

Total Technology Readiness Level: Accelerating Technology Readiness for Aircraft Design

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Accelerating breakthrough technologies and architectures faster and more seamlessly into aircraft design and production is at the next frontier of aircraft design optimization. New technologies bump into many implementation challenges hindering or halting introduction, and new breakthrough technologies can often be considered large business risk. New aircraft or vehicle design looks to a Technology Readiness Level 6 signal that new technologies are ready to be considered for application. Industry experience has been that technology readiness, TRL 6, while necessary, is not fully sufficient to assess potential for application onto a platform. Over the last three decades, this shortcoming has led to the development of Integration Readiness Level (IRL) and Manufacturing Readiness Level (MRL). Additionally, in 2006, System Readiness Level (SRL) methods were proposed to fill the gap between TRL and IRL. In this study, three joint research technology use cases - riblets, bug phobic coatings and active flow control provide the case for the Total Technology Readiness Level methodology proposed herein to integrate the traditional Readiness Levels and other key flexible factors called *-ilities* such as Affordability and Certifiability, that when identified in early development, can become game changers for technology transition. Collaboration partnership between the technologist and vehicle designer during early development is essential to accelerate successful technology readiness and transition. Learning to “design under constraint” in a more agile manner by jointly identifying specific real-world hurdles in a given application enables technologists and designers to utilize all levers to increase the transition rate of technologies to implementation on products in the market.

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I. Introduction

NASA pioneered Technology Readiness Levels in 1974 with seven levels which were not formally defined until 1989. Subsequently, the U.S. Department of Defense (DOD) put TRL's into standard practice and included Technology Readiness Assessments (TRA) in their acquisition process [1]. Enhancements and modifications have refined the criteria over time to enable a common language for technology development from TRL 1-9 [2-3]. Variants of the NASA TRL scale are now also used by the U.S. Department of Energy (DOE), Federal Aviation Administration (FAA) and other global research and industry organizations.

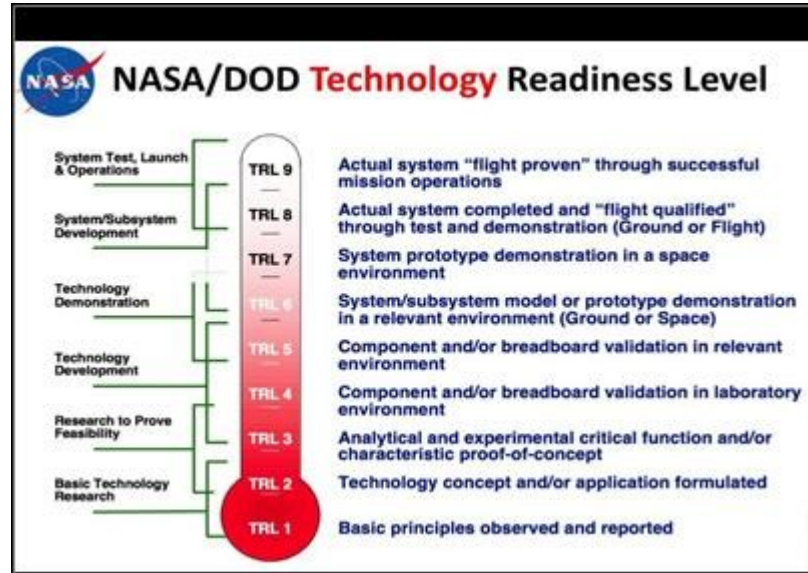


Fig. 1 NASA/DOD Technology Readiness Level

In the 1990s, there was recognition of a gap to implementation in Technology Readiness Assessments for space and DOD applications. The DOD augmented the TRL tool suite with Integration Readiness Level (IRL) and Manufacturing Readiness Level (MRL) of which a number of versions exist in the industry [4].

Manufacturing Readiness Level (MRL)		
Phase	MRL	State of Development
Phase 3: Production Implementation	9	Full production process qualified for full range of parts and full metrics achieved
	8	Full production process qualified for full range of parts
	7	Capability and rate confirmed
Phase 2: Pre production	6	Process optimised for production rate on production equipment
	5	Basic capability demonstrated
Phase 1: Technology assessment and proving	4	Production validated in lab environment
	3	Experimental proof of concept completed
	2	Application and validity of concept validated or demonstrated
	1	Concept proposed with scientific validation

Fig. 2 Manufacturing Readiness Level (MRL)

In 2006, the Systems Development and Maturity Laboratory at Stevens Institute of Technology identified the need for integration of technology into a complex system with the ability to understand the overall maturity of a whole system. They designed and defined System Readiness Level (SRL) to provide a more holistic integration between TRL and IRL.

