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LINKING TECHNOLOGY READINESS TO UNCERTAINTY REDUCTION

Katherine G. Schwartz, Dimitri N. Mavris
Georgia Institute of Technology, School of Aerospace Engineering

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Abstract

Advanced technologies and vehicle concepts are required to meet the aggressive performance and environmental goals set for the next generation of aircraft systems. Technology development programs will need to identify the appropriate technologies and put together plans to mature them. Technology maturation, or readiness, can be tracked through the technology readiness level (TRL) metric, but this provides no direct information on the uncertainty sources that exist surrounding the technologies performance. This research provides a framework that links technology uncertainty, and the reduction of it, to the graduation from one TRL to the next. The framework has been implemented on a technology mature through NASA's Environmentally Responsible Aviation (ERA) program.

1 Introduction

The next generation of aircraft systems face an aggressive set of environmental and performance goals. Achieving these goals successfully will require the integration of new, advanced technologies that are currently under development. Furthermore, advanced system concepts are also being pursued that will require thorough testing and evaluation before they can be seriously considered.

Technology developers are required to make tough decisions regarding the investment of their resources. Therefore, it is important that these decisions are made in a risk-informed manner to ensure that the investments will pay dividends in the end in terms of high performing systems that meet the objectives laid forth. A series of questions must be answered, including '*What development activities are required to mature these technologies?*'.

Key development decisions must be made with uncertain information because maturity levels are low and performance predictions are not guaranteed. Therefore, it is important that engineers utilize a framework that clearly communicates a technology's, or system's, current readiness and its anticipated performance impact. With regard to readiness, there are many attributes that need to be assessed and tracked throughout the development process. The current state of the art for tracking technology readiness is through a qualitative metric, the technology readiness level (TRL). Over the past thirty years the TRL scale has provided the engineering community with a tool to assess and communicate technology readiness to those with a varying range of disciplinary knowledge of the entity in question.

Graduation from one TRL to the next is traditionally achieved through successful completion of an experimental plan. However, the question regarding establishing when experimentation is adequate to validate TRL graduation arises. Experiments are planned for varying reasons over the course of a technology or system development life cycle. It has been observed that the characteristics that define an experiment can be mapped to the attributes of the desired TRL level. Furthermore, it is thought that the reduction of uncertainty and improved ability to pinpoint performance as a result of experimentation provides an additional justification of TRL graduation.

While the linkage of uncertainty reduction to technology readiness may seem straightforward, it can be complicated and requires a transparent quantitative analysis framework. The amount of uncertainty that exists in a system-level performance metric is a function of the uncertainty of low-level metrics or inputs, such as those that represent technology impacts, as well as the relationship between the uncertain low-level inputs and the system-level metrics. Therefore, it is important that appropriate metrics are selected for performance progression assessments of technologies.

Based on all of this provided information, the objective of this research is to explore the relationship between the TRL readiness metric and uncertainty reduction. An attempt will be made to link the graduation of TRL levels to the reduction of performance uncertainty. Previously published work by the authors will be revisited and more discussion will be provided. The results are a formalized framework that provides decision makers with relevant information that provides them better situational awareness and creates a more risk-averse decision making environment. The research will concludes with a demonstration of the outlined framework.

2 Technology and System Readiness

The Technology Readiness Level (TRL) is the current figure of merit to analyze and communicate technology readiness. TRL was established in 1995 by Mankins and is formally described as a ``systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technologies".[1] The use of the TRL metric has expanded over the years and is now utilized by all major government agencies and industries in the US and several other countries.

The wide usage of TRL implies it is a well-established metric for readiness communication; however, there are still some identified areas where the metric can be enhanced. Previous work published by the authors provides an in depth summary of the TRL enhancement areas that have been acknowledged in the literature and a method that aims to overcome how the definition of TRL through ambiguous terms.[2,3] This method utilizes morphological analysis to decompose TRL into attributes. When defined and synthesized, these attributes of readiness create the overall TRL measure. The attributes include aspects of the test environment, the entity being tested, and the overall purpose of the TRL level.

The TRL morphological analysis provides technologists with a way to ensure the experiments they are planning are appropriate for the TRL they wish to achieve. This work provides a good starting place for the framework desired for this research, and it will be expanded to include a direct link to uncertainty sources addressed during technology development.

