to Technology Development Risk Assessment

Technology development programs refer to efforts concerned with the research, development, integration, and demonstration of novel technologies. Programs such as ERA, SFD and EPFD fall under this category, where the success of such programs is contingent on whether selected technologies can meet performance benchmarks within a set programmatic timeline [4, 5]. Historically, the Technology Readiness Level (TRL) scale has been the primary metric to assess technology development risk using a scalar value to communicate the status of a technology's maturation and associated demonstration efforts [9]. However, it does little to characterize the underlying uncertainty present at each phase. By nature, technology development efforts introduce programmatic risks and uncertainties that must be communicated to allow for risk-informed decision making. Appendix G of the NASA Cost-Estimating Handbook defines risks and uncertainties in the context of technology development programs [10]:

- Risk is an event not in the project's baseline plan that is an undesirable outcome (discrete risk). This definition is similar to one that one would see in a risk matrix. This event is characterized by a probability of occurring and an expected impact if the event did occur.
- Uncertainty is the indefiniteness about a project's baseline plan. It represents the fundamental inability to perfectly predict the outcome of a future event. Uncertainty is characterized by a probability distribution, which is based on a combination of the prior experience of the assessor and historical data.

The relationship between uncertainty and risk is of utmost importance, where it is stated in the Columbia Accident Investigation Board (CAIB) report that “engineering solutions presented to management include a quantifiable range of uncertainty and risk analysis [11].” The risks posed by technology development programs are referred to as technology development risk, which is defined as the potential for performance and readiness shortfalls which may be realized in the future with respect to achieving established and stated performance requirements within a set timeline. The analysis of these risks and their related uncertainties in the context of risk-informed decision making (i.e., technology selection for the Boeing/NASA 757 ecoDemonstrator in Ref. [7]) is referred to as technology development risk assessment (TDRA) which was coined by Mathias et al. in a 2006 study on spaceflight technology development programs [12]. Other methods that address technology development risk when assessing candidate technologies for a flight demonstration effort have been used in the past, such as Kirby’s Technology Identification, Evaluation and Selection (TIES) method [13].

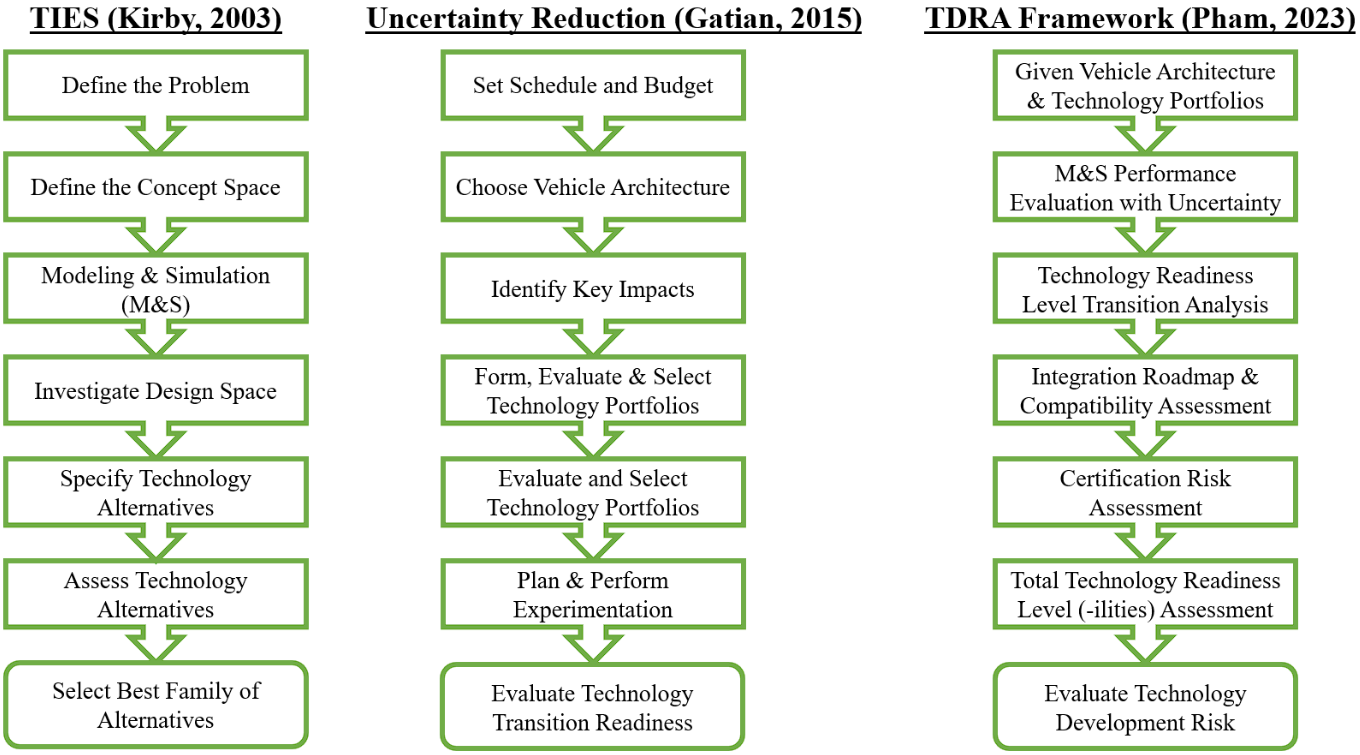


Figure 1. Overview of previous and proposed technology development risk assessment methodologies

Figure 1 provides a high-level overview of technology development risk assessment methodologies that have been used to evaluate candidate technologies and the TDRA framework that will be proposed in this study. The TIES method was developed to easily assess and trade-off the impacts of various technologies within a forecasting environment that evaluates technology development risk using point-based performance estimations and compatibility matrices to identify synergistic technologies within a portfolio [13]. Then in 2015, Gatian developed a model-based technology selection and development approach through epistemic uncertainty reduction to support ERA risk reduction efforts where “epistemic uncertainty” refers to the uncertainty incurred by lack of experimental testing and validation [14]. Gatian’s uncertainty risk reduction study focused on gauging technology readiness with the TRL scale, R&D difficulty, and modeling the technology's estimated performance impact with triangular distributions [14]. Both the TIES method and Gatian's approach are used to build and present technology portfolios to stakeholders. However, within different factors were used to gauge technology development risk: TIES focused on the categories of performance and compatibility while Gatian's approach focused primarily on TRL progression and performance.

The proposed TDRA framework in this study differs from what has been presented above in terms of application and structure. First, while both TIES and Gatian's approach are used to create technology portfolios, the motivation driving this work is creating a structured approach to evaluating technologies of an *existing portfolio* to determine which are the most suitable for integration onto a flight test demonstrator. That is, the technologies that pose the least amount of risk to the program timeline *and* have potential for real-world application past R&D and into commercial operation and use [15, 16]. Those qualities drive which factors are relevant for consideration within the proposed TDRA framework such as performance, ability to mature on time for demonstration, ease of integration, certification feasibility, and lastly, scalability into the operational environment. The process shown in Figure 1 summarizes the decomposition of these factors and how they are addressed in the TDRA framework.

1.3 Research Objective

For programs such as ERA, EPFD, SFD, and SFNP, integration of advanced aircraft technologies are crucial to meeting performance-related sustainability goals in aeronautics such as reduced fuel/energy consumption [5, 7, 17]. However, development and demonstration of novel technologies introduce significant risk and uncertainty that must be taken into consideration when selecting which technologies to incorporate onto the flight test demonstrator [8]. Assessment of technology development risk is essential to determining which technologies will pose the least risk to meeting the technical performance measures defined by the program within the project timeline and promise high return on investment. Risk characterization requires uncertainty-driven analysis of the technology's expected performance and time to mature, which relies on successful integration and certification to permit flight demonstration activities. Additionally, the question of whether a technology will be able to transition from controlled R&D test environments into commercial production and operation can be answered by consideration of factors such as ease of integration, certification, and viability within an operational environment.

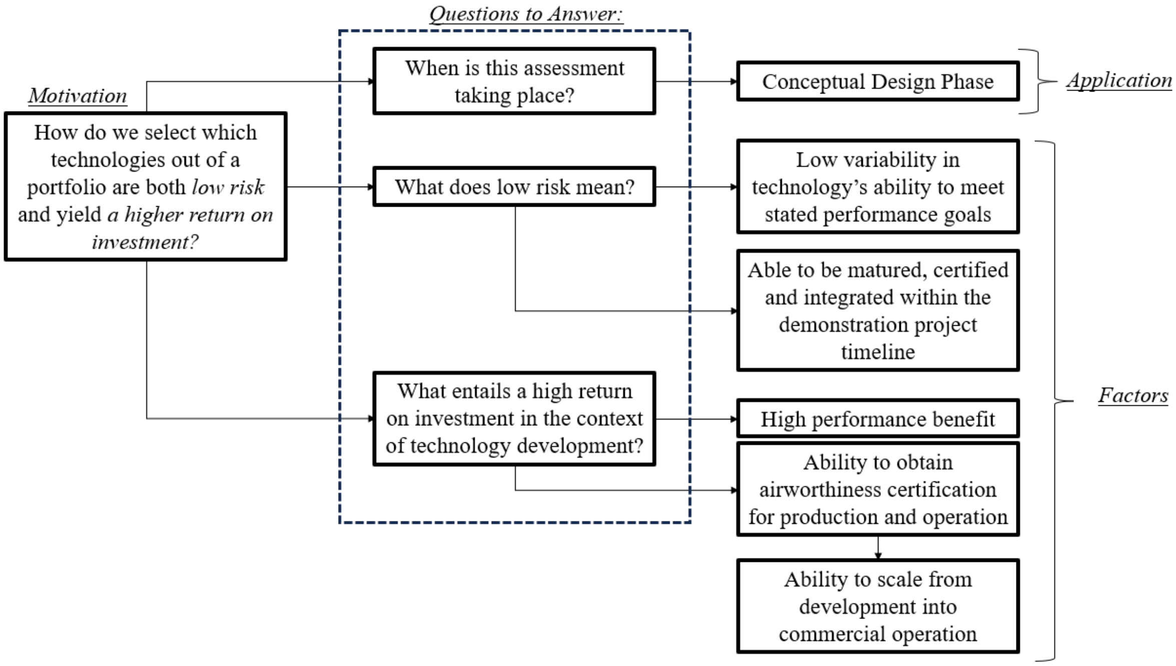


Figure 2. Motivating questions that define the application and factors of considerations to be addressed by the proposed TDRA framework.

Figure 2 outlines the questions leading to the formulation of the novel TDRA framework that will be proposed, developed, and applied within this study. The research objective is to develop a structured approach to TDRA to facilitate informed decision-making when selecting advanced aircraft technologies to incorporate onto a flight test demonstrator. The applicability of the framework is determined by *when* the assessment is conducted, which is at the conceptual design phase of a technology development program where the formal system architecture is the most volatile and decisions are the most cost-effective.

The structure of the TDRA framework is determined by the factors that must be taken into consideration when answering the research objective, which will be discussed in the Problem Formulation chapter. The factors chosen are **P**erformance, **I**ntegration, **C**ertification, **T**imeliness, and **O**perational risk (PICTO) which outline the structure of the TDRA framework. Then, to evaluate these factors to create the structured approach, the Methodology Formulation chapter details the uncertainty-driven qualitative and quantitative analyses that have been specifically tailored to the application of studying advanced aircraft technologies at the conceptual design level. Then, the TDRA Framework chapter provides a guided overview of the proposed PICTO approach with example cases on how it can be applied within the context of aeronautics. Finally, the effectiveness of the proposed TDRA framework will be demonstrated using a practical case study involving the parametric infusion of advanced aircraft technologies evaluated under the AATT project onto the ATR 42-600, which previously served as a reference turboprop aircraft for the EPFD project [18, 19].

The PICTO approach developed in this study is an original TDRA framework that employs engineering-level aircraft sizing and design tools, historical data collection, semi-empirical modeling, and uncertainty propagation techniques such as Monte Carlo methods to facilitate integrated risk mitigation efforts during the conceptual design phase. The incorporation of uncertainty propagation in assessing technology performance and schedule impacts allow for a systems-level consideration of the risk associated throughout the technology development program. Use of this novel TDRA framework will enable comprehensive assessment of advanced aircraft technology candidates within a portfolio, allowing technologists to capture potential risks and associated uncertainties early in the technology development process to support successful integration efforts for NASA ARMD programs such as EPFD, SFD, and other future flight demonstration projects.

PART II: PROBLEM FORMULATION

“The author makes no apology for the fact that his approach to airplane design may be biased by a university environment” –Egbert Torenbeek, 1978

II. PROBLEM FORMULATION

For systems analysts who often do vehicle assessments for flight demonstrators as early as the conceptual design phase, risk assessment is considered a later-stage activity after the systems-level analysis takes place [20]. Due to the lack in fidelity of performance models at the conceptual design phase, performance and schedule risk assessments at this stage are minimal and reliant on statistical generalizations and solicited SME opinion [21, 22]. However, the conceptual design phase is where uncertainty is inherently at its highest, and where risk reduction is the most impactful. This has been recognized in previous studies pertaining to risk-informed decision-making for technology development [13, 14]. Additionally, later-stage technology development risks for advanced aircraft technologies such as integration, certification, and operation are not heavily regarded during this phase, even though risks encountered at these phases can determine programmatic success or failure.

The purpose of this section is to identify which factors must be taken into consideration when assessing technology development risk, use these factors to outline the structural of the overall approach to be used in the TDRA framework, and determine how these factors are evaluated at the conceptual design phase.

2.1 Performance Evaluation and Uncertainty Propagation

The universal factor that is taken into consideration for all previous frameworks pertaining to technology development, demonstration, and risk is performance [13, 14]. Section 4.3.3.3. of the Risk Management Handbook discusses that risk-informed decision makers must assess the range of expected performance and uncertainty to determine if the bounds cross one or more tolerability thresholds [23]. The performance of advanced aircraft technologies can be estimated analytically or experimentally where validation, in the form of data, is obtained through analytical methods, wind tunnel testing, or full-scale flight demonstration. Certain ways of obtaining performance data for in-development aircraft concepts and technologies are:

1. <u>Computational simulations</u> using Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) or other types of computer simulations that can model the performance of new technologies before they are manufactured and implemented onto an aircraft. These simulations aid engineers in identifying potential design flaws or areas of improvement, along with optimize the design before it is finalized.
2. <u>Ground testing</u> in a laboratory or relevant environment that involves conducting tests on aircraft components and systems in a controlled environment on the ground. This can include stationary testbed experiments, laboratory tests to determine the durability and reliability of new materials, or wind tunnel testing of drag reduction technologies.
3. <u>Flight testing</u> to assess the performance of the vehicle-integrated technology in a “real-world” environment close to operating conditions, which will provide valuable data on the technology’s performance, safety, and reliability.

These methods have all been used in the past to qualify the performance characteristics of in-development technology for potential flight demonstrators such as the Small Transport Aircraft Technology (STAT) program between NASA Ames Research Center and Cessna Aircraft Co. in 1983 [24]. Within this report, technologies grouped under advanced airfoils and high-lift systems (aerodynamics), advanced propulsion (propulsion), advanced materials and structures (structures), and ride quality improvements were all evaluated in terms of performance using experimental methods. The qualifying metrics used were direct operating costs (DOC) and percent block fuel reduction.

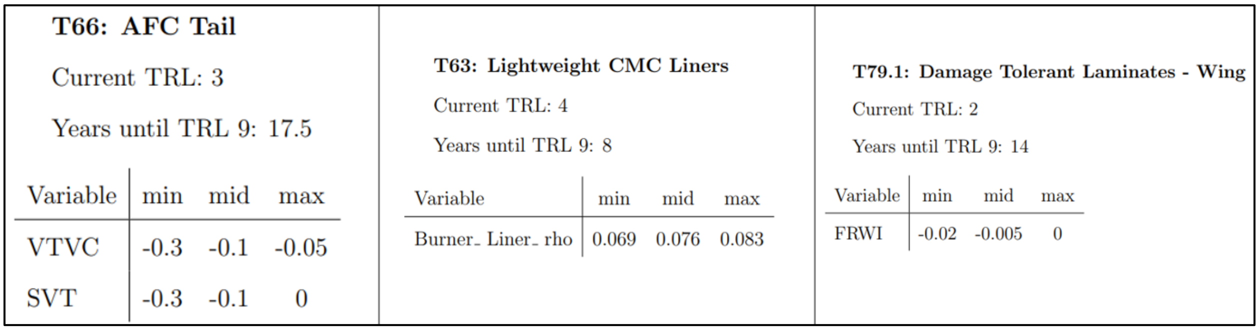
Table 1. Average effectiveness of advanced technologies given a 100 nmi stage length for the STAT Program from Ref. [24]

Technology	Percent Reduction	
	Direct Operating Costs	Block Fuel
Advanced Powerplant	10.2	23%
Advanced High Lift Systems	5.5	10.2%
Advanced Structures	5.0	4.4%
Advanced Propellers	2.5	5.7%
Advanced Airfoils	0.7	1.2%

Table 1 was used to summarize the findings from the STAT program, where reductions in DOC and block fuel from each advanced aircraft technology were reported for a 100 nmi stage length. Obtaining such performance metrics through direct experimentation and analysis incurs significant costs in manufacturing, testing, and personnel that cannot be reasonably qualified for the conceptual design stage for aircraft. The high expenses for personnel and resources required for wind tunnel testing and flight testing are usually reserved for technologically mature concepts, where performance has been quantified analytically. Furthermore, advanced computational simulations such as CFD and FEA are computationally expensive and require a high level of expertise and time investment for setup [25].

At the conceptual design phase where the candidate technology portfolios can consist of hundreds of advanced technologies, it is crucial to employ lower-order methods to estimate technological impacts on aircraft models. Lower-order modeling is done in Refs. [4, 26, 22], where performance impacts from advanced technologies are simply modeled based on a literature review of the technology that provides a generalized characterization and implemented as a point-based estimate, referred to as a “General Impact” [22]. However, these methods do not consider variability in performance encountered by some advanced aircraft technologies which are sensitive to design specifications and operational conditions. This cannot be omitted when considering the risk associated with performance impacts in Refs. [12] and [23], where performance risk is defined as a probabilistic problem in the NASA Risk Management Handbook. Specifically, Ref. [23] states that “performance risk addresses the probability that a given performance requirement will not be met, but it does not address the magnitude by which it may be exceeded (i.e., the full range of the uncertainty distribution for the performance measure.)” To address performance *risk*, probabilistic methods must be used for performance estimation.

Probabilistic performance assessments using low-order methods were previously endeavored in Ref. [14]. In this process, information was gathered by the ASDL team using literature search and initiating workshops with relevant SMEs across NASA to obtain performance impact information for each technology. Each impact for the technology was then mapped to a relevant k-factors in ASDL’s M&S tool for aircraft design, Environmental Design Space (EDS). The 3-point estimates were then used to form triangular distributions where minimum and maximum values bound the distribution and the mid-point value was the peak of the distribution.



T66: AFC Tail

Current TRL: 3

Years until TRL 9: 17.5

Variable	min	mid	max
VTVC	-0.3	-0.1	-0.05
SVT	-0.3	-0.1	0

T63: Lightweight CMC Liners

Current TRL: 4

Years until TRL 9: 8

Variable	min	mid	max
Burner_ Liner_ rho	0.069	0.076	0.083

T79.1: Damage Tolerant Laminates - Wing

Current TRL: 2

Years until TRL 9: 14

Variable	min	mid	max
FRWI	-0.02	-0.005	0

Figure 3. Example showing probabilistic analysis of performance impact from Ref. [14]

Figure 3 from Ref. [14] provides how technologies are presented by name, current TRL, projected TRL, and the 3-point triangular distribution informing the performance. While this considers the variational nature of performance, triangular distributions assume equal likelihood of outcomes within the defined range, which may not accurately reflect the true probability distribution of the performance impacts. This interpretation can lead to an underestimation of extreme outcomes or fail to capture the skewed distributions that are more common in real-world scenarios. Additionally, since the sourced values from literature review and SME consultation are provided without context on the experimental set-up or operational conditions that influence the performance data, the resulting model lacks granularity and may not accurately capture the complexities of technology performance under different conditions. Therefore, uncertainty is captured, but not characterized nor well-understood [19, 18, 27]. Omission of uncertainty analyses may lead to under- or over-design [28]. For programs such as ERA, EPFD, and AATT, coupling of M&S environments with uncertainty propagation methods is of interest for uncertainty-driven systems analysis [29]. Specifically, implementation of Monte Carlo methods in M&S environments have been found to enable successful propagation of small uncertainties throughout performance assessments [27, 28, 29].

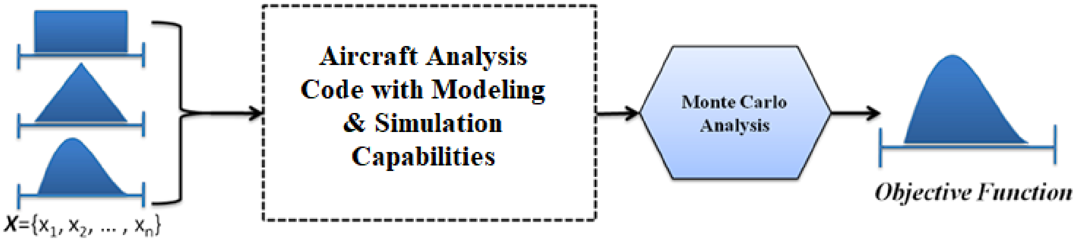


Figure 4. Monte Carlo (MC) simulation framework

Figure 4 depicts the methodology underlying the MC simulation framework. An MC simulation is a probabilistic analysis technique that uses random sampling to generate many possible outcomes and then calculates the probability distribution of those outcomes to determine likelihood of obtaining different results [20, 30]. The benefits to MC simulations for uncertainty propagation are providing the capabilities to evaluate non-linear systems (e.g., model-based aircraft systems) directly, computationally simulate the stochastic nature of errors and their impacts and produce results that reflect the influences of combinatorial effects of various uncertain parameters as physical values.

2.2 Introduction to the Technology Readiness Levels (TRL) Scale

Currently, the primary metric for measuring the maturity of a technology across agencies such as NASA, DoD and GAO is referred to as the TRL scale. While the concept of TRL began at NASA in 1974, the scale has since evolved to become the nine-level system known today, which was published as a whitepaper by Mankins et al. in 1995 [9]. The current TRL scale ranges from level 1 (basic technology research) to 9 (systems test, launch, and operations) and describes the state of a given technology.

Table 2. TRL summary from Mankins (1995) [9]

Technology Readiness Level	Definition
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of concept
TRL 4	Component and/or breadboard validation in a laboratory environment
TRL 5	Component and/or breadboard validation in a relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground and space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Table 2 depicts the TRL scale as initially defined by Mankins [9]. Usually, a technology must be at least TRL 6 or higher (which requires technology demonstrated in a relevant environment) before it can be integrated into a flight system [8]. Typically, new technology conception occurs from TRL 1 to TRL 3, development and demonstration occur between TRL 4 to TRL 6, and once a technology reaches TRL 6, the risk of the new technology is “roughly equivalent to the risk of a new design that employs standard engineering practice and is bounded by previously implemented ground-based systems" according to the NASA Technology Readiness Assessment Best Practices Guide [31]. NASA practice recommends that before the Preliminary Design Review (PDR) for a program is released, all in-development technology selected as part of the overall vehicle architecture must be TRL 6 [10].

2.2.1 Complications Applying the TRL Scale to Aeronautics

Application of the TRL scale to aeronautics technologies was first studied by Peisen et al. in a 1999 SAIC report contracted by NASA Langley Research Center [32]. In this report, a means of projecting operational readiness for NASA aeronautics technology to assess the potential impacts on national aerospace goals. Advanced aircraft technologies were selected where an investigation was then conducted into how long it has taken for technologies to go from initial concept to marketable products, using NASA's defined nine-level TRL scale [32].

By consulting NASA subject matter experts (SMEs), the Peisen et al. study compiled a list of nineteen technologies that had reached either TRL 6 or TRL 9 to trace the TRL transition histories of the technology [32]. It used TRL transition times to characterize the schedule risk for individual technologies using a combination of historical data collection and interviews with subject matter experts (SMEs) to create a dataset of aeronautics technologies and their TRL maturation histories. This is similar to the efforts conducted by Refs. [22, 12, 33].

A significant finding from Peisen et al. when applying the TRL scale to aeronautics was that the notion of technology assessments based on TRL and trajectories of "technologies moving from TRL to TRL" was not widely familiar among the NASA aeronautics research community.

Table 3. Summary of key takeaways from Peisen et al. [32]

Issue	Description

Interpretation	Several researchers commented that the definitions for TRL 1 to TRL 3 were “indistinguishable” all belonging to the same nascent stage of development aligned with theoretical and basic scientific understanding
	"Doesn't TRL 1 go back to Bernoulli?" The lack of clarity for "basic research level" prescribed by TRL 1 is unclear, which hinders the establishment of a consensus model for how research program progress is benchmarked
Contextual	Some TRL definitions apply more to space technologies than aeronautics technologies, for example TRL 7
Uncertainty	The uncertainty in TRL scale definitions and usage is non-negligible, but this does not mean efforts toward assessing the maturity of NASA technologies is infeasible.
	Potential payoffs for additional work toward development of a “research assessment framework” based on TRL that can be used within the context of aeronautics

Table 3 articulates the main takeaways from the Peisen et al.’s study on assessing technology maturity times for aeronautics technologies, where the TRL scale was used as a definitive metric. Key issues pertaining to interpretation and application of the TRL scale were raised such as the indistinguishability of earlier TRLs, lack of consensus on where the initial point of technology development efforts began, and the inherent uncertainty during the TRL assignment process. The final point describing the motivation behind a research assessment framework using TRL within the context of aeronautics served as much of the inspiration for this work. While many factors contribute to the uncertainty and variability of TRL transition times for many technologies, using the TRL scale to serve as a datum of reference for assessing the progress of a technology development program is valuable [32, 33].

TRL as a standalone metric is not a compete framework for TDRA—the same Mankins who pioneered the TRL scale used today believed that it was a metric that "did not contribute to assessing the risk of developing the technology in question [34]." Studying the time taken to progress from one TRL level to the next, however, adds a dimensionality to its usage. In 2012, El-Khoury et al., using the dataset created from Peisen et al., analyzed TRL-based schedule and cost models to develop a new decision-based framework for cost and schedule joint modeling [33]. Both studies drew a similar conclusion: the subjective interpretation of assumptions underlying TRL definitions and requirements to transition from one level to the next adds uncertainty when using TRL in the context of aeronautics.

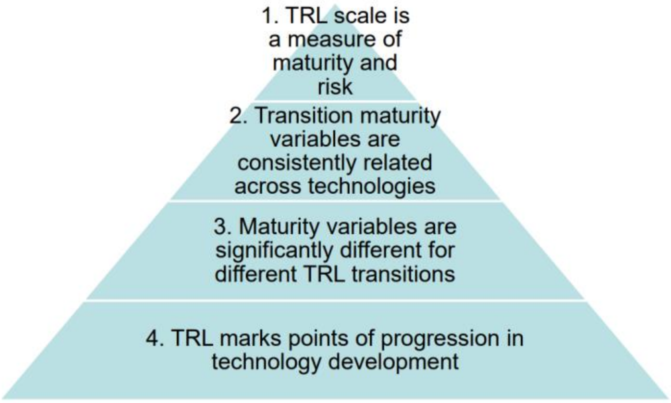


Figure 5. TRL assumptions in El-Khoury's framework [33]

Figure 5 provides the layered assumptions from El-Khoury's framework [33]. Further criticism of the TRL scale and its usage is discussed in a paper by Conrow et al. in 2011, that determines that TRL scales are ordinal coefficients—the time taken for a technology to reach TRL 8 is not twice the amount of time it took for the technology to reach TRL 4 [35]. This confers with El-Khoury's assumption on maturity variables being different across TRL transitions, where it suggests that attempting to use mathematical operations on TRL scale values such as averaging or forecasting will surely introduce errors [33, 35]. To remedy this for spacecraft technologies, Conrow uses an analytical hierarchy process (AHP) to convert TRL to a "cardinal scale" using a software called Experts Choice ® that surveys a limited pool of SMEs to rank technologies by TRL [35]. However, this methodology is neither transparent nor easily validated due to the "black box" nature of this third-party software and also, how spaceflight technologies differ from the trends observed by aeronautics technologies, which involve industry adoption.

Then, a 2021 study from Yu et al. presented at AIAA Aviation focuses on the necessity to evaluate other readiness levels outside of technology maturation, specifically system-related readiness levels such as integration with regards to novel aircraft design [8]. For aircraft design, TRL 6 signals that a new technology is ready to be considered for an application, however industry experience has shown that TRL 6, while necessary, is not fully sufficient to assess potential for application onto a platform due to other factors, referred to as the '-itilies' [8]. This includes manufacturability, certifiability, affordability, and other metrics pertaining to the integration of the technology onto the aircraft platform. Using case studies of three technologies that have been flight-tested, but have not progressed to commercial application—riblets, bug-phobic coatings, and active flow control—a new concept of a total technology readiness level is introduced that argues that assessment of these '-ilities' in the early development stage of aircraft design can become a game-changer for assessing technology transition [26].

Even in the space technology sector, shortcomings when applying the TRL scale have also been identified in past studies. Ref. [14] provides a summary of past studies critical of TRL shown in Table 2.

Table 4. Identified TRL shortcomings from Gatian et al. [14]

TRL Shortcoming	Source

TRL combines aspects of the entire system characteristics into one metric, which makes it hard to determine how each of the characteristics is affecting the overall TRL of the entity in question	Smith [36], Meystel et al. [37]
Does not mention the criticality of the technology with respect to the success of the entire system	Smith [36], Mankins [34]
TRL 9 definition does not work for systems that are constantly evolving/adapting/changing, such as software	Smith [36]
Varying level of importance of readiness throughout the acquisition lifecycle not captured	Smith [36]
Does not address the riskiness associated with the developing technology	Mankins [34]
Does not assess how difficult it will be to move from one level to the next	Mankins [34], Sauser et al. [38]
Early TRL stages are like a checklist of requirements	Meystel et al. [37]
Does not represent integration difficulty	Sauser et al. [38], Jiminez et al. [39]
Ambiguity of definitions make it difficult to use it	Tan et al. [40] and Peisen et al. [32]

Table 4 provides the classical criticisms of the TRL scale that serves as motivation to explore innovative methods to improve its usefulness. Doing so may reduce the reliance on TRL assessment and forecast by individual expert opinion, which adds more unquantified uncertainty to assessing the schedule risk of a technology development program because interpretation of the TRL scale and SME opinion incurs ambiguous levels of uncertainty due to subjective interpretation.

2.2.2 Improving TRL Scale Adaptability for Aeronautics

The TRL of an advanced aircraft technology exhibits variability based on its specific application location within an aircraft, the type of aircraft it is integrated onto, and the diverse conditions under which it undergoes ground and flight testing. exhibits variability based on several factors, including their specific application location within an aircraft, the aircraft type they are integrated onto, and the conditions encountered during ground and flight testing. Assigning TRLs within the aeronautics sector requires careful consideration of context, with the 'relevant environment' encompassing parameters such as Mach number, Reynolds number, altitude, speed, and other flow conditions that influence technology performance.

For example, the Reynolds number, determined by fluid density, velocity, characteristic length, and dynamic viscosity, holds particular significance. The wing and fuselage of an aircraft possess distinct dimensions and characteristic lengths, leading to variations in flow velocity around these structures and subsequently diverse Reynolds numbers [41]. This inherent dissimilarity in flow behaviors and aerodynamic effects explains the fluctuating TRL assignments based on the technology's specific application area on the aircraft.

Moreover, technologies within the aeronautics sector must navigate stringent certification processes that not only influence their progression along the TRL scale but also accommodate these nuanced contexts. Advancement through TRLs can vary, influenced by factors like structural integrity, criticality, and potential impact on flight safety. For instance, the active flow control technology successfully implemented on a vertical tail for the ecoDemonstrator 757 within the ERA timeframe might face greater scrutiny when applied to the wing due to structural complexities or effects on primary flight surfaces [6]. Furthermore, certain technologies that suit one aircraft class might prove unsuitable for another, as demonstrated by the distinct requirements of propellers versus turbofans owing to their varying Mach numbers. Hence, enhancing the adaptability of the TRL scale in aeronautics entails developing a framework that acknowledges and accommodates the inherent variability of TRL assignments across diverse applications, fostering more accurate assessments of technology readiness and promoting effective integration within the aviation landscape.

2.3 Late-Stage Technology Development Risk: Integration, Certification, and Operation

So far, performance evaluation and timeline risk assessment has been discussed for the TDRA framework for advanced aircraft technologies. The next part, is to address the later stages of the technology development process which can be summarized as:

1. <u>Integration</u>, where the various components and subsystems of the aeronautics technologies are integrated into the flight demonstrator where compatibility between different systems (airframe, propulsion, avionics, control systems) must be established in this phase [39].
2. <u>Certification</u>, which is an important process for aeronautics technologies specifically as experimental aircraft and technologies must undergo rigorous certification processes to meet safety and regulation standards set forth by the FAA. This process involves close cooperation with aviation authorities to demonstrate the technology's performance, reliability, and compliance with airworthiness requirements.
3. <u>Operation</u>, which is where 'technology development' transitions to 'product development' where once the technology is certified, the focus shifts to scaling up production and deploying aircraft utilizing these advanced technologies for commercial use.

These later-phase development stages can involve additional steps and iterations based on the specific project requirements, but a successful TDRA framework should be able to capture the maturity of a technology development project to successfully articulate associated risks at each stage. Usually, new aircraft or vehicle design looks to TRL 6 to signal that new advanced technologies are ready to be considered for application. However, industry experience has shown that TRL 6, while necessary, is not enough to assess the potential an application may have onto a platform as found by Yu et al [8].

To address the shortcomings in TRL, various developmental progress frameworks have been created such as Integration Readiness Level (IRL), Manufacturing Readiness Level (MRL) and System Readiness Level (SRL) [14, 8]. IRL was first proposed by Sauser et al. as a "measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points [38]." The IRL metric assigned to a technology in development indicates its level of integration maturity in relation to another technology that is intended to be incorporated into the same system.

Table 5. Integration Readiness Level (IRL) definitions

	IRL	**Definition**
Pragmatic	9	Integration is **Mission Proven** through successful mission operations.
	8	Actual integration completed and **Mission Qualified** though test and demonstration, in the system environment.
Syntactic	7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.
	6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.
	5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.
	4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.
Semantic	3	There is **Compatibility** (i.e., common language) between technologies to orderly and efficiently integrate and interact.
	2	There is some level of specificity to characterize the **interaction** (i.e., ability to influence) between technologies through their interface.
	1	An **interface** between technologies has been identified with sufficient detail to allow characterization of a relationship.

Table 5 depicts Sauser's IRL scale. Jimenez and Mavris identified four issues with the IRL metric: it is not universally applicable, is restricted to datacentric applications, does not provide architecture information until Level 8 and 9, and is meant to be independent of the TRL metric, which they view as a weakness as integration can be seen as a sub-attribute of TRL [14, 39]. Then, for SRL, the aggregation of TRL and IRL is problematic for the same reasons stated by Conrow and El-Khoury, where mathematical operations using the ordinal TRL scale propagate unknown uncertainties [33, 35].

Since new breakthrough technologies have long or uncertain lead times, Ref. [8] proposed that the most successful technology transitions rely on consideration of TRL, MRL, IRL and SRL in both the technology development and vehicle design process. From this, the concept of Total Technology Readiness Level (TTRL) was introduced by Yu et al., which considers the multi-dimensionality of technology development decision-making, particularly in the later phases of design. By considering the '-ilities', that is, other considerations throughout the later stages of the technology development timeline up to rollout into commercial operations, qualitative assessment can be done earlier to minimize future potential risks [14, 8].

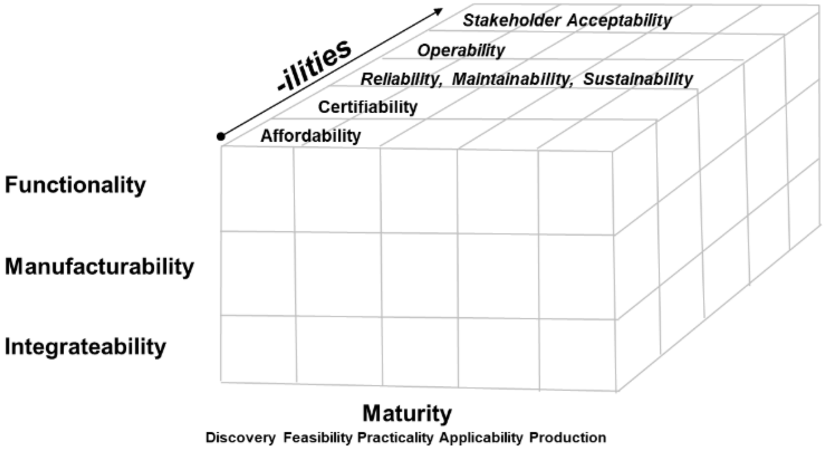


Figure 6. Presentation of technology maturity using '-ilities' [8]

Figure 6 portrays the multi-dimensional nature of technology maturity beyond TRL. Successful technology development involves not only achieving technical readiness but also ensuring that a technology can be seamlessly integrated into a flight test demonstrator and eventually certified for demonstrative or operational use, hence consideration of "Integrateability" and "Certifiability."

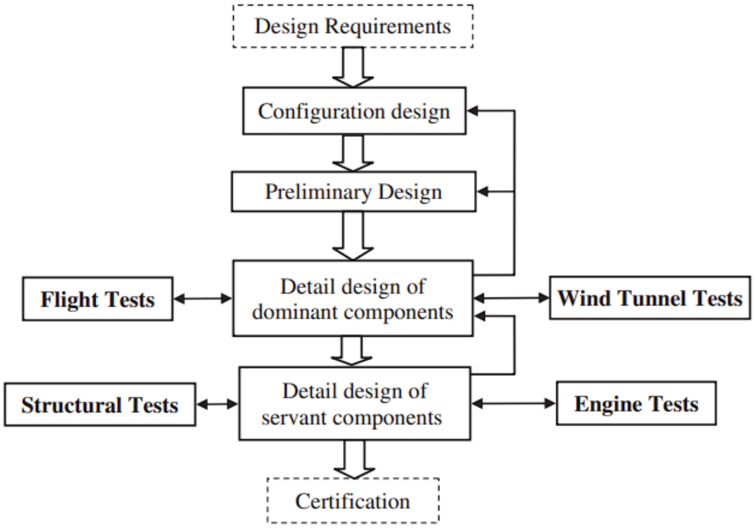


Figure 7. Certification in the aircraft design process

Figure 7 shows how the data obtained from performance evaluation tests is used to inform certification efforts. To obtain flight permissions for the general airspace, certification provided by government agencies that regulate, ratify, and collect aviation standards must be obtained. In the United States, the body that regulates aviation-related issues is the FAA who oversee aircraft design and manufacturing. The requirements put forth by the FAA are called FARs that detail the requirements that novel technologies and concepts must meet to obtain "airworthiness." For flight test demonstrations of airplanes integrated with advanced technologies, a special airworthiness certificate in the experimental category may be required for issuance. A special airworthiness certificate in the experimental category is issued to operate an aircraft that does not have a type certificate or does not conform to its type certificate and is in a condition for safe operation, such as a flight test [42].

While the technical risk management process does not explicitly call for assessment of '-ilities' such as "Integrateability" or "Certifiability", overlooking these considerations have resulted in program cancellations. For example, one of the reasons leading to the X-57 flight demonstrator cancellation was due to high vibrational levels during the ground tests of the electric motors that were not compliant with FAR Part 23, Subpart E: Powerplant Installation and a requested vibration demonstration required in Special Condition No. 20 issued by FAA regulatory authorities with respect to FAR Part 33 [43, 44]. From ground vibrational tests it was discovered that industrial-grade ball bearings were "lower grades than aviation standards" and caused unforeseen issues due to improper seating. The inability to obtain airworthiness grounded the X-57 flight demonstrator where the program ceased without a flight test demonstration.

For aeronautics technology development programs such as EPFD that require a flight test demonstration, obtaining certification is an important, non-negligible process that ensures compliance with airworthiness standards that must be met otherwise, the entire technology development program risks termination. Therefore, certain '-ilities' from Ref. [8] such as integrateability and certifiability should be assessed as its own category of risk, rather than combined with all other operational '-ilities.'

Meanwhile, the application of TTRL is well-suited for providing an overview of operational risks that extend beyond a technology development program. For projects such as EPFD and the Sustainable Flight National Partnership (SFNP) under IASP, NASA is focused on advanced aircraft technologies that are commercially viable and of interest to industry partners who will transition technology development programs that have reached TRL 6 into product development programs that will take the technology to TRL 9. When developing the TTRL framework, technologists, vehicle designers, and system analysts were asked to identify specific real-world hurdles to the operational readiness of a technology.

Affordability Favorable cost and benefit (net value proposition) within availability of resources

Manufacturability Producability of the vehicle, effectively at high quality and rate

Certifiability An acceptable path to certification approval with relevant regulatory agencies

Operability In-use operations within the vehicle system, and compatible with overall aviation system of systems (e.g. airport infrastructure, pilot training, air traffic management systems)

Integrateability Interfaces and interactions between technologies and systems within the vehicle and throughout the manufacturing / production system and overall operational environment

Reliability, Sustainability and Maintainability – Relevant market, environment, industry requirements and expectations
Reliability –Operational dispatch, airplane availability and inflight operations
Maintainability –Ease, cost, and speed of monitoring inspections and conducting servicing and overhaul
Sustainability – Lifecycle long term economic, social and environmental impact / people, planet, profit

Stakeholder Acceptability Willingness of financial investors, manufacturers, regulators, operators and the public to accept new technology (business / technical risk, disruption of development / production process, confidence in cost estimates, potential benefits, schedule)

Figure 8. Definition of key -ilities in the TTRL methodology [8]

Figure 8 shows the definition of several key '-ilities' that came from discussion of a TTRL framework that decision-makers must consider when evaluating the feasibility, practicality, and applicability of advanced aircraft technologies [8]. This framework of 'ilities' readiness lends a non-prescriptive development vector that can serve as guardrails for SMEs, technologists, programmatic-level decision makers and engineers to collaborate on highlighting future risks and risk mitigation plans that may stand in the way of demonstration and operational readiness [8].

PART III: METHODOLOGY FORMULATION

“Multi-disciplinary Design Optimization techniques truly can improve the weight and cost of an aircraft design concept in the conceptual design phase. This is accomplished by a relatively small “tweaking” of the key design variables, and with no additional downstream costs. *In effect, we get a better airplane for free*” – Daniel P. Raymer’s Ph. D Thesis, 2002.

III. METHODOLOGY FORMULATION

From the previous section, the factors used to assess technology development risk have been formalized: performance, which relates to the technology's impact on the vehicle system, is typically evaluated at the conceptual design phase through systems-level analysis within an M&S environment such as in Refs. [14, 18, 22]. The next factor, timeliness, or timeline readiness refers to whether the technology can be sufficiently matured within the program's timeframe and has been historically gauged using the TRL scale [45]. Then, later-stage efforts in a technology development program posed by integration, certification, and operation are also relevant considerations in the realm of a TDRA framework. Since ease of integration is an important characteristic in determining which technologies can be feasibly incorporated onto a demonstrator vehicle in a timely manner and potentially scale into commercial production/operations, it is important to include this factor into the TDRA framework structure [39]. Additionally, certification has not previously been factored into TDRA frameworks in the past, however, its importance in the realm of aeronautics cannot be understated [43]. If one wishes to conduct flight test operations, certification must be factored into the overall timeline of the effort, along with performance requirements [46]. Lastly, operational risk has been discussed indirectly in efforts preceding the 2015 demonstration of the NASA/Boeing 757 ecoDemonstrator and within the context of the TTRL framework but has not been included as a factor related to technology development risk [8]. Since stakeholders within EPFD, SFD, and SFNP are concerned with technologies that promise to transition into commercial operation, its inclusion adds a necessary dimension to a useful TDRA framework [47]. Therefore, an outline of these factors (PICTO) defines the structure of the proposed, new TDRA framework.

Now that the structure has been formalized, an approach to address each of these factors must be developed with consideration of the high levels of uncertainty at the conceptual design phase. Within this chapter, a novel approach to uncertainty-driven performance estimation and timeline readiness is developed for advanced aircraft technologies. This original strategy leverages probabilistic methods to account for the uncertainties present in the current fidelity of the analysis to capture performance and TRL variability using a semi-empirical, quantitative approach. An introduction to the M&S tools and methods used to build up baseline aircraft models and infuse technologies will be discussed along with the analytical set-up for the case study that the TDRA framework will be applied to. For the later-stage items such as integration, certification, and operational risk assessment, qualitative analyses to reduce the uncertainty at the conceptual design phase will be introduced that draw from previous risk reduction efforts described in Ref. [48]. While the previous section contributed to the formation of the PICTO approach, the following section details the unique quantitative and qualitative methods that the approach entails.

3.1 Vehicle Synthesis & Modeling

To assess the performance impacts of the advanced technologies at the conceptual design phase, a baseline aircraft model must be parametrically established within an appropriate modeling and simulation (M&S) environment. Establishing the reference aircraft model allows for cross-comparison between the technology infused model and baseline model to evaluate the specific performance benefits from application of the technology, such as in Refs. [9, 43, 44].

3.1.1 Modeling & Simulation (M&S) Tool Selection

For this study, sizing and mission analysis of the aircraft was performed using the NASA-developed General Aviation Synthesis Program (GASP), a parametric modeling and mission analysis tool that emphasizes fixed-wing airplanes with turboprop/turbofan propulsion systems initially developed at NASA Ames Research Center and later enhanced at the Georgia Institute of Technology in the 1990s, and as of recent years, has been currently maintained and further developed by Jeffrey V. Bowles of NASA Ames Research Center to facilitate NASA ARMD system analysis efforts [11]. Other comparable programs are NASA Langley Research Center’s Flight Optimization System Software (FLOPS), Stanford University’s Program for Aircraft Synthesis Studies (PASS), and Georgia Institute of Technology’s Electrified Propulsion Architecture Sizing and Synthesis (E-PASS) which all leverage semi-empirical models to capture aircraft performance sensitivities to input variables.