Due to long lead times of novel, new breakthrough technologies, the most successful seamless technology transitions rely on consideration of TRL, MRL, IRL, and SRL in both technology development and vehicle design at appropriate times in the technology maturation and product implementation cycle with the right timing. Research technologists have a conundrum based on two primary related challenges: (1) they must initiate technology research prior to a specific known application without the knowledge of specific requirements for that platform and (2) as product aircraft development design cycles shorten, only those technologies near TRL 6 are generally considered in trade studies for the specific product application, often leaving the researcher insufficient time to meet all the additional design requirements that are by today's process, levied after TRL 6 when the application target is known [5].

	IRL	Definition
Pragmatic	9	Integration is Mission Proven through successful mission operations.
	8	Actual integration completed and Mission Qualified through 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 the relationship.

Fig. 3 Integration Readiness Level (IRL)

II. Technology Research Use Case Studies

Three technology research use cases will be presented. The case studies include NASA's research on riblets, and joint NASA/Boeing ecoDemonstrator Program bug phobic coatings and active flow control technology flight tests in 2015. Each TRL use case provides learning for how we can enhance the TRL process.

The first use case is riblets for aircraft which the industry has pursued since the early 1980s. Riblets are applied to the exterior of an airplane skin to improve the surface aerodynamics, reducing the turbulent skin friction drag resulting in significant fuel efficiency gains. Still an elusive application, riblets were first flight tested by NASA in 1986 on a Learjet. Utilizing a lightweight plastic film application demonstrated a drag reduction capability of 8%. The Technology Readiness Assessment after flight testing indicated that the riblets were TRL 6 (flown in a relevant flight environment) and able to proceed to next steps towards application ready. While the flight demonstration proved technology readiness and significant aerodynamic benefit to be gained by adhering riblet tapes to the aircraft skin, the technology was not practically ready for transition due to many challenges in the operational environment that stalled its transition to product application. Missing from the TRL assessment were significant in-service operational environment "*-ilities*" such as Maintainability, and Reliability, including considerations such as Wearability [6].

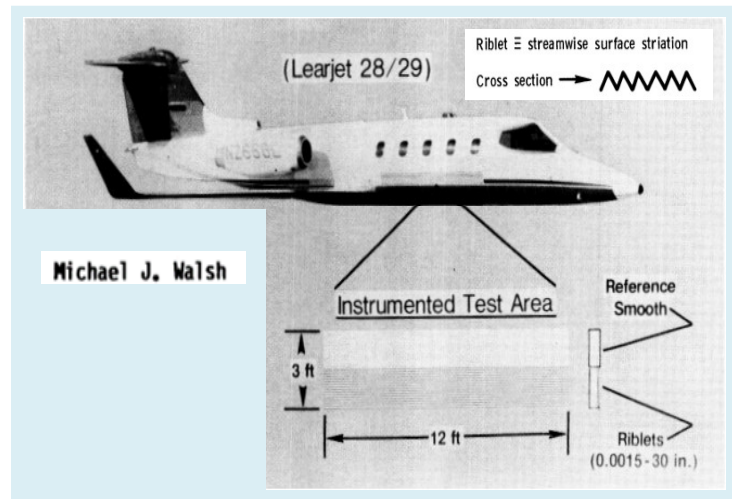


Fig. 4 1986 NASA Riblets for Aircraft

Riblet technology development and demonstration continues today, such as JAXA's paint riblet testing in 2018 where performance in relevant flight testing was verified as it was originally by Walsh in the 1980s and in May of this year, Lufthansa Technik and BASF announced they will equip Lufthansa Cargo's entire Boeing 777 Freighter fleet with eco-friendly sharkskin technology in 2022. But work remains to ascertain practicalities of the challenging in-service operational environment with regard to Maintainability and Reliability. Until such aspects can be addressed, operators will not accept the technology [7 -8].