3 Quantitative Uncertainty Analysis

Uncertainty exists in all aspects of life, including the disciplines of science and engineering. The ability to quantify and track uncertainty can assist in system risk analysis and provide decision makers with valuable trade-off information that would otherwise be unavailable or unknown. Therefore, it is important to follow well-defined, mathematically-based procedures for the identification, assessment, and treatment of uncertainty sources.

There are many sources of uncertainty in system design and development, and there is a need for a sound taxonomy to categorize the types according to the fundamental essence of the sources and how they affect the system.[4] In the literature there are several different taxonomies used by different science and engineering disciplines.[5] It is observed that the terms epistemic uncertainty and aleatory uncertainty are very prevalent in the uncertainty community, and their definitions have generally been agreed upon.

Utilizing the existing taxonomies found in the literature as a spring board, an uncertainty taxonomy for technology development has been developed and was published by the authors in a

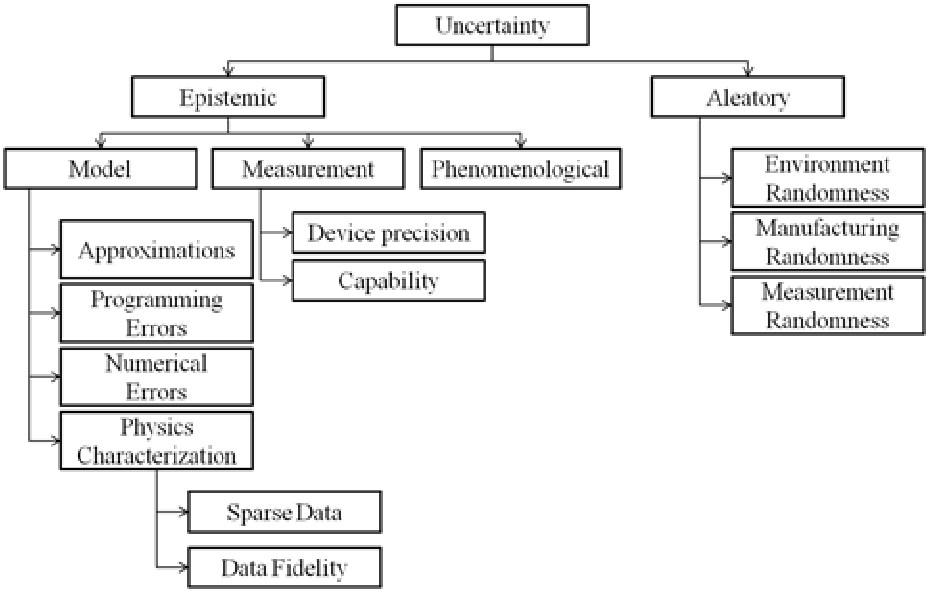

Figure 1: Technology Development Uncertainty Taxonomy

previous paper.[3] It is provided in Figure 1. The use of aleatory and epistemic has been deemed by many as desirable because it is a workable and effective uncertainty scheme.[4,6,7] Aleatory uncertainty can be defined as the inherent, or natural, variation of a measured quantity.[4,7–9] Epistemic uncertainty can be defined as uncertainty due to incomplete knowledge. .[4,7–9]

Based on this observation, the technology development uncertainty taxonomy has only two main categories of uncertainty, aleatory and epistemic. The concept of characterizing uncertainties as either reducible or irreducible will be important during the experimentation planning phase of technology development, which is one reason why the separation of uncertainty sources as either aleatory or epistemic was deemed desirable. In this context, aleatory uncertainty is considered irreducible and the definition of is consistent with the definition previously presented, which is the inherent or natural variation of a measured quantity.[4,7–9] Likewise, the definition utilized for epistemic uncertainty also follows the previously presented definition, which is uncertainty due to incomplete knowledge.[4,8,9] Epistemic uncertainty is considered reducible because it can be reduced and potentially eliminated with an increased state of knowledge.[7]

Sources of aleatory uncertainty cannot be reduced but they can be controlled. Therefore, engineers attempt to quantify the impact of aleatory uncertainty on a system or a risk analysis, but do not plan actions to reduce them. For this taxonomy, aleatory uncertainty is divided into three types: environment randomness, manufacturing randomness, and measurement randomness. *Environment randomness* is any factor in the operational or testing environment that is uncontrollable to the scientist or engineer. An example of this is the expected weather in an aircraft operating environment.