GASP is primarily used during the conceptual phase of the aircraft design process and consists of the following integrated modules: Geometry, Aerodynamics, Propulsion, Economics, Mission Analysis, and Weight and Balance. It uses modular discipline analysis construction within its computational flow to capture the interactions and synergistic effects of the various technical disciplines [49].

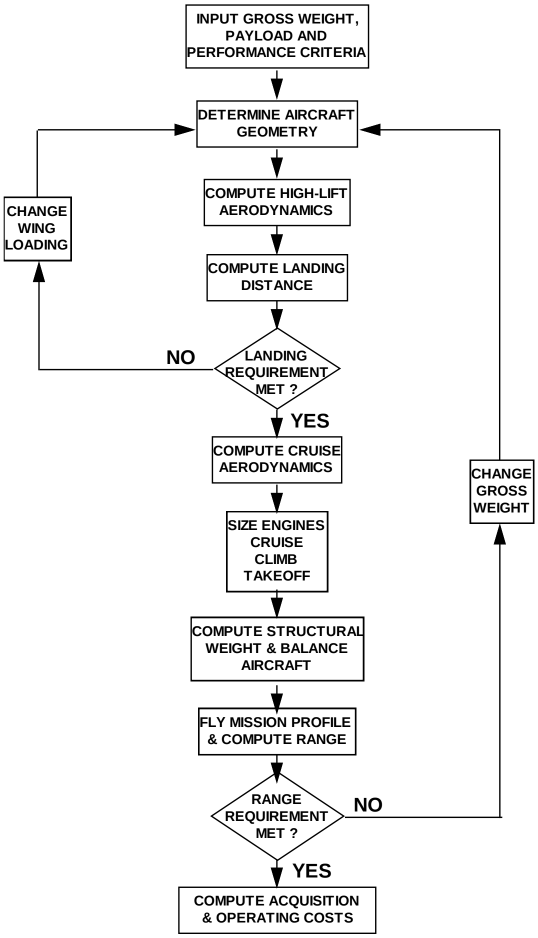


Figure 9. Flow chart of the computational sequence in GASP [49]

Figure 9 depicts the typical computational flowchart of the GASP program where interacting effects of the design variables are continuously accounted for during the aircraft sizing procedure. In the Geometry module, the aircraft components' dimensions are determined where input parameters would include the passenger count, aspect ratio, taper ratio, sweep angles, and wing and tail surface thicknesses. The cabin is assumed to have a circular cross-section, and the sizing of tail surfaces relies on established trend equations used for similar aircraft. The module's output includes various measurements such as areas, lengths, angles, etc., which might be required by other modules. Then, the Weight and Balance modules takes an input guess for the gross weight and the payload, along with the aircraft geometry and weight trend coefficients.

Here, GASP offers options to size the tip tanks and position the wing structure to ensure the aircraft maintains balance throughout its center of gravity travel, where static margin can be provided, if known. The Aerodynamics module calculates the various lift and drag coefficients of the synthesized aircraft based on inputs related to the gross configuration geometry, flight conditions, and the type of high-lift devices. The Propulsion module enables simulation of various propulsion systems including turbojet, turbofan, turboprop, and reciprocating/rotating combustion engines and provides engine thrust and fuel flow data for specific engines at any given flight condition. The module determines the engine size and performance, considering both cruise and take-off requirements of the aircraft. As of 2023, ongoing progress is being made to incorporate capabilities for modeling hybrid-electric and fully electric aircraft propulsion systems within GASP. Though not used for this study, the Economics module computes flyaway and operating costs.

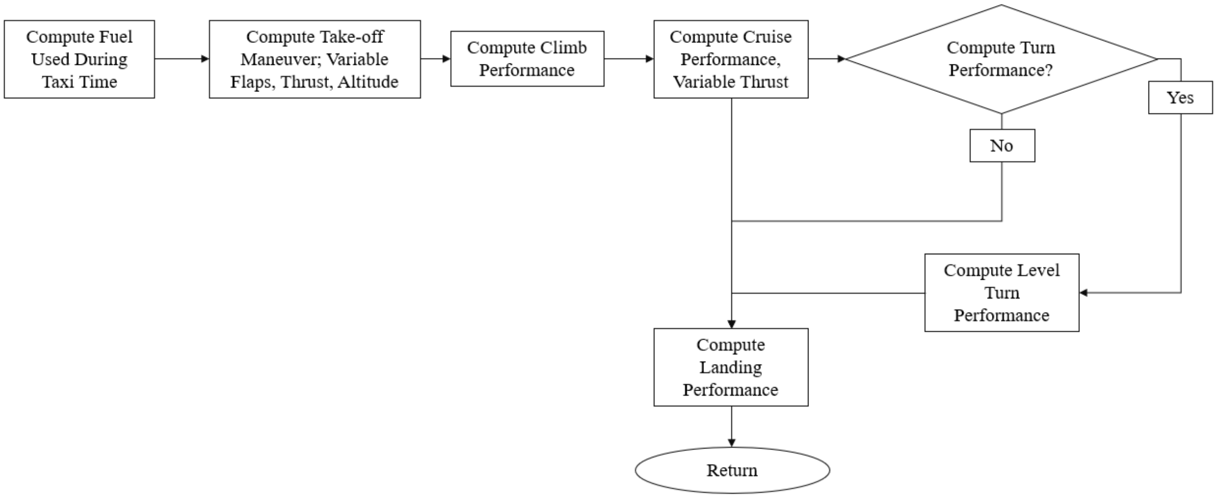


Figure 10. Mission performance module in GASP

Figure 10 depicts the Mission Performance module in GASP, which analyzes the different segments of a flight mission, including taxi, take-off, climb, cruise, and landing. It computes the total range of the aircraft. The module offers options for calculating engine out and accelerate/stop distances, best rate of climb, high-speed climb, and other operating characteristics. If a specific range is needed, the module determines the appropriate aircraft size that can achieve this range within a specified tolerance [49].

When using GASP to evaluate fuel efficiency, the relevant parameter is specific fuel consumption (SFC), which defines how much fuel that the aircraft’s engines consume to produce a given amount of thrust or power. A low SFC value is desirable because it results in reduced fuel costs, longer range capabilities, and extended endurance for missions or flights. Aircraft with low SFC can also have a smaller fuel load, leading to lighter overall weight and potentially increased payload capacity or improved operational flexibility. For turbojets and turbofans, GASP expresses this value as thrust-specific fuel consumption (TSFC). On the other hand, for turboprop aircraft with engines that produce shaft power, the BSFC is of interest as it measures the amount of fuel consumed by the engine to produce a unit of brake horsepower or shaft power. Unlike turbojet or turbofan engines that generally operate at a relatively constant power setting, turboprops are used in applications where the power output can vary significantly, such as in aircraft performing takeoff, climb, cruise, and descent. Thus, BSFC is the metric used as it considers the engine’s power output and turboprop aircraft experience a wide range of power settings. Within GASP, propeller calculations are done using Hamilton Standard propeller models [50].

In general, conceptual aircraft sizing and design procedures such as those within GASP rely on semi-empirical equations that couple theoretical principles and real-world experimental data to allow for preliminary aircraft performance estimation. Semi-empirical equations play a crucial role in aircraft multidisciplinary design optimization (MDO) by providing a pragmatic, computationally efficient means to obtain performance estimations across a variety of disciplines such as propulsion, structures, and aerodynamics. Semi-empirical models draw from a wealth of accrued historical data from wind tunnel experiments and flight test operations to generate simplified equations that quantify the sensitivity that certain aircraft sizing parameters have on aerodynamic forces. An example of a semi-empirical model is the Breguet range equation, which is used in all GASP versions to assess the distance the aircraft can travel on a given amount of fuel. For aircraft with airbreathing engines that burn fuel, the gross weight of the vehicle changes as fuel is consumed to fly the design mission. Assuming cruise-climb conditions with a constant C_L and airspeed, V, the lift force is given by the following equation.

$$L = W = \frac{1}{2}\rho V^2 C_L S \tag{1}$$

Eq. (1) is a fundamental aerodynamics equation that considers the impact of flow conditions and wing geometry on the lift characteristics at steady-flight and equilibrium of forces on the aircraft. Assuming the propeller efficiency is constant throughout the mission and that thrust is equivalent to drag for steady, level flight:

$$\eta_p P = DV \tag{2a}$$

Eq. (2a) can be rearranged to obtain the shaft horsepower in terms of the drag force, airspeed, and propeller efficiency:

$$P = \frac{DV}{\eta_p} \tag{2b}$$

For a propeller-driven aircraft, determination of the differential air distance covered, a function of airspeed and change over time, is given as:

$$ds = Vdt \tag{3a}$$

Eq. (3a) is based on the fundamental physical law that velocity is defined by change in position over time, where the right-hand side is the differential distance covered. Since the

Breguet range equation is derived on the assumption that the change in weight over time is a function of BSFC and power, the following relation is derived:

$$dW = BSFC(Pdt) \tag{3b}$$

The total range, or distance travelled, can be found by integrating Eq. (3a). Using the definitions provided in Eqs. (1), (2), and (3), ds is redefined:

$$ds = Vdt = V\left(\frac{dW}{-BSFC \cdot P}\right) = -V\left(\frac{\eta_p}{BSFC}\right)\left(\frac{dW}{DV}\right) = -\frac{\eta_p}{BSFC}\left(\frac{L}{D}\right)\left(\frac{dW}{W}\right) \tag{4}$$

Where from integrating Eq. (4), the Breguet range equation for a turboprop aircraft can be found by the semi-empirical equation:

$$R = \frac{\eta_p}{BSFC}\left(\frac{C_L}{C_D}\right)\ln\left(\frac{W_0}{W_1}\right) \tag{5}$$

Eq. (5) is used during the conceptual design phase to provide an estimate of the range achievable by an aircraft, where the air density ρ may decrease during cruise-climb. The lift-to-drag ratio C_L/C_D is equivalent to L/D and allows for assessment of the aerodynamic efficiency, while the difference in the initial aircraft weight (W_0) and final aircraft weight (W_1) is the weight of fuel consumed during cruise. The derived Breguet range equation shown in Eq. (5) is shown to be a function of propulsive efficiency, brake-specific fuel consumption, aerodynamic efficiency, and the structural weight, which are all areas of impact for advanced aircraft technologies. Hence, it is logical to use semi-empirical methods to simulate technology infusion within the M&S environment provided by GASP.

Within GASP, the benefits recognized from applying advanced technologies are implemented using technology factors that impact specific areas such as fuel flow rate, component structural weights, or component skin friction drag coefficients. When conducting technology sensitivity studies, the established vehicle must be “closed” before modifications can be applied. For a “closed” vehicle in GASP, the user inputs the desired range ARNGE(1), and

GASP will iterate on the gross takeoff weight (W_{GTO}) required to match the desired range including the reserve mission fuel [51]. The vehicle is then "closed" when the fuel available (W_{FA}) is equal to the fuel required, which is found by estimating W_{GTO}, where error = Range Required – Range Available. This is done using the Newton-Raphson iteration method [49, 51]. Thus, to size the vehicle, a desired range ARNGE(1) is input.

On the contrary, for a vehicle that is "not closed" the W_{GTO} is input, and GASP determines the empty weight based on that gross takeoff weight. Thus, the fuel available (W_{FA}) = $W_{GTO} – W_{OWE} – W_{PL}$. GASP will then analyze the mission and then determines the range of the airplane. This is done as a single pass run where the range capability is found for the input W_{GTO} and does not involve sizing. Then, the fuel required (W_{FR}) is found from flying the mission at the input W_{GTO}. Advanced technologies can be applied, but W_{FA} will not change while W_{FR} will if there is a change due to drag reduction or fuel flow rate [51]. For the technology sensitivities done as part of the TDRA framework, the target design range is set to obtain results for a "closed" vehicle where $W_{FR} = W_{FA}$ [49, 51].

3.1.2 Reference Aircraft Model Selection and Development

In previous studies such as Cai et al. that assessed the impacts of advanced technologies on regional turboprops, the Avions de Transport Régional/ Aerei da Trasporto Regional ATR 42-600 was selected as the Technology Reference Aircraft (TRA) [26, 52]. The ATR 42-600 is a regional commuter airplane produced by the French-Italian manufacturer ATR. Currently, it is the only 50-seat regional turboprops still in production because it shares most of its airframe and subsystems design with the newer, larger ATR 72 turboprop variant [26, 52]. Thus, the ATR 42-600 is selected for this study as the state-of-the-art representative of its aircraft class. The ATR 42-600 is powered by two Pratt & Whitney PW127XT-M turboprops and can carry a payload of

10,550 lbf (50 passengers) over 726 nmi with sufficient fuel reserves for an additional 100 nmi [52]. Calibration of the aircraft and engine models were done in GASP and validated against the published manufacturer data.

Table 6. Validation of GASP ATR 42-600 model from Ref. [53]

Parameter	Manufacturer Data [52]	GASP	Error
Maximum Takeoff Weight (lb)	41,005	41,005	**-**
Operating Empty Weight (lb)	25,794	25,491	**-1.18%**
Wing Planform Area (ft^2)	587	587	**0%**
Engine Rated Power (shp)	2,188	2,160	**-1.29%**
Block fuel, 300 nmi (lb)	1,733	1,789	**+3.18%**

Table 6 shows the comparison of published airplane parameters from ATR with the ATR 42-600 model synthesized in GASP, where it was determined that the calibrated model was within acceptable levels of agreement (absolute error <~3%.) Additionally, a detailed drag estimation and weight breakdown was obtained from GASP.

Table 7. ATR 42-600 drag estimation from GASP from Ref. [53]

Component	Flat Plate Area (ft^2)	CD_0
Wing	4.742	0.00808
Fuselage	4.9192	0.00838
Vertical Tail	1.2062	0.00205
Horizontal Tail	1.2139	0.00207
Engine Nacelle	1.193	0.00203
Winglet	0	0
Strut	0	0
Tip Tanks	0	0
Excrescence	0.995	0.0017
Interference	0.577	0.00098
Incremental	0.2935	0.0005
Total	15.1398	0.02579

Table 8. Detailed GASP weight breakdown for ATR 42-600 (all listed values in lb) from Ref. [53]

Subsystem	ATR 42-600
Structures	12,828

Wing	3,445
Empennage	713
Fuselage	6,112
Landing Gear	1,640
Engine Section	916
Propulsion	4,677
Primary Engines	2,198
Engine Installation	679
Fuel System	414
Propulsor	858
Flight Controls	807
Fixed Equipment	5,932
Empty Weight	24,243
Fixed Useful Load	1,248
Operating Empty Weight	25,491
Payload	10,053
Fuel	5,461
Gross Takeoff Weight	41,005

Table 7 and Table 8 are the baseline values for the drag breakdown and weight statement for the baseline ATR 42-600 model synthesized in GASP from Ref. [53]. For technology sensitivity studies, these values serve as a benchmark to assess the impacts of aerodynamics and structural technologies. For example, application of composite materials on the wing would reduce the wing weight, which is reflected in the gross takeoff weight of the overall aircraft. For this study, the impacts of advanced aircraft technologies are studied on the wing and fuselage primarily to reduce computational times and redundancy.

3.1.3 *Reference Mission Profile*

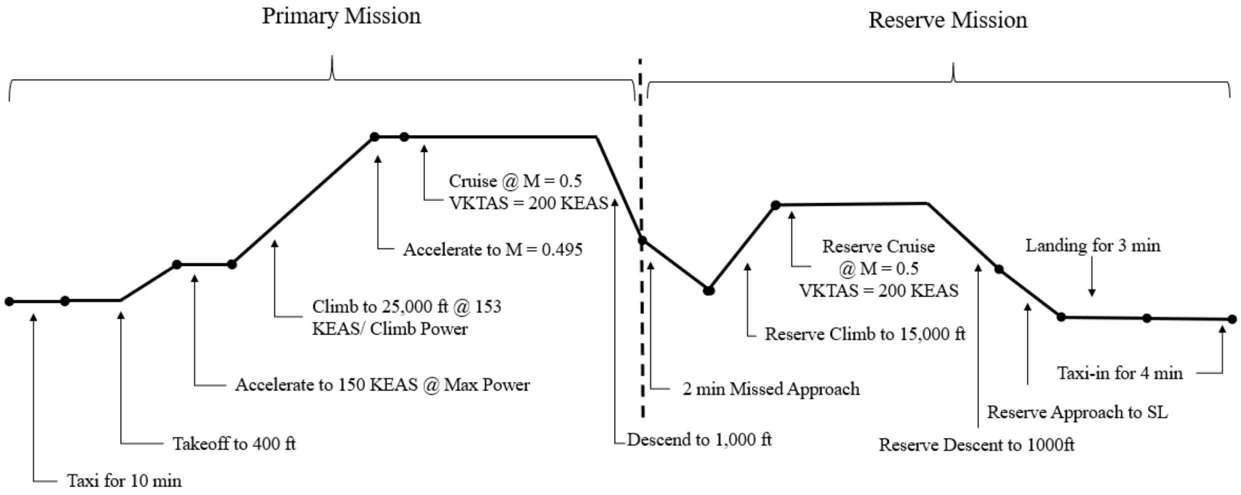


Figure 11. Reference and reserve mission profile from Ref. [53]

The reference mission flight profile used is shown in Figure 11 for the ATR 42-600 from Ref. [53]. Using these missions, GASP is then able to compute the aircraft performance. The mission profile is described, similarly to that used in Ref. [26]:

1. <u>Taxi-out:</u> Taxi for 10 minutes
2. <u>Takeoff:</u> Takeoff to 1500 ft for 1 minute and accelerate to 150 KEAS at maximum power
3. <u>Climb:</u> Climb to 25,000 ft at 153 KEAS
4. <u>Cruise:</u> Level cruise at 25,000 ft at 200 KEAS
5. <u>Descent:</u> Descend to 1,000 ft (GASP default) at 200 KEAS and a vertical speed of 1200 ft/min
6. <u>Missed Approach:</u> Missed approach while decelerating to 107 KEAS.
7. <u>Reserve Climb:</u> After missed approach, climb to 15,000 ft at 153 KEAS.
8. <u>Reserve:</u> Level cruise at 15,000 ft at Mach 0.5 (hold for 45 minutes)

9. Reserve Descent: Descend to 1,000 ft at 200 KEAS and a vertical speed of 1200 ft/min.
10. Reserve Approach: Descend to sea level (GASP default) while decelerating to 107 KEAS.
11. Landing: Final approach and landing for 3 minutes
12. Taxi-in: Taxi for 4 minutes

Within this mission, a 125 nautical mile reserves mission is included as per FAR Part 25 [54]. Shown in the profile, a level flight segment accelerates the aircraft to the best rate-of-climb speed. Descent is flown at flight idle power setting at the cruise Mach number, constrained if applicable by the fuselage pitch angle and maximum rate of sink. For the reserve mission, a 3% mission fuel reserve allowance is prescribed within GASP [51]. The missed approach is a two-minute time allocation at maximum takeoff power where there is a reserve climb out to 15,000 ft cruise altitude, followed by cruising at the nominal cruise Mach for 45 minutes to the alternate airport and flown at best endurance speed. A four-minute time allowance for approach and landing is added.

3.1.4 Advanced Aircraft Technology Portfolio Selection

The advanced aircraft technologies studied in this report have been of interest to projects such as AATT, ICAO’s LTAG reports on technologies that are linked to fuel burn improvements, which directly results in lower CO_2 emissions and lower operating costs. The technologies selected by this study are characterized by their area(s) of impact: aerodynamics, propulsion, weight reduction (through structural design/material selection), and flight systems and have been previously mentioned in technology portfolios analyzed by ICAO, NASA ARMD, and the Georgia Institute of Technology in Refs. [26, 22, 48, 16]. Aerodynamics technologies, often referred to as drag reduction technologies, improve overall aircraft performance in terms of the lift-to-drag (L/D) ratio by reducing the aircraft drag passively or actively. Since a major driving force in the turboprop aircraft market is reducing airplane-related operating costs where fuel cost is the larger contributor (40-50% for single-aisle airplanes), airline customers are keen to look at aerodynamic drag reduction technologies to lower fuel consumption [48]. This includes technologies that increase wingspan or aspect ratio and modified winglets, along with viscous drag reduction technologies such as laminar flow, high-lift technologies, micro-scale riblet geometries, hybrid and natural laminar flow control, and active flow control technologies. Structural technologies pertain to all aeronautical technologies impacting the basic structure of the aircraft such as the wings, fuselage, and empennage—primarily, reducing design and operating costs by decreasing the airframe empty weight, gross takeoff weight, and improving airframe material qualities. Propulsion technologies pertain to all innovations concerning the powerplant of an airplane—this includes improvements to the turboprop engine cycle, improved engine materials that allow for higher inlet temperatures, and component-level improvements that bolster the compressor and turbine efficiencies. Flight systems technologies encompass all technologies that play an active role during flight, including operation, navigation, and safety [21]. Technologies under the flight systems category can play a role across any, or multiple aircraft subsystems such as aerodynamics, structures, or propulsion. Work on research, development, and demonstration of these technologies are often formalized as technology development programs.

For the case study technology portfolio, a comprehensive literature review was conducted to identify representative technologies that were currently in development, expected to reach TRL 6 by 2030 according to Ref. [19], applicable to regional turboprop aircraft, and characterized by performance variability that can benefit from uncertainty-driven systems analysis. This led to the selection of six technologies encompassing aerodynamics, structures, and propulsion.

Table 9. Case study technology portfolio

Technology	Category	Description	Impact Summary
Riblets	Aerodynamics	Riblets are rectangular or V-shaped riblets placed in the turbulent region of the wing and fuselage reduce skin friction drag by constraining the motion of vortices at the near-wall region [22].	Expected to reduce the skin friction drag on a 2D airfoil section by 5-8% and 1-6% when applied on the fuselage [55].
Natural Laminar Flow (NLF)	Aerodynamics	NLF applies to technologies that reduce skin friction drag by optimizing the airfoil shape to delay the transition to turbulence [56].	Expected to reduce skin friction drag on applied components by increasing the transition location on the chord of the component [57].
Excrescence Reduction	Aerodynamics	Excrescence reduction decreases the aircraft parasitic drag by reducing surface imperfections and irregularities; this is implemented through tighter design and manufacturing tolerances [58].	Expected to reduce the existing excrescence drag on the aircraft [26, 22].
Damage-Arresting Stitched Composites (DAC)	Structures	Stitched composites are a lightweight, strong composite technology that stitches together dry fabrics, infuses resin, and cures at atmospheric pressures [59].	Expected to reduce the structural weight of the aircraft wherever it is used, replacing older composites or aluminum structures [60, 59].
Active Load Alleviation	Flight Systems	Active load alleviation systems senses and modifies significant loads on the wing (e.g., gust loads and maneuver loads) and mitigates them by actuating flight control surfaces to reduce the induced wing root bending moment.	Expected to reduce the wing root bending moment, leading to a significant decrease in the structural weight and increasing passenger comfort.
Advanced Engine Cycle & Materials	Propulsion	By the year 2030, it is expected that design improvements in turbine temperature capabilities, component design, cooling methods, thermal barrier coatings (TBCs), and pressure ratios will lead to the development of more advanced turboprop engines [26, 22, 61].	Expected to produce the same power output as baseline engines, but with reduced BSFC and specific dry engine weight [26, 22, 61].

Table 9 shows the portfolio that will be applied to the ATR 42-600 and analyzed by the proposed TDRA framework in the example case study. Each technology represents a system on the aircraft that can be improved by the infusion of advanced technologies onto baseline turboprop aircraft due to the performance variabilities inherent in their design and application.

3.1.5 Semi-Empirical Methods for Technology Impact Assessments

The impact of advanced technologies is quantified through technology characterization and semi-empirical methods within GASP. For instance, semi-empirical models can allow the systems analyst to project two-dimensional aerodynamics effects onto three-dimensional components such as the wing and fuselage to predict the sensitivity a technology has on certain high-level aircraft design parameters such as the gross takeoff weight, operating empty weight, and fuel weight. Within GASP, the equivalent flat plate area and skin friction drag from each aircraft component is computed as a semi-empirical function of the Mach and Reynolds number:

$$C_{f,total} = \frac{0.455}{\frac{1+0.144M_0^2}{\log(Re_L)^{2.58}}} \tag{6}$$

Eq. (6) represents the flat plate area calculation in GASP. In order to model the skin friction drag reduction impact from technologies such as riblets, GASP uses ‘aircraft technology factors’ to simulate the effects of drag reduction technologies which was implemented by Jeffrey V. Bowles in 2022. These aircraft technology factors are dependent on location of impact on the aircraft and type of drag reduction, for example, $f_{TECH_{EXCR}}$ pertains to excrescence drag reduction.

$$FE_i = f_{CALIB_i} * f_{TECH_i} * CK_i * C_{f_{total}} * S_{wet_i} \tag{7}$$

where:

FE_i = flat plate area for the ith component (ft^2)

f_{CALIBi} = calibration factor for ith component

f_{TECHi} = Technology adjustment factors for ith component to reflect advanced aero technology

CK_i = Form drag factor for ith component = f(Geometry Only: SWET$_i$/SREF, t/c or fineness ratio, Sweep, Mach…)

In Ref. [22], riblets on the fuselage were modeled as a reduction in the wetted area of the fuselage rather than a direct impact on the turbulent skin friction drag.

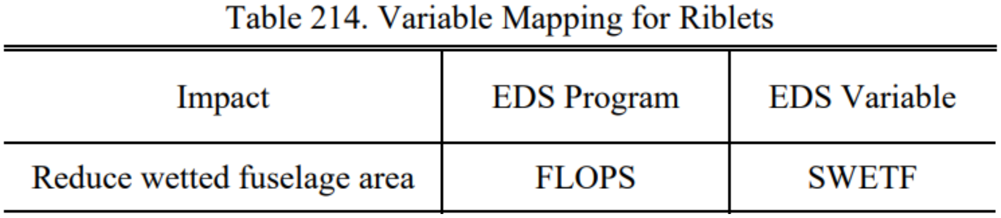


Table 214. Variable Mapping for Riblets

Impact	EDS Program	EDS Variable
Reduce wetted fuselage area	FLOPS	SWETF

Figure 12. Variable mapping for riblets from Ref. [22]

Figure 12 shows that in FLOPS, riblets were modeled by reducing the wetted fuselage area rather than directly impacting the skin friction drag, which is not treated as its own discrete component, which may lead to inaccurate predictions of their impact. In Eq. (7), the technology adjustment factors are a component in the equivalent flat plate area calculation, which allows for separation of the aerodynamic effects. Similarly, structural weight estimation in GASP makes use of semi-empirical methods by using Mass-Estimating-Relationships (MERs) to calculate subsystem weights. MERs are based on correlations to historical data for all major structural elements where for instance, wing weight can be estimated by:

$$W_{wing} = f_{TECH} * C_k * f\left(W_{GTO}, n_{ULF}, \lambda, b, \left(\frac{t}{c}\right)_{root}, \Lambda, \text{etc.}\right) \tag{8}$$

where:

f_{TECH} = technology factor representing the aircraft material (1.00 for conventional structure)

Ck = constant comes from regression analysis of the aircraft database.

Lastly, the propulsion systems in GASP are modeled using output engine models generated from the program Numerical Propulsion System Simulation (NPSS) developed by NASA Glenn Research Center that allows for the analysis and design of propulsion systems, such as the turboprop engines featured in this study. Engine performance parameters such as horsepower, fuel flow, and tail pipe thrust as a function of flight condition and power settings are provided in each engine model [27, 62].

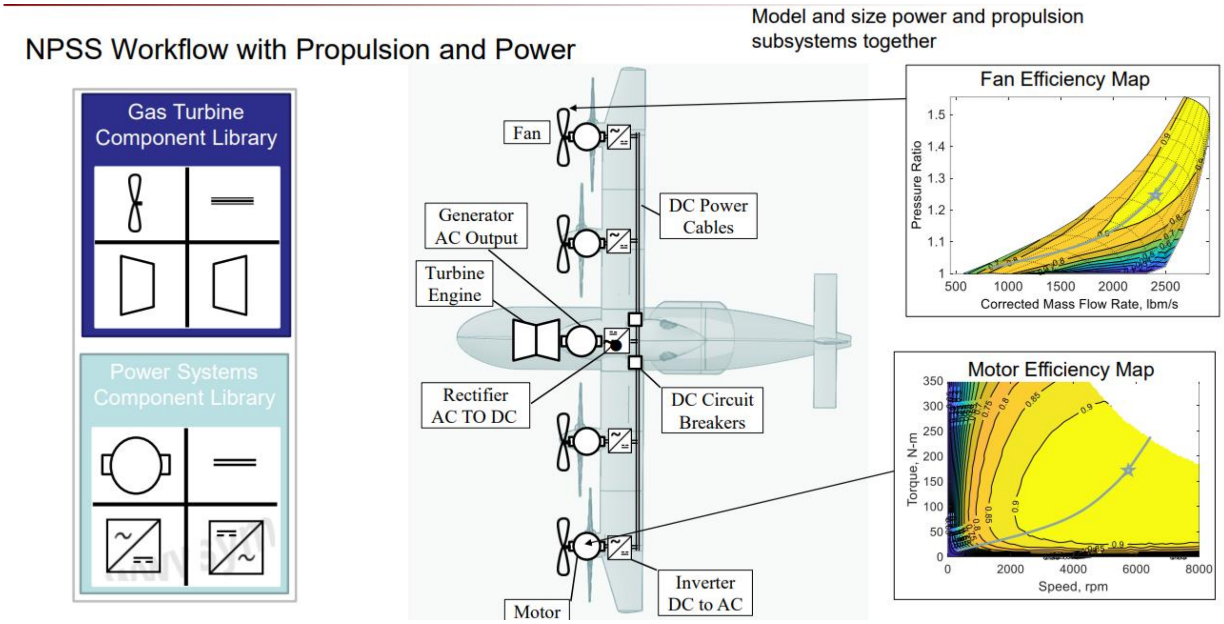


Figure 13. Typical NPSS workflow from Ref. [62]

Figure 13 depicts an example of the NPSS interface and its capabilities for modeling EAP-enabled aircraft concepts. The engine models were informed by type certificate data sheets (TCDS) publicly available online from the FAA and European Union Aviation Safety Agency (EASA), where non-proprietary engine models were synthesized that differed from publicly available data by ±3-4% to ensure omission of any proprietary information from EPFD project industry partners [27]. Then, within GASP, propeller calculations are done using Hamilton Standard propeller models [27, 63, 64]. Apart from published TCDS specifications, engine weights and dimensions were obtained from Ref. [65]. In summary, technology impact assessments in GASP are conducted by applying technology factors (based on the area of impact of the advanced aircraft technology, such as aerodynamics, propulsion, and structures), re-closing the vehicle, and performing the mission analysis in GASP.

3.1.5 Uncertainty Propagation Methodology

Within this study, Python scripts are used to create an interface between the MC simulation framework and GASP to automate the generation of input parameter probability distributions, execute GASP to perform aircraft sizing and performance calculations, and obtain performance distributions that can provide insight into the expected behavior of the vehicle system and its associated uncertainties. In this framework, the input parameters for a system are represented as probability distributions, rather than fixed values. The simulation then samples from these distributions to create user-specified number of discrete events, each with different parameter values, and computes the outcome for each scenario.

. When modeling advanced technologies within GASP using the outlined approach, MC sampling techniques are used to obtain performance distributions that capture performance-based variability. The process is outlined in the following three steps:

1. Parameters pertaining to the technology are identified in GASP (e.g., for aerodynamic technologies pertaining to the wing, this includes aerodynamics technology factors pertaining to reducing the skin friction drag of the wing and for structural technologies, the weight trend coefficient of specific components.)
2. The magnitude by which the technology influences those parameters is sourced from literature reviews, SME consultation, publicly available test data (e.g., “riblets reduce the skin friction drag of a wing section by 5-8% from Ref. [66].)
3. A probability distribution function is created based on the uncertainty bounds by which that parameter may vary operationally, and number of MC runs specified.

By aggregating the outcomes across all scenarios, MC simulations allow for a simple way of implementing uncertainty propagation to advanced aircraft technology performance assessment in the conceptual design.

3.2 Timeline Readiness Assessment Methodology

Assessing technology readiness is crucial to reducing the uncertainty and characterizing the risk of integrating new advanced technologies onto a flight demonstrator aircraft. Currently, the TRL scale is used throughout government agencies and industry to assess the maturity and readiness of in-development aerospace technologies. Because the TRL scale has heritage, widespread acceptance, and continued utilization throughout NASA ARMD programs, it is beneficial to design a framework that can improve its applicability to aeronautics rather than create a new metric to assess technology readiness altogether.

In 2020, NASA's Office of the Chief Technologist published a "Technology Readiness Assessment (TRA) Best Practices Guide" that establishes the standard definitions and best practices for conducting TRAs for flight projects and NASA's research and technology missions [67]. The TRA guide provides clarity on the levels of fidelity for hardware (ranging from proof-of-concept to functional prototype) and demonstration environment (e.g., relevant versus operational environment.) Use of the practices outlined in the TRA study allows for more reliable determination of TRLs for both technology development and flight development projects along with systematic processes to assess risk associated with technology maturation. The framework provided in the TRA has addressed many of the problems summarized in Table 3 related to uncertainty from semantic interpretation of the scale and its definitions, along with the concerns highlighted by Peisen and El-Khoury on the lack of clarity provided by the given TRL scale definitions [21, 33].

Table 10. TRL assessment and exit criteria from Ref. [67]

TRL	Definition	Description	Success Criteria
1	Basic principles are observed and reported.	Scientific knowledge generated underpinning technology concepts/applications.	Peer reviewed documentation of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental proof-of-concept of critical function and/or characteristics.	Research and development is initiated, including analytical and laboratory studies to validate predictions regarding the technology.	Documented analytical/ experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in a laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of potentially relevant environment.
5	Component and/or brassboard validated in relevant environment	A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment to demonstrate overall performance in critical areas.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. Performance predictions are made for subsequent development phases.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high-fidelity prototype of the system/subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment	A high-fidelity prototype or engineering unit that adequately addresses all critical scaling issues is built and functions in the actual operational environment and platform (ground, airborne, or space).	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and	The final product in its final configuration is successfully	Documented test performance verifying analytical predictions.

	"flight qualified" through test and demonstration.	demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	
9	Actual system flight proven through successful mission operations	The final product is successfully operated in an actual mission.	Documented mission operational results.

Table 10 provides a formal definition and decomposition of the TRL scale that can be used for flight technologies and programs across all NASA centers. Tracking technology maturity is beneficial for overall program management and by definition, the exit/success criteria given in TRL definitions can be used to track programmatic milestones [68]. By using a standard framework for TRL, the scale can now be used to outline the advancement of a single technology through the TRLs.

Table 11. Technology Readiness Level example – Terrain Relative Navigation (TRN) from Ref. [67]

TRL	Definition	Development Description	TRL Achieved
1	Basic principles are observed and reported.	Mars pinpoint landing concepts and enabling technologies were explored under the Mars Rover Sample Return mission study (A. Klumpp, "Pinpoint landing concepts for the Mars Rover Sample Return mission", AAS Paper 89-046, Annual Rocky Mountain Guidance and Control Conference, 1989).	Yes, in 1989.
2	Technology concept and/or application formulated	Formulated the concept of terrain relative navigation, its benefits, and desired performance characteristics for many solar system bodies. Responded to release of the NASA Research Announcement for the New Millennium Program Space Technology – 9 (ST-9) mission, with Appendix D on Terrain-Guided Automatic Landing System for Spacecraft (TGALS).	Yes, in 2004.
3	Analytical and experimental proof-of-concept of critical function and/or characteristics.	Studies funded by Mars Technology program provided analytical and experimental proof-of-concept of onboard registration of features seen in descent imagery to Mars orbital imagery (Y. Cheng, "Landmark based position estimation for pinpoint landing on Mars", IEEE International Conference on Robotics and Automation, 2005).	Yes, in 2005.
4	Component and/or breadboard validation in a	By the end of the Study Phase of the ST-9 mission, terrain relative navigation algorithms were tested by off-line processing of a set of IMU, descent image, and	Yes, in 2007.

	laboratory environment.	ground truth data collected during a sounding rocket flight conducted to emulate the conditions of Mars landing (A. Johnson, et al, “A general approach to terrain relative navigation for planetary landing,” AIAA Infotech@Aerospace Conference, 2007). Performance agreed with analytical predictions from planetary imagery and a simulation of Mars imagery.	
5	Component and/or brassboard validated in relevant environment	Using funding from the NASA SMD Mars technology Program, the real-time Lander Vision System (LVS) was designed and implemented on prototype computing hardware with a path to flight implementation. The compute element was interfaced to a COTS camera and IMU that met the requirements for Mars landing. The performance of the working system was demonstrated to meet processing time requirements in the lab. Short range lab test results scaled well to predicted performance at Mars EDL ranges. (A. Johnson et al., “Design and Ground Test Results for the Lander Vision System”, AAS GN&C Conference 2013).	Yes, in 2013.
6	System/sub-system model or prototype demonstration in a relevant environment.	The prototype LVS implementation was completed and tested in real-time on a manned helicopter over a wide variety of scenes. (A. Johnson et al., “Real-Time Terrain Relative Navigation Test Results from a Relevant Environment for Mars Landing” AIAA SciTech Conference 2015). The LVS preliminary design for Mars 2020 was completed and reviewed at the Mars 2020 TRN PDR, which included extensive simulation results for Mars 2020 landing.	Yes, in 2015.
7	System prototype demonstration in an operational environment	The LVS prototype was integrated with a vertical take-off and vertical landing rocket and used successfully in two closed loop pin-point landing demonstrations (N. Trawny et al., “Flight testing of terrain-relative navigation and large-divert guidance on a VTVL rocket,” AIAA Space Conference 2015).	Yes, in 2015.
8	Actual system completed and “flight qualified” through test and demonstration.	Mars 2020 LVS implementation was completed, environmentally tested, and delivered to spacecraft integration. (2018). Software and firmware completed (2019). Real-time LVS helicopter field test completed successfully and results match simulation (A. Johnson et al., “The Mars 2020 Lander Vision System Field Test, AAS GN&C Conference, 2020). All V&V completed including flight system testing (April 2020).	Yes, in 2020.
9	Actual system flight proven through successful mission operations	The 2020 Mars rover mission achieved this milestone successfully by using TRN during terminal descent.	Yes, in 2021.

Table 11 is an example of how following the definitions outlined in Table 10 can be used to follow the advancement of the technology Terrain Relative Navigation (TRN), which was featured on the 2020 Mars rover mission [67]. By using the TRA guide and literature review to illustrate the timing and progression of a technology maturation cycle, the TRL assignment process is more transparent and repeatable. Eventually, SMEs can be consulted to provide feedback on timelines such as the one provided in Table 11 which requires less input than the previous questionnaires used in Peisen’s report and the AFRL TRL calculator [39]. While the TRA is not designed to determine technology development risk as TRL is limited to only establishing the maturity of a new technology at a given time, TRL transition *behavior* can capture effects related to the degree of difficulty and risk associated with progressing to higher levels of maturity that vary across technology sectors.

3.2.1 TRL Transition Times Applied to Risk/Uncertainty Characterization

Previous literature on the TRL scale discuss its applicability to technology management within the civil and defense aviation sectors, where extensive literature exists on using TRL to monitor technology maturation, mitigate technology program risk, characterize TRL transition times, and model schedule and cost risks for technology systems and portfolios [34, 33]. When studying the relationship between TRL and technology development risk, implicit assumptions are relied upon, such as those shown in Figure 5 [33]. Particularly, the Level 1 assumption, which states that the “TRL scale is a measure of maturity and risk, is of interest [33].” This assumption essentially states the further a technology progresses through the TRL scale, the smaller the overall remaining uncertainty in maturity variable – for instance, a project at TRL 3 is subject to risks (e.g., cost, schedule, technology) on transitions TRL 3 to TRL 9, while a project at TRL 7 is subject only to risks on transitions TRL 7 to TRL 9.

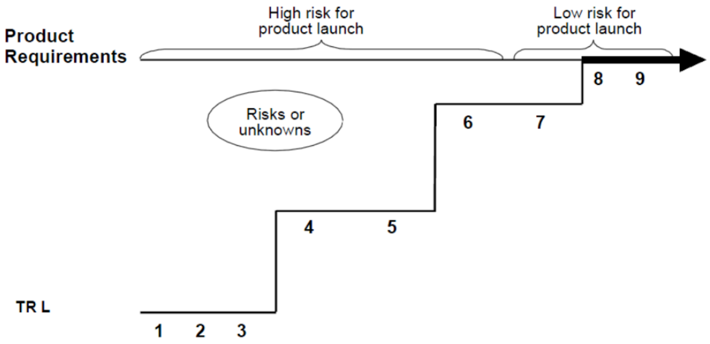


Figure 14. Programmatic risk as a function of TRL from Ref. [68]

Figure 14 depicts the uncertainty reduction from TRL progression, where it is explicitly mentioned that the transition from TRL 6 to TRL 7 as the most important step in reducing the risk of achieving a product launch. This gap, which has been highlighted in other studies such as the TDRA framework for spacecraft technologies in Mathias et al., is where a technology transitions from flight demonstration (TRL 6) to product qualification and development (TRLs 7-9) and is often referred to as one of the TRL "valleys of death." Though Figure 14 is specifically concerned with product launch, or programmatic risk, the assumption holds true for the early TRL stages as well. The variational nature of TRL transitions provide more insight on this phenomenon.

Kenley and El-Khoury studied the results of Peisen et al. by performing an analysis of variance (ANOVA) study performed by Kenley and El-Khoury, which quantified the variance of the TRL log-transition times [33].

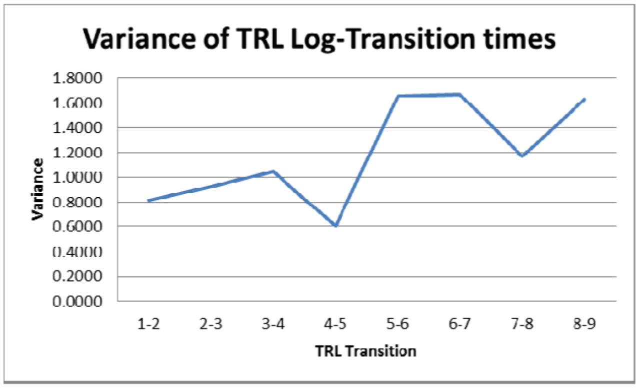


Figure 15. Variance of NASA SAIC's technology log-transition times

Figure 15 shows the calculated variance of the log-transition times of the technology histories from the SAIC report from Ref. [33]. A low variance indicates that data clusters around the average and higher variance indicates a greater degree of uncertainty. Figure 15 shows that the transition time between TRL 6 to TRL 7 has the highest variance and consequently, uncertainty which confirms the assumption in Figure 14 that technology development risk decreases after TRL 7 because past the TRL 6 to TRL 7 transition. While "average years-to-TRL" was used as the statistical generalization metric for the TRL transition dataset, El-Khoury recommends the use of median estimates (50th percentile) instead, due to the low number of datapoints and risk that forecasting techniques are overlearning the dataset.

For assessing technology development risk, there are benefits from using TRL transition times instead of simply discrete TRL values to mark technology maturity. While the TRL scale provides a one-point estimate of maturity, it falls short in its ability to encapsulate the dynamic evolution and uncertainties tied to advancement. In Mathias et al., the technology development risk assessment was conducted by determining a technology's movement through discrete development states using a discrete event Monte Carlo approach to obtain probability distribution functions (PDFs) for each transition step [12].

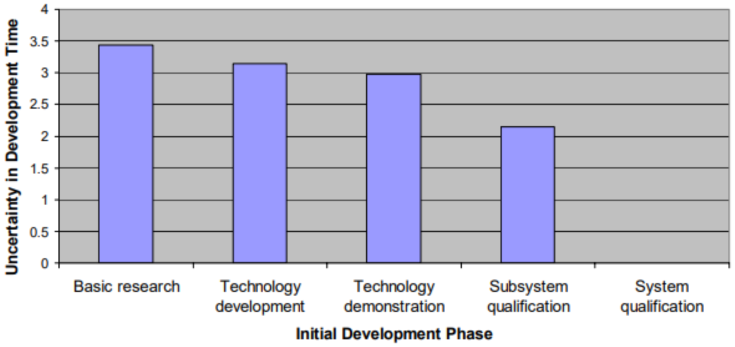


Figure 16. Uncertainty in development time shown in years to system qualification/flight test from several initial development phases [12]

From Figure 16, statistical analysis of the transition steps allows for visualization of relative uncertainty in reaching the flight test stage given the current development state, which decreases as the program persists. Incorporating TRL transition times as a risk characterization tool enriches the assessment process by capturing the evolving nature of technology development that is marked not only be achievement milestones but also encounters with setbacks and uncertainties [33].

Within NASA, several techniques for determining what is required to move a technology from one TRL to another such as the Advanced Degree of Difficulty (AD^2) method, Research and Development Degree of Difficulty (R&D^3), and Technology Need Value (TNV) have been developed as supplements to TRL for identification, scaling, and weighing of technology development risks [45]. However, real-world TRL transition data implicitly accounts for these variabilities as they all influence the transition times. In 2013, researchers from the Center for Aviation Innovation Research from The University of Tokyo investigated the TRL transition histories of propfan technologies [69]. By employing a multi-level perspective (MLP) analysis to the TRL transition history of propfan development, the study revealed interconnected economic

(1973-1974 and 1979-1980 oil embargos), geopolitical (end of the Cold War), and technological factors that posed difficulties in progressing from one TRL to another [69].