2018 JAXA Riblet Sheet

**2021 Lufthansa / BASF
Sharkskin Riblets**

Fig. 5 2018 JAXA Flight Test and 2021 Lufthansa / BASF on Boeing 777F

The second use case is bug phobic coating with the latest technologies flown on the right wing of the 2015 ecoDemonstrator, a 757. Bug phobic coating holds the promise of cleaner surfaces for aerodynamic efficiency throughout operations and is also a potential path-maker for future technologies such as natural laminar flow (which cannot withstand bug contamination). Multiple coating samples were applied across the wing leading edge to provide a side-by-side test of the bug phobic coated versus uncoated surfaces. Testing was conducted in Shreveport, Louisiana, the "bug capital" of the U.S. Testing validated the technology performance in many aspects, although it became apparent in the course of development that there were many other issues not yet considered such as installation and maintenance challenges in-service, Maintainability, Operability, and how the coatings impacted the appearance and color of the wing surface that would be in contrast to an airlines expected livery, bringing to the forefront additional *-ilities* that include Stakeholder Acceptability [9-10].

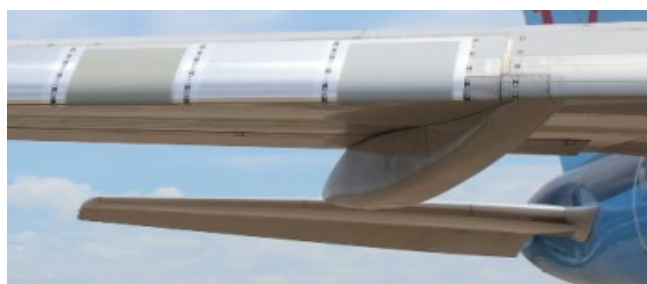


Fig. 6 NASA Bug Phobic Test on Boeing 2015 ecoDemonstrator

The third use case is an application of Active Flow Control technology flown on the 2015 ecoDemonstrator, a Boeing 757 jet with a modified tail. In order to provide the air supply for the passive momentum sweeping jet technology, modifications for flight test included an externally mounted heat exchanger.

The test data successfully proved that this technology provided the flow momentum advantage to delay flow separation that could, in future aircraft design application, enable a smaller tail size, saving significant weight.

The technology also offers the opportunity for other applications - potentially near engines where air supply would be more readily available. In the TRL 6 assessment, NASA and Boeing agreed that the technology achieved TRL 6 Technology Ready. But there was recognition that there would be significant integration and manufacturing challenges that had not been addressed in the technology development. Additionally, other *-ilities*, such as Certifiability for flight critical systems warranted much more consideration prior to including in an aircraft design trade study. Hence the research technologist's conundrum ignited a deeper discussion on TRL improvements that could tie more closely with the vehicle design process to increase the yield on technology research investments [11].

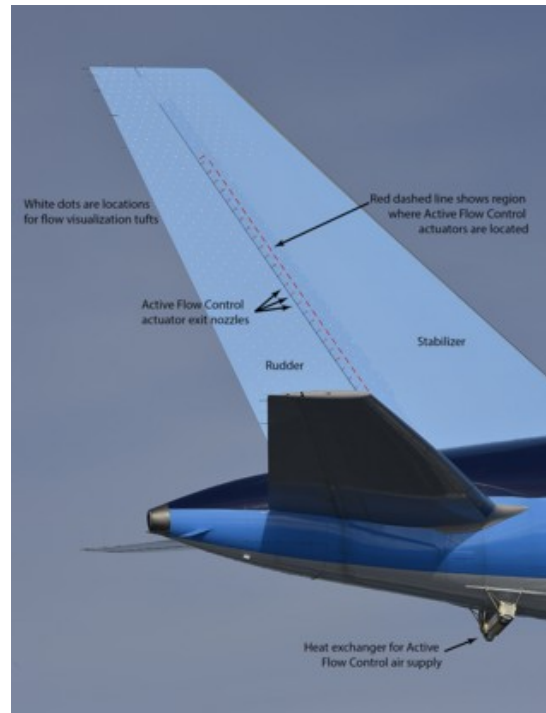


Fig. 7 Boeing/NASA Active Flow Control Tail, 2015 ecoDemonstrator Flight Test

These use cases show the need for advanced research of *-ilities* that could provide additional design requirements or testing before passing the TRL 6 gate and considered for future aircraft integration trade studies before incorporation into a production aircraft. As aircraft product development design cycles shorten, only those technologies near TRL 6 are considered for trade study, often leaving the researcher insufficient time to meet all the additional design requirements that are by today's process, levied after TRL 6 when an application target is known.