Manufacturing randomness is defined as any manufacturing factor that is out of the control of the design engineer, such as undetected manufacturing defects or slight variations in manufactured systems that have the same design. The last type of aleatory uncertainty, *measurement randomness*, is the inherent randomness that occurs when measuring a given quantity. Engineers can attempt to quantify measurement randomness by conducting repetitions or taking repeated measurements.

Epistemic uncertainty is divided into three main categories: model uncertainty, measurement uncertainty, and phenomenological uncertainty. *Model uncertainty* is defined as the uncertainty, or error, present in all mathematical models that attempt to represent a physical system. Model uncertainty is divided into approximations, programming errors, numerical errors, and physics characterization. The development of a mathematical model to represent complex phenomena requires assumptions and simplifications to be made. This includes simplifying assumptions concerning the anticipated operating environment of the modeled system and simplifying assumptions concerning the anticipated operating scenario.[6] These uncertainties are categorized under *approximations* and are epistemic sources of uncertainty because more fidelity could be built into the model if the resources were available.[10] An example of an uncertainty source that would be categorized as an *approximation* would be any uncertainty added into the analysis through the use of surrogate models.

The definition for *programming errors* is any error in the model that results from human error. *Numerical errors* refer to any mathematical approximations or limitations that affect the assessment. For example, rounding and discretization could both affect the output of an analysis. The final category of model uncertainty is *physics characterization*. This category is where the lack of understanding of the phenomena under investigation materializes. Selection of the appropriate type of mathematical model, such as linear versus exponential, and the selection of the parameters that define the chosen model are large contributors to the overall model form uncertainty. The ability to select the most appropriate model may be difficult due to the amount, or lack, of available data. Lack of appropriate data may mean there is only a limited number of point data available[11], or in the case of large system models, there is no existing data.[6]

The next main type of epistemic uncertainty, *measurement uncertainty*, is divided into device precision and measurement capability. *Device precision* refers specifically to the fidelity of the measurement device, i.e. the number of significant digits the device can capture. *Measurement capability* refers to the capabilities of the measurement devices utilized to capture the phenomena under investigation. Examples of such uncertainty sources are when the response of interest is not able to be directly measured due to an obstruction or obstacle. The final type of uncertainty included in the taxonomy is *phenomenological uncertainty*, and its definition follows the previously provided definition of ``unknown unknowns." It is important to include phenomenological uncertainty in this taxonomy because the development of new technologies deals extending the current state of the art.

After uncertainty sources are characterized through a sound taxonomy, they must be mathematically represented and then propagated if necessary. A method for mathematically representing technologies at the system level has been developed and is prevalent in the literature.[12] In this method, technologies are represented through non-dimensional technology factors, or k-factors, that act on intermediate metrics of an established modeling environment. The values of the k-factors represent the type and amount of impact a technology is anticipated to have on the metric of interest. Mathematical combination of the two, the k-factor and the metric, provides a new metric value that is then used to analyze the performance of the system. This k-factor method has been demonstrated to work on both deterministic and probabilistic performance assessments by the authors[2,3,13], and will be used throughout this research as well.

4 Proposed Experimentation Framework

The experimentation framework assembled for this research is a synthesis of the information provided by the TRL morphological analysis, the TRL definitions found in the literature, and the uncertainty taxonomy provided in Figure 1. Table 1 provides the details defined for each level in the TRL scale. It includes the experimental details provided by the morphological analysis, the experimental purpose as stated in the accepted definitions of the TRL scale, and the types of uncertainty that should/could be addressed through the experiments planned to achieve each level.

TRL 1- TRL 3 are the lowest states of maturity of a new technology or concept. This research focuses on TRL 4-6 maturity levels, but the low readiness levels can still be captured within the same framework. TRL 1 requires minimal experimental effort and its purpose is to formalize and document the new idea and observe the basic principles of the technology. The purpose of experiments designed to achieve TRL 2 is to help formulate the anticipated application system for the technology. The purpose of experimentation aimed at the TRL 3 maturity level is to demonstrate the proof-of-concept characteristics. Experiments conducted during these low maturity levels are simplified and conducted in a laboratory environment where it is expected that many simplifying assumptions have been made to isolate the technology concept. At this point no data, or not enough data, exists to numerically model the technology so quantitative uncertainty assessments are highly unlikely. However, the measurements can attempt to address some uncertainty sources. It is stated that the measurements will address physics characterization through sparse data and data fidelity. Additionally, it could capture phenomenological uncertainty because little is known about the concept and unexpected phenomena could be observed.