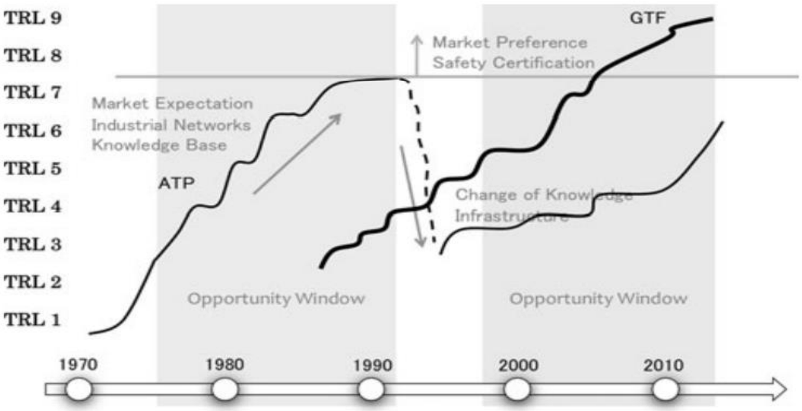


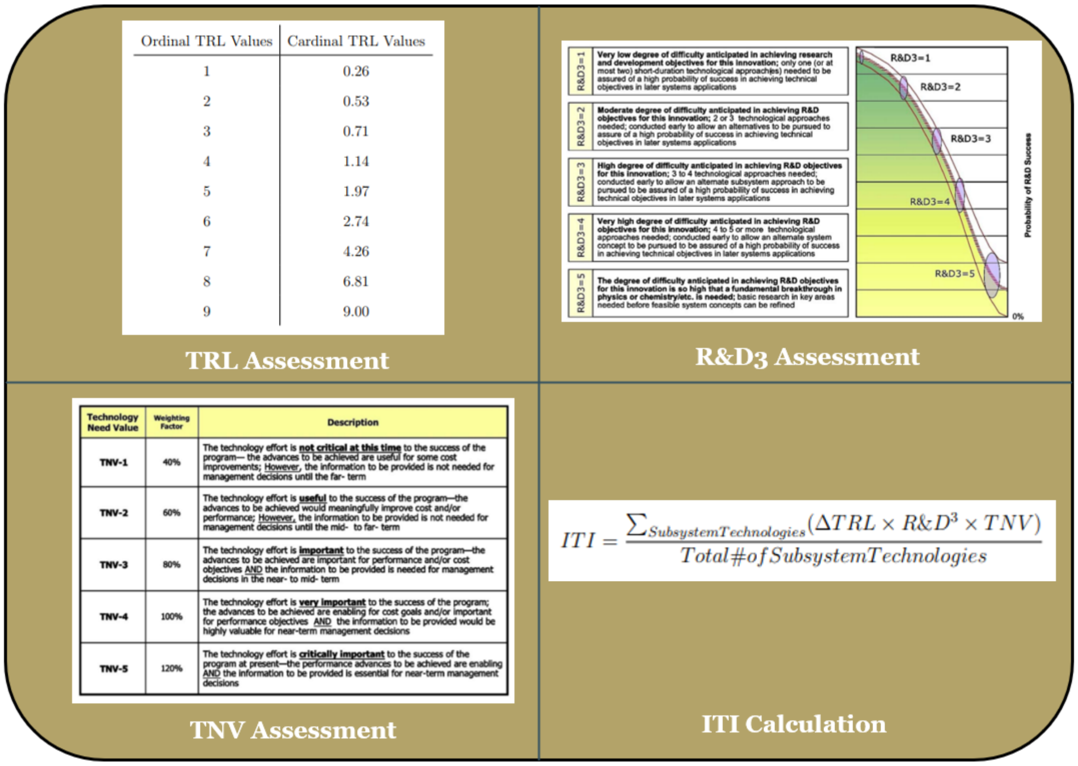
Figure 17. TRL transition history for propfan technologies and geared turbofan (GTF) with annotations [69]

Figure 17 shows the external influences on the TRL transition histories for propfan and GTF technologies. Since the TDRA framework is concerned with capturing the impact of uncertainties, rather than investigating the root-causes, the TRL transition history is sufficient as is, without the need to conduct an MLP analysis.

3.2.2 Comparison of TRL Estimation Methodologies

In previous technology development reports such as Ref. [22], TRL is presented in terms of the current TRL, expected TRL by 2020, and estimated years to TRL 9. The latter two parameters are predictions gathered through literature search and a series of workshops with relevant SMEs [14]. These processes can be considered a form of TRL forecasting, which refers to making predictions or estimations about the future development and advancement of a technology based on its current state and available information. The methodology outlined involves using existing data and expert import to predict the TRL by a specific future date and estimated time it will take for the technology to reach TRL 9. Projection curves, or mathematical trend analysis techniques to forecast the progress of technologies along the TRLs over time have also been used in the past, however, not without complication [33].

Projection curves provide a simplified representation of a technology's advancement and assume gradual and continuous progression in the form of a smooth curve. Projection curves are limited to the assumptions and simplifications that may not fully capture the complex dynamics and uncertainties inherent in the technology development progress if past progress will continue at a consistent rate. Ref. [14] approaches technology readiness risk by using a combined approach from Conrow's TRL scale translated to cardinal values using AHP, then using R&D^3 to quantify the difficulty in TRL advancement by probability of research and development success, and Mankins's TNV as a weighing factor for expected importance of technology advancement to system success [35]. This is then combined into a singular "Integrated Technology Index" to rank the technology systems using discipline-neutral metrics.



Ordinal TRL Values	Cardinal TRL Values
1	0.26
2	0.53
3	0.71
4	1.14
5	1.97
6	2.74
7	4.26
8	6.81
9	9.00

TRL Assessment

R&D3=1	**Very low degree of difficulty anticipated in achieving research and development objectives for this innovation;** only one (or at most two) short-duration technological approach(es) needed to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=2	**Moderate degree of difficulty anticipated in achieving R&D objectives for this innovation;** 2 or 3 technological approaches needed; conducted early to allow an alternatives to be pursued to assure of a high probability of success in achieving technical objectives in later systems applications
R&D3=3	**High degree of difficulty anticipated in achieving R&D objectives for this innovation;** 3 to 4 technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=4	**Very high degree of difficulty anticipated in achieving R&D objectives for this innovation;** 4 to 5 or more technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=5	**The degree of difficulty anticipated in achieving R&D objectives for this innovation is so high that a fundamental breakthrough in physics or chemistry/etc. is needed;** basic research in key areas needed before feasible system concepts can be refined

R&D3 Assessment

Technology Need Value	Weighting Factor	Description
TNV-1	40%	The technology effort is **not critical at this time** to the success of the program— the advances to be achieved are useful for some cost improvements; However, the information to be provided is not needed for management decisions until the far- term
TNV-2	60%	The technology effort is **useful** to the success of the program—the advances to be achieved would meaningfully improve cost and/or performance; However, the information to be provided is not needed for management decisions until the mid- to far- term
TNV-3	80%	The technology effort is **important** to the success of the program—the advances to be achieved are important for performance and/or cost objectives AND the information to be provided is needed for management decisions in the near- to mid- term
TNV-4	100%	The technology effort is **very important** to the success of the program; the advances to be achieved are enabling for cost goals and/or important for performance objectives AND the information to be provided would be highly valuable for near-term management decisions
TNV-5	120%	The technology effort is **critically important** to the success of the program at present—the performance advances to be achieved are enabling AND the information to be provided is essential for near-term management decisions

TNV Assessment

$$ITI = \frac{\sum_{SubsystemTechnologies}(\Delta TRL \times R\&D^3 \times TNV)}{Total\#ofSubsystemTechnologies}$$

ITI Calculation

Figure 18. Integrated technology index approach from ASDL from Ref. [61]

Figure 18 summarizes the approach used to assess technology readiness risk by the ASDL team. While these techniques are effective for quantitative forecasting, they are subject to the same concerns regarding the mathematical manipulation of TRL along with reliance on statistical projections. Furthermore, introduction of new technology maturation scales may introduce further uncertainties as 'best practices' have not been well-established to ensure consistent usage and standardized assessment.

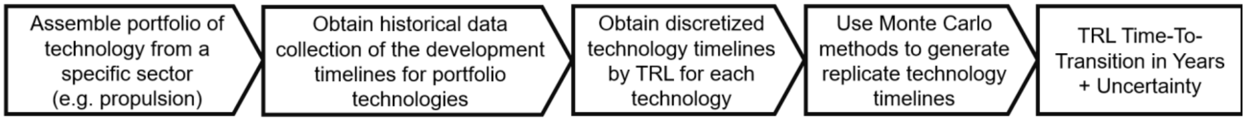


Figure 19. Incorporation of uncertainty for TRL estimation in the TDRA framework

Figure 19 outlines a new approach to using TRL for TDRA that can be used as early as the conceptual design phase, informed by historical data trends. While methodologies such as AD^2, $R\&D^3$, and TNV address the issue of conveying assessment of difficulties during the technology maturation process, they are too comprehensive for the scope of the TDRA framework which is focused on quantifying uncertainty rather than qualifying the causes of uncertainty. Instead, the approach taken will present transparent, uncertainty-driven methods to estimate the time taken for technologies to progress from one TRL level to another using statistical analysis of historical TRL transition behavior.

3.3 Overview of the Technology Integration Process

In the context of this work, the "integration" phase of a technology development program is similarly defined as "the process of testing, validating, and incorporating a technology into an overall vehicle architecture" which requires progress in the maturation of a technology before initiation. Implementation of advanced aircraft technologies requires integrating various subsystems within their host system, which introduces technical risks and uncertainties (e.g., compatibility issues and installation challenges.) Sauser et al. and Jiminez et al. have argued that TRL alone is insufficient in representing integration difficulties [38, 39].

The absence of integration risk considerations is prevalent throughout the previous frameworks mentioned in Refs. [22, 14], contributing to prevailing assumptions that integration risk assessment is considered "premature" at the conceptual design phase. Integration is not explicitly discussed until technologies reach TRLs 4-5 (e.g., in the technology maturation plan for PRSEUS under ERA), where assembly of higher fidelity prototypes and preparation for flight test demonstration calls for its consideration [70].

Challenging prevailing assumptions, integration risk assessment can indeed by conducted as early as the conceptual aircraft design phase – in fact, it is highly beneficial for risk-informed decision makers to do so. While the design is still in its formative phases, identifying potential integration challenges and risks can help inform decisions and guide the development process. Addressing integration concerns early on allows for proactive planning and mitigation strategies, ultimately resulting to a smoother integration process as the design evolves.

3.3.1 Characterization of Integration Activities from Technology Maturation Assessments

During the Methodology Formulation phase of TDRA framework development, a comprehensive review of existing integration readiness techniques was undertaken. Among these techniques, the Technology Maturity Assessment (TMA) method, introduced by Bilbro in 2007, stood out for its utilization of a product-oriented work breakdown structure (WBS) to allocate and assess technology maturity based on the TRL scale [51]. The TMA approach underscores the significance of understanding technology architecture and operating environments to gauge readiness, revealing the interconnectedness of integration and TRL. Notably, the TMA method evaluates readiness for individual WBS components by considering TRL sub-attributes, including demonstration unit fidelity, description, and environment, thereby incorporating factors such as fit and form aspects [51].

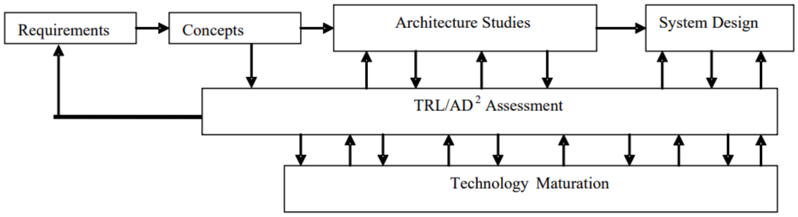


Figure 20. Architecture and technology development (TMA method) [71]

Figure 20 depicts the technology development workflow process outlined by Bilbro, where TRL and AD^2 are used to assess and inform maturity of technologies within a system.

Within this structure, integration is implicitly used as an attribute for technology readiness evaluation as the system design is composed of technologies at various TRL/AD^2 designations.

Nevertheless, some criticisms have arisen regarding the TMA method's treatment of integration within technology readiness evaluation. Jimenez and Mavris's critique the methodology's limited coverage of integration complexities and its logical flaws in employing TRL attributes for evaluation and proposed an alternative methodology [39]. Furthermore, Jimenez and Mavris proposed that due to the interconnectedness between technology readiness and integration efforts, integration readiness can be characterized using sub-attributes of technology maturity and TRL [39].

Table 12. TRL attributes with constituents reproduced from Ref. [39]

TRL	Technology/elements integration	Fidelity	Demonstrator	Environment
2	Application defined, allocated within host-system architecture	N/A	N/A	N/A
3	Basic elements not yet integrated in hardware	Low	N/A	Laboratory
4	Basic technology elements into breadboard	Low	N/A	Laboratory
5	Brassboard with realistic supporting elements, one-to-several technologies	Mid	Breadboard	Relevant
6	Prototype with supporting elements, several-to-many technologies	High	Brassboard	Relevant
7	Engineering unit with subsystems and technologies, on vehicle system	High	Prototype	Operating
8	Technology with subsystems and technologies, on vehicle system	Actual technology	Flight qualified	Operating
9	Technology with subsystems and technologies, on vehicle system	Actual technology	Flight proven	Mission/Operating

Table 12 illustrates the decomposition of TRL descriptions and definitions into constituent sub-attributes that can be used to communicate integration readiness at each level. For TRL 3 and beyond, definitions refer to integration of technology elements into a technology demonstrator of some level of fidelity; the demonstrator is integrated with other technologies and/or supporting elements of the host system at TRL 5 and 6. Within this approach, a technology is defined to be an element of a host system, endogenous interactions/interfaces pertain to the technology and its elements, and exogenous interactions and interfaces pertain to the technology (as a system) and its host-system.

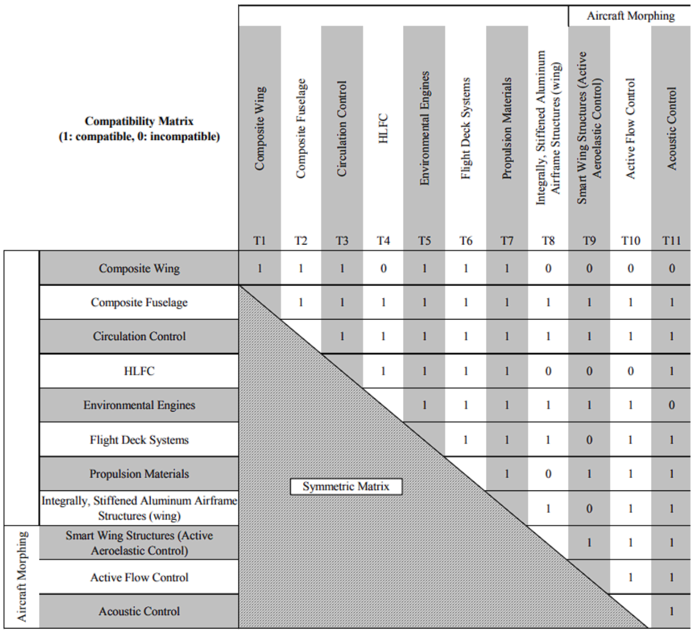
Table 13. Integration activities at each TRL

TRL #	Integration Activities
TRL-1	No integration activities are taking place. Insufficient information at this stage to initiate integration efforts.
TRL-2	Integration efforts at this level are speculative in nature (no experimental demonstrations or detailed analyses.)
TRL-3	Observational and preliminary analyses on the technology architecture (including its elements) precede the integration efforts of a critical function proof-of-concept.
TRL-4	Basic technology elements are integrated into a low-fidelity proof-of-concept breadboard to demonstrate functionality. Performance is sufficiently understood analytically, endogenous interactions understood.
TRL-5	Proof-of-concept increases in fidelity from TRL 3 and TRL 4 and now includes adjacent elements in the host-system architecture similar to a relevant environment. Analytical models now include understanding of exogenous interactions.
TRL-6	Integration efforts at this stage pertain to a flight test demonstrator (fully functional prototype) where significant groundwork is done to understand the technology’s integration
TRL-7	Technology is integrated onto the host system with all of its elements and other technologies.
TRL-8	The technology in its final form, fit, and function is demonstrated and integrated onto the host system across the entire performance envelope in the operating environment.
TRL-9	Integration is complete, no integration efforts conducted.

Table 13 summarizes the integration activities that can be backed out from the decomposition of TRL sub-attributes described in Table 12. By defining integration phases based on the TRL scale for technology maturation, this eliminates the need to create a discrete IRL scale that may propagate uncertainties when applied. Then, a preliminary integration roadmap can be created that provides a phase approach to integrating technologies into the host system. While formulation of a technology development roadmap may be considered premature at the conceptual design phase, it is still beneficial to attempt to chronologize the high-level integration efforts required for a technology development program. Such a roadmap can be constructed in the conceptual design phase that can later be reviewed by different entities within a risk reduction team.

3.3.2 Review of Technology Compatibility Matrices (TCMs)

While a roadmap can provide a high-level summary of integration activities, compatibility issues that may arise between the technology and its host system or technologies within a portfolio must be addressed. Using the TIES method, Kirby addressed the importance of highlighting potential incompatibilities with the formulation of a Technology Compatibility Matrix (TCM), which formalizes which technologies are physically compatible [13].



	Compatibility Matrix (1: compatible, 0: incompatible)									Aircraft Morphing		
		Composite Wing	Composite Fuselage	Circulation Control	HLFC	Environmental Engines	Flight Deck Systems	Propulsion Materials	Integrally, Stiffened Aluminum Airframe Structures (wing)	Smart Wing Structures (Active Aeroelastic Control)	Active Flow Control	Acoustic Control
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
	Composite Wing	1	1	1	0	1	1	1	0	0	0	0
	Composite Fuselage		1	1	1	1	1	1	1	1	1	1
	Circulation Control			1	1	1	1	1	1	1	1	1
	HLFC				1	1	1	1	0	0	0	1
	Environmental Engines					1	1	1	1	1	1	0
	Flight Deck Systems						1	1	1	0	1	1
	Propulsion Materials							1	0	1	1	1
	Integrally, Stiffened Aluminum Airframe Structures (wing)								1	0	1	1
Aircraft Morphing	Smart Wing Structures (Active Aeroelastic Control)									1	1	1
	Active Flow Control										1	1
	Acoustic Control											1

Symmetric Matrix

Figure 21. Technology Compatibility Matrix (TCM) from Ref. [13]

Figure 21 depicts a sample compatibility matrix for 11 technologies; a "1" represents compatible technologies while a "0" implies an incompatible combination. The TCM matrix is created from conducting research on the technologies and determining which ones compete either for design space or negatively impacts the others' function [13]. Technologies are defined as "incompatible" when they impact the same component on an aircraft such as the wing, thus "competing for the same space" or when one technology negatively impacts another's benefit [13]. While the TCM provided by Kirby's TIES method is a good starting point, it is worth mentioning that not every interaction between technologies can be modeled in a binary manner.

For instance, two technologies competing for the same space on the aircraft does not necessarily mean a risk-informed decision maker would have to pick one or the other, especially when it is possible for same parts of an aircraft to host more than one technology and obtain an aggregate benefit. Researchers Catalano and del Rosa et al. discovered that when using NLF and riblets together on a wing-body turboprop configuration, a maximum reduction of 20% can be achieved in the cruise condition, compared to 7% for riblets alone and 12% from NLF [72]. Though riblets and NLF are marked as “incompatible” in AATT report and Kirby’s TCM, Ref. [73] shows that there is an increased benefit from applying both NLF and riblets on the aircraft’s wing-body that is non-negligible on the order of 40 drag counts [22, 13, 73]. Additionally, it is important to capture the potential incompatibilities between the technology and elements of the host-system: for example, the benefits of NLF and riblets can be impacted by the propeller slipstream effect on turboprop aircraft or negatively impact de-icing/anti-icing systems that already exist on the aircraft.

Thus, the aim of this work is to conduct integration risk assessment by applying the TCM methodology and extending its use to characterizing the interactions between a technology and its host system that may arise during integration. This will be further informed with a write-up that will address the “grey” areas where technologies may be integrated on the same surface, but with further considerations.

3.4 Overview of the Certification Process

Aircraft are complex vehicle systems that must adhere to government mandated rules and regulations by entities such as the FAA to ensure minimal risk to operators, passengers, and public safety. When considering technologies with substantial aircraft alterations, the ability to obtain certification for experimental demonstration and operation is a pivotal decision point, profoundly impacting program success. While previous frameworks pertaining to technology development risk do not specifically address certification as it is a late-term concern, omission of certification as a factor in technology development risk assessment is untenable. This was exemplified by the X-57 program, where flight operations were suspended due to noncompliance with airworthiness standards [43]. The Code of Federal Regulations (CFR) Title 14 contains 107 FARs parts that cover various aspects of aircraft design, performance, production, and operation in the U.S. civil airspace. These FARs set requirements that must be met by new aircraft concepts and technologies prior to flight test demonstration, commercial introduction, and operation.

Table 14. Example of FARs related to advanced technology development

FAR	Title
Part 21	Certification Procedures for Products and Parts
Part 23	Airworthiness Standards for Normal, Utility, Acrobatic, and Commuter Category Airplanes
Part 25	Airworthiness Standards for Transport Category Airplanes
Part 33	Airworthiness Standards for Aircraft Engines
Part 35	Airworthiness Standards for Propellers
Part 135	Air Carrier and Operator Certification

Table 14 provides an example of FARs that may be relevant to advanced technology development: Part 21 outlines the procedures and requirements for certification of aviation products such as advanced aircraft technologies, Part 23 establishes airworthiness standards for smaller aircraft (<19 passengers and <12,500 lb maximum gross takeoff weight) while Part 25 is concerned with larger transport aircraft, Part 33/35 detail the airworthiness standards required for engines and propellers, and Part 135 pertains to operational standards such as maintenance standards and operational procedures. The four main categories of certification for aircraft operations overseen by the FAA are as follows:

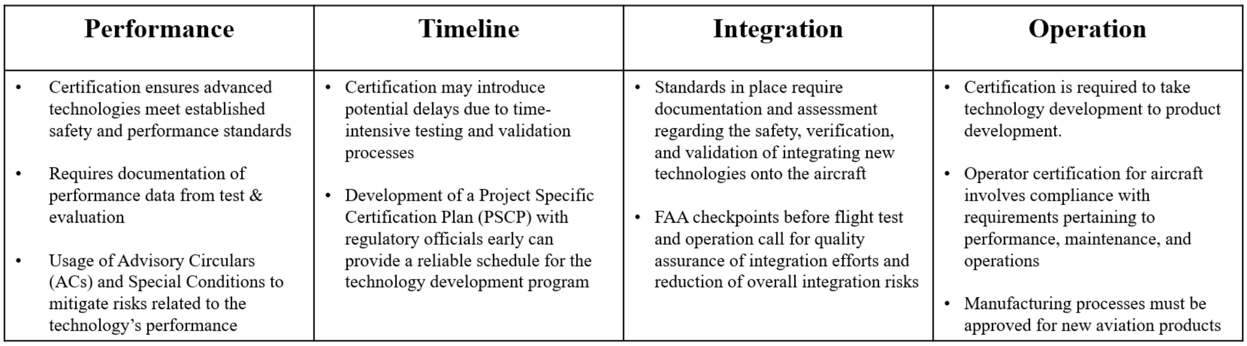
1. Type Certification: a type certificate (TC) is issued by the FAA to ensure an aircraft design conforms to airworthiness rules.
2. Production Certification: a production certificate (PC) approves the manufacturing processes to produce the approved aircraft design.

3. Airworthiness Certification: an airworthiness certificate states an aircraft is suitable for flight operations and can enter service.
4. Continued Airworthiness Certification: once an aircraft enters service, it must ensure its ability to continue operation throughout its life.

A special airworthiness certificate in the experimental category can be issued for flight test demonstrations of vehicles with advanced aircraft technologies installed that deviate from TC specifications. Traditionally, novel technologies and applications that do not conform to the assessment procedures provided by the FARs (e.g., the electric propulsion system on the X-57) are accommodated through ‘special conditions’ to ensure that the new system achieves an equivalent level of safety to existing regulatory requirements.

By design, the certification process plays an important, integrated role in the development and demonstration of advanced aircraft technologies that encompasses performance, schedule, integration, production, and operation. The regulatory process is a system of “checks and balances” with checkpoints throughout the technology development process.

Table 15. Impact of certification on technology development risks



Performance	Timeline	Integration	Operation
• Certification ensures advanced technologies meet established safety and performance standards • Requires documentation of performance data from test & evaluation • Usage of Advisory Circulars (ACs) and Special Conditions to mitigate risks related to the technology’s performance	• Certification may introduce potential delays due to time-intensive testing and validation processes • Development of a Project Specific Certification Plan (PSCP) with regulatory officials early can provide a reliable schedule for the technology development program	• Standards in place require documentation and assessment regarding the safety, verification, and validation of integrating new technologies onto the aircraft • FAA checkpoints before flight test and operation call for quality assurance of integration efforts and reduction of overall integration risks	• Certification is required to take technology development to product development. • Operator certification for aircraft involves compliance with requirements pertaining to performance, maintenance, and operations • Manufacturing processes must be approved for new aviation products

Table 15 outlines the impact that the certification process has on technology development risk factors such as performance, schedule, integration, and operation. Though certification activities are time-consuming, they are non-negligible checkpoints in the overall timeline of a technology, where compliance is the deciding factor when a technology aims to progress from TRL 5 (brassboard validation in a relevant environment) to TRL 6 (flight demonstration in a relevant environment.) Certification necessitates the documentation, planning, and validation of aircraft subsystem tests and integration efforts to verify that the technology functions as intended to minimize the potential for unexpected performance issues that could compromise safety or operational effectiveness.

The FAA CPI guide outlines the phases of the certification process for advanced aircraft technologies [74]. First, a regulatory and standards gap analysis is initiated to determine the gaps in existing regulations for the proposed technology architecture. Concurrently, draft MoC proposals are written to ensure that regulatory gaps identified can be met, where compliance planning and implementation takes shortly before flight test demonstration. A PSCP is put in plan for the technology development effort to define the technology by application and formulate a plan for its certification and further product development. Integration characterization based on TRL lends itself to the suggestion that certification progression can be inferred based off integration efforts and TRL sub-attributes, which will be the approach taken for the TDRA framework synthesized in this study. That way, methodology used to assess uncertainty inherent with the TRL scale will include integration and certification readiness without introducing a new, notional integration and certification scales that will propagate their own native uncertainties.

For this part of the TDRA framework, interviews with Herbert Schlickenmaier who serves as the Technical Lead/SME for certification requirements for projects such as ERA, EPFD/SFD, X-57, and other flight demonstrators developed by NASA were conducted. Certification efforts chronologized by TRL were discussed. Since no integration efforts take place from TRL 1 to TRL 2, there is not enough information for the creation of a PSCP for the technology as the technology architecture has not yet fully been defined. From TRL 1 to TRL 4, trade-off analyses must focus on Regulatory and Standards Gap Analysis before a PSCP can be put into place. The following attributes are part of the Regulations and Standards Gap Analysis:

- Analysis of Gaps in Regulations for the Proposed Technology Architecture
- Analysis of Alternatives (AOA) for the Technology Architecture
- Analysis of Standards to develop Means of Compliance to meet regulatory gaps

where the prioritized gap analysis completed would conclude this activity at the end of TRL 4. Then, the next stage of the certification process is “Compliance Planning & Implementation”, which takes place at TRL 5-6 and goes up to TRL 8. The following attributes of this stage involve:

- Drafting the PSCP and Type Certificate Data Sheet (TCDS) required for obtaining airworthiness certificates
- Developing issues papers at TRL 5 to 6 that will highlight potential certification risks
- Engaging regulatory authority such as FAA representatives and certification policy specialists to share the draft approach (MoCs), obtain feedback, and commence communication with the Aircraft Certification Office (ACO) to initialize the certification process
- Engage the Standards District Office (SDO) with MoCs and also Methods of Compliance which must be data-driven
- And eventually, by TRL 6, flight test technology demonstrators will be used to show confidence in the unique, novel technology where data will be collected to facilitate the collection of necessary certificates for airworthiness.

As a result of these discussions, the expression of later-stage technology development efforts discretized by the TRL scale and major milestones was created. The Phased Integration, Schedule, and Certification Events Schematic (PISCES) chart can be used to provide a clear visualization of technology maturity, integration, and certification activities to present the united efforts that take place during a technology development program.

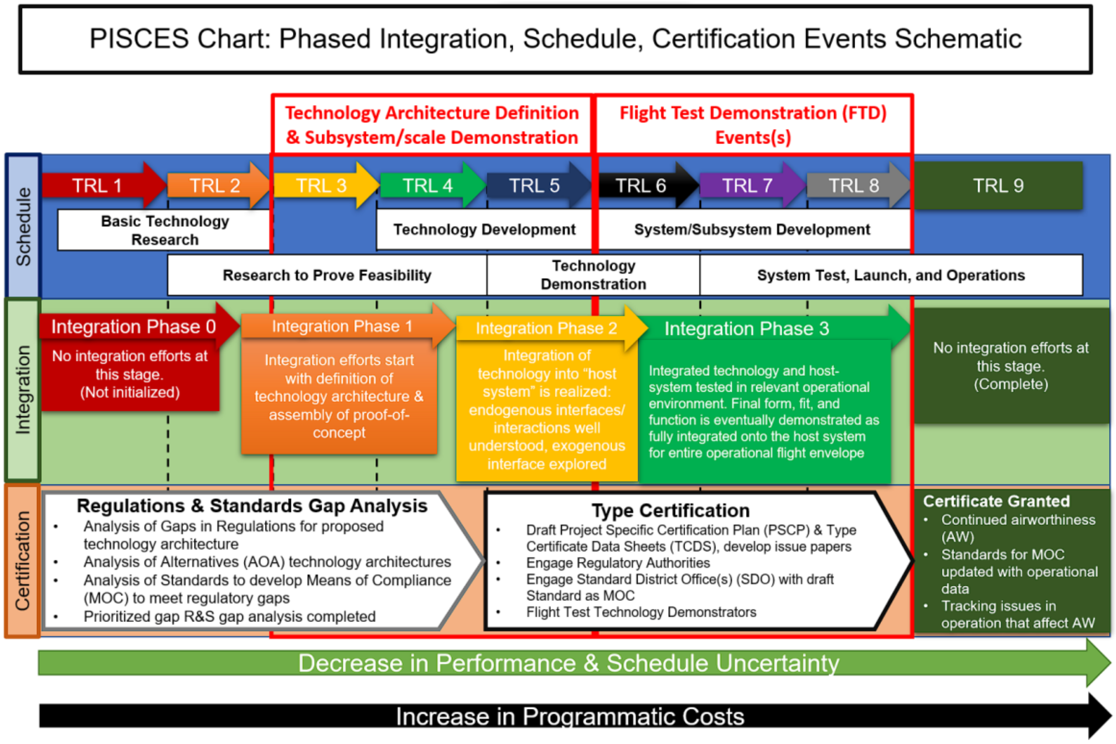


Figure 22. Phased Integration, Schedule, Certification Events Schematic (PISCES) chart

The PISCES chart created exclusively for this study is shown in Figure 22 and will enable a high-level overview of technology development efforts where it is assumed that progression across TRLs denotes lower uncertainty in the performance characteristics and schedule of the technology. Here, the various constituent timelines of a technology development program can be super-imposed to show the integrated effort required to advance the maturity of technologies and systems.

3.5 Total Technology Readiness Levels (TTRLs) for Operational Readiness

Operational risk assessment is a crucial bridge between technology development efforts and industry-driven product development and adoption of advanced aircraft technologies. While the development and initial demonstration of technologies is essential for innovation, the goal for technology developed under NASA ARMD programs is to ensure these investments translate into a real-world impact [3]. The variability in transition times from TRL 6 to TRL 7 for flight technologies—that is from the maiden flight demonstration to continued operation—has long been associated to whether a technology's viability extends past laboratory and technology demonstration into the operational environment [45]. Operational risks become relevant considerations prior to the TRL 6 milestone, denoting the point where advanced aircraft technologies are primed for flight test demonstration.

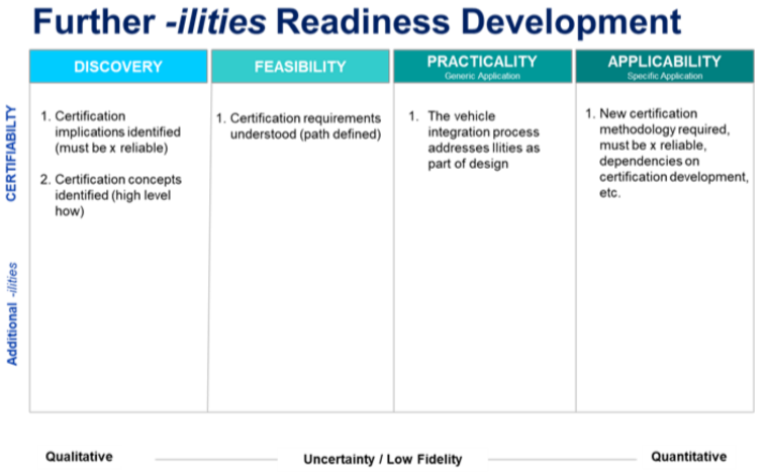
In the TTRL whitepaper, Yu et al. argue that technology assessment solely based on performance metrics and TRL can lead to incomplete insights on the viability of transitioning technologies to operational deployment [8]. These multi-faceted set of considerations that reflect a technology's readiness for operational deployment and integration were referred to colloquially as '-ilities.' Within the whitepaper, three technology research use cases were presented to argue the necessitation of engaging the '-ilities' using the TTRL framework.

Table 16. Technology research use cases from Ref. [8]

Technology Research Use Case	Related -ilities
Riblets	Maintainability, Reliability, and Wearability.
Bug phobic coatings	Maintainability, operability, and Stakeholder Acceptability since the coatings impact the coloration and appearance of the wing surface in contrast to an airline's expected livery.

Active Flow Control (AFC) Tail	Integrateability, Certifiability, and Manufacturability.

Table 16 presents the cases used in Yu et al. to demonstrate how attainment of high performance levels and advancement to TRL 6 does not inherently guarantee the successful transition of a technology to practical application. By integrating the concept of '-ilities', operational risks can be systematically identified and factored into consideration when presented alongside metrics such as TRL or performance impact. Through assessing the '-ilities' throughout the development phases beginning with Discovery (TRL 3), Feasibility (TRL 5), Practicality (TRL 6), Applicability (TRL 7), and Production (TRL 9), technologists are able to identify if plans are in place to mitigate the risks posed by certain '-ilities.'


Further *-ilities* Readiness Development

	DISCOVERY	FEASIBILITY	PRACTICALITY Generic Application	APPLICABILITY Specific Application
CERTIFIABILTY	1. Certification implications identified (must be x reliable) 2. Certification concepts identified (high level how)	1. Certification requirements understood (path defined)	1. The vehicle integration process addresses Ilities as part of design	1. New certification methodology required, must be x reliable, dependencies on certification development, etc.
Additional *-ilities*				

Figure 23. TTRL framework example: certifiability [8]

Figure 23 shows how certain '-ilities' can be continually assessed during the technology lifecycle such as certification. Stoplight scoring (e.g., green to denote if a plan has been formulated and successfully carried out, yellow to denote if a plan is in-progress, and red if a plan does not exist or is program-critical) can then be used to communicate progress. Since its conception, the TTRL framework has been used in technology maturation reports such as in Ref. [70]. The proposed TDRA framework leverages the confluence of “-ilities” factors and operational risks to create a synergistic assessment methodology.

PART IV: THE TECHNOLOGY DEVELOPMENT RISK ASSESSMENT FRAMEWORK

“Keep it simple.” – C. P. (Case) van Dam, 2023.

IV. THE TECHNOLOGY DEVELOPMENT RISK ASSESSMENT (TDRA) FRAMEWORK

After conducting a comprehensive review of the prevailing frameworks employed for assessing technology development risks for advanced aircraft technologies, a novel TDRA framework was created. The multi-dimensional approach to risk assessment encompassing key dimensions such as Performance, Integration, Certification, Timeline (Timeliness), and Operation (PICTO) was developed to provide a structured methodology that facilitates early technical risk management in the conceptual design phase, where new methods to assess performance, integration, certification, timeline readiness, and operational risk were synthesized.

Table 17. TDRA framework: PICTO & PISCES

	Technical Risk	Definition	Deliverables	
P	Performance	Performance risk refers to the uncertainty or potential issues related to achieving the desired performance characteristics of an advanced aircraft technology.	*Advanced Technology Modeling Methodology* *Performance Evaluation with Uncertainty*	
I	Integration	Integration risk refers to the potential difficulties or uncertainties associated with integrating various components, subsystems, or technologies within an advanced aircraft system	*Technology Integration Roadmap (TIR)* *Endogenous and Exogenous Compatibility Matrices*	Phased Integration, Schedule, Certification Events Schematic (PISCES)
C	Certification	Certification risk relates to the challenges and uncertainties involved in obtaining regulatory approvals and certifications for advanced aircraft technology. This includes compliance with applicable aviation regulations, safety standards, and airworthiness requirements.	*Certification Assessment Primer Schematic (CAPS)*	
T	Timeline	Timeline risk refers to the potential for schedule disruptions	*Technology Readiness Level (TRL) Assessment*	

		or technology maturation barriers during the development of advanced aircraft technology.	*Uncertainty-Driven TRL Transition Analysis (U-TTRANS)*	
O	Operation	Operational risk refers to the potential hazards, challenges, or uncertainties associated with the actual operation of advanced aircraft technology once it is deployed or put into service.	*Total Technology Readiness Level (TTRL) “-ilities” Chart*	

Table 17 outlines the elements of the created TDRA framework where PICTO defines the core aspects that contribute to technical risk and uncertainties and the PISCES chart captures the interdependencies between technology maturity, integration readiness, and certification checkpoints that set system requirements. The PICTO approach and PISCES chart are novel contributions to the field of technology development risk centered around aeronautics. By leveraging these deliverables for each category, this new TDRA framework allows for systems analysts, technologists, aircraft designers, and architecture-level decision makers to communicate and address technology development risks that may impact the timely success of a flight demonstration project. This chapter will go into depth into the PICTO approach and its applications, which is the main contribution to this work as the unified methodologies and overarching structure is unlike existing TDRA frameworks.

4.1 Performance Risk Assessment Overview

In the previous sections, the baseline airframe configurations and engine models were calibrated and validated against publicly available data. With the baseline aircraft models established and technology portfolio synthesized, a robust methodology for modeling advanced aircraft technologies in GASP was formulated. Improving upon fixed-point estimates, the process for modeling advanced technologies involved historical data collection, literature review, formulation of semi-empirical models, and coupled iterative MC and GASP simulations to obtain performance distributions with uncertainty. For this study, advanced aircraft technologies are only applied to the wing-body structure, specifically the wing and the fuselage though extending the application methodology to the horizontal/vertical tails would be identical to that of the wing.

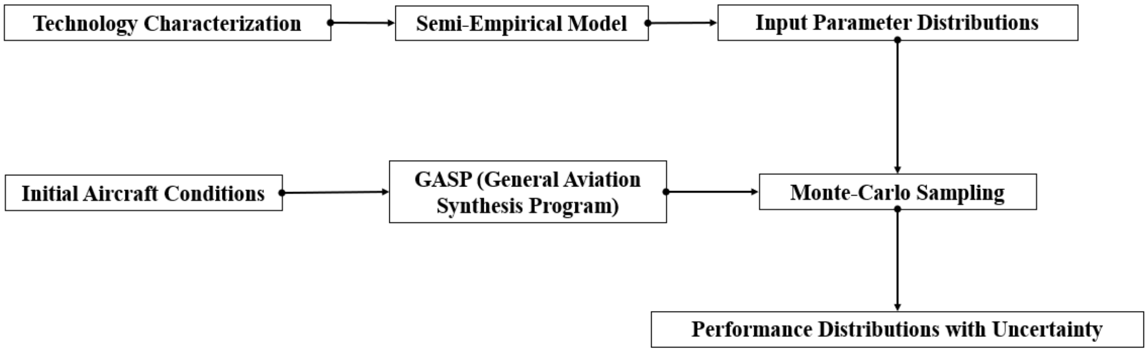


Figure 24. Advanced aircraft technology modeling and analysis

The overall methodology for modeling advanced technologies is summarized in Figure 24. After the technology is identified, technology characterization is conducted which involves researching past literature, historical data, and expert opinion to understand the fundamental characteristics and benefits of the technology. Then, semi-empirical methods or equations are used to incorporate theoretical analysis and empirical data to predict performance improvements or changes that can be modeled in GASP.

Table 18. Technology characterization example: riblets

Technology	Type	Technology Characterization
Riblets	Aerodynamics	Reduction in skin friction drag between 5-8% for airfoil sections and 1-6% on the fuselage [66]. In AATT, 2-8% skin friction drag on aircraft components is estimated [19].

Table 18 provides an example of technology characterization for riblets. To model the performance of riblets on an aircraft, empirical methods such as wind tunnel testing and flight testing have been done in the past, while modern-day CFD tools able to capture boundary layer effects can be used, but require significant computational set-up, time, and resources [75]. Previous research on riblets have demonstrated net friction drag reductions of up to 5% in wind tunnel and flight tests, however, the increased manufacturing and maintenance costs have detracted from its adoption [55]. With optimized riblets, skin friction drag reduction in the range of 5–8% have been measured on 2D airfoils at low incidence and in mild adverse pressure gradients; strong evidence exists at low speeds to indicate that riblets are more effective in adverse pressure gradients. Limited data available on wing-body configurations show that total drag reduction of about 2–3% is likely, where 1-6% skin friction drag reduction on the fuselage has been demonstrated. A semi-empirical model for riblets is determined as a function of wetted area coverage, the skin friction drag reduction cited in Table 18, and the ratio of skin friction to profile drag.

$$\Delta C_{D_{\mathrm{profile,riblet}}} = \Delta C_f \frac{S_{\mathrm{wet,riblet}}}{S_{\mathrm{wet,turb}}} \frac{C_{D_{\mathrm{friction}}}}{C_{D_{\mathrm{profile}}}} \tag{9}$$

where:

$\Delta C_{D_{\mathrm{profile,riblet}}}$ = the change in airplane profile drag in percentage (%)

ΔC_f = percent reduction in riblet induced turbulent skin friction (%)

$S_{\mathrm{wet,turb}}$= wetted area of airplane covered by turbulent boundary layer (ft^2)

$S_{\mathrm{wet,riblet}}$= wetted area of airplane covered by riblets (ft^2)

$\frac{C_{D_{\mathrm{friction}}}}{C_{D_{\mathrm{profile}}}}$ = ratio of friction drag and profile drag

From Eq. (9), a probability of percent reduction in riblet induced turbulent skin friction can be determined from the technology characterization detailed in Table 18, which is 5-8% for a wing section and 1-6% for a fuselage [66].

Table 19. Performance variability for riblets

Factor	**Impact**
Design	• Improper sizing and spacing of riblet geometry can lead to boundary layer instability, negating the drag reduction effects of riblets
Operating Conditions	• High angles of attack disrupt regular flow behavior leading to separated, turbulent flow that reduces effectiveness • At low Reynolds numbers/low velocities, flow may not be turbulent enough to fully engage with riblets • Severe flow separation can reduce riblets effectiveness • Surface contamination from certain operating conditions (icing, debris, insect accretion)
Manufacturing/Quality	• Surface contamination • Surface degradation can impair performance over time, where any irregularity can hinder flow attachment and vorticity generation

Table 19 summarizes factors and impacts that contribute to performance variability, where the drag reduction capabilities of riblets are significantly impacted by surface quality, flow conditions, and design complexity. Thus, when modeling riblets, it is important to take a probabilistic approach that accounts for the possibility of reduced, or even negated drag reduction benefit from riblets. For riblets, the PDF is likely not a normal distribution due to the variable performance of riblets which are sensitive to off-design conditions, film degradation over time, and/or residue build-up. Thus, for an input parameter distribution, the reduction in profile drag from application of riblets is best reflected as a skewed project evaluation and review techniques (PERT) distribution. A PERT distribution can be defined by the minimum, mode, and maximum values that a variable can take, where in the case of riblets on the wing, a minimum of 2% drag reduction is expected as stated in Ref. [19], a median of 5% and a maximum of 8% from Ref. [66]. These values are substituted into ΔC_f values while $\frac{S_{wet,riblet}}{S_{wet,turb}}$ and $\frac{C_{D_{friction}}}{C_{D_{profile}}}$ vary for each aircraft. Then, with the minimum, mode, and maximum $\Delta C_{D_{profile,riblet}}$ values specified, an input PERT distribution is obtained and input into the MC-GASP framework to obtain the performance distributions.

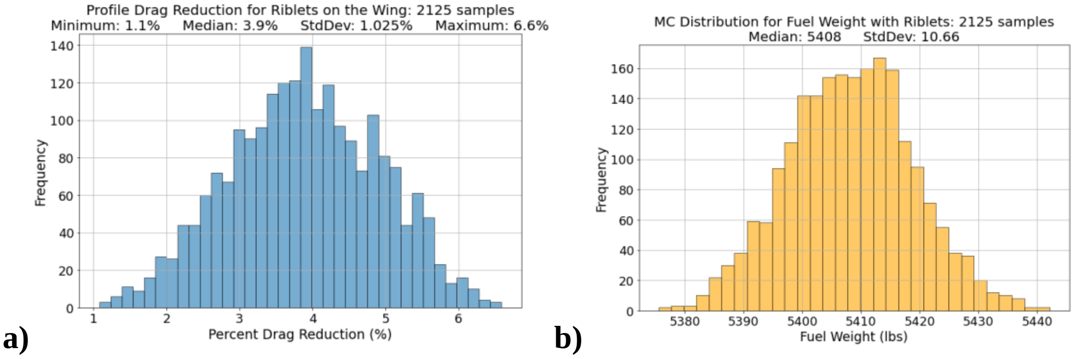


Figure 25. a) Input and b) output PERT distribution of Riblets technology sensitivities on the ATR 42-600

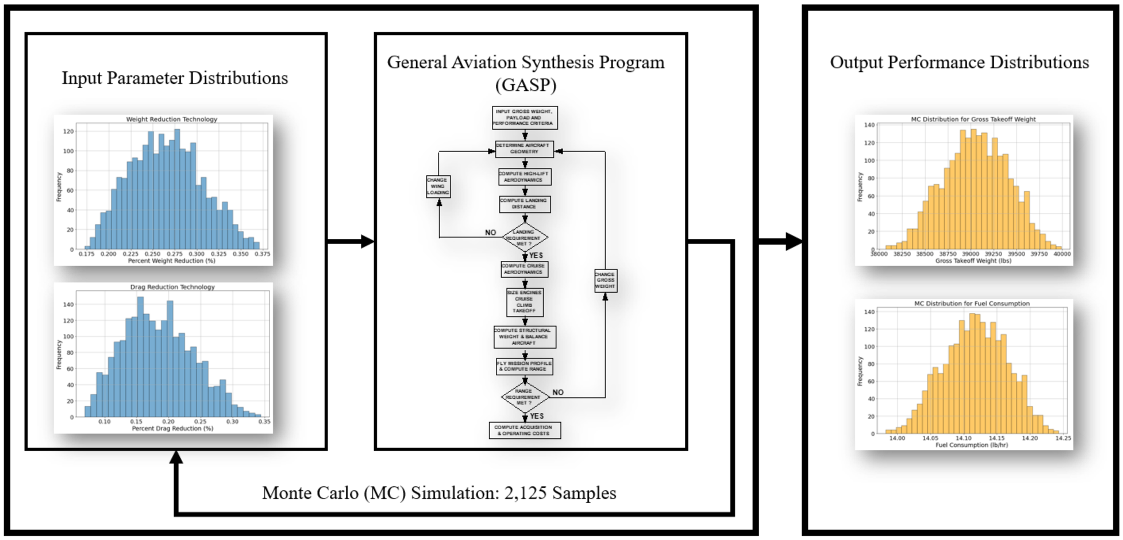


Figure 26. Monte Carlo-GASP simulation framework

Figure 25a depicts an example of the input probability distribution for riblets in terms of percent drag reduction while Figure 25b depicts the output performance distribution resulting from the coupled MC-GASP performance analysis, which is outlined in Figure 26. Here, the 50th percentile impact of riblets on the fuel weight is determined to be approximately 1% for the entire aircraft when applied on the aircraft wing-body. Aggregate technology build-ups can also be performed to demonstrate the capability of analyzing multiple technologies simultaneously and analyzing cumulative impact on aircraft performance.