III. Analysis

A. Current Readiness Level Analysis and Gaps

Standard Technology Readiness matures progressively through phases of Discovery, Feasibility, Practicality, Applicability, Production Ready and Operation Ready. The technology readiness process helps to inform the researcher on what criteria must be satisfied to move towards technology readiness maturity and ultimately application readiness.

Prior to TRL 6, technologists in the Discovery stage consider “What’s Possible?” It is important in the Discovery stage that the creative space stay expansive and not be overly constrained so that breakthroughs in thinking can be enabled. In the Feasibility stage, the technologist considers, “Can I do it?” It is when the technology approaches TRL 6 that the question, “Can I reasonably do it?” becomes the center of any number of applications which each bring additional criteria. These application specific criteria are often not sufficiently available, nor included in the march up to TRL 6. As a result, many technologies stall and are not considered for continued development or require additional development late in the TRL process and risk falling into the “Valley of Unused Technologies.” Thus, there is broad industry agreement that TRL 6 is essential, but not fully sufficient, to graduate a technology to application. It does not help that research, development, and demonstration costs can increase substantially because of late identification of additional criteria when approaching TRL 6. This diminishes the yield or rate of technologies transition which is a common metric of government, university and industry success.

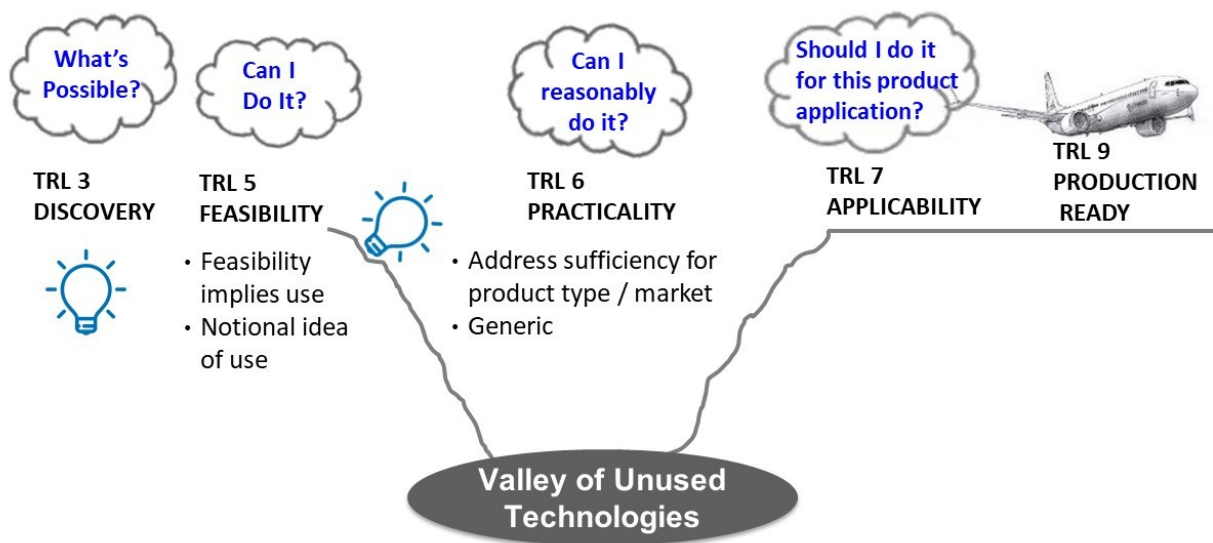
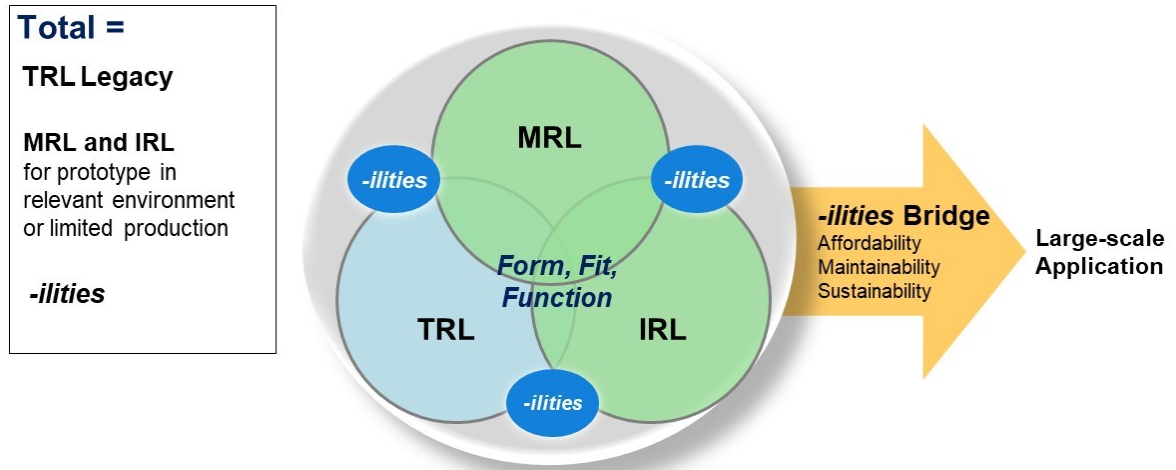