Achieving TRL 4 will require a validation of the performance in a laboratory environment. Validation implies that there will be an expected performance before the experimentation takes place, which can be a results of numerical simulations and analysis. Therefore, TRL 4 will involve both physical and non-physical evaluations. The fidelity of the laboratory environment can vary from a simplified environment with assumptions to more of a controlled environment. In this context the term controlled implies that realistic operating scenarios are being considered, but it is still within a laboratory environment. The uncertainty sources again mirror those of TRL 2 and TRL 3 because it is expected that higher fidelity data will be collected.

Experimentation planned to achieve TRL 5 will, potentially, for the first time involve a test article that is representative of more than just the technology in isolation. It will still be a sub-scale prototype that is not fully functional, but could include other components or subsystems that are deemed importance with regards to either their physical compatibility or functional compatibility.

The environment is similar to the laboratory environment from TRL 4, but should be more of a realistic yet controlled environment. The purpose of this experimentation is to validate the performance of the single technology in a relevant environment. Again, validation implies non-physical experimentation will be involved and numerical simulations will be required. The uncertainty reduction again will be achieved through the collection of more, higher fidelity data. The data will increase in fidelity because fewer assumptions will be made to the laboratory environment and more, advanced measurement devices can be used. Phenomenological uncertainty is relevant because the test article now includes other pieces of the system and unexpected interactions could be observed. Lastly, a new uncertainty type, measurement capability, can be addressed. Up until this point required inputs, or interactions, with components has had to be 100% emulated, if included at all. Now, since more parts will be included in the experiments fewer emulations will be required.

Achieving TRL 6 requires the successful demonstration of an integrated system or sub-system prototype. The environment should be a relevant environment, but is still a controlled, laboratory environment. While validation is no explicitly stated, numerical simulations are still expected at this phase of maturity because performance data representative of a more complete system will become available for model development, calibration, and validation. Quantitative uncertainty assessments that system level should be possible, and quantifying the reduction of uncertainty from each experiment performed can be accomplished.

Table 1: Integrated uncertainty/experimentation TRL guidelines

TRL	Experiment Details	Experiment Purpose	Uncertainty Sources
1	• Simplified, lab environment with many assumptions • Sub-scale, non-functional prototype • Single technology/entity	Observe and report basic principles of the technology/concept	• Physics characterization o Sparse data • Phenomenological
2	• Simplified, lab environment with many assumptions • Sub-scale, non-functional prototype • Single technology/entity	Formulate the application for the technology/ concept	• Physics characterization o Sparse data o Data fidelity • Phenomenological • Measurement o Device precision
3	• Simplified, lab environment with some assumptions • Sub-scale, non-functional prototype • Non-physical simulations • Single technology/entity	Demonstrate through analytical and experimental means the critical or characteristics proof-of-concept	• Physics characterization o Sparse data o Data fidelity • Phenomenological • Measurement o Device precision
4	• Simplified, lab environment with some assumptions <u>OR</u> a controlled lab environment • Sub-scale, non-functional prototype • Non-physical simulations • Single technology/entity	Validate the performance of the singular technology/ concept in a laboratory environment	• Physics characterization o Sparse data o Data fidelity • Phenomenological • Measurement o Device precision
5	• Controlled, relevant lab environment • Sub-scale, semi-functional prototype • Non-physical simulations • Single technology/entity <u>OR</u> technology integrated with other functionally/physically important components/ sub-systems	Validate the performance of the singular technology/ concept in a relevant environment	• Physics characterization o Sparse data o Data fidelity • Phenomenological • Measurement o Device precision o Capability
6	• Controlled, relevant lab environment • Sub-scale, semi-functional prototype • Non-physical simulations • Technology integrated with other functionally/physically important sub-systems	Demonstrate an integrated system or sub-system prototype in a relevant environment	• Physics characterization o Sparse data o Data fidelity • Phenomenological • Measurement o Device precision o Capability
7	• Controlled, relevant lab environment <u>OR</u> operational environment • Sub-scale <u>OR</u> full scale, functional prototype • Non-physical simulations • Technology integrated with all functionally/physically important sub-systems <u>OR</u> entire integrated system	Demonstrate integrated system in the planned operational environment	• Physics characterization o Sparse data o Data fidelity • Phenomenological • Measurement o Device precision o Capability
8	• Operational environment • Full-scale, actual hardware • Non-physical simulations • Entire integrated system	Qualify/Certify the performance of the completed system in the operational environment	• Physics characterization o Sparse data o Data fidelity
9	• Operational environment • Full-scale, actual hardware • Non-physical simulations • Entire integrated system	Successfully prove/verify the performance of the actual system in the operational environment	• Physics characterization o Data fidelity

The uncertainty sources that will be addressed are physics characterization due to the increase in data and the increase in fidelity of the data.