4.2 Timeline Readiness Risk Assessment Overview and U-TTRAN Code

For timeline readiness risk assessment, the approach taken is data-driven and informed by historical data of TRL transition timelines for technologies within a specific sector, which are informed by documented advancements and measurable time durations.

First, development timelines for advanced aircraft technologies are collected through a comprehensive literature review and categorized by sector. Recall that sector specificity is an important determination, as each technology sector has its own distinct milestones and native terminology [12]. At this point, a qualitative summary of the technology development process is recorded with citations. Using geared turbofan (GTF) technology development as an example, the summarized development history includes recorded milestones and citations to document progress. For instance, GTF development started at Pratt and Whitney after the cancellation of GE’s advanced turboprop program in 1985, where serious development continued through the early 1990s [69]. GTF engines now currently fly on short-haul and mid-haul aircraft such as Canada Regional Jet and Mitsubishi Regional Jet as early as 2013 [69]. The milestones obtained from the literature review are used to construct the TRL-based timeline. Figure 17 depicted the annotated TRL transition histories for GTF and propfan technologies from Ref. [69]. By following the TRL definitions given in Table 10, the milestones can be matched to specific TRL levels.

Table 20. TRL transition history for GTF

TRL	Time to TRL 6 from indicated TRL (Yrs)	Time to TRL 9 from indicated TRL (Yrs)	Approx. time period at indicated TRL
1	15	28	1985
2	10	23	1990
3	9.5	22.5	1990-1991
4	9	22	1991
5	6	19	1994
6	0	13	2000
7		6	2007
8		3	2010
9		0	2013-Present

Table 20 depicts the chronology and TRL transition times for GTF technologies based on matching the milestones to specific dates. Though GTF has reached TRL 9 by the time of this report, let us assume for this example that this analysis is being conducted when the technology is still at TRL 8 (2010) where the sample objective is to estimate the “years-to-next-TRL” time (TRL 8 to TRL 9). To do so, a dataset of twenty technologies within the same sector (e.g., propulsion) is consolidated, MC simulations are used to generate TRL transition histories that reflect the variability inherent in the data, obtain PDFs of the transition steps from one TRL to another, and probabilistic analysis is employed to estimate the “years-to-next-TRL” time. First, a dataset of propulsion technologies is constructed to obtain TRL transition histories through literature review using TRL assignment techniques such as that in Table 11.

Table 21. TRL Transition history for propulsion technologies

Years		Carbon-6 Thermal Barrier	Graphite Fiber Stator Vane Bushings (Tribology)	Propfan development	Fiber Preform Seal	Particulate Imaging Velocimetry	Low Emissions Combustors	ATP Program	Adv. Gearbox development	Low Drag Liner	Combustor Noise Plug Liner	Fixed Geometry Core Chevron	Zero Splice Inlet	Ax. Staged Combustor	RQL Combustor	P&W PT-6 Development	Integrally Bladed Rotor	Ax. Compressor	Add. Manufactured Components	Variable Pitch Prop	Thrust Vectored Nozzle
from TRL	**to TRL**																				
1	**2**	0.4	1.9	2.5	1	2	1	3	1	0.5	1	2	3	1	0.5	2	2	3.5	3	2	2.3
2	**3**	0.4	1.9	1	1.5	4	1	2	1.5	0.5	1	3	3	1	5	1	4.5	3	1	4	4.7
3	**4**	0.4	1.9	1.5	1.5	2.5	1	2	3.5	2	2	1	4	2	1	3	7	3	7	2	24
4	**5**	0.5	1.9	2.5	1.5	3	2	4	3	3	1	4	5	2	0.5	2.5	3	3	4	4	2
5	**6**	0.2	1.9	1	6	0.5	4	2	6	7	4	15	7	3	8	3.5	7	6	10	7	7.6
6	**7**	2	1.9	2.5	2	6	5	3	7	2	3	5	2	1	4	2	2	3	1	2	5
7	**8**	3	1.9	2	3	1	1	1	3	4	2	5	3	1	0.5	1	6	3	2	2	1
8	**9**	1	1.9	1	1	1	3	1	3	2	1	10	5	2	1	4	14	4	3	9	6

Table 21 is the result of collecting the TRL transition history data of twenty technologies within the same sector as GTF technologies. Some elements were derived from the histories provided in Peisen et al, where for “unfinished” technology histories were updated to reflect the technology’s current state in the present year [32]. Other histories were obtained through literature review where milestones were collected and mapped to appropriate TRLs. The results from Table 21 are then used as an input dataset to the Uncertainty-Driven TRL Transition Analysis code (U-TTRAN) which is a Python-based module created for the purpose of the TDRA framework.

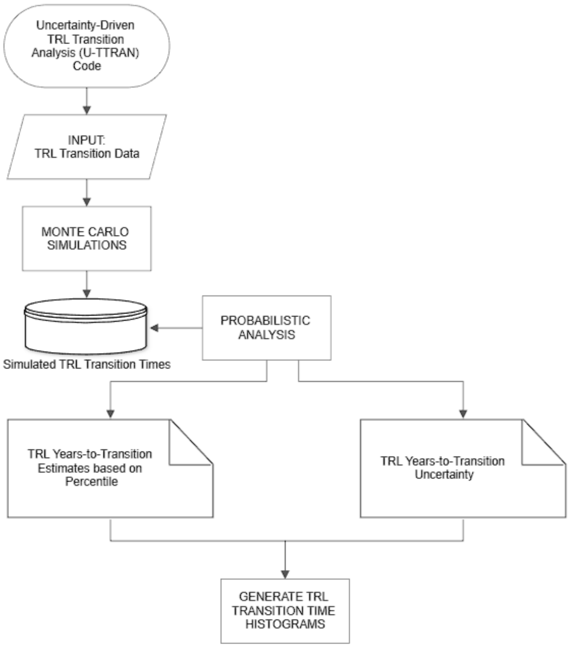


Figure 27. Block diagram for U-TTRAN Code

Figure 27 represents the processes used in the code to estimate TRL transition times and uncertainty from existing TRL histories of technologies within a specific sector. From the twenty propulsion technologies, replicate TRL transition histories were generated in a Monte Carlo fashion, where probability distribution functions (PDFs) were created to represent each "TRL transition band" (e.g., TRL 2 to TRL 3, TRL 4 to TRL 5) in order to use probabilistic analysis to observe TRL transition behavior. The purpose of this code is to perform Monte Carlo simulations to estimate the time required for technologies to progress from one TRL to another by generating a large number of simulated transition times based on the input dataset of transition histories of technologies within the same sector. In summary, the code reads the input data from a text file containing TRL transition information for technologies within a particular sector, such as propulsion and performs Monte Carlo simulations to generate a set of simulated TRL transition times. It iterates over each TRL transition and technology, calculates the 50th percentile estimate and standard deviation, and samples from a normal distribution to generate the simulated times. Within the code, percentiles and uncertainties are calculated for each TRL transition band. The results are then output in a CSV file and data visualization tools provide the histograms of probability distribution functions for each TRL transition.

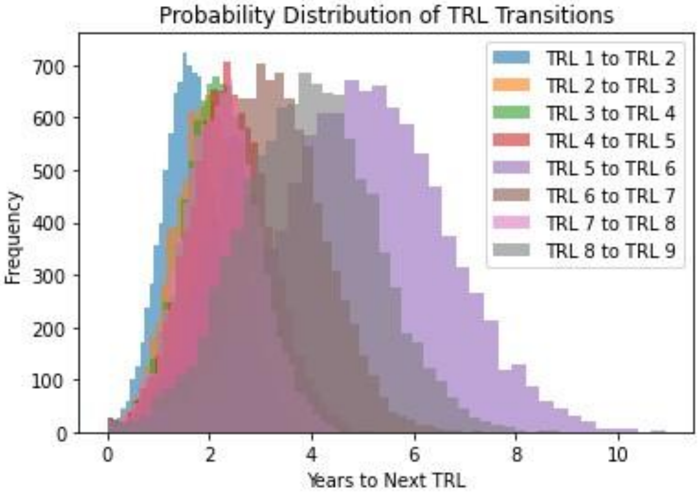


Figure 28. Probability distribution functions of TRL (10,000 MC samples)

Figure 28 depicts the probability distribution functions (PDFs) of each TRL transition band overlayed on the same plot for 10,000 MC simulations based on the TRL transition histories. It depicts a comprehensive visualization of the estimated transition times, associated uncertainties, and the range of transition times for each TRL band based on existing propulsion technology TRL transition times. For instance, the uncertainty in transition times from TRL 5 to TRL 6, TRL 8 to TRL 9, and TRL 6 to TRL 7 is clearly observed compared to other transition bands. This captures the same developmental phenomenon captured in Figure 14 [76]. The “valley of death” is a well-studied concept that describes “the gaps between research-based innovations and their commercial application” for technology development programs [76]. For the GTF example, it can be observed that the transition between TRL 4 to TRL 5 is three years, the transition from TRL 5 to TRL 6 is six years, and then seven years for progressing from TRL 6 to TRL 7. When consulting the literature review, it is shown that the concept of GTF existed in the mid-1980s, but it was not until a decade later until Pratt & Whitney revitalized efforts to turn previous research into development due to potential commercial applications for short-haul and mid-haul aircraft [69]. The “valley of death” can be visualized in the PDFs of the propulsion technology TRL transition data, which inherently reflects the difficulties that may contribute to uncertainty and longer transition times. This is further observed when looking at the PDFs for each transition band.

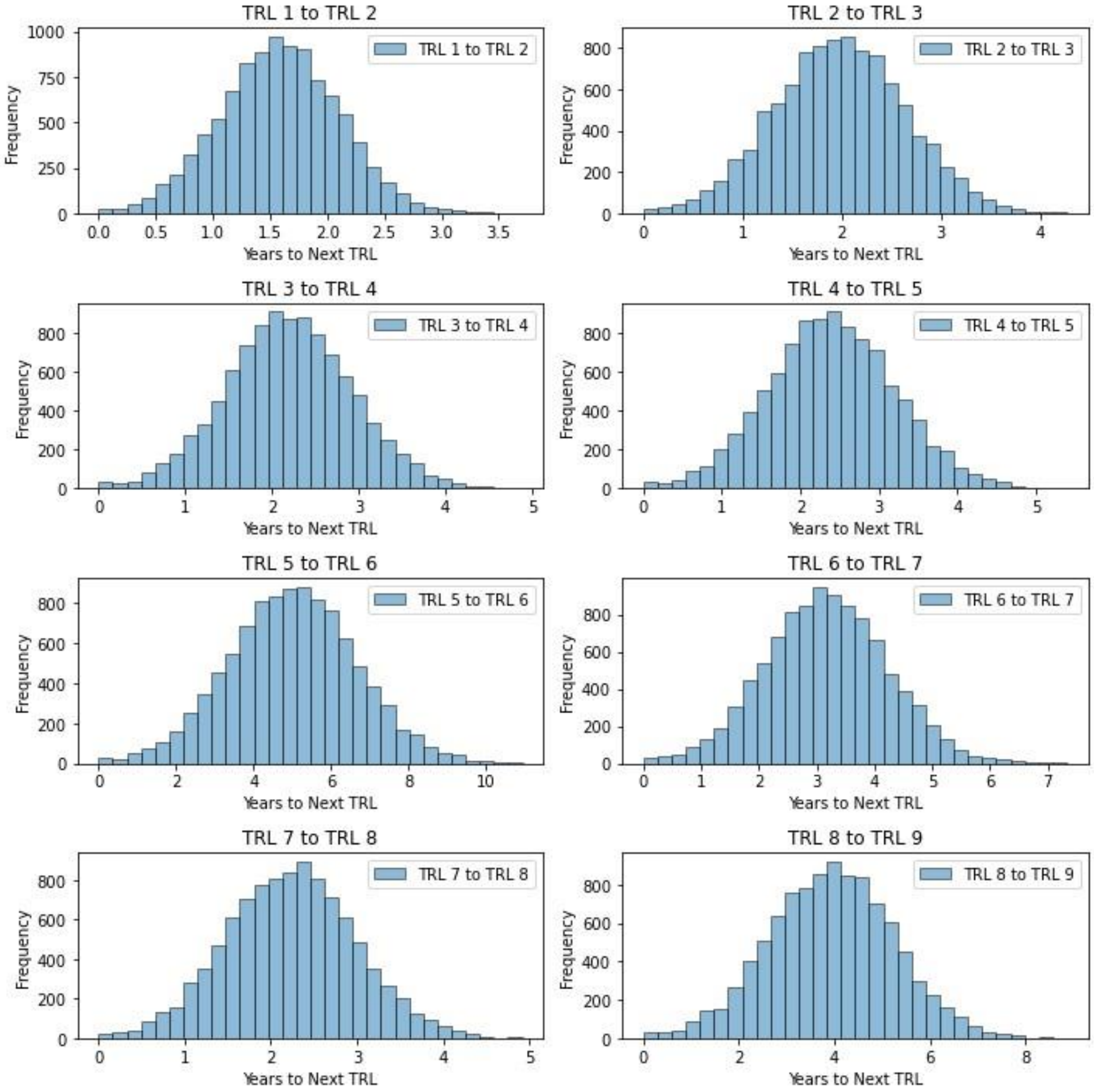


Figure 29. Monte Carlo PDFs for TRL transition bands

Figure 29 represents identical data to the overlayed histograms in Figure 28 that show the TRL transition behavior for propulsion technologies, except with a clear view of each TRL band separate from one another, where “Years-to-Next-TRL” for each transition band is clearly observed. For example, TRL 5 to TRL 6 marks the technology moving from a sub-scale prototype to one that is “flight-proven” which involves the production of a flight test demonstrator. For the U.S. airspace, before an experimental aircraft may be flight-tested, the special airworthiness certificate process involves engagement with FAA representatives to ensure compliance with safety requirements and that the installed technology meets necessary standards across the aircraft’s design, systems, and operational use before issuance of the certificate, which takes time [42]. Additionally, the time between TRL 6 and TRL 7 is also subject to high variability as for many NASA programs such as EPFD, “technologies must reach a TRL of 6 [5].” Oftentimes, technology development will halt at TRL 6, where further development efforts depend on whether industry entities choose to invest in further development for a commercial application. Another high-uncertainty transition band is TRL 8 to TRL 9, where the technology transitions from “successful demonstrations in an operational environment” to operating within its intended environment—which, for aeronautics technologies refers to commercial operation. The path to commercial operation involves rigorous testing and validation (e.g., safety and functionality), regulatory and certification, and manufacturing challenges from taking a functional prototype to full-scale production of that same system, and also, stakeholder collaborations (e.g., businesses, government agencies, markets, and addressing barriers-to-entry.) All these factors contribute to the time it takes for technologies to reach full maturity, and each technology introduces unique complexities and considerations that add uncertainty to that timeline. The variability is clearly shown when conducting a probabilistic analysis of TRL for development of propulsion technologies.

Table 22. Results for TRL transition histories for propulsion technologies

TRL Transition Band	Years-to-Next-TRL Estimate (50th Percentile)	Uncertainty
TRL 1 to TRL 2	1.59	0.52
TRL 2 to TRL 3	1.98	0.66
TRL 3 to TRL 4	2.20	0.73
TRL 4 to TRL 5	2.38	0.79
TRL 5 to TRL 6	4.97	1.66
TRL 6 to TRL 7	3.15	1.06
TRL 7 to TRL 8	2.23	0.74
TRL 8 to TRL 9	3.93	1.30

Table 22 represents the Years-to-Next-TRL matrix with uncertainties, where the highest uncertainty is between TRL 5 to TRL 6, which is where a technology is transitioned from laboratory tests to a full-scale flight demonstrator. Returning to the example question, an estimate of how long GTF will remain at TRL 8 can be answered by the results in Table 22. The code calculates the 50th percentile (median) and uncertainty based on the simulated TRL transitions times, where according to Table 22, the estimated time for a propulsion technology to progress from TRL 8 to TRL 9 is 3.93 years with an uncertainty of 1.30 years.

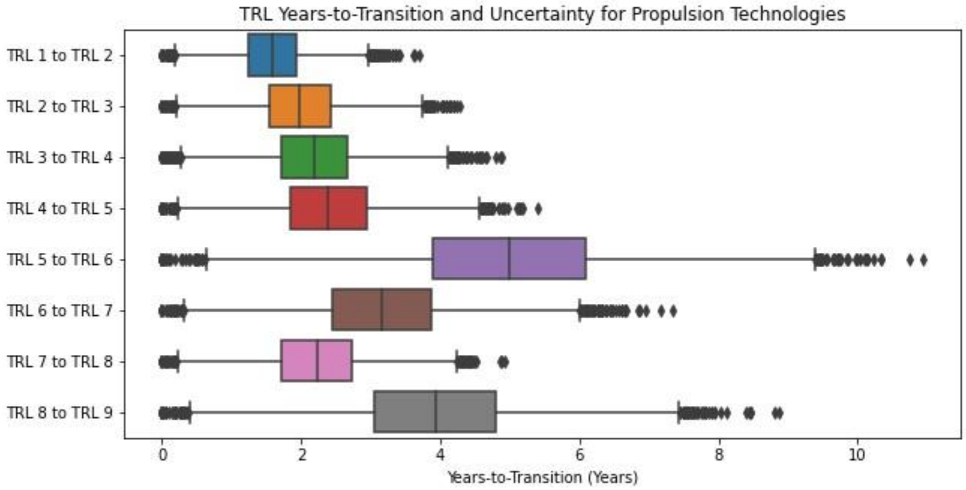


Figure 30. TRL transition and uncertainty for propulsion technologies

Figure 30 uses box-and-whisker plots to illustrate the TRL Transition data and uncertainty, where outliers are marked as dots and the whiskers extend to the upper and lower quartiles while the "boxes" mark the 25th, 50th, and 75th percentiles. The results can be understood as follows: the estimated time of 3.93 years represents the median or average duration expected for the technology (GTF in this case) to progress from TRL 8 to TRL 9. This is the central value around the transition time is expected to cluster, where 1.30 years indicates the range or variation around the estimated time. It signifies the degree of unpredictability or potential deviation from the median estimate. In this case, the uncertainty suggests that the "actual" time for the transition could be higher or lower than the estimated 3.93 years by up to 1.30 years, which is designated as 3.93 ± 1.30. From Table 20, this is known to be ~3 years, which is captured in the uncertainty bands which range from 2.63 years to 5.23 years.

In order to calculate the years-to-transition and uncertainty for progression through several TRLs (such as TRL 6 to TRL 9) one could take the sum of years-to- transition (3.15 + 2.23 + 3.93 = 9.31 years) and the root-sum-square (RSS) of the uncertainties ($\sqrt{1.06^2 + 0.75^2 + 1.30^2} = 1.84$ years) to obtain the estimated years to transition and uncertainty. Regarding the worst-case scenario where the technology may remain at the same TRL for an indefinite amount of time, this result can be seen as an outlier or extreme possibility. The U-TTRAN module effectively encapsulates these intricate processes related to TRL transition analysis, allowing for a streamlined and organized implementation of the TDRA framework.

4.3 Integration Risk Assessment Overview

Integration risk assessment plays a pivotal role in the TDRA framework where potential risks and uncertainties may arise from integration of a new technology onto a flight demonstrator. Some technologies such as advanced aircraft engines are integrated systems of elements with their own endogenous interfaces and interactions that must be well-understood before assembly. Resolution of exogenous interfaces and interactions is equally important, that is, the technology within its host system. The integration risk assessment section of the TDRA framework aims to provide risk-informed decision makers with a Technology Integration Roadmap (TIR) along with exogenous/endogenous compatibility assessments to highlight the key events and potential risks that may arise during the integration phase of a technology development program.

4.3.1 Characterization of Integration Readiness Using TRL

Jimenez and Mavris proposed characterization of the technology integration process using sub-attributes of TRL scale definitions [39]. Using this methodology, integration activities could be inferred from the TRL definitions used by NASA to benchmark technology maturity. Unlike the IRL scale developed by Sauser, this approach does not require using a separate scale to assess integration readiness and instead, makes use of an existing, familiar metric that has been commonly used by stakeholders [38]. For each TRL, integration activities are detailed where the timeline for Pultruded Rod Stitched Composite Structures (PRSEUS) is used as a working example.

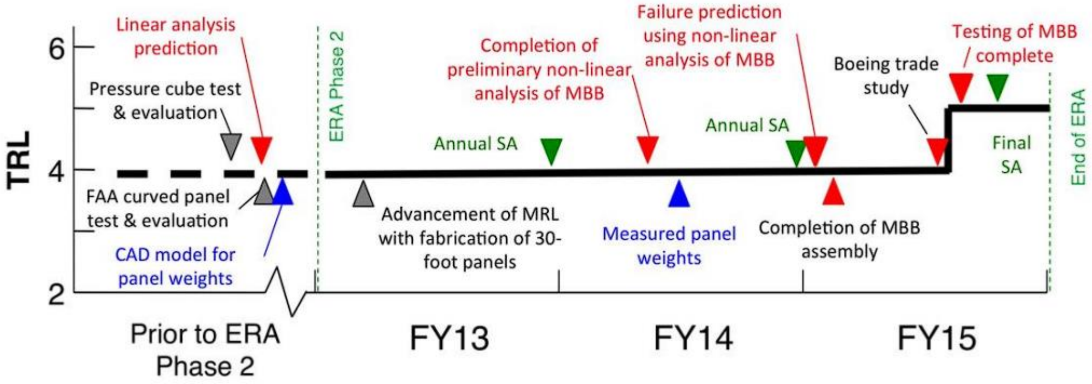


Figure 31. PRSEUS technology maturation roadmap for ERA Phase 2 from Ref. [60]

Figure 31 represents the technology maturation roadmap for PRSEUS, which was used in Jimenez and Mavris's paper to demonstrate how the TRL scale can be used to discretize the timeline where an advanced aircraft technology is integrated into a flight demonstrator such as the hybrid-wing body [60].

Table 23. Technology Integration Roadmap (TIR) for PRSEUS reproduced from Ref. [39]

TRL #	**PRSEUS Development Efforts from Ref.** [60]	**Integration Activities described by Ref.** [39]
TRL-1	Principles of composite stitching leads to observation that composite stitching has favorable damage-arresting characteristics	None.
TRL-2	Pultruded rod stitched composite structure (PRSEUS) is conceptually formulated as an application	Speculative estimates of PRSEUS impact or vehicle attributes and performance relative to conventional materials are determined.
TRL-3	Critical functions and characteristics are identified for PRSEUS elements	Demonstration begins with testing of technology elements that come together to form the technology system of interest.
TRL-4	Low-fidelity PRSEUS samples are integrated to test functionality via loading tests in a laboratory rig.	Integrated, critical function proof-of-concepts are developed to obtain test data that will inform trade studies of the host-system (HWB airframe).
TRL-5	Subassembly and flat panel units are replaced and tested within the NASA Langley Combined Loads Test Facility	Proof-of-concept fidelity increases significantly where the technology system

		prototype is tested within an environment like the host-system
TRL-6	A full-scale, fully functional PRSEUS demonstrator(s) for the HWB center body is tested.	Integration efforts support the flight demonstration of a functional prototype of the host-system.
TRL-7	A full-scale, fully functional demonstrator of the entire airframe is integrated with all subsystems and structural systems of the HWB.	Integration of the PRSEUS HWB airframe is demonstrated.
TRL-8	A production unit of the HWB with a full PRSEUS airframe is test flown.	The technology (PRSEUS) in its final form, fit, and function.
TRL-9	PRSEUS is demonstrated through successful operations of the HWB.	Integration at this stage is complete; no integration efforts required.

Table 23 which is reproduced from Jimenez and Mavris's paper, presents a generalized technology readiness/integration roadmap that allows for early insight into the integration efforts required for PRSEUS integration into an HWB-type vehicle. Under NASA's ERA program, PRSEUS achieved TRL 4 at the end of Phase 1 and TRL 5 by the end of Phase 2 [60]. While the TIR can be refined over time by stakeholders, technologists, and further information, this approach serves as strategic planning tool for prioritizing critical integration tasks and supporting transparent communication among stakeholders when tracking technology integration progress with predefined milestones.

4.3.1 Technology Compatibility Matrix (TCM) for Interfaces/Interactions

While TCM in Figure 21 using the TIES method provides valuable insights into the compatibility of technology portfolio elements on one another, it offers an incomplete assessment that may not fully capture the impacts on the overall system [13]. In addition to identifying compatibility between advanced technologies on one another, a comprehensive assessment must consider further intricate interactions.

Table 24. Comparison of TCMs from previous approaches to PICTO TDRA

	TCMs from Refs. [22, 13]	**TCMs from PICTO TDRA Approach**

Matrices	☐ Impact of Technologies on Existing Aircraft Systems ☐ Impact of Existing Aircraft Systems on Technologies ☑ Impact of Advanced Technologies on Each Other	☑ Impact of Technologies on Existing Aircraft Systems ☑ Impact of Existing Aircraft Systems on Technologies ☑ Impact of Advanced Technologies on Each Other
Legend	0 = Incompatible 1 = Compatible	🟩 Positive Interaction/ Enhances Performance 🟨 Negligible or Unknown Interaction 🟥 Negative Interaction/ Reduces Performance Note # Combination of Effects in Note #

Table 24 highlights the extended TCM approach used in this study to better capture the interactions of advanced aircraft technologies on the existing aircraft system (and vice versa) and each other. By using a new legend with improved definition compared to the previous binary, more complex interactions can be captured that may not be easily categorized as completely incompatible, but rather, can be compatible with further design considerations and optimization. Now, interactions can be effectively mapped to ensure that technologies align with the overall system architecture where TCMs serve as visual guides to anticipate potential areas of concern and aid in early-stage risk assessment and mitigation.

4.4. Certification Risk Assessment

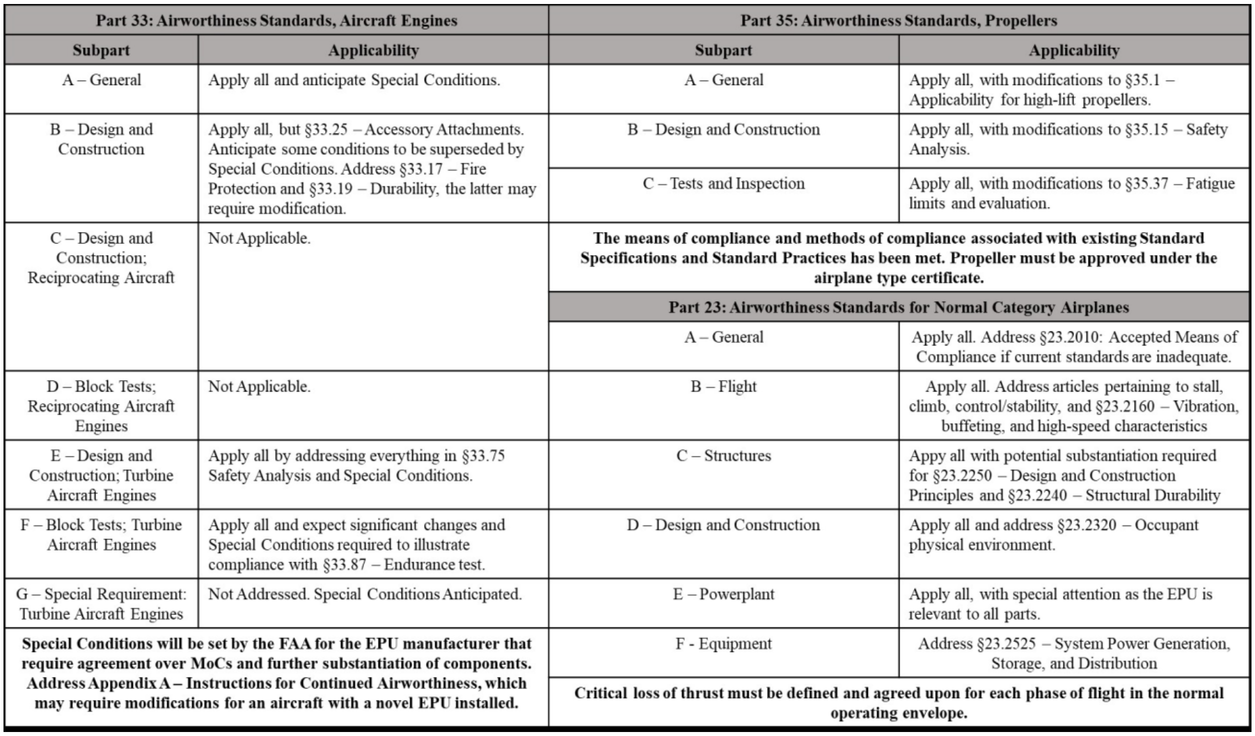
FAA guidelines, any technology that involves substantial alterations to an aircraft's design or operation, deviating from its baseline TCDS necessitates the engagement of regulatory processes and authority in creating a structured plan for obtaining certification for experimental demonstration or operation [74]. The PISCES chart provided in Figure 22 outlines the required certification efforts required for flight test demonstration and commercialization of advanced aircraft technologies, which is closely tied to integration readiness and technology maturity levels.

Certification risk depends on the regulatory gap analyses for the concepts, where risk is evaluated based on the standards that will need to be developed to address the means of compliance with the gaps in regulations. For novel technologies, a ‘Special Condition’ will be formulated for the specific FAR to address the regulatory gap through data-driven demonstration. For the X-57’s novel propulsion configuration, a Special Condition to Part 33 was included in the certification process, which requested the further vibration demonstrations [44]. The exhaustive process for a regulatory gap analysis involves examination of all relevant FARs (pertaining to the technology and vehicle), meetings with Designated Engineering Representatives (DERs) with authority and specialization in these FARs and regulatory specialists to formalize the gap analysis matrix and debrief sessions before finalizing the detailed gap analysis.

The first step of this process is not completely out-of-scope at the conceptual design phase as sufficient information from technology characterization allows for informing a structured methodology to initiate the consideration of certification implications. The use of a Certification Assessment Primer Schematic (CAPS), created within this study, offers a preliminary overview of the certification process that identifies key regulatory areas of concern by highlighting relevant FARs before engaging regulatory specialists.

For instance, the X-57 was developed from a turboprop aircraft certified under 14 CFR Part 23 with engines and propellers certified under Parts 33, and 35 respectively. Installation of a novel electric propulsion unit (EPU) requires significant modifications that deviate from the original TCDS of the baseline aircraft, the Tecnam P2006T, which necessitates the creation of a CAPS to outline potential regulatory barriers in the existing FARs [44].

Table 25. CAPS overview example for the X-57



Part 33: Airworthiness Standards, Aircraft Engines	
Subpart	**Applicability**
A – General	Apply all and anticipate Special Conditions.
B – Design and Construction	Apply all, but §33.25 – Accessory Attachments. Anticipate some conditions to be superseded by Special Conditions. Address §33.17 – Fire Protection and §33.19 – Durability, the latter may require modification.
C – Design and Construction; Reciprocating Aircraft	Not Applicable.
D – Block Tests; Reciprocating Aircraft Engines	Not Applicable.
E – Design and Construction; Turbine Aircraft Engines	Apply all by addressing everything in §33.75 Safety Analysis and Special Conditions.
F – Block Tests; Turbine Aircraft Engines	Apply all and expect significant changes and Special Conditions required to illustrate compliance with §33.87 – Endurance test.
G – Special Requirement: Turbine Aircraft Engines	Not Addressed. Special Conditions Anticipated.
Special Conditions will be set by the FAA for the EPU manufacturer that require agreement over MoCs and further substantiation of components. Address Appendix A – Instructions for Continued Airworthiness, which may require modifications for an aircraft with a novel EPU installed.	

Part 35: Airworthiness Standards, Propellers	
Subpart	**Applicability**
A – General	Apply all, with modifications to §35.1 – Applicability for high-lift propellers.
B – Design and Construction	Apply all, with modifications to §35.15 – Safety Analysis.
C – Tests and Inspection	Apply all, with modifications to §35.37 – Fatigue limits and evaluation.
The means of compliance and methods of compliance associated with existing Standard Specifications and Standard Practices has been met. Propeller must be approved under the airplane type certificate.	
Part 23: Airworthiness Standards for Normal Category Airplanes	
A – General	Apply all. Address §23.2010: Accepted Means of Compliance if current standards are inadequate.
B – Flight	Apply all. Address articles pertaining to stall, climb, control/stability, and §23.2160 – Vibration, buffeting, and high-speed characteristics
C – Structures	Appy all with potential substantiation required for §23.2250 – Design and Construction Principles and §23.2240 – Structural Durability
D – Design and Construction	Apply all and address §23.2320 – Occupant physical environment.
E – Powerplant	Apply all, with special attention as the EPU is relevant to all parts.
F - Equipment	Address §23.2525 – System Power Generation, Storage, and Distribution
Critical loss of thrust must be defined and agreed upon for each phase of flight in the normal operating envelope.	

Table 25 presents a CAPS overview for the X-57 which is constructed after a thorough review of relevant technology-specific regulations. Since the EPU is a novel technology, Special Conditions will be set forth by the FAA that may require demonstration and validation that must be factored for in the overall technology development timeline of the aircraft – for instance, operating limits for all critical flight conditions must be established for FAR Part 25, additional means/methods of compliance must be established for the novel engine technologies under FAR Part 33, and documentation of the performance characteristics of high-lift propellers must be properly demonstrated prior to obtaining a special airworthiness certificate in the experimental category. The CAPS overview provides a structured approach to capturing these concerns while acknowledging that a more comprehensive regulatory analysis can be carried out once the technology architecture(s) are better defined and regulatory specialists are engaged. In later stages of the certification process, the CAPS can be matured later into a regulatory gap analysis or certification basis when developing an Airworthiness Validation Plan (AVP.)

4.5 Operational Risk Assessment Overview

Operational risk assessment is an important consideration for programs such as EPFD/SFD, SFNP, and AATT that look to demonstrate and transition advanced aircraft technologies from research and development to flight operations such as a flight test demonstrator or continued commercial operations. As part of the PICTO approach outlined in the TDRA framework, operational risk is addressed through application of the TTRL methodology from Ref. [8] using the '-ilities' to define potential risks that arise from both demonstration and operation at the conceptual design phase. This early identification is pivotal in shaping the trajectory of the technology flight demonstration project as it involves exploring the feasibility of bridging the gaps between TRL 5 to 6 (laboratory testing to flight test demonstration) and TRL 6 to TRL 9 (technology demonstration to product development, production, and operation) prior to finalization of the overall system architecture.

Assessment of '-ilities' throughout certain phases of the technology development process is addressed in Figure 23, where certifiability is continually assessed through the discovery (TRL 1 to TRL 3), feasibility (TRL 3 to TRL 5), practicality (TRL 6), and applicability (TRL 7) phases. In 2015, NASA and Boeing worked together to define specific -ilities critical to commercial aircraft design readiness such as Affordability, Certifiability, Reliability, and Manufacturability after completion of flight tests of the prototype AFC system on the ecoDemonstrator [8]. The definitions of the various '-ilities' are provided in Figure 8, where detailed information on the integration and testing efforts of the prototype AFC system onto the ecoDemonstrator are provided by Ref. [77]. The AFC Enhanced Vertical Tail demonstration marked the culmination of extensive technology maturation through various testing methods, aiming to showcase successful integration, evaluate rudder impact, and gather in-flight data for comparison, ultimately contributing valuable insights for future active flow control applications despite highlighting the necessity for further integration and manufacturing readiness for commercial use. Because of its known successful demonstration and satisfaction of core '-ilities' it serves as a good benchmark case for the demonstration of the PICTO approach to operational risk assessment using the TTRL framework.

🟩	Plan in place, executed.
🟨	Plan in progress, outstanding issues.
🟥	No plan in place.

Figure 32. Stoplight scoring for operational risk

Table 26. Example of operational risk assessment with -ilities: demonstration vs. operation

-ilities	Demonstration (TRL 6)		Operation (TRL 9)	
	Scoring	Rationale	Scoring	Rationale
Integrateability	🟩	Successfully executed for the Boeing 757 ecoDemonstrator.	🟥	The installation methods used for the AFC system on the ecoDemonstrator would not be appropriate for production design.
Reliability	🟩	The AFC Safe-to-Fly Process ensured the aircraft was configured for safe testing of the prototype AFC system.	🟨	Operational deployment requires more extensive testing, analysis, and regulatory compliance to ensure reliability under a wider range of conditions.
Certifiability	🟩	Successfully executed for the Boeing 757 ecoDemonstrator.	🟥	Certifying the AFC system for operational use will raise further concerns.
Manufacturability	🟩	Successfully executed for the Boeing 757 ecoDemonstrator.	🟥	Transitioning from one-off demonstration installation to mass production for commercial aircraft poses unaddressed challenges such as scalability and quality control

Maintainability/ Sustainability/ Inspectability	🟩	Successfully executed for the Boeing 757 ecoDemonstrator.	🟥	Long-term maintenance, availability of spare sparts, integration with existing maintenance processes, long-term sustainability, and required repeatable inspection training and protocol for maintenance personnel was not addressed.
Affordability	🟨	Development and demonstration were funded through specific budget allocations for the ecoDemonstrator and through ERA. Plan in progress for cost-effectiveness.	🟥	Not addressed.

Table 26 shows the PICTO approach for operational risk assessment used in the proposed TDRA framework where the '-ilities' of the AFC system in terms of demonstration and eventual operational deployment are identified and assessed. For integrateability, the installation methods used for the ecoDemonstrator were sufficient for demonstration, but external mounting of the heat exchanger and routing of the flow tubes due to limited access points would be unacceptable for large scale production and stakeholder acceptability [77]. Since no plan currently exists for improving the integrateability and manufacturability of the AFC system, a scoring of "red" was given, which is in line with the conclusions from Ref. [77]. Then when addressing reliability, the flight tests executed addressed handling qualities and the impact of rudder effectiveness at the tested flight conditions, which partially addresses the requirements for operational readiness, but still lacks validation of in-flight operational performance and regulatory requirements. Lastly, while affordability was not a concern of the flight test demonstration where higher initial costs from research, testing and engineering activities may have been factored in the budget, it is a significant concern that must be investigated when considering the commercial operations of the technology.

4.6 Summary of Contributions

This study introduces a new, structured framework for systematic assessment of technology development risks, with a particular focus on the dimensions of performance, integration, certification, timeline, and operational considerations. Within this framework, the PICTO approach emerges as a novel and noteworthy contribution to technology development risk assessment:

1. The TDRA framework is the first of its kind to employ a comprehensive PICTO approach to structure how technology development risk is broken down and assessed. Integration, certification, and operation are added as important considerations, with processes adapted to address these concerns.
2. A novel approach to modeling advanced technologies at the conceptual design phase coupled with performance evaluation with uncertainty was developed for the TDRA framework, using semi-empirical methods, Monte Carlo simulation, and M&S codes such as GASP to allow for performance estimation that captures variability.
3. The U-TTRAN module allows for uncertainty-driven analysis of TRL transition timelines to provide empirically based estimation of the time required to mature technologies to a specific TRL.
4. Integration is addressed through utilization of TIRs, similar to Ref. [39], where the concept of TCMs from Ref. [13] is expanded to include host-system and technology interactions.
5. Certification is addressed through formulation of CAPS that provide an overview of potential certification risks with regards to FARs.

6. Operational risk for flight test demonstration and commercial operation is examined using the TTRL framework, where '-ilities' are used to provide further clarity on risks that may be encountered prior to TRL 6 and TRL 9.

In summary, the PICTO approach created in this study contributes to the research objective by providing the structure, tools, and means of analysis to conduct comprehensive analysis of technology development risk, particularly during the conceptual design phase.

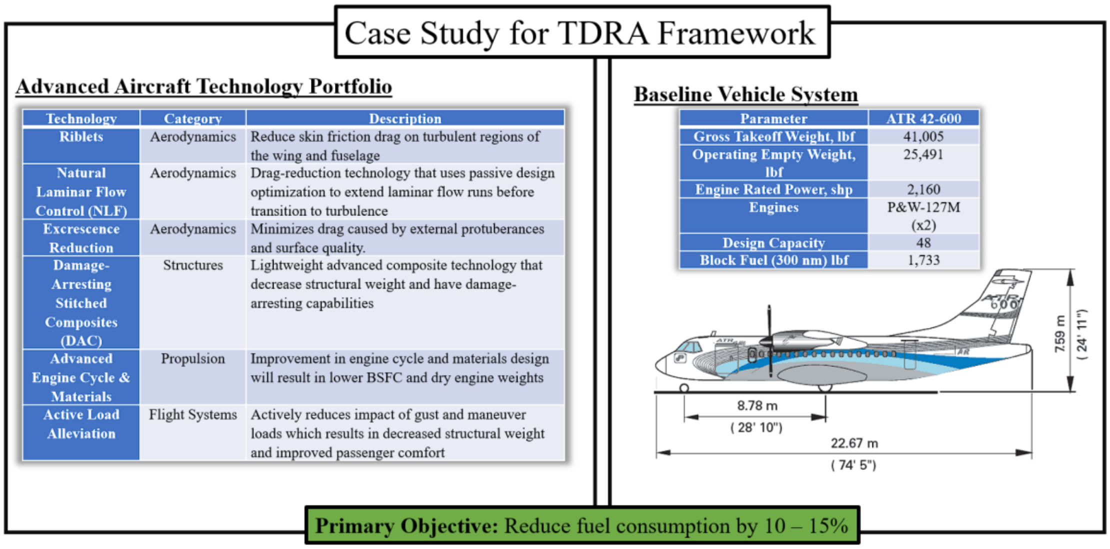
PART V: CASE STUDY – APPLICATION OF THE TDRA FRAMEWORK

“Flying straight is boring.” – Susan X. Ying, 2006

V. CASE STUDY: APPLICATION OF THE TDRA FRAMEWORK TO AN ADVANCED TURBOPROP MODEL FOR THE EPFD PROGRAM

5.1 Case-Study: Technology Reference Aircraft and Candidate Technologies Portfolio

To demonstrate the application of the TDRA framework in initiating risk assessment and uncertainty analysis during the conceptual design phase, a practical, relevant case study is used. Results will also be provided for each section of the framework. Under IASP, the EPFD project concerns itself with flight demonstrators belonging to the regional turboprop (50-passenger) size class as potential platforms for electrified aircraft propulsion (EAP) concepts. The AATT project has provided a portfolio of technologies with significant fuel burn reduction capabilities in Ref. [22]. For this case study, the stakeholder's objective is to improve the fuel and performance efficiency of a regional turboprop aircraft designed to accommodate 48-50 passengers. In 2022, the aircraft manufacturer ATR released a turboprop market forecast based on existing and regulatory technological conditions. According to ATR's projections, the global demand for turboprops is expected to reach approximately 2,450 aircraft due to rising fuel prices and carbon taxation. In the U.S., replacing regional jet routes spanning up to 500 nautical miles with turboprops could result in a 28% reduction in CO_2 emissions compared to current emission levels [78]. Moreover, NASA ARMD programs such as EPFD, SFD, and AATT offer early opportunities for integrating and introducing disruptive technologies such as lower-emission propulsion systems to the regional turboprop aircraft market.



Case Study for TDRA Framework

Advanced Aircraft Technology Portfolio

Technology	Category	Description
Riblets	Aerodynamics	Reduce skin friction drag on turbulent regions of the wing and fuselage
Natural Laminar Flow Control (NLF)	Aerodynamics	Drag-reduction technology that uses passive design optimization to extend laminar flow runs before transition to turbulence
Excrescence Reduction	Aerodynamics	Minimizes drag caused by external protuberances and surface quality.
Damage-Arresting Stitched Composites (DAC)	Structures	Lightweight advanced composite technology that decrease structural weight and have damage-arresting capabilities
Advanced Engine Cycle & Materials	Propulsion	Improvement in engine cycle and materials design will result in lower BSFC and dry engine weights
Active Load Alleviation	Flight Systems	Actively reduces impact of gust and maneuver loads which results in decreased structural weight and improved passenger comfort

Baseline Vehicle System

Parameter	ATR 42-600
Gross Takeoff Weight, lbf	41,005
Operating Empty Weight, lbf	25,491
Engine Rated Power, shp	2,160
Engines	P&W-127M (x2)
Design Capacity	48
Block Fuel (300 nm) lbf	1,733

Primary Objective: Reduce fuel consumption by 10 – 15%

Figure 33. Case study for TDRA framework

Figure 33 summarizes the case study objectives, technology portfolio, and baseline vehicle for application of the TDRA framework. For the baseline aircraft, a parametric model of the ATR 42-600 was built in GASP to serve as a demonstrative vehicle system.

Table 27. Baseline performance estimation from GASP

Performance Parameter	**ATR 42-600**
AEO T.O. distance, ft	3163
CEI T.O. distance, ft	3630
Accelerate-Stop distance, ft	3634
2nd Segment CEI Rate -of-climb, fpm	394
Time to Climb to Cruise Altitude, min	20
Cruise Speed / Altitude, ktas/ft	200 / 25,000
Cruise Lift-to-Drag Ratio	14.37
Equivalent Flat Plate Area, ft^2	15.12
Breguet Range Factor, nm	9221
Specific range, nm/lb	0.2294
BSFC, lb/hr/hp	0.4669
TSFC, lb/hr/lbf	0.4656

Table 27 establishes the baseline aircraft characteristics estimated by GASP for the mission profile in Figure 11. Since manufacturer data are not explicitly available for certain parameters, the engineering-level estimates from GASP to serve as a datum for comparison are relied upon. Advanced aircraft technologies impacting aerodynamics, structures/materials, flight systems, and propulsion were selected for the technology portfolio used in this case study displayed in Figure 33, following recommendations from AATT and the ICAO LTAG Technology Report [16].

5.2 Performance Evaluation of Advanced Aircraft Technologies

The performance risk assessment process involves technology selection, characterization from literature review, semi-empirical modeling, uncertainty quantification, and MC simulations coupled with parametric M&S tools. The proposed methodology draws from a combination of these techniques to make informed performance estimates with uncertainty and allow for design space exploration at the conceptual design phase.

Table 28. Advanced aircraft technology characterization

Technology	Type	Technology Characterization
Damage-Arresting Stitched Composites (DAC)	Structures	Reduction in airplane component weights by at least 10 percent [60].
Active Load Alleviation	Flight Systems	Reduction in wing bending weight by 1.7% and load factor reduction from 2.5g to 1.8g [79, 7]
Riblets	Aerodynamics	Reduction in skin friction drag between 5-8% for airfoil sections and 1-6% on the fuselage [66]. In AATT, 2-8% skin friction drag on aircraft components is estimated [19].
NLF	Aerodynamics	50% chord laminar flow on upper surface where applied [79] or, up to 80% chord laminar flow for multi-element wings and/or vortex generators [80, 81]
Excrescence Reduction	Aerodynamics	Reduction of 15-24% in profile drag equating to 8-12% reduction in cruise drag assuming full excrescence reduction [19] or, 7% of total drag reduction assuming full excrescence drag reduction [82].
Advanced Turboprop Engine Cycle & Materials	Propulsion	Approximately 10-15% improvement in engine BSFC due to improved OPR and T4 values and 4% reduction

		in specific engine weight from historical data-based projections [27, 83].

5.2.1 Riblets

To meet fuel burn goals, cruise drag reduction using integrated technologies is considered in many programs, including ERA. For subsonic transport aircraft, the two constituents of the cruise drag are viscous drag (skin friction and form drag) and lift-induced drag. Riblets are a skin friction reduction technology applied on the wing-body in areas of turbulent flow to constrain the development of large eddies in the boundary layer using longitudinal, V-shaped grooves aligned with the freestream flow [75]. While the riblets has been demonstrated in flight proving its significant drag reduction capabilities and timeline readiness since the 1980s, the technology has faced setbacks with regards to commercial adoption [8]. Since riblets represent a case where performance and timeline risk are low yet cannot seem to make the transition into widespread use, it is a good candidate to stress test the proposed TDRA framework. Performance modeling for riblets is detailed in Section 4.1 of this study, as it was used as a working example for the PICTO approach to performance risk assessment of an advanced aircraft technology.

5.2.2 Natural Laminar Flow (NLF)

NLF technologies capitalize on this benefit to significantly reduce the wing and fuselage profile drag, where up to 3.3% total drag reduction for a single-aisle aircraft with an NLF wing with insect accretion mitigation (IAM) coatings was determined during the ERA project's study of Innovative Flow Control Concepts for Drag Reduction [6]. The viscous drag reduction related to NLF will significantly improve cruise efficiency, takeoff, and climb performance where specific improvements depend on the extent of laminar flow compared to the total wetted area and operational mission. Flight test demonstrations have shown that extended runs of laminar flow can be obtained over regions of favorable pressure gradients on smooth airplane surfaces, thus providing a significant reduction in profile drag [84].

While NLF yields significant benefits, there are still factors that put the technology's performance impact at risk that must be captured in the probabilistic performance analysis. For instance, the applicability of NLF is limited to lower wing sweeps and chord Reynolds numbers which is a significant constraint for transport wing design [15]. NLF performance is also governed by physical factors related to boundary layer stability such as Tollmien-Schlichting (T-S) instabilities, crossflow (CF), and attachment line transition, where developments in wind tunnel test techniques and modern-day CFD are still working to capture this phenomena for more accurate prediction and analysis [85]. For straight-wing turboprop aircraft, concerns with loss of laminar properties for an NLF wing in the areas impacted by propeller slipstream effects must be taken into consideration. A study between DASA/Dornier Luftfahrt GmbH and DLR Braunschweig determined that for a Do 228, the undisturbed laminar flow region (x_{tr}=0.55) had a 50% profile drag reduction compared to the turbulent value (x_{tr}=0.05), while the profile drag reduction in the area of the wing impacted by the propeller slipstream was 14% [86]. While losses in laminar flow were incurred by the viscous propeller-blade wake, laminar flow was not totally lost in the slipstream affected region, and further design optimization can be performed to achieve the desired boundary-layer stability N-factor. However, certain operational conditions such as surface contamination, high angle-of-attack, and highly turbulent flow conditions can negate the benefits of NLF.

Table 29. Performance variability for NLF

Factor	Impact
Design	• Change in geometry due to flight loading may negate benefits from NLF wing and fuselage

	• Difficult to design in according to boundary layer transition behavior (which is difficult to model) • High design complexity due to advanced modeling, precise geometric specification, and tolerances. The surface tolerance requirements dictate anti-/de-icing system.
Operating Conditions	• Loss of laminar flow due to insect accretion, rain, icing conditions, clouds, and surface erosion after continued use • Propeller slipstream effect on wing may negate NLF benefits by inducing earlier transition • Highly sensitive to off-design conditions (Reynolds number, angle of attack, Mach numbers, altitude)
Manufacturing/Quality	• Stringent manufacturing requirements must be employed/maintained in order to get full benefit of NLF • Surface degradation as well as surface quality changes can lead to losses in performance for NLF wings • NLF benefit losses from integration with airframe-propulsion

Table 29 addresses the sources of performance variability from NLF technologies. Since the risk of losing NLF is high, the worst-case scenario must reflect the potential for 0% drag reduction benefit. In this case, the transition location will be set to default in GASP. For an upper bound, utilization of vortex generators to energize the turbulent boundary layer and delay the transition location to ≥80% chord and design of 2-element airfoils to allow for 80% chord transition location can also increase NLF benefits [80, 81]. To assess airfoil profile drag estimation including the effect of laminar flow is modeled based on methods from Torenbeek and Hoerner [41, 87]. The semi-empirical model for minimum profile drag at subsonic conditions is:

$$c_{d,\min} = 2C_f[1 + f(t/c)] \tag{10a}$$

$$f(t/c) = 2.7\frac{t}{c} + 100\left(\frac{t}{c}\right)^4 \tag{10b}$$

Eqs. (10a) and (10b) determine the minimum sectional profile drag that can be obtained as a function of the thickness-to-chord ratio and skin friction coefficient, the latter of which is determined by the Reynolds number and transition location. Where mean skin friction coefficient C_f can be obtained from Fig. F-4 in Torenbeek or the following chart, which is also programmed in GASP's subroutine for calculating the mean skin friction coefficient as a function of Reynolds number [41]:

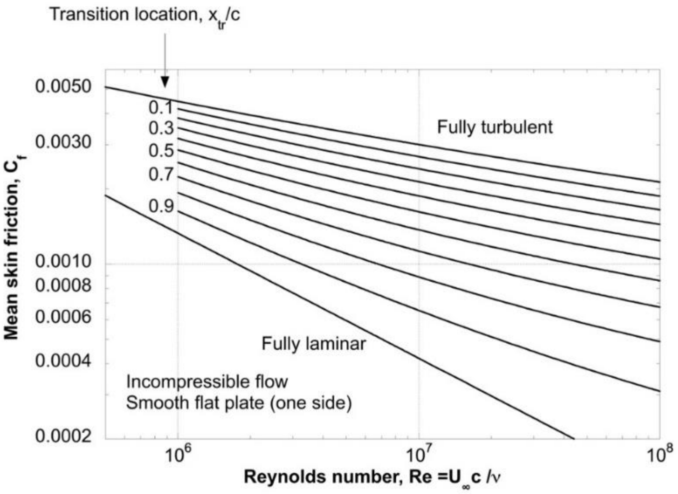


Figure 34. Flat plate skin friction as a function of transition location and chord Reynolds number at incompressible flow conditions

The flat plate skin friction is obtained from reading Figure 34.The turbulent flow results are based on the approximate Prandtl-Schlichting equation while the laminar flow results are based on the Blasius equation and the profile drag coefficient is provided as a function of $c_{d,min}$ [88].

$$C_f = \frac{0.455}{(\log \mathrm{Re})^{2.58}} - \frac{x_{tr}}{c}\left\{\frac{0.455}{\left[\log\left(\mathrm{Re}\frac{x_{tr}}{c}\right)\right]^{2.58}} - \frac{1.3282}{\sqrt{\mathrm{Re}\frac{x_{tr}}{c}}}\right\} \tag{11}$$

$$c_d = c_{d,min} + k_p(c_l - c_{l,min})^2 \tag{12}$$

Ref. [89] lists typical values for the profile drag to lift parameter k_p which varies significantly with the lift coefficient. However, assuming the application of a cruise flap, the cruise flap will allow the airfoil to operate inside the laminar bucket during cruise and climb. Therefore, $c_d \simeq c_{d,min}$ for Eq. (12).

$$c_d \simeq c_{d,min} = 2C_f\left[1 + 2.7\frac{t}{c} + 100\left(\frac{t}{c}\right)^4\right] \tag{13}$$

Eq. (13) is the semi-empirical estimation for obtaining the minimum profile drag as a function of thickness-to-chord ratio, C_f, Reynolds number, and transition location. To verify the accuracy of the semi-empirical equation for NLF, two cases are used for validation.

Table 30. Validation for semi-empirical NLF model using NLF(1)-0414F airfoil

Item	Value
Airfoil Name	NLF(1)-0414F
t/c	0.142
Reynolds Number	10.0 million
Upper/lower surface, x_{tr}	0.70
C_f from Figure 34	0.00113
Semi-Empirical $c_d = c_{d,min}$ from Eq. (13)	0.0032
Experimental Results for $c_{d,min}$ [90]	0.0027

Table 31. Validation for semi-empirical NLF model using HSNLF(1)-0213 airfoil

Item	Value
Airfoil Name	HSNLF(1)-0213
t/c	0.13
Reynolds Number	9.0 million
Upper/lower surface, x_{tr}	Upper surface $x_{tr} = 0.50$ Lower surface $x_{tr} = 0.70$
C_f from Figure 34	0.00141
Semi-Empirical $c_d = c_{d,min}$ from Eq. (13)	0.0039
Experimental Results for $c_{d,min}$ [91]	0.0040

Table 30 and Table 31 show validation for the derived semi-empirical model for NLF using low-speed and high-speed NLF, where for NLF-0414F there is a difference of -0.0005 between the semi-empirical and experimental results, and then a difference of -0.0001 for the HSNLF(1)-0213 results. Overall, fair agreement between semi-empirical method for the prediction of profile drag of laminar flow airfoil and experimental results. Then, the calculation for profile drag reduction with NLF on the fuselage can be determined using similar methodology using Eq.(F-38) of Ref. [41].

$$\mathrm{C}_{\mathrm{D}_{\mathrm{fuselage}}} = \mathrm{C}_{\mathrm{f}}(\frac{S_{f_{wet}}}{S_{ref}})(1+\phi_f) \tag{14}$$

where:

$\mathrm{C}_{\mathrm{D}_{\mathrm{fuselage}}}$ = fuselage profile drag coefficient
C_{f} = skin friction drag coefficient based on x_{tr} using Figure 34 which is $x_{tr}=0$ for no laminar flow
$\mathrm{S}_{\mathrm{f}_{\mathrm{wet}}}$= wetted area of the fuselage (ft^2)
$\mathrm{S}_{\mathrm{ref}}$ = the aircraft reference area (ft^2)
ϕ_f = the fuselage shape factor from Fig. F-9 from Ref. [41]

5.2.3 Excrescence Reduction

Another component of airframe drag is excrescence drag – any item that disturbs the otherwise smooth flow of air over the surface of an aircraft. For regional turboprop airplanes, the scale of the disturbance to the overall aircraft size increases the effect of excrescence items on the aircraft [92]. Contributions to excrescence drag include but are not limited to surface roughness, internal airflow, mismatches and gaps, and discrete items. Excrescence reduction is less of a technology and more of an advanced aerodynamic technique that reduces the number of external protrusions or irregularities on an aircraft's surface. Excrescence reduction is not just a technology; rather, it represents an advanced aerodynamic and manufacturing technique aimed at minimizing external protrusions or irregularities on an aircraft's surface. These disturbances encompass various elements such as antennas, structural components, sensors, and even the quality of the airframe surface. Semi-empirical methods from Hoerner and similar reference material provide methodologies to estimate the effects of each gap, step, bump, inlet, exit, antenna, or other excrescence items [87]. However, the process is simplified in GASP to obtain the excrescence drag as a percentage of the zero-lift drag contributions of the wing, nacelles, pylon bodies, and empennage of the aircraft. For the ATR-42-600, it was found that excrescence drag accounted for 6.59% of the total drag. Other technology calibration factors are added for other types of drag in GASP such as interference drag, induced drag, and compressibility drag. Impacts are modeled as distributions due to the potential uncertainty that can be propagated during analytical and experimental data acquisition for aerodynamics technologies, loss of laminar flow from off-design conditions, residue build-up and surface degradation over time, and other factors that may impede the technology’s effectiveness.

Regarding interaction between the technologies applied on wing-body surfaces, NLF defines areas designed for laminar flow, while riblets are applied in areas designed for turbulent flow. For NLF and riblets to be successful, excrescences must be minimal in areas where laminar flow is designed to occur on the wing and fuselage. Steps, gaps, rivets, and features exceeding a specific height limit (which is dependent on unit Reynolds number and shape of disturbance) can cause premature transition that leads to loss of laminar flow. Excrescence reduction has positive synergy between both technologies. Despite what is stated in the AATT report from FY2019, these technologies can be carefully integrated on the same surface with several factors in mind

[22]. For the advanced turboprop case study, NLF was applied to the wing and fuselage, where the area after the transition location on each surface would be covered with riblet film. From this method of application, the aggregate benefit can be assessed.

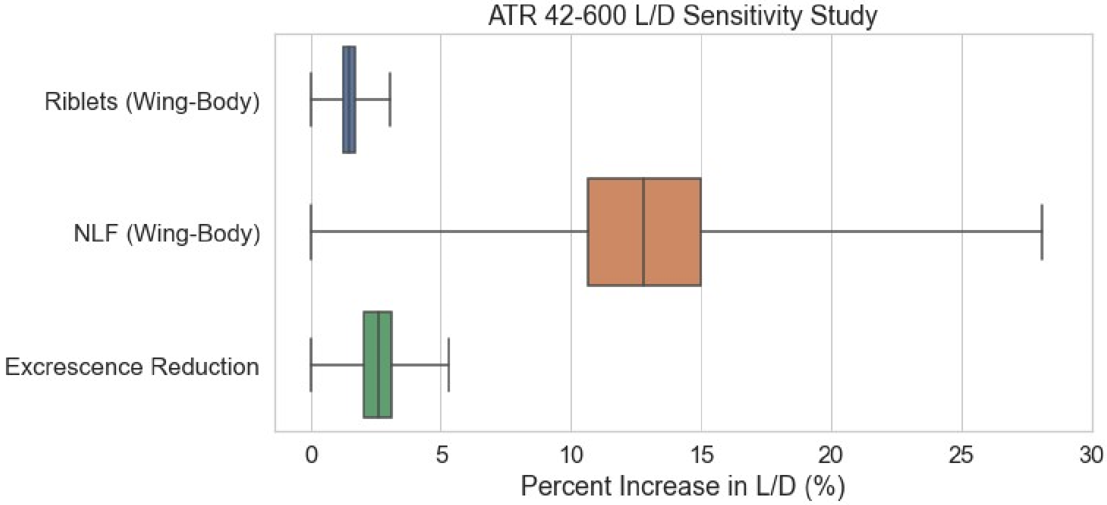


Figure 35. L/D sensitivity study from aerodynamics technologies applied

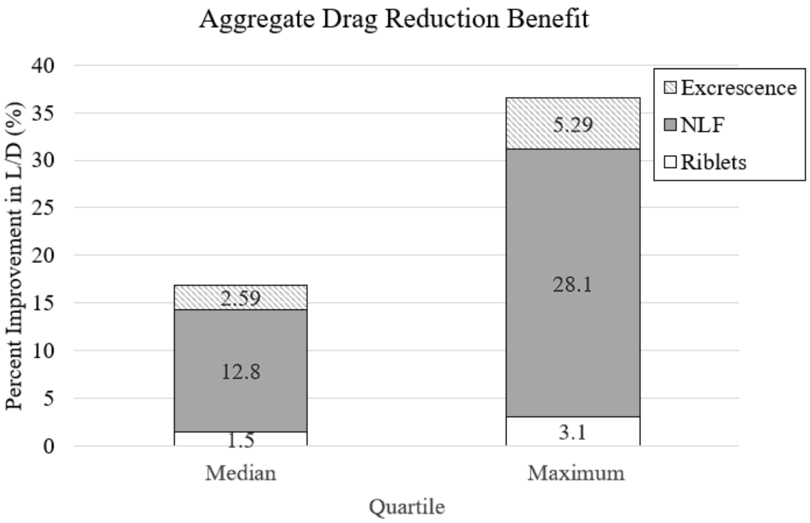


Figure 36. Aggregate drag reduction benefit from aerodynamics technologies applied

Figure 35 and Figure 36 capture the impacts of the aerodynamics technologies on the cruise L/D showing aggregated benefits that can be achieved through optimal design and application.

5.2.4 Damage-Arresting Stitched Composites (DAC)

Since damage-arresting composites (DAC) are a structural technology of interest to the EPFD program, uncertainty quantification of its performance has been done empirically and reported in the technology maturation report (TMR) detailed in Ref. [70]. The purpose of the TMR was to summarize the development and results of a DAC demonstration to observe the weight savings and fuel burn reduction capabilities from utilization of lightweight DAC primary structures (wing and fuselage). Though the advanced composites anticipated for this turboprop aircraft study do not make full use of the PRSEUS technology and omit the use of pultruded rod structures, there are expected weight savings from using stitched composite structures such as DAC that can be modeled using structural technology factors similar to what is done for aerodynamics technology factors. Compared to traditional carbon composites which consist of 20% of the total body weight of the ATR 42-600 and 7% of the body weight of the Saab 340B, DAC is considered an advanced composite with higher weight savings benefits and structural efficiency.

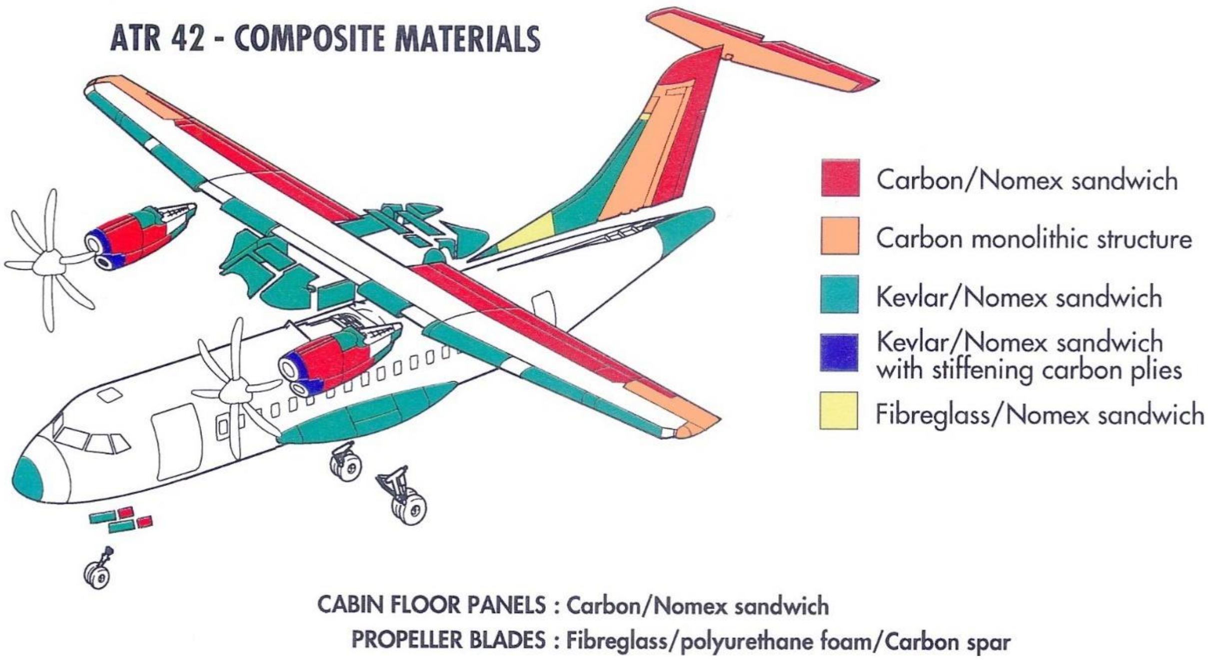


Figure 37. Composite material usage on the ATR 42-600 [93]

Figure 37 shows the material composition on the ATR 42-600. Since the ATR 42-600 makes use of both aluminum and composites for the airframe structure, this must be reflected in the technology factors. As mentioned in the TMR, sources of uncertainty propagated through the weight estimation environment stem from model fidelity and panel imperfections which lead to variation in material stiffness and densities [60]. The technology factors provided by SMEs, TMR, and Boeing DAC trade study in the ERA report summarized in the TMR capture these bounds, which were used in GASP to resize the vehicle [70, 94].

Table 32. Turboprop aircraft percent weight reduction distributions from DAC application

Component	Tech. Factor	Minimum	Mode	Maximum
Wing	Aluminum to DAC ($f_{Al\rightarrow DAC}$)	17%	26%	39%
	Composites to DAC ($f_{C\rightarrow DAC}$)	5%	10%	10.8%
Fuselage	Aluminum to DAC ($f_{Al\rightarrow DAC}$)	6%	16%	30%

	Composites to DAC ($f_{C\rightarrow DAC}$)	7%	10%	10.6%

Table 32 shows the technology factor minimum, mode, and maximum values. The wetted area of sections unaffected by the weight reduction are considered S_{null} for the purpose of the semi-empirical modeling and analysis. The composite types used in the construction of each primary structure is detailed above. It is advised that replacement of Kevlar/Nomex structures with DAC will not significantly reduce the structural weight, hence only the sections made of aluminum and carbon-based composites will be replaced with DAC [94]. The impact of DAC on the weight of the aircraft is modeled using the semi-empirical equation:

$$\mathrm{W}_{\mathrm{struct,DAC}} = W_{struct,baseline}[\frac{S_{null}}{S_{struct}} + \frac{S_C}{S_{struct}} f_{C\rightarrow DAC} + \frac{S_{Al}}{S_{struct}} f_{Al\rightarrow DAC}] \tag{15a}$$

and

$$S_{null} + S_C + S_{Al} = S_{struct} \tag{15b}$$

where:

$\mathrm{W}_{\mathrm{struct,DAC}}$ = weight of the structure (e.g., wing or fuselage) with DAC applied (lb)

$\mathrm{W}_{\mathrm{struct,baseline}}$ = weight of the structure from GASP (lb)

S_{struct}= wetted area of the structure (ft^2)

$\mathrm{S}_{\mathrm{null}}$ = surface area of the structure where weight reduction from DAC is negligible (e.g., advanced composites already applied or minimum gauge) (ft^2)

S_c = surface area made of composites that can be upgraded to DAC (ft^2)

S_{Al} = area of the structure made of aluminum (ft^2)

$f_{Al\rightarrow DAC}$ = aluminum to DAC technology factor

$f_{C\rightarrow DAC}$ = composites to DAC technology factor

This methodology takes into consideration the wetted area coverage of the structural technology and its areas of impact. Because the objective of the case study is to achieve best fuel efficiency, which is driven by cruise performance, the impacts of aerodynamic and structural technologies play a role in driving these metrics and should be captured at the conceptual design phase [6]. Further CFD and FEA simulations later can refine these bounds.

5.2.5 Active Load Alleviation (ALA) Systems

A key design objective for a civil transport airplane is to achieve best possible cruise efficiency with a low structural weight being an integral part this efficiency. Excessive structural weight will not only increase capital cost but also increase the total weight of the airplane and thereby increase the aerodynamic drag. Maneuver loads (typically a positive design load factor n_{max} = 2.5g for civil transport jets) and gust loads must be considered in the structural design of the airframe with gust loads being a likely critical contributor for relatively low wing-loading airplanes with high aspect ratio wings. The next technology, Active Load Alleviation (ALA) is a flight systems technology with both aerodynamic and structural characteristics that aims to reduce maneuver loads (typically a positive design load factor n_{max} = 2.5 g for civil transport jets as in Part 25) and gust loads applied to the airframe. The stochastic nature of gust loads, estimations in forces and moment calculations, and the ability of the maneuver load control (MLC) system to deploy optimally when encountering in-flight loads are sources of uncertainty propagation in performance assessment of ALA.

As the load factor n is changed as a result of a maneuver (turn or pull-up) or a gust, the wing root bending moment (WRBM) is changed accordingly. Then, the wing weight can be calculated as a function of the wing-root bending moment, such as demonstrated in Ref. [95], which provided a parametric analysis for studying the effects of wing root bending moment alleviation. Other studies modeling the impact of ALA at the conceptual design phase such as Ref. [79] use multi-point design optimization to determine the optimal design point for an aircraft encountering specific gust and maneuver loads with the goal of minimizing fuel burn.

However, a more probabilistic method of accounting for the effects of ALA is favored where in-flight availability of MLC system is considered, which is based on the frequency of exceedance of maneuver load factors per flight determined by NASA from data acquired on three types of jet-propelled civil transports [96]. Within this report, a design load factor of 2.5g without the MLC system activated can be equated with a design load factor of 1.8g for an aircraft with the MLC system on, assuming an in-flight system availability of 99.90%. The maneuver acceleration data from Ref. [96] was plotted with an added curve-fit through the NASA data to obtain the MLC-on versus MLC-off load factor requirements.

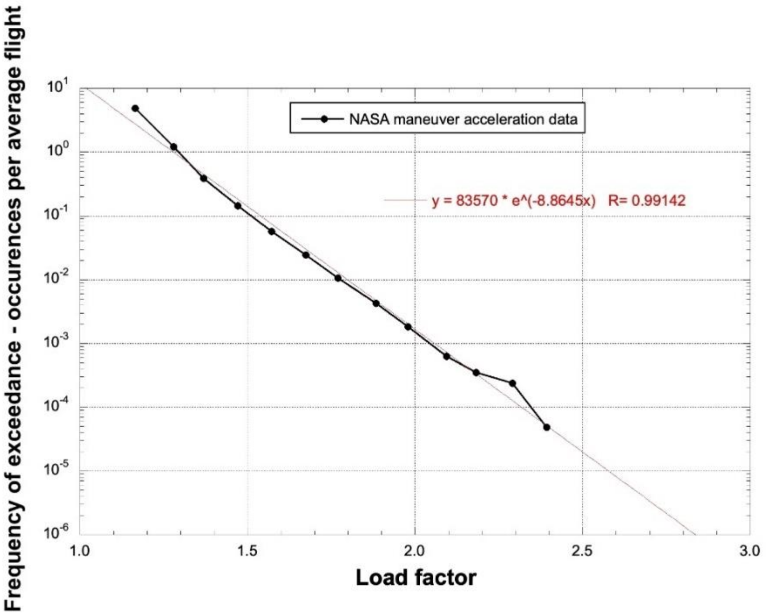


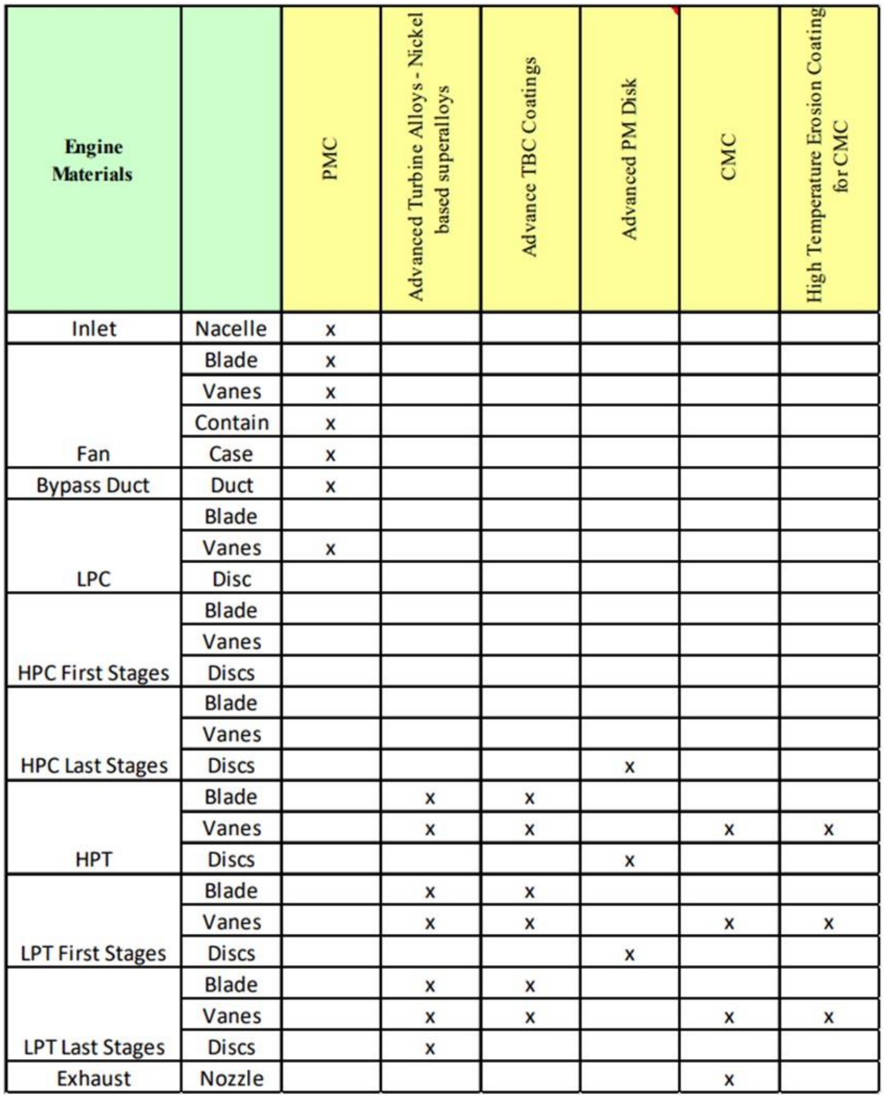
Figure 38. Frequency of maneuver load factor exceedance for civil transport airplanes as determined by NASA based on analysis of in-flight data

Figure 38 depicts the MLC-on versus MLC-off load factor requirements for a range of system availabilities with the earlier equivalence (2.5g to 1.8g) highlighted in red. As a second example, if a load factor combination of $n_{MLC\text{-}on}$ =2.535 and $n_{MLC\text{-}off}$ =1.350 is selected, an availability of 99.9990% would be required. Thus, to simulate the effects of an ALA system, a PERT distribution is used where for the best-case scenario, a design load factor of 2.5g without the

MLC system activated can be equated with a design load factor of 1.8g which is a 28% decrease in GASP model's load alleviation factor with a mode of 20% (2.0g). The full derivation for semi-empirical methods in modeling an ALA system can be found in Appendix A.

5.2.6 Advanced Turboprop Engine

Lastly, the capability of modeling performance distributions from application of advanced propulsion technologies was demonstrated. The 'advanced turboprop engine' pertains to cumulative enhancements across engine components that align with the historical trends of increased efficiency, all contributing to the overall improvement of engine performance expected by 2030. These improvements are based on published technology projections that assume evolutionary improvements in engine cycle and materials that lead to overall lower fuel burn and specific engine dry weight [83]. Examples of improvements include advanced materials that permit higher turbine inlet temperatures, higher pressure ratios, and higher turbomachinery component efficiencies.



Engine Materials		PMC	Advanced Turbine Alloys - Nickel based superalloys	Advance TBC Coatings	Advanced PM Disk	CMC	High Temperature Erosion Coating for CMC
Inlet	Nacelle	x					
Fan	Blade	x					
	Vanes	x					
	Contain	x					
	Case	x					
Bypass Duct	Duct	x					
LPC	Blade						
	Vanes	x					
	Disc						
HPC First Stages	Blade						
	Vanes						
	Discs						
HPC Last Stages	Blade						
	Vanes						
	Discs				x		
HPT	Blade		x	x			
	Vanes		x	x		x	x
	Discs				x		
LPT First Stages	Blade		x	x			
	Vanes		x	x		x	x
	Discs				x		
LPT Last Stages	Blade		x	x			
	Vanes		x	x		x	x
	Discs		x				
Exhaust	Nozzle					x	

Figure 39. Advanced engine materials for component improvement [22]

Figure 39 shows how many of the engine fuel burn technologies used include advanced materials placed throughout the engine [22]. With improvements in engine design, materials and CFD tools, engine designers can better optimize performance which leads to significant increases in engine efficiencies on the order of magnitude of 0.25% to 0.5%, resulting in a BSFC improvement of 10-15% and 4% reduction in the specific engine weight. In GASP, engine performance models are generated by NPSS, which is developed by NASA Glenn Research Center [97]. Modeling the impacts of propulsion technologies is done by implementing changes in the baseline PW127M NPSS engine model where engine parameters are changed to create an advanced turboprop engine. The advanced turboprop engine models in NPSS assume fixed engine architecture, improved OPR and turbine temperatures, improved component efficiencies (e.g., compressor and turbine), turbine cooling technologies, and engine weight projections from Refs. [83, 98]. The expected engine performance was set at a mode of 10% improvement in BSFC with a maximum of 15% BSFC while the specific engine weight was expected to vary from 2-4% to account for the lower and upper bounds of the technology projections estimates. In GASP, this is done by impacting the form factor for installed engine fuel flow and the maximum sea level static horsepower parameters [63].

5.3 Performance Risk Assessment Results

The individual and aggregate performance benefits of each technology on gross takeoff weight (GTOW), operating empty weight (OEW), and fuel weight are shown for each turboprop configuration. Since the output of the MC-GASP simulations are performance distributions with uncertainty, box and whisker plots are used to capture the distribution of data, where the whiskers capture the range of values, the center line of the box depicts the 50th percentile (median), and the edges of the box show the first quartile and third quartiles respectively. For this study, 2,125 samples were sufficient in characterizing the input and output distributions.

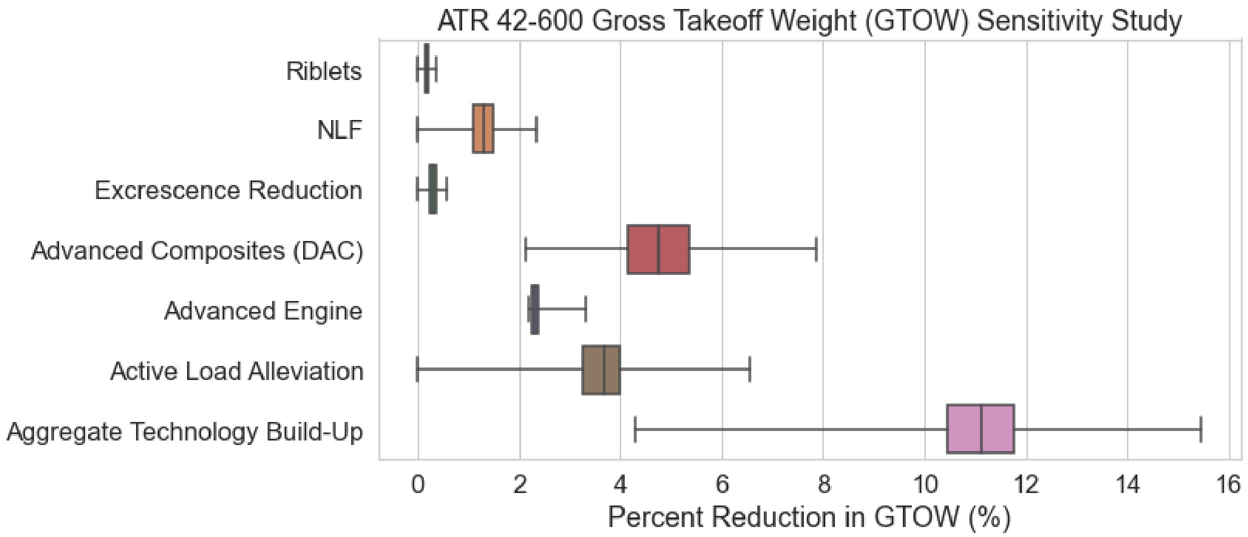


Figure 40. Technology performance sensitivity for GTOW

For the aggregate technology benefit on GTOW for the ATR 42-600, the minimum is 4.28% to a maximum of 15.46% reduction with a median of 11.10%, showing that the median falls closer to the maximum than the minimum. In Ref. [26], NLF was predicted to have a 1.8% GTOW reduction on the ATR 42-600 whereas in this study, NLF has a minimum of 0% GTOW reduction, maximum of 2.33% reduction, with a median of 1.3%, showing that the value of 1.8% falls between the third quartile and maximum. Overall, the technology sensitivity studies show that the most effective technology for reduction in GTOW is advanced composites (DAC) followed by ALA. This is expected as structural weight accounts for most of the GTOW and technologies that impact structural weight of primary components such as DAC and ALA will have the highest impact. The benefit of the box-and-whisker plot visualization of the results allows for improved conceptualization of not only the performance benefit, but also the width of the range of expected performance and where the median performance benefit falls in the distribution.

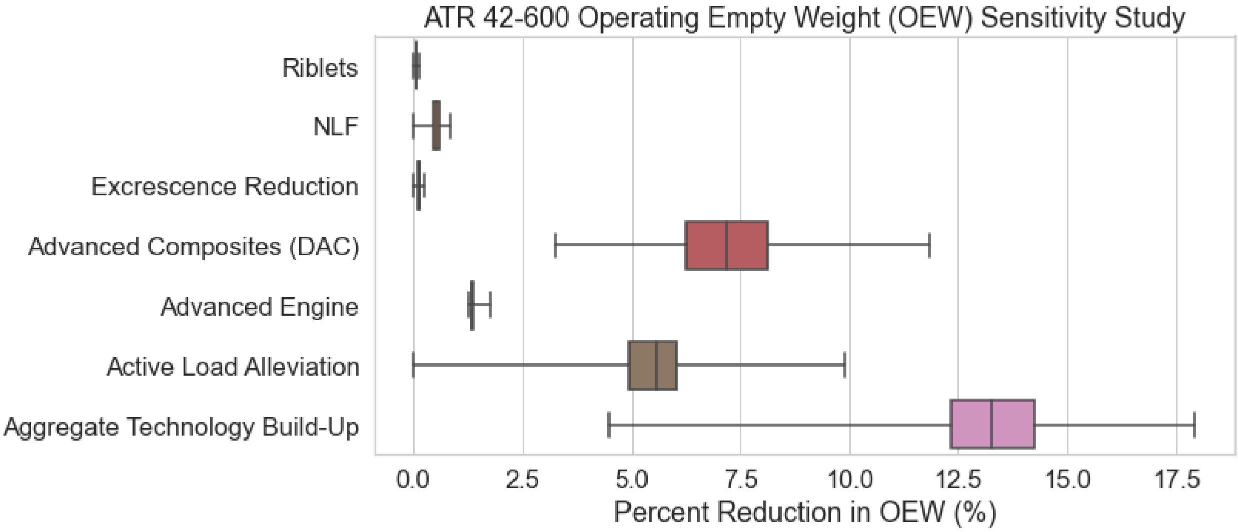


Figure 41. Technology performance sensitivity for OEW

Figure 41 assesses the sensitivity of the advanced aircraft technologies on OEW, which is an important top-level parameter that represents the weight of the aircraft when empty of fuel and payload. OEW impacts fuel efficiency, payload capacity, maintenance costs and must fall within weight limits required by regulatory compliance. With the applied technologies, a 4.5% to 18% reduction in OEW can be expected with a median of 13.3%.

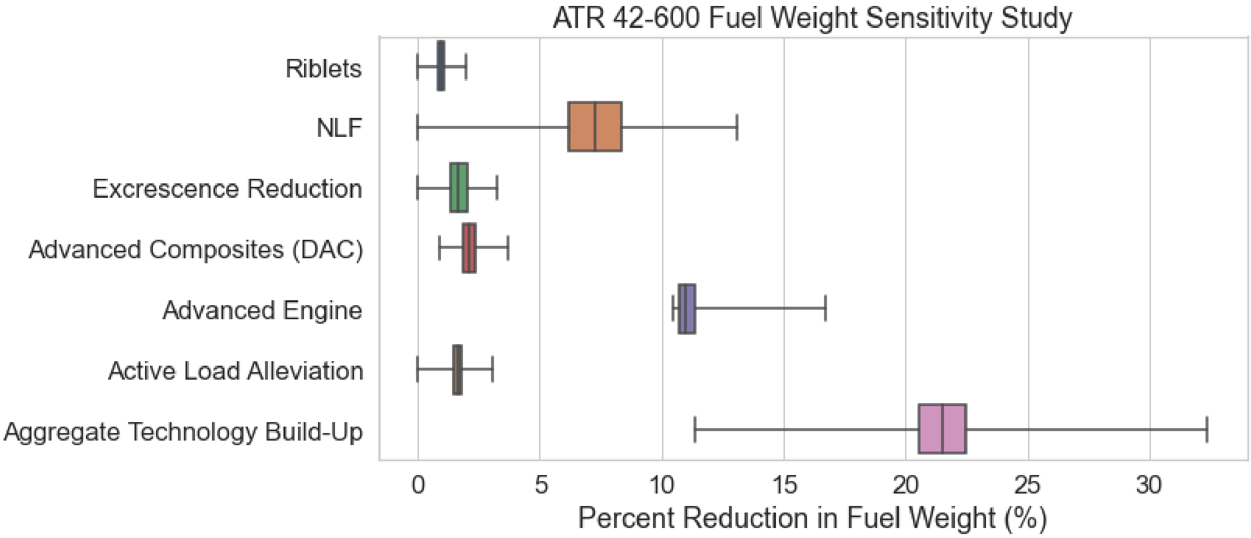


Figure 42. Technology performance sensitivity on fuel weight

Figure 42 shows the impact of the advanced aircraft technologies on the overall fuel weight. As observed, the highest impact technology is the advanced turboprop engine as it directly impacts fuel efficiency. The definition of fuel weight in this study represents the total fuel load which includes both the primary mission and reserves. It is observed that significant, though volatile benefits from drag reduction technologies such as NLF on fuel weight with an aggregated benefit of 11.4% to 32.4%, where the lower limit is estimated at a worst-case scenario where benefits from aerodynamics technologies and ALA systems are null. The aggregate benefit of aerodynamics technologies assuming best-case performance is 9.89%.

Table 33. Impact of advanced technologies on baseline ATR 42-600

Performance Parameter (% Diff.)	**50th Percentile Impact**
AEO T.O. distance, ft	2895 (-8.47%)
CEI T.O. distance, ft	3228 (-11.1%)
Accelerate-Stop distance, ft	3428 (-5.67%)
2nd Segment CEI Rate -of-climb, fpm	459 (+16.5%)
Time to Climb to Cruise Altitude, min	13.47 (32.7%)
Cruise Speed, ktas	200 (0%)
Cruise Lift-to-Drag Ratio	19.84 (+38%)
Equivalent Flat Plate Area, ft^2	9.2123 (-39%)
Breguet Range Factor, nm	13,794 (+49.6%)
Specific range, nm/lb	0.34093 (+48.6%)
BSFC, lb/hr/hp	0.4156 (-11%)
TSFC, lb/hr/lbf	0.4298 (-7.69%)

Table 33 summarizes the advanced aircraft technology impacts with uncertainty for the baseline ATR-42-600 aircraft. Significant reductions in T.O. distance, and improvements in cruise L/D, and specific fuel consumption TSFC and BSFC are observed for the advanced configurations. The aggregate technology build-up depicts the propagation of uncertainties when analyzing the individual technologies in a package. When assessing the benefits of an in-development technology at the conceptual design phase, this methodology provides a rational approach to inform decision-makers of not only the technology's impact but uncertainty present in the impact of these technologies at the early design stages.

5.4 Timeline Readiness Risk Assessment Results

The purpose of the timeline readiness risk assessment is to determine the current technology maturity of a technology using independent literature review and best-practices TRL assignment that accounts for the variability, use the uncertainty-driven TRL transition analysis to obtain transition estimations for the technology, and determine the likelihood of technologies meeting the goal of TRL 6 by 2030, in line with the advanced turboprop flight demonstrator used in the case study.

5.4.1 Current TRL Assessment

In the assessment, a systematic approach to evaluate the developmental journey of each advanced aircraft technology is provided. Through independent, historical literature review on what is available in the public domain, the evolution of these technologies is traced through a sequence of distinct stages, beginning with their inception from fundamental principles to practical application on a flight demonstrator. Leveraging these timelines, the key milestone of each TRL progression is documented and clarity provided on the specific context of their application, aircraft type they are integrated into, and distinguish the environment within with the technology is demonstrated.

Table 34. TRL assessment for riblets on the wing and fuselage

TRL	Definition	Development Description	TRL Achieved (Wing)	TRL Achieved (Fuselage)
1	Basic principles observed and reported.	In 1978, M.J. Walsh and L.M. Weinstein examined the drag characteristic of small, longitudinal fins that would later be called riblets [99].	Yes.	Yes.
2	Technology Concept/Application Formed	In 1980-1983, Walsh continued his experimental research on "Drag Characteristics of V-Groove and Transverse Curvature Riblets" where up to 7% drag	Yes.	Yes.

		reduction was observed on applied surfaces. Riblets for aeronautics are discussed [100].		
3	Analytical and experimental proof-of-concept and critical function tested and/or characteristic	Research and development for using riblets to reduce turbulent skin friction drag begins with testing of riblet geometries on surfaces at NASA Langley Research Center [100].	Yes.	Yes.
4	Component and/or breadboard validation in a laboratory environment	From previous wind tunnel tests, it is discovered that V-shaped groove riblet geometries are the most effective. Following advice from 3M Co., vinyl riblet films are tested in low-speed wind tunnel tests at NASA Langley Research Center [100].	Yes.	Yes.
5	Component/brassboard validation in a relevant environment.	In 1991, D.W. Bechert and other researchers conduct experiments of a 1:4.2 model of a Dornier Do 328 commuter turboprop were conducted in the German-Dutch wind tunnel showing up to 1-6% drag reduction [75].	Yes.	Yes.
6	Flight test demonstration in a relevant environment with a full-scale demonstrator	Riblets have been flown on an experimental Learjet 28/29 – a business jet flight demonstrator in 1988 [100].	No. Testing has been done at a higher Mach number and Reynolds number.	Yes.
7	System prototype demonstration in an operational environment.	Riblet film was demonstrated on an A320. Though the swept-wing configuration is dissimilar from that of a straight-wing turboprop aircraft, the fuselage design is similar in 1990 [75].	No. See above.	Yes.
8	Actual system completed and flight-qualified through test demonstration.	Cathay Pacific applied riblet film to cover 30% of an Airbus 340-300 that is flown on commercial routes in 1994 [75].	No. See above.	Yes.
9	Actual system flight-proven during commercial operation.	Riblet film has been demonstrated on an A320, Boeing 777, and Boeing 747 and has been flown by airliners such as Cathay Pacific and Lufthansa [75]. However, it has not undergone flight test demonstration on any commuter turboprop similar to the ATR 42-600.	No. The operational conditions for the wing do not match that of the advanced turboprop demonstrator.	Yes.
For the advanced turboprop demonstrator, riblets for the wing is at TRL 5 and TRL 9 for the fuselage.				