The data fidelity increases because the environment and test article increase in fidelity. Phenomenological uncertainty is again a possibility because more components are integrated into the test article. Likewise, measurement capability uncertainty can also be reduced.

It is likely that TRL 7 will still involve prototype test articles, but they will be closer to full-scale, if not 100% full-scale. The test article will be representative of the technology plus all functionally and physically important subsystems and components, or could potentially be representative of the entire integrated system. The purpose of the experiments are to demonstrate the performance of the system in the planned operational environment. For some systems, testing in the operational environment is not trivial and may not be possible. An example would be a spacecraft meant to operate on the lunar surface. However, if a laboratory environment must be utilized, it should be as realistic as possible. The uncertainty sources addressed during these experiments are the same as in TRL 6, and the data will be used to quantitatively show how the uncertainty continues to be reduced.

The experimentation planned to achieve TRL 8 will focus on certifying the performance of the entire system in the operational environment. The environment will be the intended operational environment and the test article will be a fully functional, full-scale integrated system. The experiments will involve pre-determined certification points that will be used to assess the performance and safety of the system. The data collected will be of the highest fidelity possible, and can be used to validate numerical models. It is anticipated that the only uncertainty sources addressed are the sparse data and data fidelity. Phenomenological uncertainty and measurement capability are no longer anticipated because TRL 7 involved a fully integrated system and the connections and interactions have already been observed. Furthermore, it is anticipated that he measurement devices utilized in TRL 7 will be the best available and similar to those utilized in TRL 8.

Achieving TRL 9 requires successfully completing an intended mission of the system. TRL 9 differs from TRL 8 because TRL 8 only involved very specific certification points, and not a complete mission. Upon the successful achievement of TRL 8 the uncertainty should be extremely low, if not non-existent. This should be apparent though numerical simulation and the existing experimental data. However, if any uncertainty remains it would be due to data fidelity issues that arise due to mission test points not yet tested.

It is important to note that not all systems are able to achieve TRL 8 before TRL 9 is attempted. Referencing a lunar surface system, the system will not be able to operate certification tests on the lunar surface and then be re-launched for an intended mission due to the high costs. Therefore, previous lab-based experiments and the numerical simulations the results of these experiments enable must be utilized to show that the uncertainty surrounding the performance, and the inherent risk, has decreased to a level that is deemed acceptable and the system can be confidently launched.

5 Experimental Apparatus

A demonstration of the framework described in Section 4 was conducted on a use case motivated by the next generation of commercial aircraft systems. As previously mentioned, aggressive environmental goals have been laid forth and government agencies and companies are currently developing technologies and system concepts aimed at bridging the performance gap. Table 2 provides an enumeration of the different sets of goals that entities are working towards. NASA established the Environmentally Responsible Aviation (ERA) program to mature technologies and concepts that fall within the N+2 generation. The authors have worked closely with the ERA program and have utilized it as the motivating case study for this demonstration.

The experiment design framework was demonstrated on a structural technology currently under development by The Boeing Company and NASA. The technology is called Pultruded Rod Stitched Efficient Unitized Structure, or PRSEUS.[14] PRSEUS is being developed specifically for the centerbody, or fueslage-like area, of the hybrid wing body (HWB) vehicle concept. It aims to address both structural and manufacturing challenges that face the HWB design.

Table 2 NASA Subsonic Transport System Level Metrics for all Technology Generations

Technology Benefits*	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Fuel Burn*** (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

**ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

*** CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used

The HWB concept has the potential to provide a lighter aircraft with increased performance and a smaller noise footprint. However, the configuration faces a challenge in creating a non-circular pressure cabin that is lightweight as well as economical to produce. Additionally, the HWB concept faces a unique bi-axial loading pattern that occurs during maneuver loads. Therefore, it requires the design of an improved fuselage panel that is bi-directionally stiffened to ensure the wing bending loads are handled by the frame and the fuselage bending loads are handled by the stringers.

Current state-of-the-art materials cannot overcome these challenges, so a new composite material was required. This led to the development of PRSEUS. PRSEUS enables a one piece panel design that has seamless transitions and damage-arrested interfaces. It provides unprecedented levels of fiber tailoring and the potential for structural optimization.

As mentioned, PRSEUS is being developed by Boeing with assistance from NASA. It was one of eight technologies selected for further development during Phase 2 of the NASA ERA program. A series of experiments were performed and have been well-defined and published. The PRSEUS test plan is shown in Figure 2.

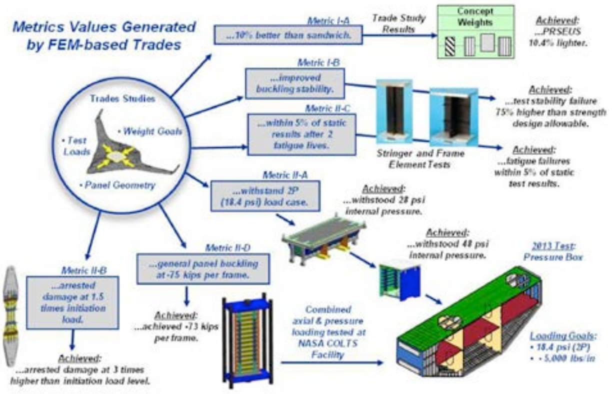

Figure 2: PRSEUS Experimental Plan

The experimental plan for PRSEUS provides the amount of detail needed to implement the framework, but a means for quantitative uncertainty assessments is also required. An integrated aircraft modeling and simulation environment known as the Environmental Design Space (EDS) was available and utilized for this research. EDS is capable of predicting the fuel burn, NO_x emissions, and noise metrics in a single environment with an automated link to provide necessary data for a fleet level assessment. The majority of EDS analysis components are NASA developed programs which have been integrated using the object oriented software, Numerical Propulsion Simulation System (NPSS).[15,16] EDS is capable of modeling the thermodynamic performance (NPSS) of any engine cycle coupled with a parametric component map generation tool (and with a 1-D aeromechanical design/analysis for flowpath and weight estimation purposes. The propulsion simulation module is coupled with the mission analysis module in an iterative fashion to ensure that all coupling variables are internally consistent and have converged. EDS ensures this convergence and consistency in order to provide more accurate mission fuel burn results and more accurate data to the noise prediction module to assess acoustic impacts, including the generation of engine state tables from NPSS and the resulting aircraft noise flight trajectories for the sized vehicle. This data is used within ANOPP to generate the three certification noise values for sideline, cutback and approach.

EDS coupled with a well-structured technology assessment approach utilizing deterministic and probabilistic methods enables accurate tradeoffs between performance, noise, and emissions for advanced concepts and emerging technologies. For this research, a 300 passenger size HWB vehicle model was utilized for the quantitative, probabilistic performance assessments. Furthermore, appropriate technology k-factors were identified to represent the impacts of the PRSEUS technology at the vehicle level and uncertainty distributions were assumed through background research.

6 Framework Demonstration

To begin the demonstration, details of the described PRSEUS experimentation was studied to establish the progression of experiment fidelity as TRL is expected to increase. Table 3 provides a summary of the experiment details, experiment purposes, and the TRL they are addressing. For the test article level, it begins with coupon testing and progresses to a multi-bay box. However, the MBB is not the final test article level for PRSEUS; in the future, experimentation will continue until a full-scale HWB with a PRSEUS centerbody is tested. In the context of PRSEUS, the fidelity of the test environment can be represented by the type of loading scenario applied to the model. The loading scenarios progressed from a single load type in isolation to the realistic load scenario planned for the MBB test. The only option missing would be the actual flight loads from a flight test.

The experiment progression described in Table 3 for the graduation from TRL 3 to TRL 6 appears to follow the structure presented in Table 1 for this framework. The fidelity of the test environment and the fidelity of the test article increase from level to level. Furthermore, the scale of the test articles and the number of integrates components in each test article increases over time.

What is not represented in Table 3 is the uncertainty reduction observed after each experiment set is completed. Therefore, quantitative uncertainty assessments were performed utilizing the EDS environment previously discussed. Four different technology factors were identified to adequately represent the impacts of the technology. The factors are one fuselage weight factor and three wing weight factors. They operate on the fuselage weight and wing weight metrics that are calculated within the EDS environment.