Table 34 provides the methodical TRL assignment for riblets on both the wing and fuselage and its readiness for integration onto an advanced turboprop flight demonstrator. In the context of the advanced turboprop demonstrator for the case study, riblets are currently at TRL 5 for the wing and TRL 9 for the fuselage.

Table 35. TRL assessment for NLF on the wing and fuselage

TRL	Definition	Development Description	TRL Achieved (Wing)	TRL Achieved (Fuselage)
1	Basic principles observed and reported	Stüper in 1934 did some of the earliest flight experiments on boundary layer development and transition from laminar to turbulent flow on wings [101].	Yes	Yes
2	Technology concept/application formed	In mid-late 1930s application of NLF to reduce airplane drag is explored theoretically resulting in development of NACA 6-series airfoil family [102].	Yes	Yes
3	Analytical and experimental proof-of-concept and critical function tested and/or characteristic	R&D of NLF to reduce wing profile drag incl wind tunnel and flight testing in late 1930s to mid-1940s. Focus on low sweep, propeller driven airplanes [101, 102].	Yes	Yes
4	Component and/or breadboard validation in a laboratory environment	Wind tunnels capable of achieving flight Reynolds numbers had too high turbulence levels to effectively study laminar flow and transition on airfoils. Low-Turbulence Pressure Tunnel at NACA Langley became operational in 1941 allowing for wind tunnel testing of NLF airfoils [103].	Yes	Yes
5	Component/breadboard validation in a relevant environment.	In 1939, NACA B-18 flight test of NLF glove on port wing achieve a transition Reynolds number of 11.3 million (transition at x/c = 0.425). Also evaluated impact of engine & propeller noise on transition.	Yes	Yes
6	Flight test demonstration in a relevant environment with a full-scale demonstrator	Extended runs of NLF have been demonstrated on aircraft similar in size and speed as turboprops Piaggio P.180 (wing & fuselage), Cessna Crusader (fuselage), Dornier Do 328 (wing), Hondajet (wing & fuselage) [85, 104].	No. While the laminar flow glove has been tested on a regional turboprop, a laminar flow wing has not been fabricated and flown on the specific flight test demonstrator.	Yes
7	System prototype demonstration in an operational environment.	In mid 1940s flight tests of production aircraft designed with laminar surfaces (e.g., P-51 wing) demonstrate that NLF is not practical. Not until improved materials and manufacturing techniques in 1970s does NLF become practical [102].	No. See above.	Yes
8	Actual system completed and flight-qualified through test demonstration.	No existing NLF wing design for FAR Part 25 turboprop airplanes. Especially combination of effective de-/anti-icing system combined with NLF wing design is a challenge. NLF nose of fuselage is at TRL 8 as demonstrated by Piaggio P.180, Cessna Crusader, Hondajet [104].	No. See above.	Yes
9	Actual system flight-proven during commercial operation.	No NLF design for FAR Part 25 turboprop airplanes. Especially combination of effective de-/anti-icing system combined with NLF wing design is a challenge.	No. See above.	No
For the advanced turboprop demonstrator, NLF for the wing is at TRL 5 and TRL 8 for the fuselage.				

From Table 35, NLF technologies on the wing are at TRL 5 while NLF for the fuselage is at TRL 8 for the advanced technology demonstrator. Further efforts for design and validation of an NLF wing for commuter aircraft must be pursued.

For excrescence drag reduction, comprehensive TRL assignment is complicated by the nature of the technology, unlike other portfolio elements, it is not an “applied” technology, but rather recommended techniques pertaining to the overall design, development, and manufacturing of an aircraft. Wind tunnel tests for excrescence drag reduction brought it to at least TRL 6 according to a 1981 AGARD report on the subject [92]. The AATT report places excrescence reduction at TRL 9 as it is a design consideration used for production of all Boeing airliners, though for the advanced turboprop demonstrator, its actual TRL will match that of the lowest TRL for riblets and NLF where applied [22].

Table 36. TRL assessment for DAC

TRL	Definition	Development Description	TRL Achieved (Wing)	TRL Achieved (Fuselage)
1	Basic principles observed and reported.	Under the Advanced Composites Technology (ACT) program in the 1990s, NASA, McDonnell-Douglas, and Boeing explore composite technologies to develop lighter primary structures [70].	Yes.	Yes.
2	Technology Concept/Application Formed	Following ACT Phase C, a stitched carbon-epoxy material system was developed with the observed potential to reduce the structural weights and costs of aircraft wing structures. At this point, damage-arresting capabilities were not understood, but demonstrated by these test efforts [59].	Yes.	Yes.
3	Analytical and experimental proof-of-concept and critical function tested and/or characteristic	In 2005, Boeing files a patent related to damage-arresting structures and in 2004-2006, the AFRL released a report covering Boeing’s work on damage-arresting stitched composites. At this point, experimental test assembles of a breadboard level of fidelity were subject to controlled loads testing [105].	Yes.	Yes.
4	Component and/or breadboard validation in a laboratory environment	Under the 2009-2015 ERA project, damage-arresting stitched composites were experimentally and tested as a component of the PRSEUS system. Panel fabrication, specimen fatigue characterization, design studies and bulkhead load tests load to reduction of performance uncertainty [70].	Yes.	Yes.

5	Component/brassboard validation in a relevant environment.	Full-scale tests for DAC fuselage panels are done to assess damage containment features in 2011, but a full-scale fuselage has yet to be tested. Subscale assemblies have been tested and validated to acquire critical load data, though development has remained at this stage since the end of the ERA project [70].	No.	No.
For the advanced turboprop demonstrator, damage-arresting stitched composites are at TRL 4.				

Table 36 shows the TRL assessment for DAC, placing the technology at TRL 4 in the context of an advanced turboprop demonstrator, though with regards to the HWB, the technology is at TRL 5. This distinction shows the importance in understanding that technology readiness varies based on application, such as consideration of the aircraft type. For DAC, while systems analysis efforts have estimated weight reduction in an advanced tube-and-wing configuration, however modeling, fabrication, and test efforts of a turboprop wing-body has yet to be conducted.

Table 37. TRL Assessment for ALA systems

TRL	Definition	Development Description	TRL Achieved
1	Basic principles observed and reported.	In 1957, NACA Report 1321 details methodology to calculate the power spectra of rolling and yawing moments of a wing in random turbulence [106]. This begins development efforts toward developing a flight control system that would allow for load alleviation.	Yes.
2	Technology Concept/Application Formed	In 1965, G. Skelton at Honeywell Inc. wrote a technical document on "Wind Effects on Aerospace Vehicles" and then "Design of a Load Relief Control System." This began efforts at Boeing to initiate a "Technical Development Program for a Flight Control System" investigating wind load alleviation technologies [107].	Yes.
3	Analytical and experimental proof-of-concept and critical function tested and/or characteristic	In 1966, engineers at NASA Langley Research Centers develop a wind-tunnel technique for measuring the frequency-response functions for gust load analyses, which permitted future wind tunnel tests of gust load alleviation systems [108]. The Load Alleviation and Mode Stabilization (LAMS) program was started for the B-52 [107].	Yes.
4	Component and/or breadboard validation in a laboratory environment	For the C-5A, active lift distribution control system (ALDCS) is developed with sub-scale prototypes, full-scale flight demonstration,	Yes.

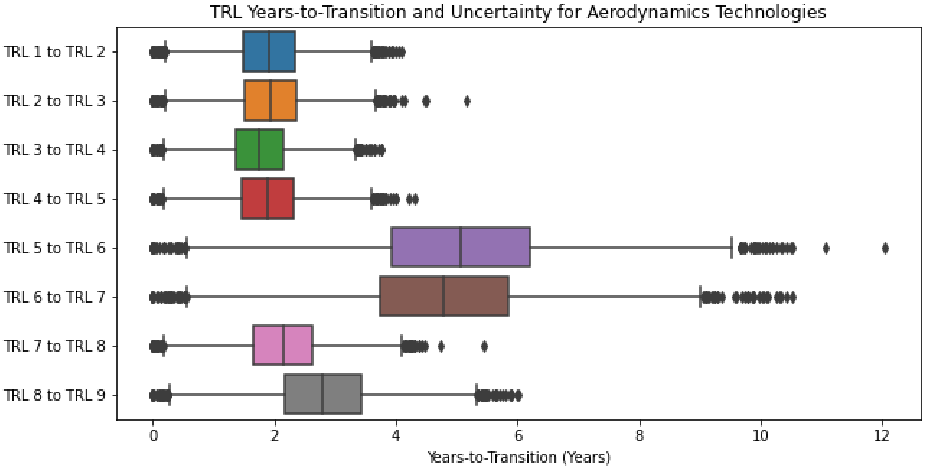
5	Component/brassboard validation in a relevant environment.	production system fabrication, and airplane fleet installation work done by Lockheed-Georgia Co. in 1976. It is found to reduce wing fatigue damage from maneuver and gust loads [109]. From 2015-2019, research activities pertaining to active load alleviation for regional turboprops was funded under EU-HORIZON 2020 Societal Challenges - Smart, Green, and Integrated Transport. Sizing, design, and computational modeling was put toward this effort with sub-scale component demonstrations tested in wind tunnels [110]. As of March 2019, ALA for regional turboprops remains at around TRL 4.	No. For advanced turboprops, only component-level wind tunnel tests have been completed.
6	Flight test demonstration in a relevant environment with a full-scale demonstrator		No. While ALA has flown on larger aircraft, aerodynamic data from flight tests for turboprop aircraft is not currently available.
7	System prototype demonstration in an operational environment.	In 1981, the design and application of a digital active control system for load alleviation for the L-1011 was designed where on the -500 variant, maneuver and gust load alleviation for the extended wingtip was achieved [111].	No. While ALA is certified on the L-1011, it has not been operationally tested for regional turboprops.
8	Actual system completed and flight-qualified through test demonstration.	In 1985, a patent for maneuver load alleviation systems for commercial airliners (US4796182A) is filed to automatically reduce wing root bending modes during aircraft maneuvers that exceed a threshold limit. This will be applied to the 787.	No. While commercial airliners such as the L-1011 and C-5A have flight-qualified ALA systems, it has not been flight-qualified for aircraft within the same class as the flight demonstrator. Hence, development efforts in line with TRL 5 must be planned if technology is selected for the advanced turboprop vehicle.
9	Actual system flight-proven during commercial operation.	The Boeing 787 Dreamliner which was first flown in 2009 and introduced in 2011 has an active gust and maneuver load alleviation system that has attained FAA airworthiness certification and is currently in operation [16].	No. See above.
For the advanced turboprop demonstrator, ALA for wing load alleviation is at TRL 4.			

Table 37 shows that ALA systems for an advanced turboprop demonstrator is currently at TRL 4, where the relevance of the environmental testing conditions come into play as to why the technology has reached TRL 6 for some applications, but not the scenario presented by the case study. Design, development, fabrication, and validation of an optimized ALA system for a regional turboprop is still pending.

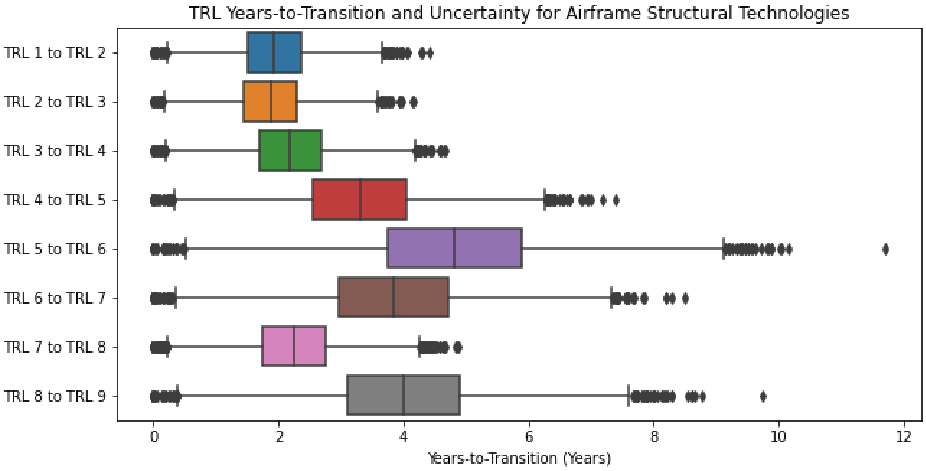
Finally, the advanced turboprop engine is a composite of multiple innovative aspects across a turboprop engine system. The distinction of these elements defies a straightforward TRL assignment due to its composite nature and absence of a specific discernible technology that makes up the bulk of these improvements, however, it falls between the range of TRL 3-4. For more conservative estimation, the lower bound of TRL 3 will be used as a "starting point" to define what the current TRL is prior to the initiation of the advanced turboprop technology development program.

5.4.2 Uncertainty-Driven TRL Transition Analysis

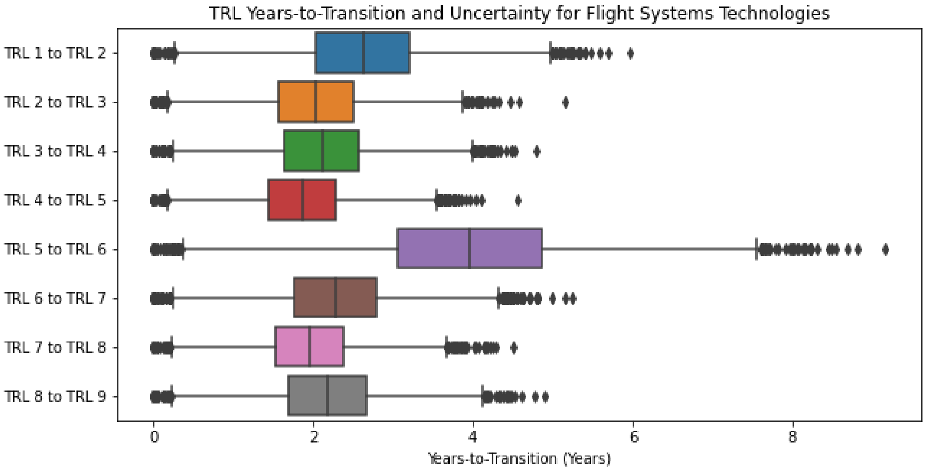
To create the TRL transition dataset, a literature review was performed to map the TRL milestones for developed technologies within each sector. Using this process, it was possible to document the TRL transition timelines that would be used to inform the uncertainty-driven TRL transition analysis captured in the U-TTRAN code. The timelines can be found in Appendix B, except for propulsion technologies which is shown in Table 21.



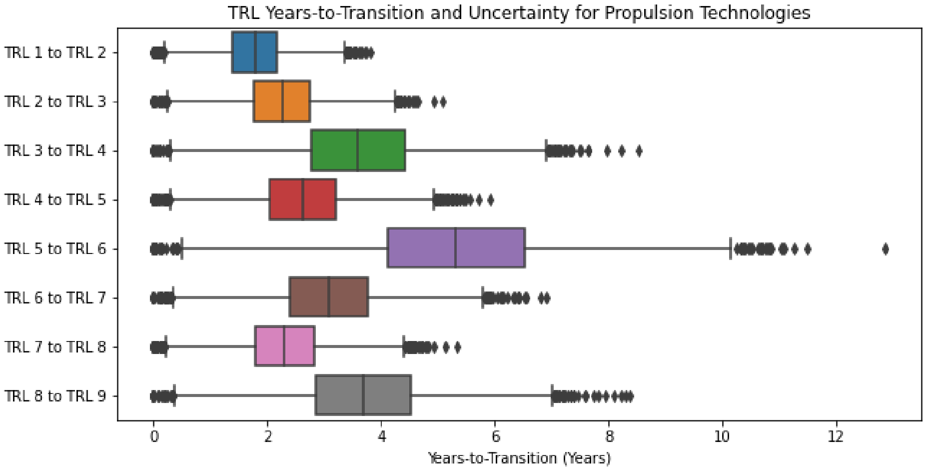
a) Aerodynamics Technologies



b) Structural Technologies



c) Flight Systems Technologies



d) Propulsion Technologies

Figure 43. TRL transition and uncertainty

Figure 43 shows the box and whisker plots capturing the estimated TRL transition times with uncertainty, allowing for visualization of the distribution of quantitative TRL transition times across each sector. The quartiles are depicted within the box, with whiskers to illustrate the broader distribution and marked outliers using an inter-quartile range criterion. This approach allows for comparison of transition times – for instance, the highest variances are observed from TRL 5 to TRL 6 and TRL 6 to TRL 7.

Table 38. TRL Transition Times with uncertainty for advanced aircraft technologies

	Aerodynamics		**Structures**		**Flight Systems**		**Propulsion**	
TRL Transition Band	**Years to Next TRL**	**Uncertainty**	**Years to Next TRL**	**Uncertainty**	**Years to Next TRL**	**Uncertainty**	**Years to Next TRL**	**Uncertainty**
TRL 1 to TRL 2	1.91	0.63	1.94	0.63	2.62	0.87	1.59	0.52
TRL 2 to TRL 3	1.94	0.65	1.88	0.63	2.03	0.68	1.98	0.66
TRL 3 to TRL 4	1.74	0.58	2.19	0.73	2.11	0.70	2.20	0.73
TRL 4 to TRL 5	1.88	0.63	3.30	1.08	1.86	0.62	2.38	0.79
TRL 5 to TRL 6	5.07	1.67	4.81	1.58	3.97	1.34	4.97	1.66
TRL 6 to TRL 7	4.79	1.57	3.84	1.29	2.28	0.76	3.15	1.06
TRL 7 to TRL 8	2.14	0.72	2.25	0.75	1.96	0.65	2.23	0.74
TRL 8 to TRL 9	2.80	0.94	4.00	1.35	2.18	0.72	3.93	1.30

Table 38 summarizes estimated TRL transition times (50th percentile) and associated uncertainties for each sector. Several observations can be made:

- The time required to advance from one TRL to the next generally increases as the technology progresses. Notably, the transition time from TRL 1 to TRL 2 appears consistent across all sectors, suggesting an initial phase of foundational development.
- The presence of uncertainty, quantified by the second column representing uncertainty values, is evident throughout the transition process. This underscores the variability and complexity inherent in technology development across all sectors.

- While certain sectors exhibit similar transition times for specific TRL transitions (e.g., TRL 2 to TRL 3 in aerodynamics and flight systems), differences emerge among sectors and specific TRL advancements. Notably, propulsion technologies show the longest time spans for some transitions, possibly reflecting the intricacies of propulsion system development.
- Notably, the transition from TRL 6 to TRL 7 is relatively consistent across sectors in terms of transition times, suggesting the veracity of the “valley-of-death” governing technologies and their transition from demonstration to operation.
- Transition from TRL 8 to TRL 9 tends to exhibit higher uncertainties, especially for structures and propulsion technologies. This might indicate that the final stages of technology development involve complex integration or operational factors that introduce more uncertainty.

Then, combining the results from the current TRL assessments with the distributions from Table 38, the timeline readiness risk assessment can be conducted.

Table 39. Timeline readiness risk assessment

Technology	**Current TRL**	**Estimated Years to TRL 6**	**Risk Level for 2030 (7 Years)**
Riblets (Wing)	5	5.07 ± 1.67	Low
Riblets (Fuselage)	9	0	Low
NLF (Wing)	5	5.07 ± 1.67	Low
NLF (Fuselage)	8	0	Low
Excr. Reduction	5	5.07 ± 1.67	Low
Adv. Composites (DAC)	4	8.11 ± 1.91	Medium
ALA System	4	5.83 ± 1.48	Medium
Adv. Turboprop Engine	3	9.55 ± 1.98	High

Table 39 uses the estimated years to TRL and uncertainties to set the potential bounds for years to progress from the current TRL to the TRL 6 required for the flight test demonstration. If the higher uncertainty limit is lower than years to the EIS date of the flight demonstrator, the risk is considered “low.” If the lower uncertainty bound is lower than years to the EIS date, but the upper uncertainty limit is higher, than the technology poses a “medium” risk. If the estimated years to TRL bounds both exceed the years to the EIS date, the technology is marked as a “high” risk to meeting the schedule of the technology demonstrator. While SME input can further inform the limits and risk levels, this methodology allows for a preliminary assessment that can be further substantiated with additional information and stakeholder engagement.

5.5 Integration Risk Assessment

Integration risk assessment undertaken by the PICTO approach involves constructing integration roadmaps using TRL level sub-attributes and investigating the exogenous/endogenous compatibilities.

5.5.1 Technology Integration Roadmaps

Table 40. TIR for riblets

TRL #	**Technology Development Efforts**	**Integration Activities**
TRL-1	Initial investigation into riblets for drag reduction at flow conditions like that experienced operationally by a regional turboprop aircraft begins.	None.
TRL-2	Plans for research and implementation of riblet film on the advanced turboprop demonstrator is advanced through basic experimentation and conceptual design studies on riblet geometry.	Speculative estimates of riblet performance based off previous analytical and experimental data validation done, plans for subscale demonstrations are initiated.
TRL-3	Parametric testing of optimum riblet geometries is done. The models are tested in low-speed wind tunnels to characterize the relationships between design parameters and skin friction drag reduction. Riblet scaling parameters are identified to further inform future bread/brassboard tests.	First prototypes demonstrating optimum riblet geometry concepts are fabricated. Groundwork computational analysis is done to predict skin friction drag reduction from riblets application on wing-body surfaces for the turboprop demonstrator.
TRL-4	Riblet scaling parameters are used to inform the design of a flight-capable device that could be practically fabricated. Vinyl or aluminum riblet film with an adhesive backing (which has previously been done by 3M Co. on wide-body airliners) is created and subject to testing to obtain drag data.	Manufacturing of a prototypical riblet film with adhesive backing is done to prepare for technology testing and validation. Critical function testing to obtain drag data and determine yaw sensitivity is done to validate that the drag reduction from riblets is suitable for turboprop aircraft application.
TRL-5	The physical dimensions of a riblet film suitable for drag reduction at flight conditions	Ground testing of the riblet film applied to the wing-body is done to obtain necessary drag, yaw,

	is finalized, with micro-photographs taken for documentation and yaw sensitivity tests conducted to determine the critical angle-of-attack for riblets to continue providing a net drag reduction benefit.	and potential slipstream interactions data to ensure drag reduction benefit is realized during operation. Because riblets can be applied as a film, integration onto the host-system is standard and able to be done at this phase. Minimization of near-wall turbulence at operational conditions is a focus before flight testing.
TRL-6	The full-scale, flight-ready advanced turboprop demonstrator with riblet film applied to the wing and fuselage is tested in the simulated, operational environment that replicates most of all the loads expected for the aircraft.	Integration efforts support the flight demonstration of riblet film applied to the wing and fuselage of the advanced turboprop aircraft. This is a high-fidelity prototype that can provide high-fidelity data to inform any future design iterations.
TRL-7	Extensive development and testing have been done for riblets on the advanced turboprop aircraft. Full-scale prototypes have been integrated into the design and subjected to rigorous testing that informs the operational limits for full drag reduction benefit. The effectiveness of riblets have been demonstrated, with the fuel burn reduction performance goal the prime focus of continued flight tests.	Integration of the functional airframe and riblets is demonstrated where testing and evaluation at this stage (turbulent drag flight tests, edge-case flight tests) is done to support certification and commercialization efforts for riblets on advanced turboprop. Endogenous/exogenous iterations are well known and qualified.
TRL-8	A production unit of the advanced turboprop with riblets applied to the wing and fuselage is test flown in its final configuration.	Riblets for advanced turboprop aircraft have been fully integrated onto an operational version of the aircraft. The technology is in its final form, fit, and function with performance well known within the operational envelope.
TRL-9	Riblets are demonstrated through successful, commercial operations on advanced regional turboprop aircraft	Integration at this stage is complete; no integration efforts required.

Table 41. TIR for NLF technologies

TRL #	Technology Development Efforts	Integration Activities
TRL-1	Initial research and development efforts into redesigning the advanced turboprop wing for extended regions of NLF on the upper and lower surface during cruise begins. This involves multidisciplinary optimization studies and fast CFD methods to rapidly design and select appropriate geometries.	Speculative estimates of drag reduction from NLF along with analytical characterization of off-design design points/wing-body effects that may impact performance are obtained from CFD validation. While no integration activities have formally begun, this data will be used to better understand exogenous interactions between the NLF wing and aircraft, along with understanding how geometry changes impact NLF benefit.
TRL-2	Once NLF geometries have been finalized, adaptation onto a wing planform and further conceptual optimization studies for an NLF aircraft configuration are computationally analyzed.	Estimates of NLF wing-body performance are obtained from detailed CFD analysis, where analytical data acquired will serve as a benchmark for experimental data. Plans for subscale wing fabrication and experimental testing begins.
TRL-3	Experimental tests to observe laminar flow maintenance on wings with moderate sweep for chord Reynolds numbers in the range of 12-16 million (similar to operating conditions on a regional turboprop) are conducted.	Subscale of NLF wing and fuselage concepts are fabricated. Wind tunnel experimentation is done to validate and inform the estimates made from previous CFD results and further shape the geometrical constraints, 3D wing requirements and characterize the drag of the laminar profile. These will further inform future design iterations.

TRL-4	Critical function wind tunnel tests are performed to characterize the drag characteristics, influence of surface disturbances (to ensure laminar flow at Re ~ 15 million), and comparison with theoretical results are done with a subscale wing-body test article.	Integration of the NLF wing and fuselage begins with test and validation of sub-scale prototypes. The influence of surface imperfections, geometry, and flow conditions on transition location are better understood. Modifications at this stage align with “rapid prototyping efforts” before a to-scale test article is finalized for ground tests.
TRL-5	The NLF wing and fuselage geometry has been finalized with a full-scale prototype fabricated. Higher scale wind tunnel tests with sophisticated measurement equipment is used to observe boundary layer stability over the NLF surfaces and the behavior of the laminar boundary layer influenced by the propeller slipstream is studied in wind-tunnel and ground test investigations. At this point, all test efforts are used for documentation in achieving a special airworthiness certificate in the experimental category.	Propeller-airframe interactions are quantified through ground testing to observe propeller slipstream effects. Integration of the technology onto the host-system begins at this stage, which will be a critical, time-consuming effort. Any CFD analysis at this stage will be used to simulate the operational environment experienced during flight while wind-tunnel and ground tests will be focused on documenting high-fidelity performance data on drag reduction characteristics and potential failure modes.
TRL-6	The full-scale, flight-ready advanced turboprop demonstrator with an NLF wing and fuselage is outfitted with flight test equipment (such as a moveable wake-rake system and infrared camera) to collect experimental data that will be used to validate whether analytical/ground test predictions hold in the operational environment.	Flight test demonstrations allow for the assessment of potential integration challenges for an NLF wing body. The interface between the technology and its host system has been finalized with future efforts focused on manufacturing/production. High-fidelity is obtained where focus on characterizing and controlling exogenous interactions such as propeller slipstream effects and maintenance of laminar flow over the wing.
TRL-7	At this phase, all efforts focus on testing the full-scale advanced turboprop demonstrator in the simulated flight environment to assess the operational performance, aerodynamic behavior, and structural integrity of the NLF airframe.	The NLF wing and fuselage technologies have been integration into the advanced turboprop demonstrator's design. This entails ensuring compatibility with existing systems, optimizing aerodynamic and structural interfaces, and fine-tuning control systems to achieve optimal performance while adhering to safety and operational standards. These integration efforts will focus on validating the technology's effectiveness in a comprehensive operational context.
TRL-8	A production unit of the advanced turboprop with an NLF airframe is test flown in its final configuration.	NLF wing and fuselage structures for advanced turboprop aircraft have been fully integrated onto an operational version of the aircraft. The technologies are in its final form, fit, and function with performance well known within the operational envelope, with interactions between other technologies such as riblets and the propeller slipstream well-known and within acceptable margins.
TRL-9	The NLF airframe is demonstrated through successful, commercial operations on advanced regional turboprop aircraft	Integration at this stage is complete; no integration efforts required.

Table 40 and Table 41 show the TIRs constructed for riblets and NLF. Given that both technologies are currently TRL 5 prior to the initiation of the technology development program, these roadmaps can provide a notion of which integration activities must be prioritized to ensure seamless integration and maturation required for flight demonstration. Constructing a comprehensive TIR for excrescence drag poses challenges due to its interdependent relationship with other technologies, specifically NLF and riblets. Excrescence drag reduction is intricately linked with the successful implementation of NLF and riblet technologies, as these advancements synergistically contribute to minimizing drag in aerodynamic profiles. The incorporation of excrescence reduction hinges upon the successful integration of NLF and riblets within the broader framework of an aircraft's design. Therefore, any timeline for excrescence drag reduction necessitates a nuanced understanding of the developmental stages of NLF and riblet technologies, as their effective implementation forms a foundational prerequisite for realizing the benefits of reduced excrescence drag. This interdependency underscores the intricacies of aerodynamic technology integration and highlights the need for a cohesive timeline that acknowledges the sequential and integrated nature of these advancements.

Table 42. TIR for DAC

TRL #	Technology Development Efforts	Integration Activities
TRL-1	Work on earlier composites observed properties of carbon fibers and multi-axial fabrics. Principles of composite stitching and resin infusion leads to observation that composite stitching has favorable damage-arresting characteristics	None.
TRL-2	Damage-arresting stitched composites is conceptually formulated as an application and described as a system with a defined architecture.	Speculative estimates of DAC impact or vehicle attributes and performance relative to conventional materials may be reproduced via extrapolations of models and empirical data for similar materials.
TRL-3	Critical functions and characteristics are identified for damage-arresting stitched composites elements and architecture is refined with respect to the arrangement of elements and definition of endogenous interfaces between them. Stitching thread material	Groundwork for integration of a proof-of-concept for demonstration begins with testing of technology elements that come together to form the technology system of interest.

	characteristics are experimentally tested separately.	
TRL-4	Low-fidelity DAC samples are integrated to test functionality via loading tests in a laboratory rig; the proof-of-concept is subjected to testing of loading modes, static axial compression/tension, and static loading.	Integrated, critical function proof-of-concepts are developed to obtain test data that will inform trade studies of the advanced turboprop demonstrator – at this point, endogenous interactions are better understood, and work begins on characterizing exogenous interactions.
TRL-5	Subassembly and flat panel units are replaced by test specimen representative of turboprop demonstrator sections close to or at full scale and tested within a controlled environment.	Proof-of-concept fidelity increases significantly where the technology system prototype is tested within an environment similar to the host-system to prepare for integration of the technology system and its elements into a function, flight proven host-system prototype
TRL-6	A full-scale, fully functional DAC demonstrator(s) for the advanced turboprop fuselage and wing is tested in a simulated operational environment that replicates most or all of the loads expected for the full performance envelope of the advanced turboprop demonstrator	Integration efforts support the flight demonstration of a functional prototype of the host-system: the technology system is integrated into a prototypical version of the final host-system and flight-tested.
TRL-7	A full-scale, fully functional demonstrator of the entire airframe is integrated with all subsystems and structural systems of the host-system.	Integration of the DAC advanced turboprop airframe is demonstrated; testing and evaluation at this stage support the certification efforts of the advanced turboprop demonstrator where all endogenous and exogenous interactions are well-understood, with interfaces built to facilitate compatibility.
TRL-8	A production unit of the advanced turboprop demonstrator with a full DAC airframe is test flown.	The technology (DAC) in its final form, fit, and function is demonstrated as fully integrated onto the host system (advanced turboprop demonstrator) across the entire performance envelope in the operating environment.
TRL-9	DAC is demonstrated through successful operations of the advanced turboprop demonstrator.	Integration at this stage is complete; no integration efforts required.

Table 43. TIR for ALA systems

TRL #	**Technology Development Efforts**	**Integration Activities**
TRL-1	Research and literature review is conducted on aerodynamic and structural principles that could lead to wing weight reduction for a regional turboprop. Previous work on active load alleviation is reviewed as passenger ride quality strongly impacts turboprop adoption and acceptance.	None.
TRL-2	Initial conceptualization of load alleviation techniques specific to turboprop aircraft. Identification of potential sensors, actuators, and control strategies for load mitigation.	Preliminary design on the basic layout, components, and structure of the overall control system begins with selection of components. Endogenous interfaces/interactions are studied.
TRL-3	Laboratory tests and simulations to validate the feasibility of the load alleviation concept. Small-scale component testing to demonstrate	Integration efforts for active load alleviation focus on demonstrating the viability of the core technology concept in a simplified environment. Activities involve component integration, control

	basic functionality of sensors, actuators, and control algorithms.	logic implementation, laboratory tests, and performance validation of components to characterize endogenous interfaces and interactions.
TRL-4	Further refinement of individual components through component-level testing. Assessing sensor accuracy, actuator response, and control algorithms in controlled environments.	The prototype ALA system is demonstrated in conditions of higher fidelity where certain activities are component refinement to ensure they are closer to specifications required for the actual aircraft integration, system integration on a test rig, aircraft compatibility assessments (beginning of exogenous interface/interaction studies and planning), and acquiring data to verify and validate the system's behavior, performance, and impact.
TRL-5	Integrating individual components into a representative subsystem and testing it in a relevant environment. Simulating load conditions and verifying system interactions. Developing a complete prototype of the active load alleviation system and subjecting it to controlled ground tests in simulated flight conditions. Refining algorithms and verifying system-wide performance.	The ALA system, or at least a complete prototype, is integrated with integration efforts now focused toward integration onto the host-system. Ground testing of this system is conducted to validate the technology’s load alleviation capabilities and compatibility with the overall advanced turboprop demonstrator.
TRL-6	Integrating the prototype system onto an actual aircraft and conducting flight tests to validate its performance under real flight conditions. Collecting data to fine-tune algorithms and validate load reduction capabilities.	Extensive flight tests are planned to evaluate performance and potential operational risks. This stage involves extended testing to validate system reliability, effectiveness, and integration within the aircraft's operational framework.
TRL-7	The full-scale advanced turboprop engine has been extensively flight tested within the operational envelope – tests at this point are used for validation and documentation efforts pertaining to FARs (Part 21 and 33.)	Feedback from previous flight tests is incorporated into the ALA system design, where all outstanding risks from exogenous interactions are addressed to ensure seamless integration and further safe operation.
TRL-8	A production unit of the advanced turboprop is test flown in its final configuration. Finalizing the active load alleviation system design based on flight test data and operational feedback. Refining components, materials, and control algorithms for optimized efficiency and reliability.	The ALA system has been prepared for production and certification, where engine fabrication and assembly has been approved by the FAA and ensured “safe and repeatable” prior to commercial launch.
TRL-9	Integrating the fully developed and qualified system into production aircraft models. Achieving certification from aviation authorities and demonstrating sustained load alleviation benefits during regular operations.	Integration at this stage is complete; no integration efforts required.

Table 44. TIR for advanced turboprop engine

TRL #	Technology Development Efforts	Integration Activities
TRL-1	After conducting a review of existing turboprop engines and technologies, conceptualization of a lower-emissions advanced turboprop engine concept leveraging advancements in engine component design is initiated.	None.

TRL-2	Preliminary design studies for the research and development of an advanced turboprop engine with improved cycle efficiencies and materials begins. Selection of specific engine components and improvements that will be featured on the advanced turboprop is done through focused studies and systems analysis.	Integration activities at this stage involve evaluating various engine configurations, identifying key components, and obtaining initial performance estimates that justify further investments toward research and development efforts.
TRL-3	Detailed design and development of advanced turboprop engine components and subsystems are performed at this stage.	Initial prototypes of the engine components are fabricated as laboratory tests are used to validate design assumptions and characterize the endogenous interactions between the subsystems within the engine system.
TRL-4	Sub-scale, advanced turboprop engine subsystems are tested and validated in controlled environments.	Individual engine components (such as compressor and turbine blades) are integrated and tested in a controlled environment prior to full technology system assembly.
TRL-5	The advanced turboprop engine subsystems are assembled; ground-testing of the full engine is used for static testing, thrust characterization, loads analysis, and all required engine tests prior to host-system integration. At this point, development efforts take place on an engine testbed under simulated flight conditions.	Integration of the engine subsystems is required for assembly of the advanced turboprop engine for ground testing and validation. At this point, all endogenous interfaces and interactions are well-understood and further integrations efforts will focus on exogenous interactions between the installed engine and vehicle system.
TRL-6	The full-scale advanced turboprop engine is flight-proven after integration onto the host-system.	The advanced turboprop engine is installed on the flight demonstrator where extensive flight tests are planned to evaluate performance and potential operational risks.
TRL-7	The full-scale advanced turboprop engine has been extensively flight tested within the operational envelope – tests at this point are used for validation and documentation efforts pertaining to FARs (Part 21 and 33.)	Feedback from previous flight tests is incorporated into the engine design, where all outstanding risks from engine installation are addressed to ensure seamless integration and further safe operation.
TRL-8	A production unit of the advanced turboprop is test flown in its final configuration.	The engine has been prepared for production and certification, where engine fabrication and assembly has been approved by the FAA and ensured “safe and repeatable” prior to commercial launch.
TRL-9	The advanced turboprop engine has been mission-qualified on commercial operations on advanced regional turboprop aircraft	Integration at this stage is complete; no integration efforts required.

Table 42, Table 43, and Table 44 are the TIRs developed for damage-arresting stitched composites, active load alleviation, and the advanced turboprop engine respectively. These TIRs present a rational approach of determining integration activities from TRL designation alone, offering significant benefits for conducting integration risk assessments for advanced aircraft technologies at the conceptual design phase. By delineating the progression of technology from its conceptual stages (TRL 1) to operational deployment (TRL 9), these roadmaps inherently capture a granular analysis of endogenous and exogenous interactions within the technology and its host system. This systematic breakdown allows for the identification and assessment of potential integration challenges and risks at each critical stage of development.

5.5.2 Compatibility Matrices

Capturing the intricate compatibilities among various aspects of advanced aircraft technologies is of paramount importance for a comprehensive integration risk assessment. TCMs offer insights into the complex interactions between advanced technologies and existing aircraft systems, as well as their mutual influence on one another.

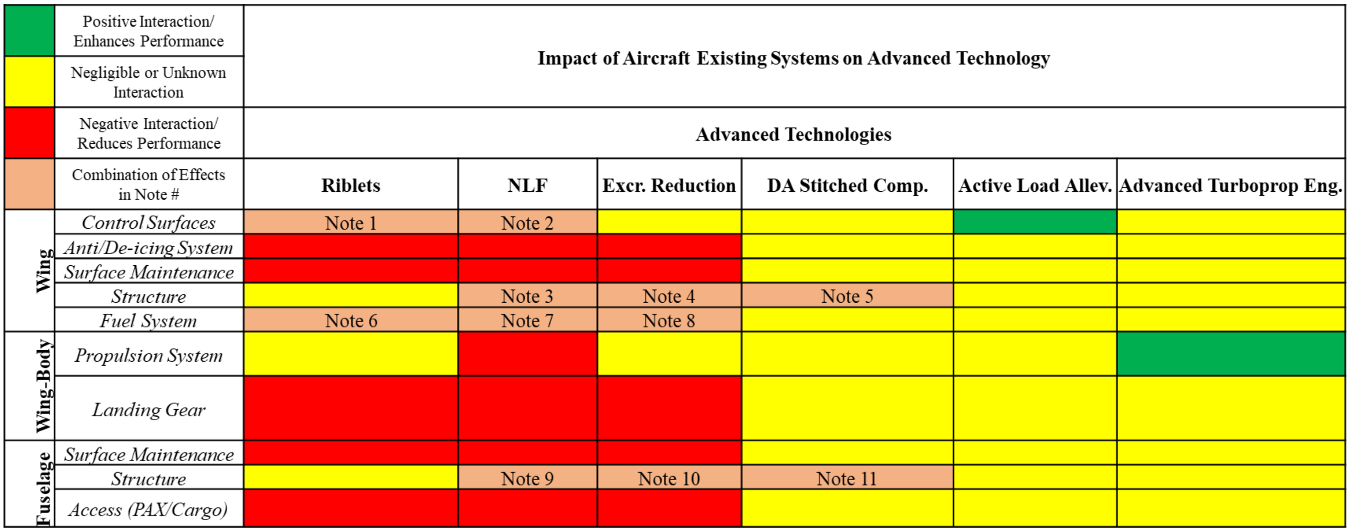
Table 45. Impact of advanced technologies on existing aircraft systems

🟩 Positive Interaction/ Enhances Performance
🟨 Negligible or Unknown Interaction
🟥 Negative Interaction/ Reduces Performance
Note # Combination of Effects in Note #

	Vehicle System WBS									
	Wing					**Wing-Body**		**Fuselage**		
Technology Portfolio Elements	*Control Surfaces*	*Anti/De-icing System*	*Surface Maintenance*	*Structure*	*Fuel System*	*Propulsion System*	*Landing Gear*	*Surface Maintenance*	*Structure*	*Access (PAX/ Cargo)*
Riblets	🟨	🟥	🟥	🟨	🟨	🟨	🟨	🟥	🟨	🟨
NLF	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟥	🟨	🟨
Excr. Reduction	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟨
DAC	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟨
ALA	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟩	🟨
Adv. Turboprop	🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨

Table 45 shows the TCM for the advanced technologies on the existing aircraft systems which is broken down into their respective WBS. Addressing the incompatibilities, surface maintenance procedures, such as cleaning and repair, can inadvertently disrupt the delicate flow characteristics crucial for both riblets and NLF. Abrasive cleaning or uneven repairs could alter the precise surface conditions necessary for riblets to function optimally and for NLF to maintain its laminar boundary layer, potentially leading to increased drag and reduced efficiency due to negative interactions between these technologies and maintenance practices. As for the interaction with the anti-icing system on the ATR 42-600, riblets could potentially hinder the effectiveness of the anti-icing system by altering the airflow patterns near the surface. The presence of riblets might disrupt the uniform distribution of heat required to prevent ice accumulation, leading to uneven anti-icing coverage and potential inefficiencies in the system's performance. These interactions underline the complexity of integrating advanced technologies onto existing aircraft and systems and the importance of using such a TCM to identify these risks. The next TCM will be for the impact of existing aircraft systems on the advanced technologies.

Table 46. Impact of aircraft existing systems on advanced technologies



🟩	Positive Interaction/ Enhances Performance	**Impact of Aircraft Existing Systems on Advanced Technology**					
🟨	Negligible or Unknown Interaction						
🟥	Negative Interaction/ Reduces Performance	**Advanced Technologies**					
🟧	Combination of Effects in Note #	**Riblets**	**NLF**	**Excr. Reduction**	**DA Stitched Comp.**	**Active Load Allev.**	**Advanced Turboprop Eng.**
Wing	*Control Surfaces*	🟧 Note 1	🟧 Note 2	🟨	🟨	🟩	🟨
	Anti/De-icing System	🟥	🟥	🟥	🟨	🟨	🟨
	Surface Maintenance	🟥	🟥	🟥	🟨	🟨	🟨
	Structure	🟨	🟧 Note 3	🟧 Note 4	🟧 Note 5	🟨	🟨
	Fuel System	🟧 Note 6	🟧 Note 7	🟧 Note 8	🟨	🟨	🟨
Wing-Body	*Propulsion System*	🟨	🟥	🟨	🟨	🟨	🟩
	Landing Gear	🟥	🟥	🟥	🟨	🟨	🟨
Fuselage	*Surface Maintenance*	🟥	🟥	🟥	🟨	🟨	🟨
	Structure	🟨	🟧 Note 9	🟧 Note 10	🟧 Note 11	🟨	🟨
	Access (PAX/Cargo)	🟥	🟥	🟥	🟨	🟨	🟨

Table 46 captures the impact of existing aircraft systems on advanced technologies using a TCM to identify how the integration of new technologies may be influenced by the constraints and characteristics of the aircraft’s pre-existing systems. The associated notes are:

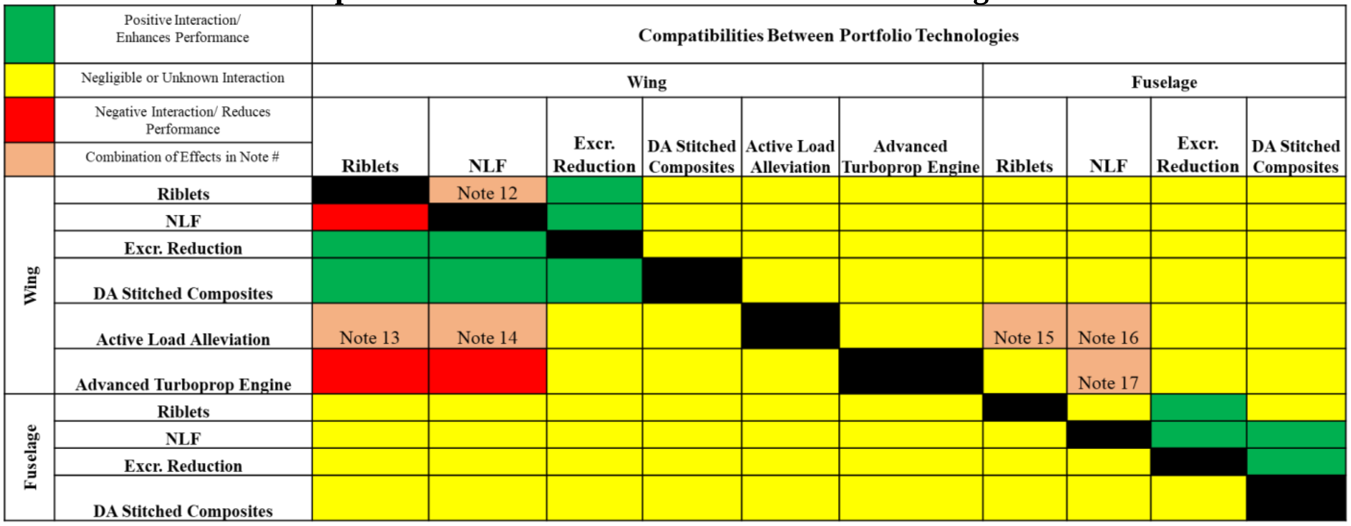
1. Deployment of wing control surfaces changes the pressure distribution of a wing and, hence, affect the flow pattern encountered by riblets. This could increase or decrease their effectiveness.

2. Deployment of wing control surfaces changes the pressure distribution of a wing and, hence, affect the laminar boundary layer development about the wing. This could increase or decrease the extent of the laminar runs.
3. Wing structure can have a positive and negative impact on laminar flow. Rivets, skin joints, and structure related surface waviness can cause premature transition. Smooth wing surfaces will delay transition.
4. Wing structure can have a positive and negative impact on excrescence drag. Rivets, skin joints, and structure related surface waviness can cause more drag. Smooth wing surfaces will cause negligible drag increments.
5. Wing structure requirements can have a negative and positive impact on the applicability of damage arresting stitched composites.
6. Fuel system access panels will have negative impact on riblet effectiveness. Temperature of fuel in wing will create hot/adiabatic/cold wall conditions for the boundary layer flow. Any temperature differences between the boundary layer and the fuel will affect riblet effectiveness.
7. Fuel system access panels will have negative impact on laminar flow and transition. Temperature of fuel in wing will create hot/adiabatic/cold wall conditions for the boundary layer flow. Any temperature differences between the boundary layer and the fuel will affect laminar flow and transition.
8. Fuel system access panels will likely increase excrescence drag. Temperature of fuel in wing will create hot/adiabatic/cold wall conditions for the boundary layer flow. Any temperature differences between the boundary layer and the fuel will affect excrescence drag.

9. Fuselage structure can have a positive and negative impact on laminar flow. Rivets, skin joints, and structure related surface waviness can cause premature transition. Smooth fuselage surfaces will delay transition.
10. Fuselage structure can have a positive and negative impact on excrescence drag. Rivets, skin joints, and structure related surface waviness can cause more drag. Smooth fuselage surfaces will cause negligible drag increments.
11. Fuselage structure requirements can have a negative and positive impact on the applicability of damage arresting stitched composites.

The final TCM is focused on the compatibilities between the technologies in the portfolio with one another, with the center diagonal blocked out to avoid redundancy. This comprehensive approach to capturing compatibility interactions between advanced technologies and existing aircraft systems allows stakeholders to strategically build technology portfolios by considering how each technology interacts with the others and how their integration could collectively enhance overall aircraft performance and operational efficiency.

Table 47. Compatibilities between advanced aircraft technologies



🟩	Positive Interaction/ Enhances Performance
🟨	Negligible or Unknown Interaction
🟥	Negative Interaction/ Reduces Performance
🟧	Combination of Effects in Note #

		Compatibilities Between Portfolio Technologies									
		Wing						Fuselage			
		Riblets	NLF	Excr. Reduction	DA Stitched Composites	Active Load Alleviation	Advanced Turboprop Engine	Riblets	NLF	Excr. Reduction	DA Stitched Composites
Wing	Riblets	⬛	Note 12	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	NLF	🟥	⬛	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Excr. Reduction	🟩	🟩	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	DA Stitched Composites	🟩	🟩	🟩	⬛	🟨	🟨	🟨	🟨	🟨	🟨
	Active Load Alleviation	Note 13	Note 14	🟨	🟨	⬛	🟨	Note 15	Note 16	🟨	🟨
	Advanced Turboprop Engine	🟥	🟥	🟨	🟨	🟨	⬛	🟨	Note 17	🟨	🟨
Fuselage	Riblets	🟨	🟨	🟨	🟨	🟨	🟨	⬛	🟨	🟩	🟨
	NLF	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬛	🟩	🟩
	Excr. Reduction	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬛	🟩
	DA Stitched Composites	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	⬛

Table 47 shows the mutual influences that different elements of the technology portfolio have on one another, along with where on the aircraft the technology is applied. The negative interaction between riblets and NLF can arise due to the altering of surface characteristics caused by the presence of riblets. Riblets can modify the natural laminar flow pattern over surfaces, potentially disrupting the carefully controlled laminar boundary layer and leading to increased skin friction drag. This negative impact can diminish the overall performance benefits that NLF aims to achieve, though if applied on different regions of the wing, an aggregate benefit such as that analyzed in the performance section can be determined. Additionally, the propeller slipstream effects from the engine may negatively impact. The associated notes along with Table 47 are as follows:

12. Riblets, if small enough compared to the laminar boundary layer thickness, will not cause premature transition. However, larger riblets will likely cause premature transition.
13. Active load alleviation systems, when activated, will change the pressure distribution of a wing and, hence, affect the flow pattern encountered by riblets. This could affect their effectiveness.
14. Active load alleviation systems, when activated, will change the pressure distribution of a wing and, hence, affect the laminar boundary layer development about the wing. This could affect the extent of the laminar runs.
15. Active load alleviation systems, when activated, will change the pressure distribution of a fuselage and, hence, affect the flow pattern encountered by riblets. This could affect their effectiveness.

16. Active load alleviation systems, when activated, will change the pressure distribution of the fuselage and, hence, affect the laminar boundary layer development about the fuselage. This could affect the extent of the laminar runs.
17. The pressure fluctuations created by propellers may affect the laminar flow boundary layer and transition on the fuselage. This could affect the extent of the laminar runs.

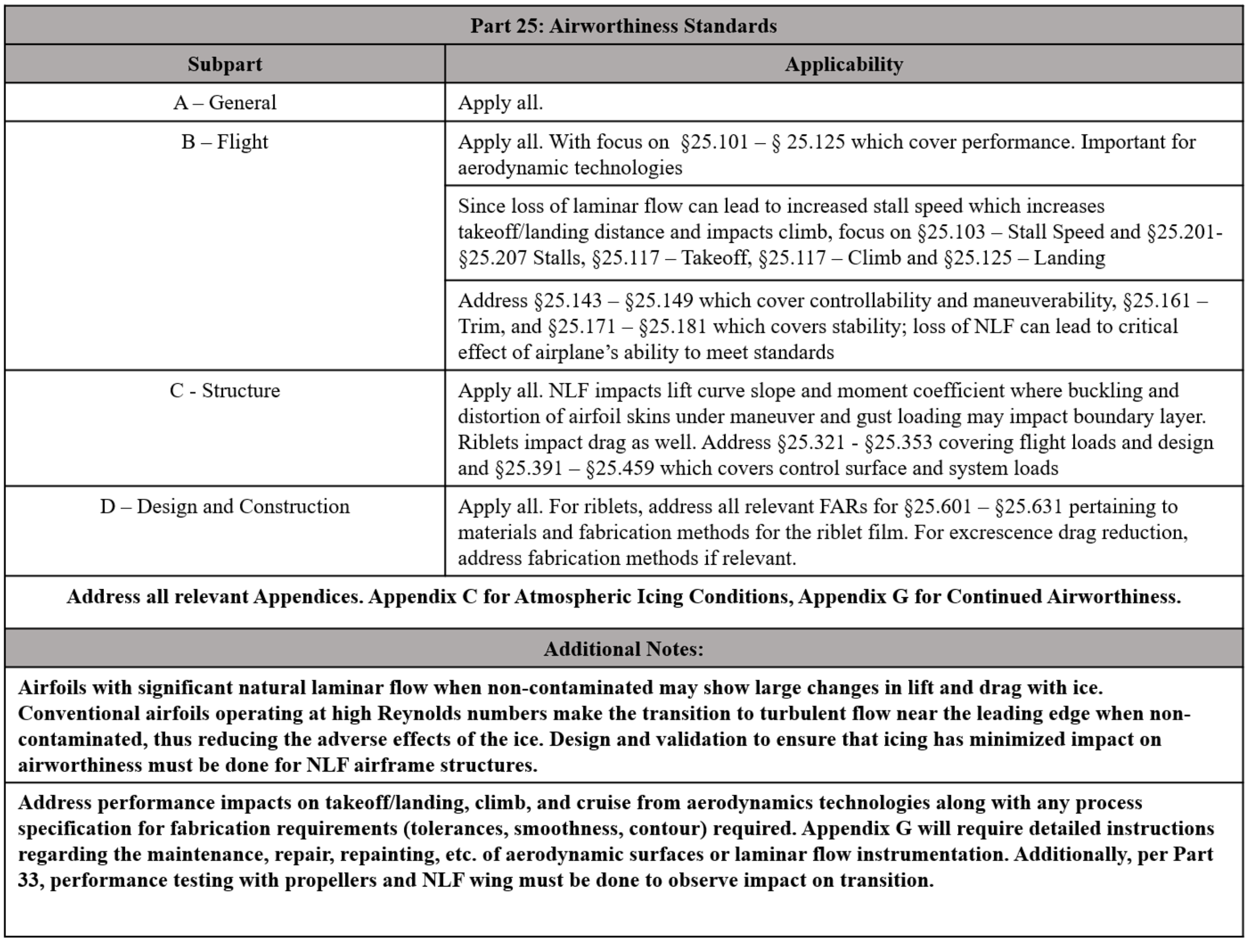
The associated notes provide stakeholders with a dynamic mechanism to make informed decisions when it comes to forming technology portfolios. By acknowledging the complex interdependencies and potential trade-offs, stakeholders can strategically navigate the integration landscape and maximize the overall benefits of combined technologies while mitigating potential risks.

5.6 Certification Risk Assessment

For the certification risk assessment portion of the PICTO approach outlined by the TDRA framework, a CAPS was constructed for each technology. In this certification primer, riblets, NLF, and excrescence reduction technologies are collectively examined due to their shared impact on the same FAR Part 25 airworthiness standards. While riblets and excrescence reduction may not individually necessitate substantial changes to the aircraft’s TCDS, the integration of NLF into the wing structure would likely influence the certification process. This combined assessment is warranted as these technologies jointly affect common aspects of certification requirements, streamlining the evaluation process while encompassing potential variations in their implementation.

For riblets, NLF, and excrescence reduction technologies, adherence to Part 25 standards becomes pivotal, as their integration into the aircraft's design and structure can potentially impact its overall performance, stability, and safety. Part 25 regulations encompass a wide range of critical aspects such as structural design, systems, performance, and safety considerations for larger commercial aircraft.

Table 48. CAPS overview for aerodynamics technologies (NLF, riblets, excrescence reduction)

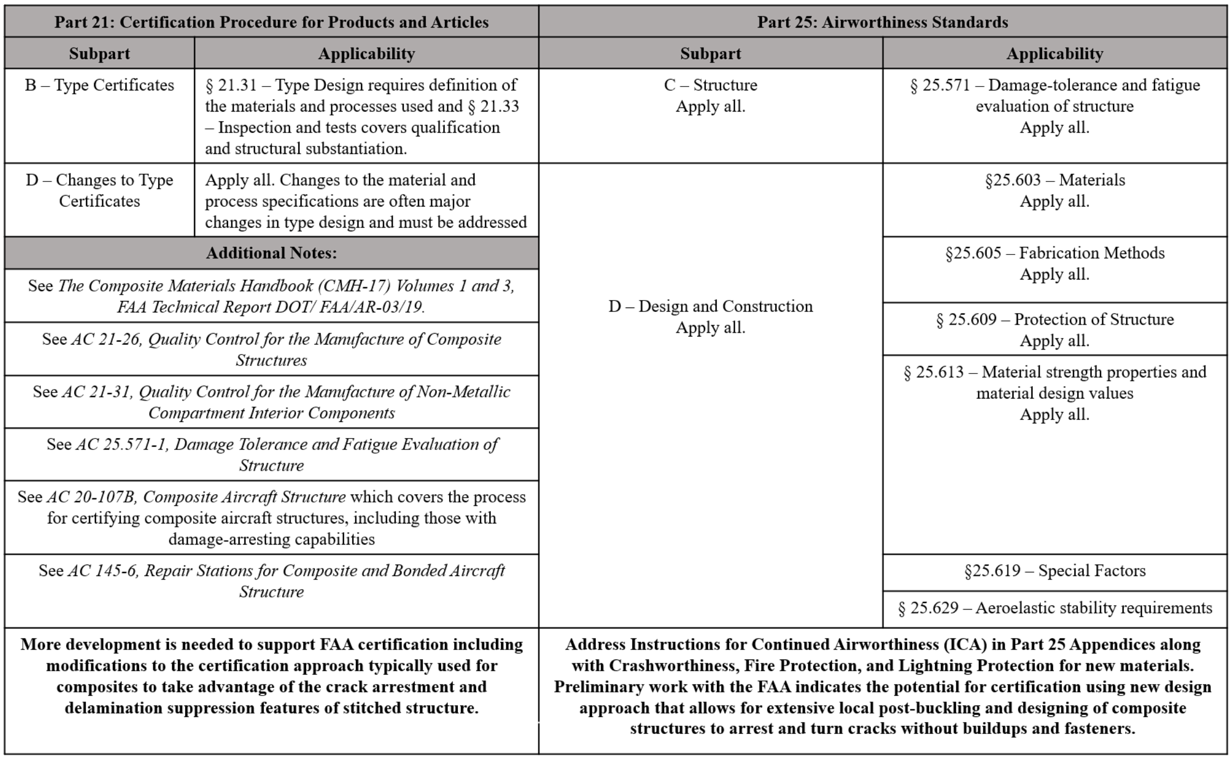


Part 25: Airworthiness Standards	
Subpart	**Applicability**
A – General	Apply all.
B – Flight	Apply all. With focus on §25.101 – § 25.125 which cover performance. Important for aerodynamic technologies
	Since loss of laminar flow can lead to increased stall speed which increases takeoff/landing distance and impacts climb, focus on §25.103 – Stall Speed and §25.201- §25.207 Stalls, §25.117 – Takeoff, §25.117 – Climb and §25.125 – Landing
	Address §25.143 – §25.149 which cover controllability and maneuverability, §25.161 – Trim, and §25.171 – §25.181 which covers stability; loss of NLF can lead to critical effect of airplane's ability to meet standards
C - Structure	Apply all. NLF impacts lift curve slope and moment coefficient where buckling and distortion of airfoil skins under maneuver and gust loading may impact boundary layer. Riblets impact drag as well. Address §25.321 - §25.353 covering flight loads and design and §25.391 – §25.459 which covers control surface and system loads
D – Design and Construction	Apply all. For riblets, address all relevant FARs for §25.601 – §25.631 pertaining to materials and fabrication methods for the riblet film. For excrescence drag reduction, address fabrication methods if relevant.
Address all relevant Appendices. Appendix C for Atmospheric Icing Conditions, Appendix G for Continued Airworthiness.	
Additional Notes:	
Airfoils with significant natural laminar flow when non-contaminated may show large changes in lift and drag with ice. Conventional airfoils operating at high Reynolds numbers make the transition to turbulent flow near the leading edge when non-contaminated, thus reducing the adverse effects of the ice. Design and validation to ensure that icing has minimized impact on airworthiness must be done for NLF airframe structures.	
Address performance impacts on takeoff/landing, climb, and cruise from aerodynamics technologies along with any process specification for fabrication requirements (tolerances, smoothness, contour) required. Appendix G will require detailed instructions regarding the maintenance, repair, repainting, etc. of aerodynamic surfaces or laminar flow instrumentation. Additionally, per Part 33, performance testing with propellers and NLF wing must be done to observe impact on transition.	

Table 48 shows the CAPS overview for the aerodynamics technologies in the case study portfolio. Note that Appendices in this context refer to the appendices in the FARs. As NLF introduces alterations that can significantly influence the aircraft's lift, drag, and stability attributes, compliance with Part 25 standards becomes paramount. Riblets may also, to a lesser extent, impact these same characteristics while excrescence reduction is inherently tied to NLF. Ensuring that NLF-enhanced wings meet the rigorous criteria set forth by Part 25 regulations is crucial to guarantee safe and reliable flight operations. By adhering to these standards, potential technology development risks associated with NLF, such as changes in stability margins or controllability, can be thoroughly assessed and mitigated, paving the way for the successful integration of this technology into commercial aircraft operations.

For composite technologies, such as damage-arresting stitched composites, the regulatory frameworks of FAR Part 21 and Part 25 are pivotal in navigating technology development risks. Composite materials offer enhanced structural efficiency and weight savings, but their integration demands adherence to rigorous airworthiness standards to ensure safety and reliability. These standards encompass not only the manufacturing processes but also the damage tolerance, durability, and fatigue resistance of composite structures. The innovative nature of damage-arresting stitched composites requires careful consideration of how they align with existing certification criteria, as these materials offer unique properties that could influence structural response and overall system behavior.

Table 49. CAPS overview of DAC

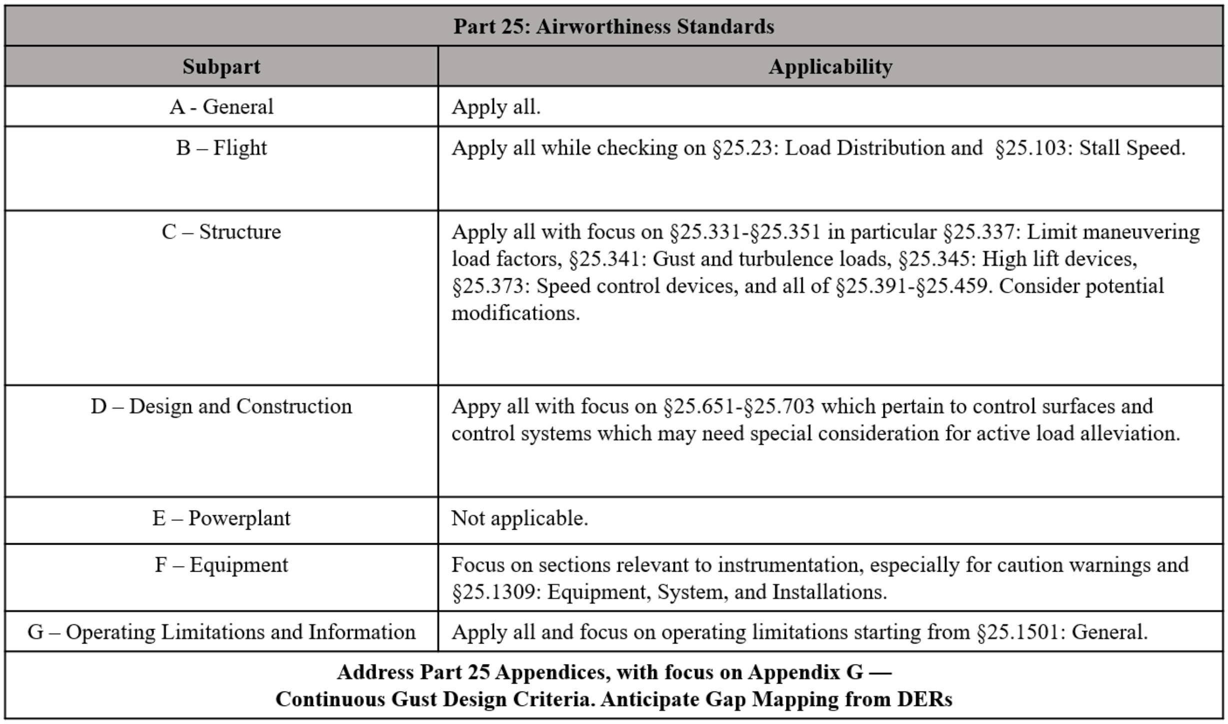


Part 21: Certification Procedure for Products and Articles		**Part 25: Airworthiness Standards**	
Subpart	**Applicability**	**Subpart**	**Applicability**
B – Type Certificates	§ 21.31 – Type Design requires definition of the materials and processes used and § 21.33 – Inspection and tests covers qualification and structural substantiation.	C – Structure Apply all.	§ 25.571 – Damage-tolerance and fatigue evaluation of structure Apply all.
D – Changes to Type Certificates	Apply all. Changes to the material and process specifications are often major changes in type design and must be addressed	D – Design and Construction Apply all.	§25.603 – Materials Apply all.
Additional Notes:			§25.605 – Fabrication Methods Apply all.
See *The Composite Materials Handbook (CMH-17) Volumes 1 and 3, FAA Technical Report DOT/ FAA/AR-03/19.*			§ 25.609 – Protection of Structure Apply all.
See *AC 21-26, Quality Control for the Manufacture of Composite Structures*			§ 25.613 – Material strength properties and material design values Apply all.
See *AC 21-31, Quality Control for the Manufacture of Non-Metallic Compartment Interior Components*			
See *AC 25.571-1, Damage Tolerance and Fatigue Evaluation of Structure*			
See *AC 20-107B, Composite Aircraft Structure* which covers the process for certifying composite aircraft structures, including those with damage-arresting capabilities			
See *AC 145-6, Repair Stations for Composite and Bonded Aircraft Structure*			§25.619 – Special Factors
			§ 25.629 – Aeroelastic stability requirements
More development is needed to support FAA certification including modifications to the certification approach typically used for composites to take advantage of the crack arrestment and delamination suppression features of stitched structure.		**Address Instructions for Continued Airworthiness (ICA) in Part 25 Appendices along with Crashworthiness, Fire Protection, and Lightning Protection for new materials. Preliminary work with the FAA indicates the potential for certification using new design approach that allows for extensive local post-buckling and designing of composite structures to arrest and turn cracks without buildups and fasteners.**	

Table 49 shows the CAPS overview for damage-arresting stitched composites. Among with FARs, relevant ACs are provided as the history of advanced materials in aviation has required additional guidance on obtaining certification for such materials. The ACs included in the CAPS overview can provide additional guidance for stakeholders. For DAC in particular, the need to develop further Special Conditions with regards to inspection and verification of crack arrestment and delamination suppression can be addressed later in a formal regulatory gap analysis. A CAPS can ensure that these issues are brought to the surface during meetings with stakeholders and technologists.

Active load alleviation systems, particularly in the realm of control systems, necessitate a thorough consideration of certification processes to effectively manage technology development risks. These systems introduce adaptive and real-time adjustments to the aircraft's control surfaces to mitigate aerodynamic loads, enhance structural integrity, and improve overall performance.

Table 50. CAPS overview for ALA systems

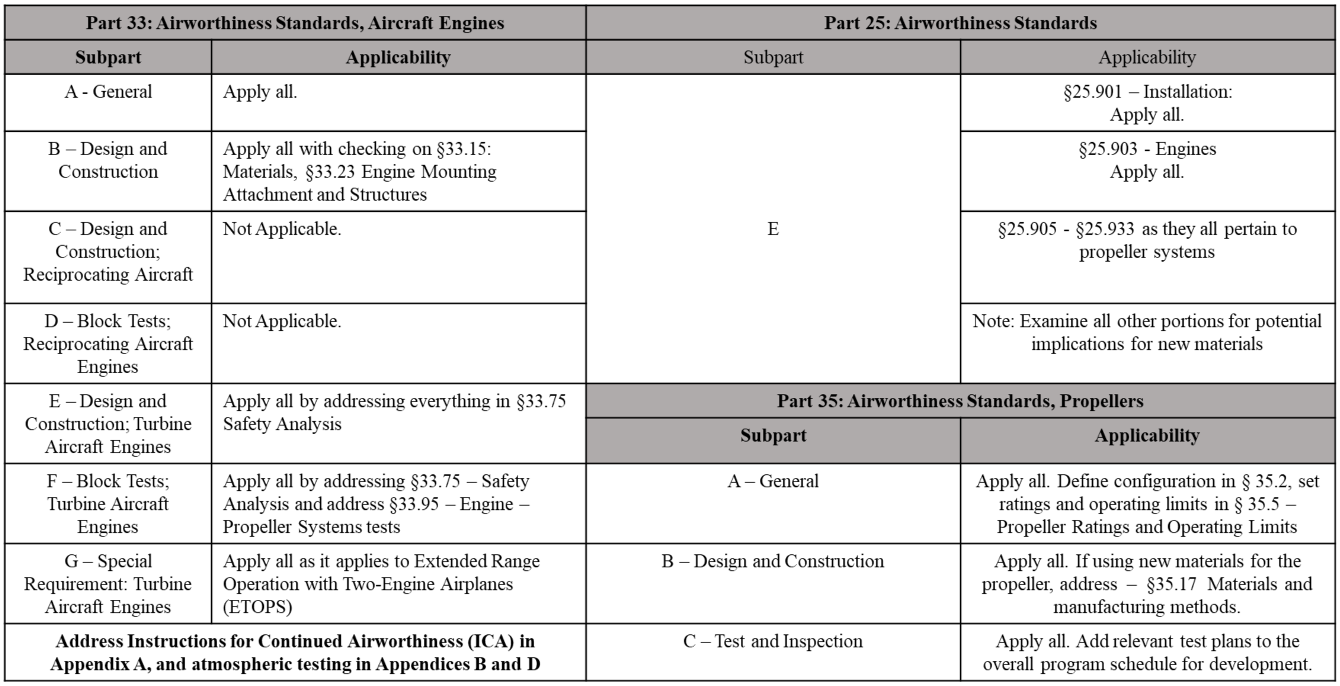


Part 25: Airworthiness Standards	
Subpart	**Applicability**
A - General	Apply all.
B – Flight	Apply all while checking on §25.23: Load Distribution and §25.103: Stall Speed.
C – Structure	Apply all with focus on §25.331-§25.351 in particular §25.337: Limit maneuvering load factors, §25.341: Gust and turbulence loads, §25.345: High lift devices, §25.373: Speed control devices, and all of §25.391-§25.459. Consider potential modifications.
D – Design and Construction	Appy all with focus on §25.651-§25.703 which pertain to control surfaces and control systems which may need special consideration for active load alleviation.
E – Powerplant	Not applicable.
F – Equipment	Focus on sections relevant to instrumentation, especially for caution warnings and §25.1309: Equipment, System, and Installations.
G – Operating Limitations and Information	Apply all and focus on operating limitations starting from §25.1501: General.
Address Part 25 Appendices, with focus on Appendix G — Continuous Gust Design Criteria. Anticipate Gap Mapping from DERs	

Table 50 shows the CAPS overview for active load alleviation – the autonomous nature of the technology may require gap mapping from structures and control systems DERs well-versed in Part 25 which is mentioned in the CAPS. The integration of an ALA system involves intricate interactions between the control laws, sensors, actuators, and the aircraft's response, demanding compliance with stringent airworthiness standards to ensure safety and stability. FAR Part 25, which governs transport category airplanes, is particularly relevant for certifying active load alleviation systems as they directly influence flight control and handling characteristics. The CAPS underscores the need for a meticulous evaluation of the control system's performance, robustness, and its impact on overall flight dynamics.

The evaluation of advanced turboprop engines within the context of airworthiness regulations is a multifaceted process, encompassing FAR Part 21, Part 33, and Part 35, each contributing to the comprehensive certification readiness assessment. Part 21 pertains to the certification procedures for aircraft and their components, involving rigorous analyses of design, production, and performance.

Table 51. CAPS overview for advanced turboprop engine



<table>
<tr><th colspan="2">Part 33: Airworthiness Standards, Aircraft Engines</th><th colspan="2">Part 25: Airworthiness Standards</th></tr>
<tr><th>Subpart</th><th>Applicability</th><th>Subpart</th><th>Applicability</th></tr>
<tr><td>A - General</td><td>Apply all.</td><td rowspan="4">E</td><td>§25.901 – Installation:
Apply all.</td></tr>
<tr><td>B – Design and Construction</td><td>Apply all with checking on §33.15: Materials, §33.23 Engine Mounting Attachment and Structures</td><td>§25.903 - Engines
Apply all.</td></tr>
<tr><td>C – Design and Construction; Reciprocating Aircraft</td><td>Not Applicable.</td><td>§25.905 - §25.933 as they all pertain to propeller systems</td></tr>
<tr><td>D – Block Tests; Reciprocating Aircraft Engines</td><td>Not Applicable.</td><td>Note: Examine all other portions for potential implications for new materials</td></tr>
<tr><td rowspan="2">E – Design and Construction; Turbine Aircraft Engines</td><td rowspan="2">Apply all by addressing everything in §33.75 Safety Analysis</td><th colspan="2">Part 35: Airworthiness Standards, Propellers</th></tr>
<tr><th>Subpart</th><th>Applicability</th></tr>
<tr><td>F – Block Tests; Turbine Aircraft Engines</td><td>Apply all by addressing §33.75 – Safety Analysis and address §33.95 – Engine – Propeller Systems tests</td><td>A – General</td><td>Apply all. Define configuration in § 35.2, set ratings and operating limits in § 35.5 – Propeller Ratings and Operating Limits</td></tr>
<tr><td>G – Special Requirement: Turbine Aircraft Engines</td><td>Apply all as it applies to Extended Range Operation with Two-Engine Airplanes (ETOPS)</td><td>B – Design and Construction</td><td>Apply all. If using new materials for the propeller, address – §35.17 Materials and manufacturing methods.</td></tr>
<tr><td colspan="2">Address Instructions for Continued Airworthiness (ICA) in Appendix A, and atmospheric testing in Appendices B and D</td><td>C – Test and Inspection</td><td>Apply all. Add relevant test plans to the overall program schedule for development.</td></tr>
</table>

Table 51 shows the CAPS overview for the advanced turboprop engine, which holds for improved component design, advanced materials, and cycle improvements described as constituents of this system. Part 21 pertains to the certification procedures for aircraft and their components, involving rigorous analyses of design, production, and performance. For advanced turboprop engines, adherence to Part 21 ensures that the engine's integration into the aircraft is compliant with the established safety standards, covering aspects such as installation, fuel systems, and fire protection. Moving to Part 33, which deals specifically with the certification of aircraft engines, the assessment focuses on engine performance, emissions, and durability. Advanced turboprop engines' technological enhancements, such as improved cycle efficiencies and innovative materials, demand thorough evaluations to ensure compliance with Part 33 criteria. Finally, Part 35 addresses the propeller's certification process, considering its design, manufacturing, and performance. Given the interconnected nature of advanced turboprop engines with their associated propellers, compliance with Part 35 requirements is integral to achieving seamless integration and optimal system performance. The CAPS overview examines these airworthiness regulations and details how each part contributes to the overall readiness of the advanced turboprop engine technology for commercial aviation. Then, when regulatory specialists are involved later in the technology development process, the CAPS can be matured into a certification basis and/or regulatory gap analysis.

5.7 Operational Risk Assessment

The final deliverable outlined by the PICTO approach to assessing technology development risk involves readiness evaluation for flight test and commercial operations. In pursuit of a comprehensive operational risk assessment for the integration of advanced technologies into commercial aircraft, this section meticulously evaluates a spectrum of relevant -ilities, encompassing factors critical to technology demonstration and subsequent operational viability. By dissecting the nuanced interplay of affordability, manufacturability, integrateability, wearability, inspectability, maintainability, reliability, and repairability, the strengths and potential vulnerabilities inherent in each technology are captured, thus facilitating an informed decision-making process that paves the way for successful technology integration and safe commercial operation.

Table 52. Operational risk assessment for riblets

Relevant -ilities	**Demonstration**	**Operation**	**Summary Rationale for Stoplight Scoring**
Affordability	Green	Red	Previous efforts to implement plastic riblet film onto aircraft surfaces suggested high initial costs from production and installation that negated potential economic benefits from reduced fuel burn.

Manufacturability/ Tolerability	Yellow	Red	Drag-reduction performance is sensitive to geometric features of the riblets, hence stringent manufacturing requirements that increase costs. Height and spacing within 10% of the desired design are sufficient, but height and spacing should not vary rapidly in the streamwise direction from design specifications.
Integrability/Certifiability	Green	Green	Riblet film can be easily applied onto aircraft surfaces, lending well to retrofits and have been flight-qualified through commercial operations.
Wearability	Yellow	Red	By design, groove patterns on riblet film have heights on the order of 50 microns that are sensitive to contamination and film degradation. Due to poor wearability, riblet film is considered a short lifespan technology.
Inspectability, maintainability, reliability	Yellow	Red	By design, inspection is difficult to observe (requires microscopy), high maintenance and cleaning requirements, low useful life (> 5 years)
Repairability	Green	Green	Riblet film removal and replacement lends well to fast repairs, however due to low product lifecycle, replacement may occur at a high frequency.

Table 52 shows the scoring of the -ilities pertaining to demonstration and operation of riblets. Riblets have demonstrated their readiness for flight test demonstration by securing a green status in the relevant -ilities categories, highlighting their successful integration into aircraft surfaces. However, their journey towards full operational readiness faces challenges predominantly in the realms of affordability, manufacturability, wearability, and maintainability, as indicated by red and yellow scores. These identified gaps bear significance as they directly impact stakeholder acceptability, underscoring the need for further research and development to address these operational barriers before achieving complete operational readiness and fostering wider adoption within the aviation industry.

Table 53. Operational risk assessment for NLF

Relevant -ilities	**Demonstration**	**Operation**	**Summary Rationale for Stoplight Scoring**
Certifiability	Yellow	Yellow	NLF is subject to additional rules and regulations regarding airworthiness for Part 23 and Part 25 aircraft.
Manufacturability/Retrofitability	Green	Red	Surface quality, integration, and manufacturing are huge concerns when it comes to NLF. Higher tolerances required. Entire re-design and fabrication of wing may be required. For demonstration, a laminar flow glove can be used such as in Ref. [112], hence green scoring.
Durability	Yellow	Red	Surface quality degradation and geometry changes under flight condition
Inspectability, maintainability, reliability	Yellow	Yellow	Sensitive to geometry changes under flight loading Higher tolerances, more specifications, more difficulties with integration especially based on where propulsors are mounted.
Operability	Green	Red	Loss of laminar flow in operation from insect accretion, rain, ice, clouds, surface erosion, anti/deicing methods and some loss in laminar flow from propeller-blown wings. For controlled demonstration, this is acceptable, but not for operation.
Designability/Tailorability	Green	Yellow	Design space for NLF wings requires advanced modeling of viscous flow/boundary layer interactions and precise geometric specifications due to the airfoil geometry being the largest driver of the technology's effectiveness
Affordability/Sustainability	Green	Green	When successfully integrated, NLF leads to significant drag reduction improvements that improve fuel economy [104].

Table 53 shows the operational risk assessment for NLF demonstration and commercial operation. The -ilities assessment of NLF reveals a nuanced landscape spanning from demonstration to operational readiness; the technology's promise of enhanced aerodynamic performance is validated by green scores in sustainability and affordability, showcasing its capacity for significant drag reduction and improved fuel efficiency. However, the transition from demonstration to operational deployment introduces multifaceted challenges, as indicated by red and yellow scores in several -ilities categories. The integration of NLF technology necessitates meticulous considerations of manufacturability, retrofitability, and durability, as well as heightened standards for inspectability, maintainability, and reliability.

Table 54. Operational risk assessment for excrescence reduction

Relevant -ilities	Demonstration	Operation	Summary Rationale for Stoplight Scoring
Certifiability	Green	Green	Excrescence drag reduction techniques have been used on commercial transport aircraft.
Manufacturability	Yellow	Red	Higher tolerances and surface quality required. Maintaining the necessary manufacturing standards and quality control is essential for successful operational deployment, which has yet to be formally addressed.
Implementability	Yellow	Yellow	Since excrescence reduction can be implemented through methods that vary by application and installation difficulty, review which techniques are selected.
Inspectability, maintainability, reliability	Yellow	Red	Inspection and maintenance are required for the technology to remain reliable (sand grain roughness <400 microinches.) At the same time, some excrescence reduction techniques such as surface coatings can reduce dirt and insect adhesion, thus reducing washing frequency. For operational readiness, details must still be provided to maintenance personnel on how to properly inspect, maintain, and uphold the reliability of such surfaces.
Sustainability	Yellow	Yellow	Degradation of surfaces can lead to reduced impact, though the drag reduction benefit at optimal performance will prove sustainable over time. More research into the sustainability over prolonged operation needs to be done.
Stakeholder Acceptability	Yellow	Red	Dependent on excrescence drag reduction technique, but reduction of protrusions through flush-mounting may impact stakeholder acceptability due to concerns about electromagnetic interferences. Additionally,

	🟨	🟥	some surface coatings may cause wing surface discoloration [8].

Table 54 provides the -ilities assessment for excrescence drag reduction technologies, where many of the operational issues are similar to those experienced by riblets and NLF.

Table 55. Operational Risk Assessment for Damage-Arresting Stitched Composites

Relevant -ilities	Demonstration	Operation	Summary Rationale for Stoplight Scoring
Tailorability	Green	Red	Demonstrated more tailorable than state of composites because of its ability to concentrate load away from the surface, create very thin skins with post-buckled designs. However, maintaining its performance and tailoring benefits in real-world operational conditions could be complex and uncertain.
Manufacturability	Green	Yellow	Successfully manufactured six aerospace quality PRSEUS panels for ERA. Used aerospace assembly techniques to assemble large-scale fuselage box with the complexity of aircraft structure. Panel quality acceptable for aerospace structures and panel dimensional tolerance was so accurate, little shimming was required. However, challenges remain somewhat outstanding when considering large-scale production.
Durability	Green	Yellow	Repeatedly demonstrated the ability of stitched structures to arrest damage and turn cracks. Fatigue on small articles demonstrates little to no impact on behavior. The operational environment might expose DAC to more diverse and severe conditions, potentially affecting its ability to repeatedly arrest damage and turn cracks.
Inspectability, maintainability, reliability	Green	Yellow	State of the start visual and ultrasound inspection techniques were demonstrated to find areas of damage, composite maintenance techniques also applicable. Translating this success to real-world aircraft operations could present challenges that have only been partially addressed.
Repairability	Yellow	Red	Work has been initiated but not complete in repairability of damage-arresting stitched composites. Un-addressed for the operational environment.
Certifiability	Yellow	Red	Preliminary work with FAA indicates the potential for certification using new design approach. New design approach allows for

	🟨	🟥	extensive local post-buckling and for designing composite structures to arrest and turn cracks without buildups or fasteners.

Table 55 addresses the operational risks from application of DAC. Overall, during the demonstration phase, the DAC shows promising results in several -ilities, such as tailorability, manufacturability, durability, inspectability, maintainability, and reliability. However, certain aspects like repairability and certifiability require further development and validation, as indicated by the yellow scores. These demonstration scores lay the groundwork for refining and advancing the technology for operational implementation, where challenges and uncertainties may lead to different assessment outcomes.

Table 56. Operational risk assessment for ALA systems

Relevant -ilities	Demonstration	Operation	Summary Rationale for Stoplight Scoring
Reliability/Safety	Green	Yellow	Work to ensure the installed ALA system prioritizes safety and does not introduce unintended failure modes must be done. ALA software and hardware components must undergo thorough testing to verify reliability under different operating conditions and scenarios.
Passenger Ride Quality	Green	Green	Active gust and maneuver load alleviation contributes to noticeable improvements in passenger comfort during turbulence.
Certifiability	Yellow	Red	Compliance with relevant FARs (e.g., Part 25) must be evaluated with a regulatory gap analysis to address potential modifications or special conditions regarding autonomous load control.
Durability/Maintainability/Sustainability	Green	Green	ALA systems reduce the wing root bending moment

	🟩	🟩	by mitigation of gust and maneuver loads, this increases wing fatigue life and improves aircraft service life, as observed on the Lockheed C-5A.
Operability/Controllability/Stakeholder Acceptability	Yellow	Red	Adequate documentation on operation, control, and installation must be provided to operators before obtaining stakeholder acceptance. Assurance that the autonomous component of the ALA system can be manually terminated or engaged with pilot discretion. Additional pilot training must be required to familiarize operators with the system prior to commercial deployment.
Integrateability/ Manufacturability	Red	Red	ALA system integration requires extensive airframe modifications for successful implementation. This involves software and hardware modification, installation of sensors, actuators, structures, and control systems that add to the complexity of integration. This will also play a role in the producibility of the technology.

Table 56 shows the operational risk assessment for the ALA system on the advanced turboprop demonstrator. In the operational environment, the ALA system's reliability and safety must be proven to handle real-world challenges and emergencies. Without actual operational flight data, there could be uncertainties in how the system performs in all conditions, leading to a yellow score. Additionally, while the ALA system might have demonstrated potential for certification, the actual process and the technology's compliance with rigorous certification standards could not be fully assessed during the demonstration phase. The yellow score reflects the uncertainty surrounding the certification process. Integrateability/manufacturability remains and outstanding challenge for retrofitting the ALA system onto an existing aircraft system because careful consideration and integration with the current controls system must be considered.

Table 57. Operational risk assessment for advanced turboprop engine

Relevant -ilities	Demonstration	Operation	Summary Rationale for Stoplight Scoring
Adaptability/ Stakeholder Acceptability	Yellow	Yellow	Drawing from lessons learned from previous novel turboprop engine development programs, adaptability is an important design consideration as it will allow for faster, easier, and safer installation of the engine onto various aircraft configurations, thus improving its acceptability.
Reliability/Maintainability/Sustainability	Green	Green	Improved component efficiencies and usage of advanced materials will lead to less overhaul, maintenance, emissions, and improved operational reliability by design.
Integrateability	Yellow	Red	Novel propulsion systems will incur the longest lead times for technology development programs due to number of parts in the system, engine cost, installation efforts, and fabrication/manufacturing costs.
Durability	Green	Green	Durability is improved by use of advanced materials in the propulsion system. However, higher operating temperatures and pressures may negatively impact lifespan

Certifiability	Green	Yellow	Follow procedure outlined in FAR Part 21 for product certification and ensure compliance with Part 33 and additional powerplant requirements in Part 25, Subpart E.
Affordability/Manufacturability	Yellow	Red	Novel engine development is a high-cost effort that requires extensive cost analyses to observe whether the projected reduction in fuel costs is worth the high manufacturing costs associated.

Table 57 addresses the operational risks concerned with the advanced turboprop engine. In the assessment of the advanced turboprop engine's “-ilities”, the demonstration phase sheds light on critical factors influencing the engine's performance, integration, and acceptability. Drawing from past turboprop engine development programs, adaptability emerges as a noteworthy aspect that could enhance stakeholder acceptability by facilitating efficient installation on various aircraft configurations. Furthermore, the engine's demonstrated reliability, maintainability, and sustainability indicate a promising reduction in maintenance needs, emissions, and enhanced operational reliability through the utilization of advanced materials and component efficiencies.

This comprehensive approach to operational risk assessment uniquely empowers stakeholders with a nuanced understanding of technological viability and associated risks, thereby facilitating informed decisions in allocating resources towards high-impact innovations. By systematically evaluating a spectrum of critical -ilities across demonstration and operational phases, this framework not only highlights the potential of advanced technologies but also delineates nuanced challenges, ultimately guiding the delineation of compelling investments in promising developments, accentuating its pivotal role in fostering transformative advancements within the aerospace domain.

PART VI: CONCLUSIONS AND FUTURE WORK

“If you look at airplanes today and airplanes back in 1960s, they’ve got an aspect ratio and a much higher bypass ratio on the engine sure, some have those composite structures, but oh boy, if you look at the overall design of these turboprop type aircraft… they kind of look the same, don’t they?” – Jeffrey V. Bowles

VI. CONCLUSIONS AND FUTURE WORK

The Technology Development Risk Assessment (TDRA) framework presented in this thesis was synthesized to provide a systematic methodology to perform uncertainty-based risk assessment required for successful advanced technology integration into an aircraft system under development. The PICTO approach, a novel contribution, redefines how technology development risk can be systematically evaluated to provide useful information to decision-makers by revolutionizing how performance and schedule risk is assessed while also incorporating later-stage efforts such as integration, certification, and operation as critical factors. The PICTO approach also includes improvements to existing processes such as TIRs, TCMs, and TTRL tailored to addressing these risks. Additionally, new processes such as CAPS and the PISCES chart to streamline the process of identifying, mitigating, and modeling these risks. The results and significance of this work will be detailed for each key dimension of the framework.

6.1 Performance Risk Assessment – Conclusions and Future Work

The PICTO approach employs a new strategy to modeling technologies at the conceptual design phase, leveraging MDO principles, semi-empirical methods, and uncertainty propagation techniques to assess performance impact from the integration of advanced aircraft technologies. MDO principles along with semi-empirical methodologies allow for determination of how the technology’s performance is impacted by the mission environment and MC simulation techniques allow for capturing the performance variabilities of certain technologies. The overall impact on fuel reduction was studied by comparing the baseline model of the turboprop demonstrator, the original ATR 42-600, to the advanced turboprop model with technologies parametrically infused using the methods outlined in the case study.

Table 58. Impact of integrating advanced technologies on the performance and development of the studied aircraft

Advanced Technology	**Percent Fuel Reduction: Minimum % to Maximum % (Median %)**
	ATR-42-600
Riblets	0% to 2% (0.97%)
NLF	0% to 13.1% (7.25%)
Excrescence Reduction	0% to 3.25% (1.67%)
DAC	0.90% to 3.68% (2.11%)
Advanced Engine	10.5% to 16.7% (11.0%)
Active Load Alleviation	0% to 3.06% (1.65%)
Aggregate Technology Build-Up	11.4% to 32.4% (21.5%)

Table 58 depicts the performance impact of each integrated technology onto the ATR 42-600 demonstrator, where presentation of the minimum, maximum, and median values communicate the variability inherent for each technology. The wider the bounds of the distribution along with the location of the median can help inform the margins of risk posed by each technology. For instance, the variability for NLF is high suggesting higher risk than DAC but provides a higher performance benefit for most cases. Overall, the fuel consumption reduction benefits range from 11.4% to 32.4% which exceeds the objective underlined in Figure 33.

This approach allows for an uncertainty-driven understanding of performance that can be further informed through SME input and provision of higher fidelity data later in the design phase. Since many of these technologies have yet to be validated through experimentation, with minimal empirical data present, comparison between real-world values and estimation is limited, however for some cases such as NLF some information exists. Using the new, uncertainty-driven methods to modeling advanced aircraft technologies, the cruise L/D of the

ATR 42-600 with NLF applied to the wing and fuselage noise results in a cruise L/D of 14.37 minimum, to a maximum of up to 18.31 and a median of 16.18. These results can be compared to those obtained in Ref. [113] which used wind tunnel test data on NLF on the wing and tail surfaces from the NASA Ames Research Center 12 ft wind tunnel to approximate the impact of NLF on a baseline ATR 42-600, where the L/D with NLF technologies was found to be ~15. This determined value falls between the lower and upper limits given by our analysis, where the median is off by a $\Delta\frac{L}{D} \sim 1.1$ and the added benefits from optimized riblets and excrescence reduction can improve the total aerodynamic benefits, leading to an overall maximum fuel burn reduction of 18.35%.