Distributions were assumed for each phase of the development. While these distributions are not meant to be the *actual* performance assessments observed by the ERA program, they are representative of realistic values and ranges. For the TRL 3 assessment, uniform distributions were assumed for the four k-factors. At this point of development a uniform distribution is likely because technologists will have an idea of an appropriate impact range, but may not know enough information to specify a most expected value within that range. For each scenario simulated after TRL 3 (TRL 4-6), truncated normal distributions were utilized. The distribution ranges were set to fall within the original range set for TRL 3, and different values for the mean and standard deviations were assumed. The uncertainty was propagated to the system level metric of interest, fuel burn reduction, through a surrogate model that was fit around the EDS output metric for the 300 passenger HWB concept.

Figure 3 displays a set of results that illustrates a successful graduation from TRL 3 to TRL 6. The figure depicts the results of the uncertainty propagation assessment from the weight factors to fuel burn reduction. At TRL 3, the uncertainty is at its highest because this is when the impacts are represented with uniform distributions. In the scenario depicted in Figure 3 the standard deviation reduces after each experiment set and the overall uncertainty reduction is 63.7%. This reduction in uncertainty, paired with the assessment of the experiments provided in Table 3, would be indicative of successful TRL graduation over time.

It is important to note that the only uncertainty tracked during this assessment was the uncertainty surrounding the four technology impacts and the resulting uncertainty surrounding fuel burn reduction. In reality, there would be other key metrics that should be tracked for their uncertainty reduction. A sensitivity analysis would provide all vehicle metrics that the technology effects based on the technology impact factors it is mapped to.

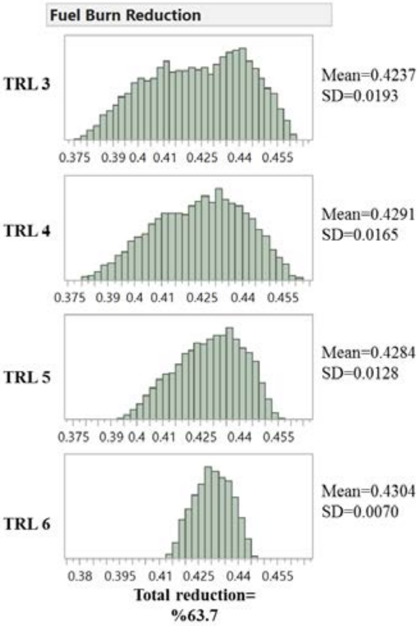

Figure 3: Simulated Best Case Scenario PRSEUS Uncertainty Reduction

In addition to the successful graduation scenario, two others were simulated as well to illustrate what an unsuccessful TRL graduation would look like. These two scenarios are illustrated in Figure 4. The top set of figures in Figure 4 provide the TRL 4 uncertainty depiction from the successful scenario used in Figure 3. The bottom two, labeled TRL 4-a and TRL 4-b show two unsuccessful graduation scenarios for going from TRL 4 to TRL 5. The TRL 4-a scenario is representative of a situation where the experiments performed to achieve TRL 5 provide minimal uncertainty reduction. The only uncertainty reduction observed is in the first and third wing weight reduction factors. The small reductions in these two variables, and the zero reduction in the other two factors, provides minimal uncertainty reduction in fuel burn reduction. The TRL 4-b scenario is representative of a phenomenological uncertainty source being discovered during experimentation. The uncertainty in the technology factors increases from 4 to 4-b, which means the fuel burn reduction uncertainty also increases. This is an example where the uncertainty may not necessarily decrease through experimentation.

While the uncertainty results provided in Figure 4 are just assumed scenarios, it is not impossible that they could arise even when the experimentation is conducted according to plan. These scenarios illustrate the need to link proper experiment planning and quantitative uncertainty analysis to TRL graduation assessments. If experiments are planned without considering the types of uncertainty sources they should be addressing and no analysis is conducted after the experiments are performed to ensure the uncertainty has reduced an acceptable amount and not stagnated or increased, then TRL graduation should not be achieved.