Future advancements to this approach can be bolstered through real-world insights and empirical data that can enrich the models with real-world insights. For example, while the impact of propeller slipstream effects on NLF was inherently captured by assuming a lower bound for the performance distribution inclusive of loss of NLF effects, this case was not sufficiently modeled. However, in the study of NLF technology on the Do 228, investigation of propeller slipstream effects on laminar flow was validated through data showing that NLF benefits were reduced, but not completely lost for the region impacted by the propeller wake [91]. Further work on performance evaluation methods at the conceptual design phase can look toward incorporation of higher fidelity analysis tools to improve technology performance estimates.

6.2 Integration Risk Assessment – Conclusions and Future Work

The new TDRA framework proposed a new systematic way to evaluate integration risk at the conceptual design level, using TRL definitions to characterize the TIRs and TCMs to capture interactions and characterize the risk posed by such interactions. The TIRs use the existing TRL framework to foreshadow what necessary integration steps must happen to incorporate a technology onto a demonstrator. For example, in the case study, to advance ALA systems from TRL 5 to TRL 6, the TIR states that: “A complete prototype must be integrated onto the host-system after extensive ground testing to validate the technology’s load alleviation capabilities and compatibility with the overall advanced turboprop demonstrator.” Then the TCM defines what compatibility entails, where for the ALA system (which impacts the overall control system) does not pose risks to other candidates in the technology portfolio.

Further work on the integration portion of the TDRA framework would focus on obtaining stakeholder and SME feedback to validate and improve the integration roadmap, and improving the readability of the TIRs, which are detail heavy. Visualization using an annotated program timeline may be the second step in how the TIR is presented.

6.3 Certification Risk Assessment – Conclusions and Future Work

The third dimension within the PICTO framework, certification was addressed through the construction of a Certification Assessment Primer Schematic (CAPS) overview, where understanding of technology characteristics derived from the performance and integration risk assessment are used to determine the relevant and applicability of technology specific FARs and regulatory articles such as ACs. According for the CAPS overview for DAC, more development is needed to support FAA certification, such as modifications to the certification approach for composites to take advanced of the crack arrestment and delamination suppression features of stitched structures. This in turn, provides less uncertainty in actions that will be required as part of the technology’s overall maturation plan, as future testing may pose a risk to the timeliness of the demonstration since time must be taken to work with the FAA on a new certification approach. Use of a CAPS will allow for identification and mitigation of risks posed by compliance with FARs that previously hindered the X-57 flight demonstration program much earlier.

Further evolution of this process can be improved with the emergence of the regulatory Model-Based Systems Engineering (MBSE) framework proposed by researchers at Georgia Institute of Technology's ASDL lab [114]. This tool provides an automated way to systematically evaluate the entirety of regulations required for each conceptual design. Utilizing the MBSE tool, technologists undertake initial assessments, crafting foundational gap analyses for subsequent stages [114]. This output is then validated in collaboration with DERs enhancing assessment accuracy.

6.4 Timeline Readiness Risk Assessment – Conclusions and Future Work

For timeline readiness assessment, the Uncertainty-Driven TRL Transition Analysis code (U-TTRAN) was developed by implementing the uncertainty-driven TDRA methodologies presented by Mathias et al. that drew from existing TRL transition histories to estimate maturity times for in-development technologies [12]. When used, the U-TTRAN code can obtain median number of years to the next TRL accompanied by an associated measure of uncertainty, allowing for a transparent TRL forecasting method that grounds predictions in real-world empirical data. Table 39 provides the results given by U-TTRAN for the case study technology portfolio, where technologies whose estimated development timelines exceed that of the allotted program timeline are highlighted for further consideration. In the example case, these are:

Table 59. Technologies identified to pose potential risks to the development timeline from U-TTRAN

Technology	**Current TRL**	**Estimated Years to TRL 6**	**Risk Level for 2030 (7 Years)**
Adv. Composites (DAC)	4	8.11 ± 1.91	Medium
ALA System	4	5.83 ± 1.48	Medium
Adv. Turboprop Engine	3	9.55 ± 1.98	High

Table 59 shows the results of the case study that identify DAC, ALA, and advanced turboprop engine as technologies that may require significant development time that exceeds the seven years allotted for the program. Because DAC is a material/structural technology, fabrication efforts are expected to drive the timeline, while ALA and the advanced turboprop engine require significant modifications to the airframe, which is typical of propulsion and flight systems technologies. When faced with this information, risk-informed decision makers can decide if these uncertainty bounds are within acceptable margins of risk acceptance.

With stakeholder collaboration, the precision and reliability of these methods can be improved in future studies by obtaining TRL transition histories directly from SMEs and obtaining feedback on the veracity of these predictions.

6.5 Operational Risk Assessment – Conclusions and Future Work

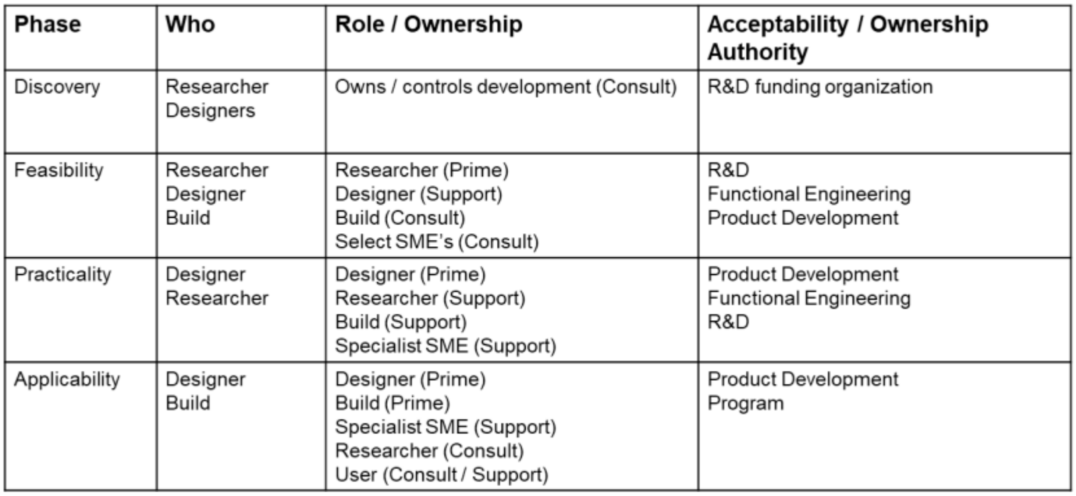
Lastly, operational risk assessment was conducted using the TTRL framework, using assessment of the -ilities prior to demonstration and operation to highlight potential inhibitors to demonstration, production, commercial adoption, and stakeholder acceptability. From the results of the case study, the issues facing commercial acceptance of riblets determine why the technology remained at TRL 6 for a significant amount of time. This suggests that when having to select between riblets and a technology such as DAC that may require more work for demonstration, but have better chance of scaling into commercial operations, the TTRL framework can provide structured insight into considerations that must be considered to make that decision. Improvements to operational risk assessment can be done through improved standardization of which -ilities are universally relevant and SME input to better inform the stoplight scoring.

6.6 Overall Conclusions and Future Work

The PICTO approach to technology development risk assessment encapsulates a synthesis of existing knowledge, identification of potential shortfalls, and the integration of key risk dimensions for advanced aircraft technologies. Future avenues of exploration can stress-test its usage on different aircraft concepts such as HWB where the modeling methodologies can be applied to other technologies. Now, the current approach is flexible to application for different classes of technologies, such as EAP systems as well as new aircraft concepts that fall under the conventional takeoff and landing category (CTOL). Currently, the M&S tool used in this study, GASP, does not study vertical takeoff and landing (VTOL) aircraft.

As the proposed TDRA framework takes its form and is applied, it is essential to underscore that its introduction does not negate the significance of stakeholder and SME input. Instead, it offers a strategic refinement, streamlining their engagement in a purposeful manner. Future work will include incorporating feedback through solicited stakeholder engagement to better refine the applicability and effectiveness of the TDRA framework. Formal identification of stakeholders and assignment of roles/ownership can determine which parties can provide feedback on the deliverables obtained from the PICTO approach to TDRA and allow for construction of a comprehensive PISCES chart.

Table 60. Identification of Stakeholders for Collaboration from Ref. [8]



Phase	Who	Role / Ownership	Acceptability / Ownership Authority
Discovery	Researcher Designers	Owns / controls development (Consult)	R&D funding organization
Feasibility	Researcher Designer Build	Researcher (Prime) Designer (Support) Build (Consult) Select SME's (Consult)	R&D Functional Engineering Product Development
Practicality	Designer Researcher	Designer (Prime) Researcher (Support) Build (Support) Specialist SME (Support)	Product Development Functional Engineering R&D
Applicability	Designer Build	Designer (Prime) Build (Prime) Specialist SME (Support) Researcher (Consult) User (Consult / Support)	Product Development Program

Table 60 identifies stakeholders throughout the technology development phases presented in Ref. [8]. Here, the discovery phase applies up to TRL 3, feasibility up to TRL 5, practicality at TRL 6, and applicability addresses all phases after TRL 7.

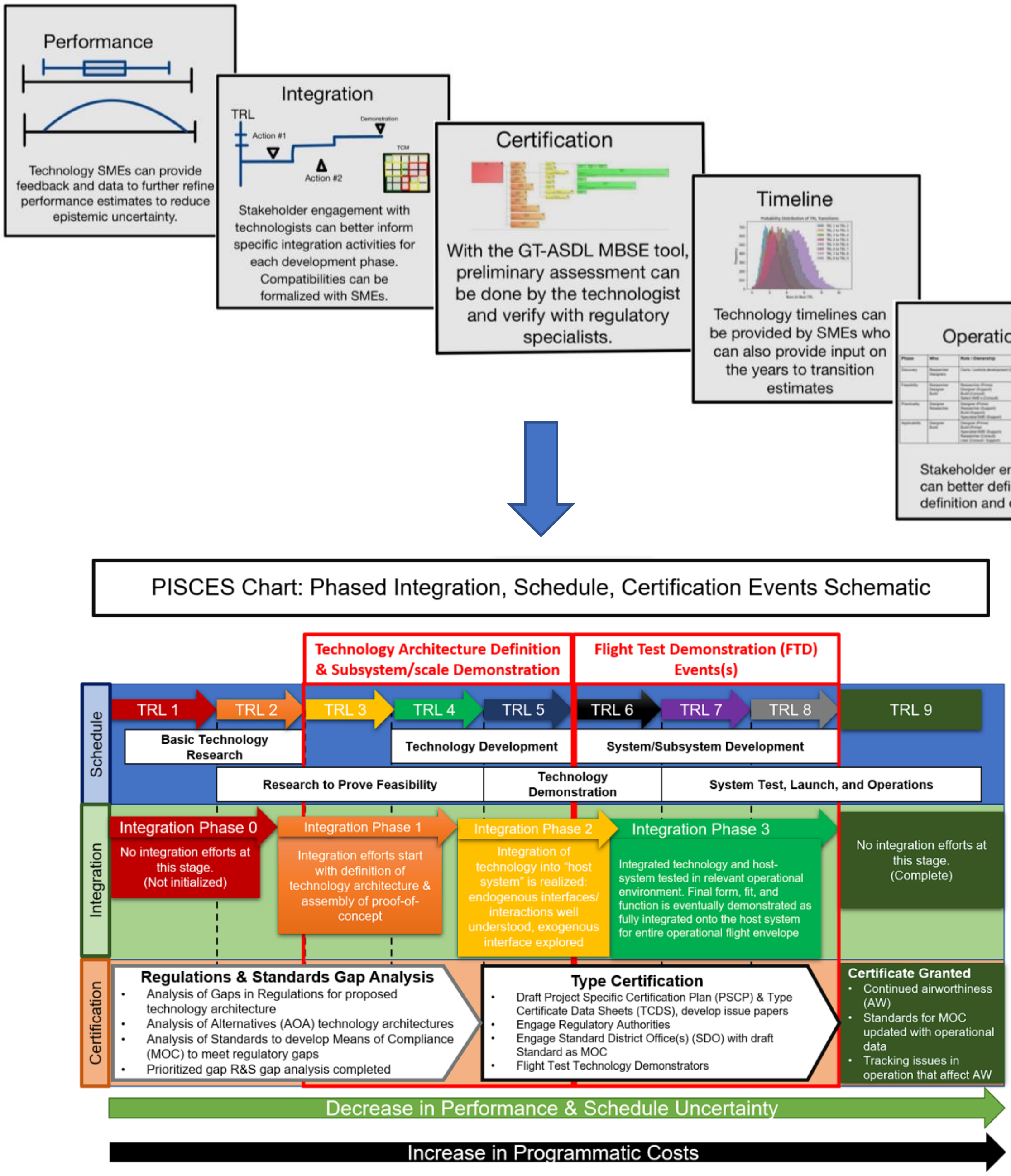


Figure 44. Significance of Stakeholder Collaboration and Input to Using the PICTO Approach for TDRA

Figure 44 summarizes the important of integrated efforts and collaboration throughout the TDRA process. By systematically presenting risks delineated element by element, the TDRA framework can be used to harness expertise and feedback in a synergistic manner aligning with the iterative, spiral approach to technology development. Essentially, the PISCES chart and

PICTO approach show how the TDRA framework can serve as a bridge between technologists and stakeholders to facilitate risk-informed decision making for programs such as EPFD, SFD, AATT, and SFNP. This holistic TDRA framework represents a paradigm shift in risk assessment, uniting technical rigor, uncertainty-driven analysis methods, and collaborative insight to pave the way forward for advanced aircraft technologies.

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Appendix A. Modeling ALA Systems

Active Aerodynamic Load Alleviation

A key design objective for a civil transport airplane is to achieve best possible cruise efficiency at a minimum cost in structural weight. Excessive structural weight will not only increase capital cost but also increase the total weight of the airplane and thereby increase the aerodynamic drag. Maneuver loads (typically a positive design load factor $n_{max} = 2.5$ g for civil transport jets) and gust loads must be considered in the structural design of the airframe with gust loads being a likely critical contributor for relatively low wing-loading airplanes with high aspect ratio wings.

The purpose of this writeup is to present a rational and transparent method to predict the impact of active aerodynamic load alleviation on airplane efficiency and weight during the conceptual design stage. This instead of relying on widely varying empirical data on the impact of active load alleviation on airplane efficiency and weight presented in the literature (e.g., see Table 2 in Regan & Jutte[1]).

Consider an airplane encountering a vertical gust or executing a turn or pully-up maneuver:

$$W = nC_L 0.5\rho_\infty {V_\infty}^2 S = nC_L 0.5\rho_o {V_c}^2 S$$

where in cruising flight at steady conditions, $n = 1$.

Focusing on gust loads, consider a gust speed $\pm U_{de,c}$ at a design cruise speed V_c where according to FAR Part 25, $U_{de,c} = 56.0$ ft/s at sea level, reducing linearly to 44.0 ft/s at 15 kft, and reducing linearly to 26.0 ft/s at 50 kft.

As a result of a gust:

$$n = 1 + \frac{\Delta L}{W} = 1 + K_g \frac{C_{L_\alpha} \frac{U_{de}}{V} 0.5\rho_o V^2 S}{W} = 1 + K_g \frac{C_{L_\alpha} U_{de} 0.5\rho_o V}{W/S}$$

where the gust alleviation factor K_g accounts for the fact that the airplane flies into the gust and, hence, the gust does not act on the entire airplane instantaneously.

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$$K_g = \frac{0.88\mu_g}{5.3 + \mu_g}$$

$$\mu_g = \frac{W/S}{C_{L_\alpha} c_{av}\, g\, 0.5\rho_o}$$

If U_{de} is specified in ft/s, C_{L_α} in rad^{-1}, the equivalent airspeed V in knots, W/S in lb/ft^2, and

$\rho_o = 0.0023769$ slug/ft^3:

$$n = 1 + K_g \frac{C_{L_\alpha} U_{de} V}{498\, W/S}$$

as specified in the FAR.

As the load factor n is changed as a result of a maneuver (turn or pull-up) or a gust, the wing root bending moment (WRBM) is changed accordingly. As indicated by Heyson et al.[2], wing root bending moment is a satisfactory index of the effect of changes in spanwise loading on wing structural weight. The bending moment at spanwise station y is:

$$M_l(y) = \int_y^{y_t} \left(y_t - y\right) c_n(y)\, c(y)\, q\, dy$$

where in cruising flight (low α) $c_n \approx c_l$. Heyson et al.[2] then derive for the weight of the wing bending material:

$$W = k \int_0^{y_t} \frac{|M_l(y)|}{c(y)}\, dy$$

Where k is a constant and the absolute value of the bending moment is required because “positive cover-plate area is required to resist the moment regardless of whether the moment is positive or negative.”

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[2] Heyson, H.H, Riebe, G.D., and Fulton, C.L., “Theoretical Parametric Study of the Relative Advantages of Winglets and Wing-Tip Extensions,” NASA TP-1020, Sep. 1977.

Figure 1 shows the weight of the bending material in the wing (nondimensionalized by that of a baseline wing) as a function of WBRM (nondimensionalized by that of the baseline wing). The results indicate a close to linear relation between the weight of the bending material in the wing and WRBM.

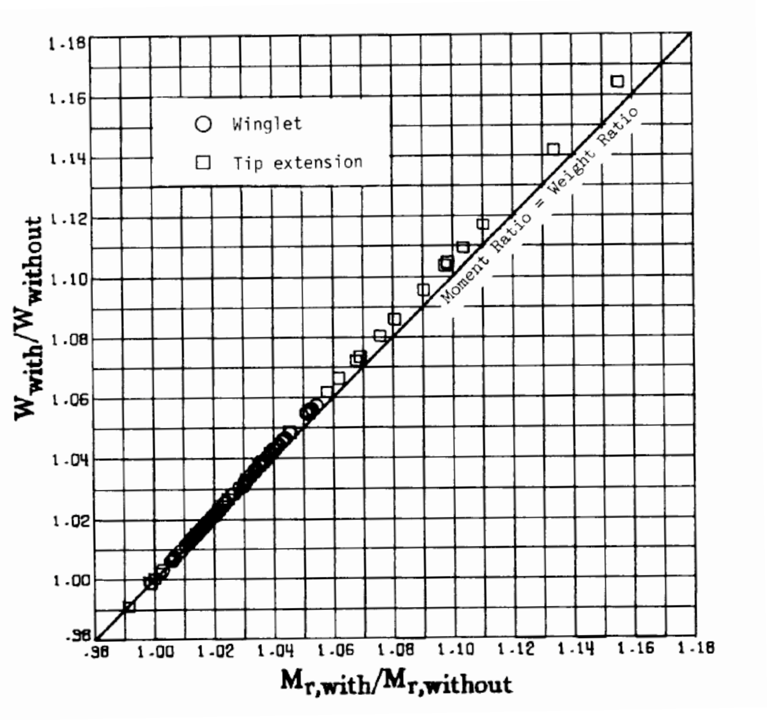
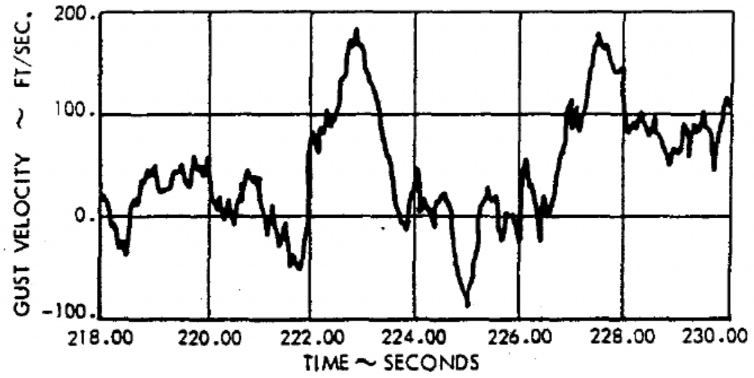


Fig. 1 – Effect of wing root bending moment M_r on minimum weight of bending material in wing W.[2]

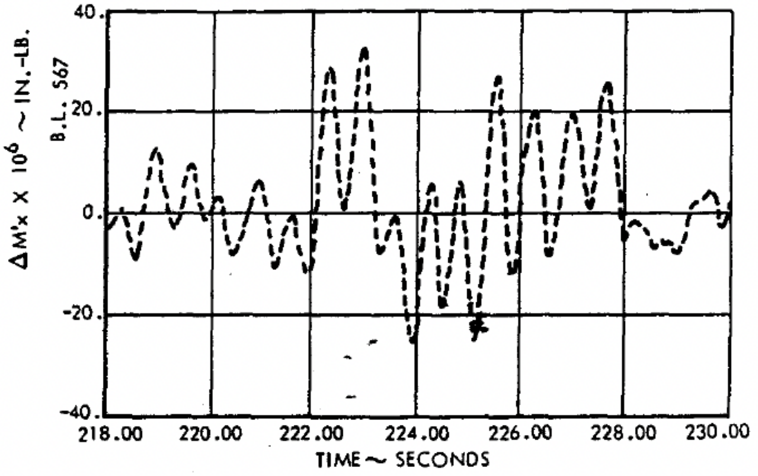
Heyson et al.[2] indicate that the total weight of the bending materials in the wing of civil jet transports tends to represent 5-7 % of the maximum takeoff weight and approximately 12-20 % of the operating empty weight.

Now as the airplane executes a maneuver or encounters a gust (e.g., n = + 2.0), the lift coefficient will increase by the factor n and with that the WRBM. The idea is to activate a load alleviation system that will mitigate the maneuver/gust induced increase in lift and WRBM.

Regarding the use of WRBM to quantify the impact of gust loading on wing weight, the results obtained for the L1011 indicate that this is a reasonable metric and, hence, applicable for use in the early design stages of an airplane. Later models of the L1011 incorporated a gust alleviation system that allowed an increase in wingspan of 9 ft without having to enhance the wing structure to deal with the resulting increased aerodynamic loads.[1] The system involved symmetrical aileron deflections to mitigate bending moment increases due to gusts. In Fig. 2 simulation results for the L1011 are presented in terms of time histories for a very high 65 ft/s root mean square (rms) gust velocity with the active control system (ACS) off.[3] Figure 2a shows the gust velocity time history with the peak gust encountered at t = 223 s. Figures 2b and 2c show the corresponding wing bending moment histories at y/(b/2) = 58% (BL 567) and 71% (BL 700), respectively, with the peak moment at these wing stations occurring at the peak gust velocity t = 223 s. This correspondence between peak gust velocity and peak wing bending moment provides a reasonable argument for analyzing the impact of gust load mitigation in an identical manner as maneuver load mitigation.



(a) Gust velocity (65 ft/s rms)



(b) Wing bending moment at BL 567

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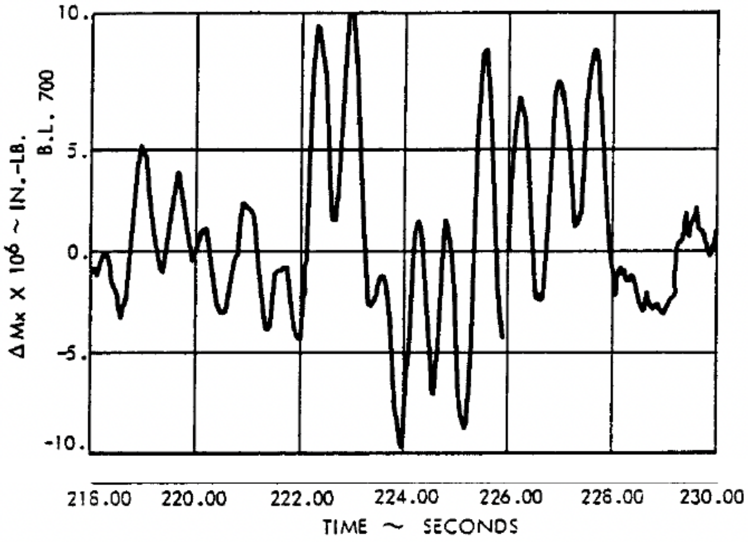
[3] Gould, J.D., “Effect of Active Control System Nonlinearities on the L-1011-3 (ACS) Design Gust Loads,” AIAA Paper 85-0755, 1985



(c) Wing bending moment at BL 700

Fig. 2 – Time histories of vertical gust velocity and corresponding wing bending moments (65 ft/s rms, ACS off). [3]

The maneuver load mitigation system could be based on a simple lookup-table-based algorithm were based on airplane weight and equivalent airspeed, a change in load factor from unity results in an action of the load alleviation system to nullify the increase in wing bending moment. The load alleviation includes the ailerons and wing flaps (if they are of the simple hinged type that can deflect up and down or if they are cruise flaps used to allow a laminar flow wing to operate in the laminar bucket) and the elevators for longitudinal trim. The gust load alleviation system includes one or more sensors to sense the gust (e.g., forward looking lidar[4,5]), as well as the above lift and moment control surfaces. More advanced options consist of actively controlled tabs (e.g., Gardner et al.[6]) or pneumatic jets near or at the trailing edge of the wing to control the lift of the control surfaces.

Assume:

$$W_{wing} = a_0 + a_1 WRBM$$

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[4] Cates, M.C., Paranto, J.N., and Larsen, T.A., "Multifunction Aircraft Light Detection and Ranging (LIDAR)," US Patent 8,508,721, 13 August 2013.

[5] Walton, V.M., Borland, C.J., Siu, T.L., Najmabadi, K., Coleman, E.E., Marquis, D.P., McMullin, D.L., and Milligan, K.H., "Vertical Gust Suppression System for Transport Aircraft," US Patent 8,774,987, 8 July 2014.

[6] Gardner, A.D., Nitzsche, J., Neumann, J., Richter, K., Rosemann, H., and Voss, R., "Adaptive Load Distribution Using Mini-TEDS," ICAS 2006, Paper 216, 2006.

where the first term on the RHS represents the basic weight of the wing and the second term the weight contribution of the bending materials with $a_1 \approx 1.0$ lb/(ft lb).[2]

Figure 3 depicts the spanwise load distribution as a result of the activation of a maneuver load control system.

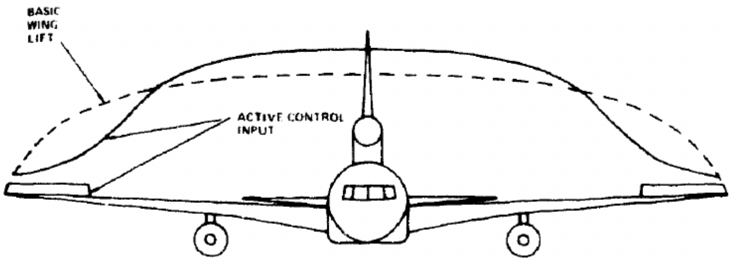

Fig. 3 – Impact of aileron-based active maneuver load control system on spanwise load distribution of L1011.[7]

Figure 4 illustrates the impact of a gust on airplane lift and Fig. 5 illustrates the impact of a gust and partial alleviation on the spanwise lift distribution. In Fig. 5, the gust alleviation is depicted to alleviate most but not the entire impact of the gust.

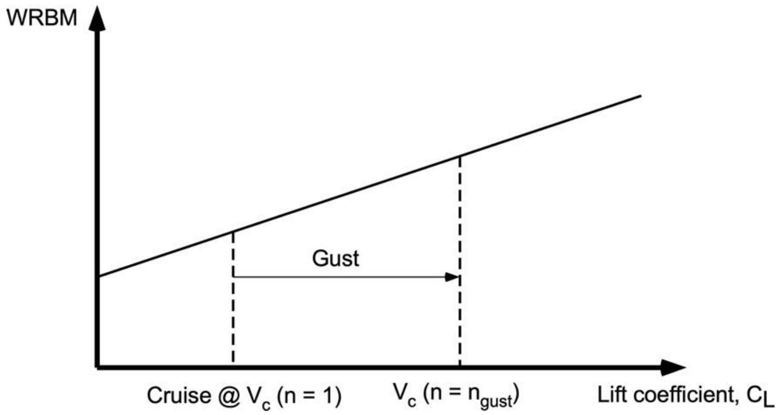

Fig. 4 – Impact of positive gust on airplane lift coefficient and wing root bending moment.

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[7] Ramsey, H.D., and Lewolt, J.G., "Design Maneuver Loads for an Airplane with an Active Control System," AIAA Paper 79-0738, 1979.

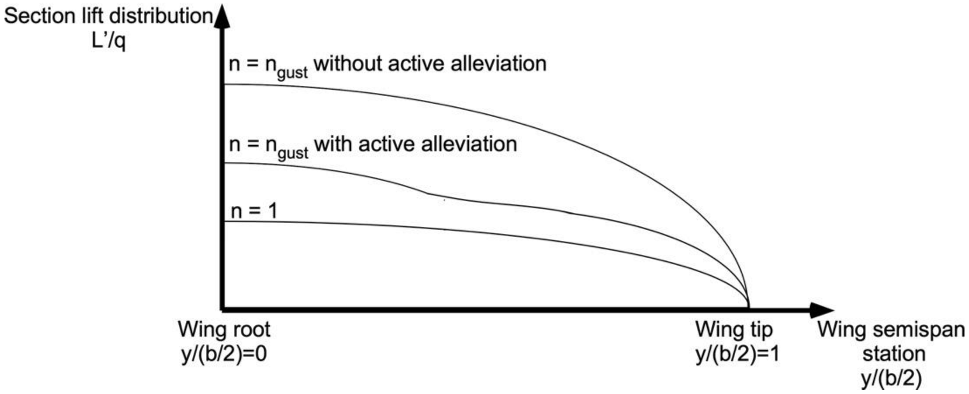

Fig. 5 – Impact of positive gust on the spanwise lift distribution of the wing and effect of an active gust alleviation system with actuators along the entire span.

Gust loading ATR42-600:

AR = 11.1

W = 41,000 lb

S = 586 ft^2

b = 81 ft

c_{av} = S/b = 7.3 ft

V_{cruise} = 300 KTAS at 25,000 ft, Equivalent airspeed V = 300 $\sqrt{\frac{\rho}{\rho_0}}$= 201 KEAS

$M_\infty = M_{cruise}$ = 300/601.9 = 0.50

U_{de} at 25,000 ft = 39 ft/s

The lift curve slope for an airplane can be approximated by the following expression[8] where the quarter chord sweep angle is approximately 0.

$$C_{L_\alpha} = \frac{2\pi\, AR}{2+\sqrt{4+\frac{AR^2\left(1-M_\infty{}^2 cos^2\Lambda\right)}{cos^2\Lambda}}} = 2\pi\frac{AR}{11.82} = 5.90 \text{ rad}^{-1}$$

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[8] Lowry, J.G., and Polhamus, E.C., "Method for Predicting Lift Increments due to Flap Deflection at Low Angles of Attack at Incompressible Flow," NACA TN-3911, Jan. 1957.

$$\frac{C_{L_\alpha} U_{de} V}{498\ W/S} = 1.33$$

$$\mu_g = \frac{W/S}{C_{L_\alpha} c_{av}\ g\ 0.5\rho_o} = 42.5$$

$$K_g = \frac{0.88\mu_g}{5.3+\mu_g} = \frac{0.88 \times 42.5}{5.3+42.5} = 0.78$$

$$n_{gust} = 1+0.78 \times 1.33 = 2.04$$

Gust load factor is lower than the limit maneuver load factor of 2.50. Higher aspect ratio would increase gust load factor. E,g, increase to AR = 20 would increase n_{gust}. A lower operating altitude would increase U_{de} and increase n_{gust}. A lower wing loading, required on account of optimizing operating conditions with extensive NLF and/or shorter takeoff distances, would further increase n_{gust} and may cause gust loads to supersede design maneuver loads.

Ramsey & Lewolt[7] present a rational method to account for the maneuver load alleviation system to reduce design loads and thereby achieve a reduction in the structural weight of the wing. This method accounts for the in-flight availability of the maneuver load alleviation system, and it is based on the analysis of gust load alleviation systems presented in FAA-ADS-53[9]. Hence, instead of a deterministic approach to maneuver load analysis a probabilistic approach is advocated. Analysis is based on Fig. 6 depicting the frequency of exceedance of maneuver load factors per flight determined by NASA from data acquired on three types of jet-propelled civil transports (total of 7397 operational flights plus 1394 check flights).

The following example based on Fig. 6 illustrates how a design load factor of 2.5g without maneuver load alleviation (MLC-off) can be equated with a design load factor of 1.8g with a maneuver load alleviation system (MLC-on) assuming an in-flight system availability of 99.90%.

1. From Fig. 6, determine frequency of exceedance of maneuver limit load factor of 2.5g:
   $E_R = 3.20 \times 10^{-5}$ per flight
2. Select the design load factor with MLC-off. In this example: $n_{MLC\text{-}off} = 1.80g$
3. From Fig. 6, determine frequency of exceedance of limit load factor of 1.8g: $E_C = 930 \times 10^{-5}$ per flight
4. Select an in-flight availability of 99.90%, hence unavailability 0.10%
5. Calculate resulting exceedance $0.001 \times E_C = 0.93 \times 10^{-5}$:
   $E_{MLC\text{-}off} = 0.93 \times 10^{-5}$ per flight

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[9] Hoblit, F.M., Paul, N., Shelton, J.D., and Ashford, F.E., "Development of a Power-Spectral Gust Design Procedure for Civil Aircraft," FAA-ADS-53, Jan. 1966.

6. To achieve baseline exceedance value $E_R = 3.20 \times 10^{-5}$ per flight:
   $E_{MLC\text{-}on} = 3.20 \times 10^{-5} - 0.93 \times 10^{-5} = 2.272 \times 10^{-5}$ per flight

7. From Fig. 6, determine corresponding design load factor:
   $n_{MLC\text{-}on} = 2.54g$

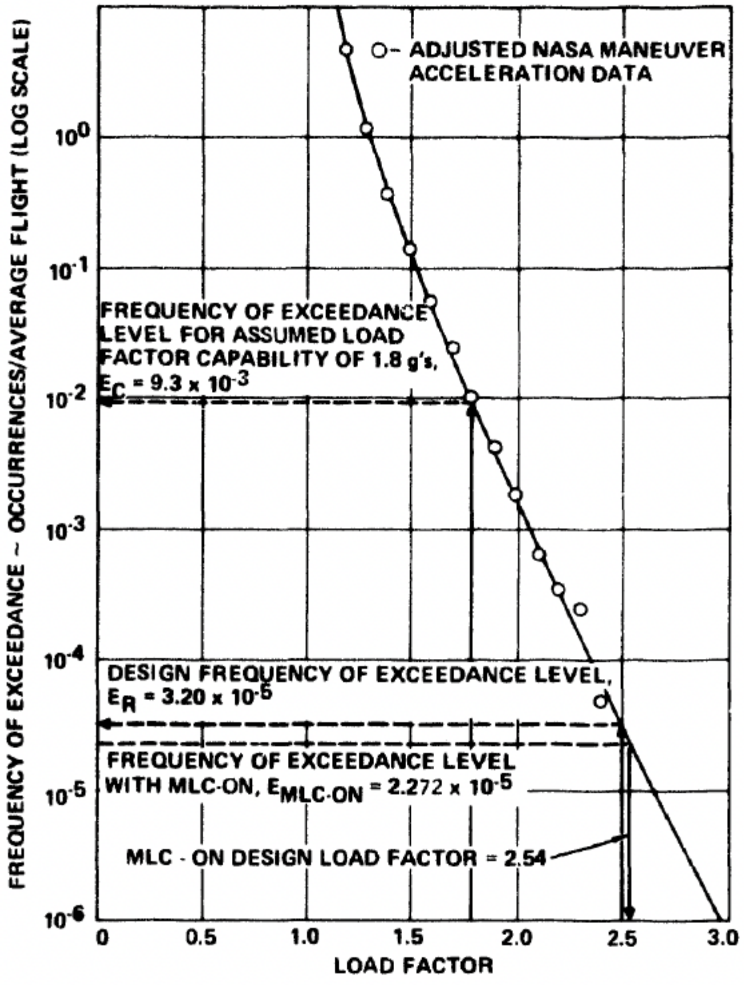

Fig. 6 – Example of accounting for in-flight availability of a maneuver load control (MLC) system in establishing design maneuver load factor.[7]

Figure 7 depicts the adjusted NASA maneuver acceleration data from Fig. 6 plus a curve fit to this data. This curve fit expression is used for further analysis. Note because of slight differences between the curve fit applied by Ramsey & Lewolt[7] and the curve fit depicted in Fig. 7, the present relationship between $n_{MLC\text{-}off}$ and $n_{MLC\text{-}on}$ is as a result slightly altered as illustrated in Fig. 8.

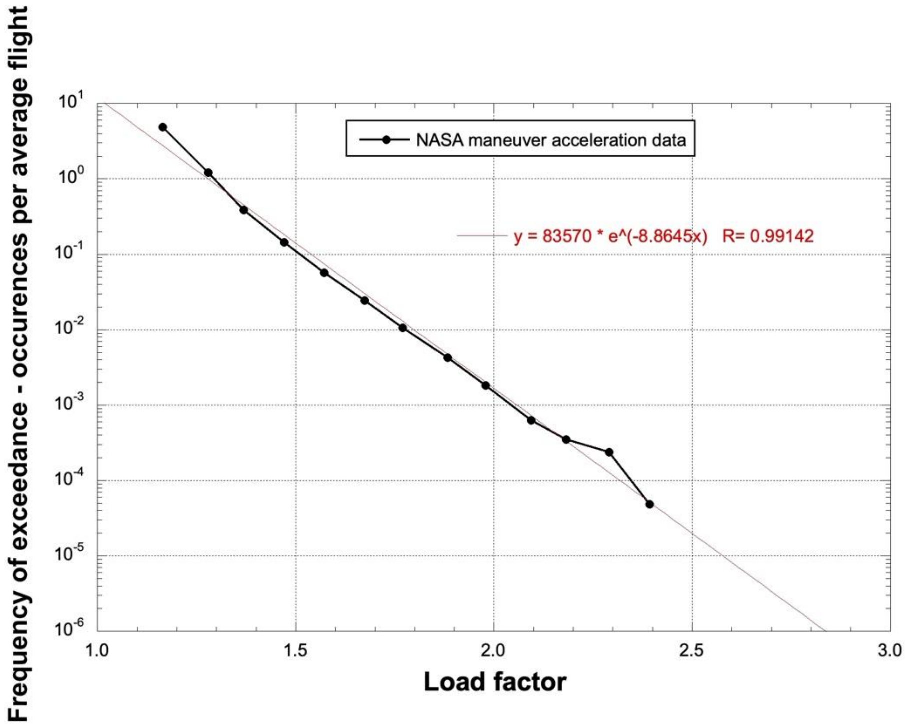

Fig. 7 – Frequency of maneuver load factor exceedance for civil transport airplanes as determined by NASA based on analysis of in-flight data.

Figure 8 depicts the MLC-on versus MLC-off load factor requirements for a range of system availabilities with the earlier example highlighted in red. As a second example, if a load factor combination of $n_{MLC\text{-}on}$ =2.535 and $n_{MLC\text{-}off}$ =1.350 is selected, an availability of 99.9990% would be required.

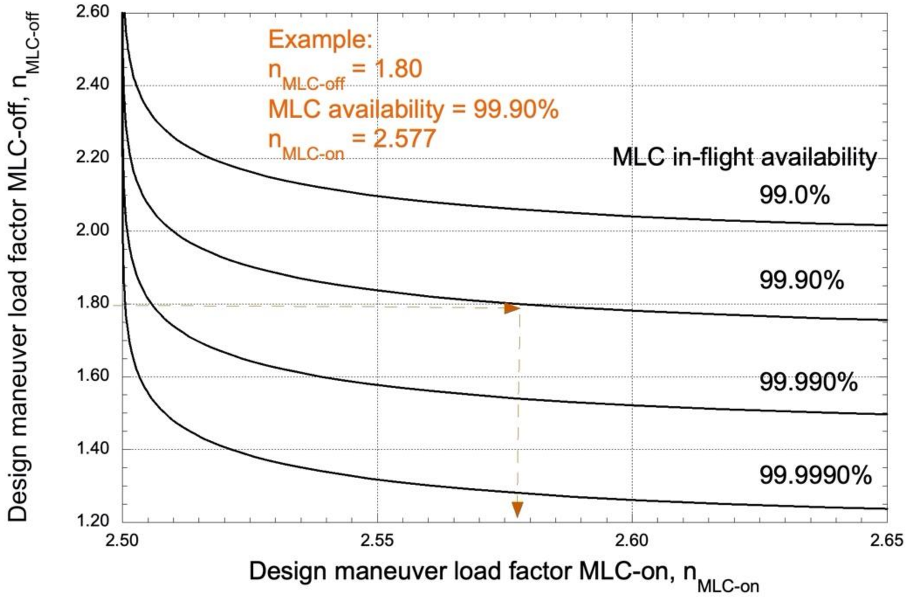

Fig. 8 – Impact of in-flight availability of a maneuver load control (MLC) system on design load factor requirements.

This method proposed by Ramsey & Lewol[7] provides a rational approach to meeting the objective that the probability of exceeding design limit loads shall not be greater for an airplane design with MLC than for an airplane without MLC.

Appendix B. TRL Transition Histories for Aerodynamics, Structural, and Flight Systems Technologies

Table 1. Aerodynamics Technologies

Years		GA Wing	Supercritical Wing	Winglets	Passive LFC Fuselage	3M Riblet Film for Wide-Body Airliners	Vortex Generator	Leading Root Extension	De-Icing Boots	Anti-Shock Bodies	Drooped Leading Edge	HLFC on Vertical Tail for B787	Integrated Transonic Wing Design	Integrated Aerodynamic Airframe	NLF Fuselage on Business Jets	Adaptive External Hinge Single-Slotted Flap	Laminar Nacelles	Rubber IAM Coating	Adv. Surface Coatings	Sharklets	Active Wingtip Device
from TRL	**to TRL**																				
1	**2**	0.5	1.5	1	2	1	1	3	2	2	2	8	1	2	1	1	4	1	1	1	2
2	**3**	0.5	1	1	1	1	1	2	1	2	1	12	1	2	1	3	3	3	0.5	1	1
3	**4**	0.5	1	1	1	3	2	1	1	0.5	1	5	1	2	1	1	0.5	7	0.5	1	4
4	**5**	3	1	1	2	1	4	1	2	6	3	0.5	1	2.5	1	1	0.5	1	1	3	2
5	**6**	0.5	1	2	7	1	9	5	4	5	3	26.5	2	3	2	1	7	5	5	5	7
6	**7**	1.5	1	1	14	10	4	2	1	2	2	23	6	1	1	1	7	2	3	4	9
7	**8**	3	12	1	1	4	4	2	1	1	1	1	2	2	1	1	1	1	2	1	1
8	**9**	4	1	1	2	1	11	3	1	2	1	6	4	2	1	2	6	1	3	2	2

Table 2. Structural/Materials Technologies

Years		Composite Fuselage	CNT-MMC	Ceramic Matrix Composites	Monocoque Fuselage	Geodetic Airframe	Chemically Straightened Cockpit Windowshields	Subsonic Flying Wing Structure	GLARE Composites	CFRC for Primary Structures	Narmco T300/5208 graphite/epoxy material system	Duramold Fuselage	Titanium Aircraft Structures	2024/2524/7075 Al Fuselage Skins	Nylon Hex Mesh Fabric	Truss Wing Spar	Strut-Bracing for Wings	Semi-Crystalline Polymers	Thermoplastic Curing	CFRP Outer Flaps	Electron Beam Welded Structures
from TRL	**to TRL**																				
1	**2**	2	1	3	2	1	3	2	1	1	1	2	1	2	1.8	3.2	2	2.5	1	2	4
2	**3**	2	3	6	1	1	2	3	1	2	1	1	2	1.9	1.4	2.9	1	1	0.5	2	2
3	**4**	2	2	1	2	2	1	1	2	3	3	3	4	2.1	1.8	3.8	1	1.5	0.5	4	3
4	**5**	3	1	4	5	1	5	10	5	5	1	2	5	3	1.6	2.8	1	2.5	1	5	2
5	**6**	1	5	2	10	7	8	8	5	2	1	5	7	2	6.1	8.7	4	1	5	6	2
6	**7**	12	3	1	2	1	6	2	7.5	3.5	1	4	1	5	4.5	4.6	2	2.5	3	7	4
7	**8**	1	1	1	1	1	3	2	1	3	1	3	1	4	4	5	2	6	2	1	2
8	**9**	2	8	10	2	3	3	4	4	4.5	5	4	3	1	5	5	3	1	3	5	5

Table 3. Flight Systems Technologies

Years		Electro-Expulsive De-Icing Systems	Engine Monitoring	Flow Visualization	ADS-B	Fly-By-Light	Gust Load Alleviation	Surface Movement Advisor	FADEC	Tiltrotor System	Hydromechanical Systems	Engine Health Monitoring	Flight Control Systems	Stability Augmentation Systems	Electronic Flight Instrumentation System	Terrain Awareness and Warning System	Inward Retractable Landing Gear	Automatic Direction Finder	Vertical Navigation (VNAV) Systems	Cabin Pressurization	Autothrottle Control
from TRL	**to TRL**																				
1	**2**	0.5	1	5	4	2.5	1.4	3.4	4	3	3.3	2.3	3	2	3	2	3	2	3	1	3
2	**3**	0.5	1	1	1	5	1.5	2.6	3	1	0.6	1.7	2	1	3	1	3	4	2	3	2.6
3	**4**	1	1	3.5	1	7.5	2	2.3	3	1	2.7	1.8	1	2	2	1	2	2	2	2	1.5
4	**5**	1	1	1	1	4	1	2	3	1	1.5	1.5	1	2	2	1	3	3	3	4	0.2
5	**6**	1	1	0.5	1	1.5	8	1.65	3	22	5.2	3.4	1	4	2	1	4	3	3	5	8.4
6	7	6	1	0.5	1	1.5	2	1.3	3	8	3.2	3.7	1	3	1	1	1	1	2	2	2.4
7	**8**	0.5	5	0.5	1	1.5	5	1.3	2	1	0.5	3.6	1	2	1	1	2	2	2	2	4
8	**9**	5.5	0	0.5	1	1.5	2	0.1	1	11	3	2.4	1	3	2	1	1	1	2	1	3.6