7 Conclusions

The research presented in this paper was motivated by the desire to ensure that experiments planned to mature developing technologies will provide successful TRL graduation the uncertainty surrounding its performance will shrink over time. Linking technology uncertainty to technology readiness has been acknowledged in the literature, but a framework that directly links the two did not exist. The framework formulated in this research provides a level-by-level description of each TRL with respect to the experimentation

Table 3: PRSEUS Experimentation Details

TRL	Experiment Details	Experiment Purpose
3	• Single-stringer panel • Tested under compression loading conditions	The purpose of the experiment was to characterize the buckling stability for the stringer components and assess the damage arrestment of the stitching after the loading is applied.
	• Single-frame panel • Tested under compression loading conditions	The purpose of the experiment was to characterize the buckling stability for the frame components and assess the damage arrestment of the stitching after the loading is applied.
	• Single-frame panel • Tested through fatigue cycling	The purpose of the experiment was to characterize the fatigue performance and assess the damage arrestment of the stitching under fatigue.
4	• A panel • Tested for chordwise tension	The purpose of the experiment was to demonstrate damage-arrest design advantages and validated the HWB minimum-gauge fuselage geometry.
	• Panel • Tested for spanwise compression • Preliminary FEM analysis was conducted to determine the critical compressive load	The purpose of the experiment was to assess the buckling stability of the PRSEUS integral frame feature.
5	• Pressure box • Tested through multiple loading conditions	The purpose of the experiment was to confirm the PRSEUS panels will contain the design load internal pressure and isolate the secondary bending effects. The experiment established the overall structural viability of the PRSEUS design.
	• A pressure cube	The purpose of the experiment was to demonstrate the feasibility of containing pressure with all PRSEUS panels, verifying the panels would hold the load cases, and development of appropriate fittings for PRSEUS joints.
6	• A large scale PRSEUS model: a 30 foot long multi-bay box (MBB) that consists of eleven total PRSEUS panels • Pre-test FEM analysis was performed to predict the deflections, stresses, strains, and failures.	The purpose of the experiment was to demonstrate PRSEUS' performance under combined loading conditions of a realistic operational environment.

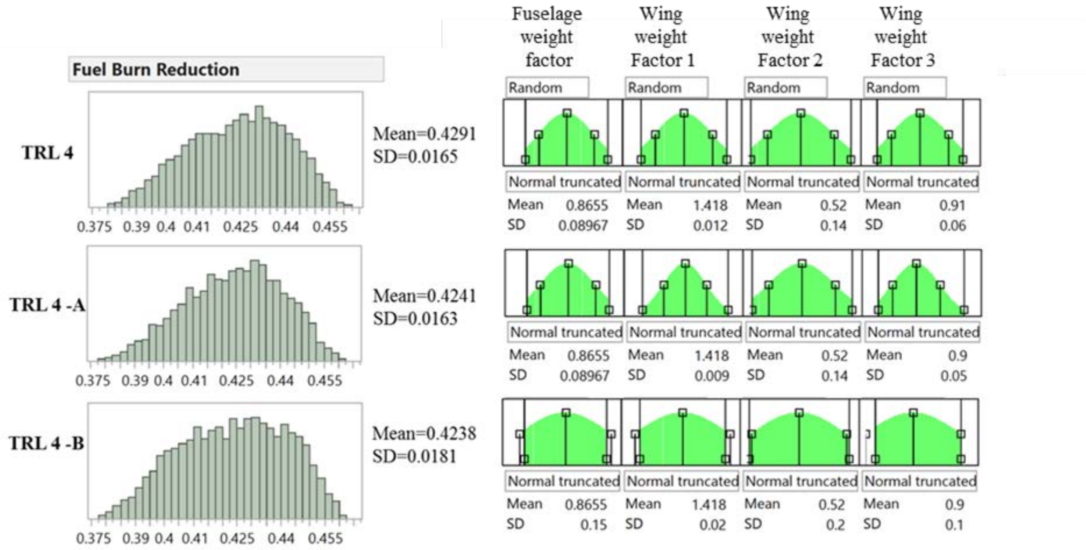

Figure 4: Simulation of Unsuccessful TRL Graduation

purpose, experiment standards, and the type of uncertainty that should be reduced through the resulting data that is generated. This framework can help technologists with both the planning of future experiments, by planning out the type of measurements, and with ensuring TRL graduation has indeed been achieved through the performed experiments. The framework was demonstrated by applying it on the PRSEUS technology from the ERA program. Details about each experiment in the PRSEUS experimental plan were extracted from the publicly available information in the literature. This information paired with the performance assessments conducted through the EDS environment provided example depictions of how much knowledge is, or isn't, gained through the outlined experiments. The scenarios presented in Figure 4 illustrate why it is important to link the uncertainty reduction with TRL graduation. It demonstrates that there could be situations where well-planned experiments with the 'right' characteristics may not provide the desired uncertainty reduction, so it is important to ensure the uncertainty assessments are performed after each set of data is collected.

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Contact Author Email Address

mailto:kgatian3@gatech.edu

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