Fig. 8 TRL is Essential, But Not Sufficient

Total Technology Readiness Level (TTRL) builds on the established Readiness Levels (RL) which have evolved over time in an attempt to bridge the gap from Discovery to Feasibility to Practicality to Applicability. TRLs were initially developed to understand new technology and its improved performance or functionality. NASA’s space agency added MRL and IRL in R&D consideration of planned development on prototypes in relevant environments or limited production. IRL and SRL were added to challenge the technologist to also consider technology integration into a system or whole product, so that form, fit and function were better addressed at the intersection of TRL and IRL, just as Producability and scale live at the intersection of TRL and MRL. Today, technologists or vehicle designers may impose the Manufacturing, Integration, or System Readiness levels (MRL, IRL, or SRL) to augment the Technology Readiness Assessment.



F

ig. 9 Total Technology Readiness Level

Gaps remain when considering other real-world challenges. Several *-ilities* gaps were discovered in the technology use cases of this study; Integrateability, Reliability, Sustainability, Maintainability, Operability, Manufacturability, Certifiability and Stakeholder Acceptability. In each case, these *-ilities* required a pause at TRL 6 to work through practicalities prior to realistic consideration for product vehicle integration and are important earlier in the technology development process. Total Technology Readiness serves as a holistic model that can encompass all elements to more sufficiently bridge a new technology into an application. What is critical, is the partnership between technology developers and vehicle designers to discern the comprehensive set of readiness level criteria and *-ilities* constraints that should be considered for a particular target application. Appropriate early-*-ilities* work would ensure a balanced approach to promote creative technology or design configuration solutions that are timely, and ensure focus on research investments on these aspects necessary to support targeted product market opportunities.

B. New Technology and Aircraft Design Technology Methodology

Early TRL development requires an open expanse to spur novel creation. An approach is needed that balances both the ability to promote Discovery, and simultaneously, provide a rigorous enough framework that enables a faster and more successful technology maturation into implementation. An adaptable methodology to the technology development and potential applications are essential to create a healthy and productive technology research environment.

A Total Technology Readiness methodology is proposed for tying together the TRL, MRL, IRL and *-ilities* into a more robust toolset for technologist and vehicle designers. The TTRL process can accelerate technology readiness and enable an earlier pragmatic understanding of Feasibility, Practicality and Applicability. When the technologist and vehicle designer are together responsible for identifying significant *-ilities* for a particular application, the transition success rate is higher, risks are reduced and costs decreased.

-ilities provide a 3 dimensionality for Total Technology Readiness complementary to the readiness level maturity across the phases of Discovery, Feasibility, Practicality, Applicability and Production that can help technologies navigate more successfully to application, as seen in Fig. 10. Co-creation of *-ilities* definitions by the technologist and the vehicle designer is important to provide a common TTRL language and foundation for tighter checkpoint coordination to reveal early potential challenges during development that must be considered on the critical path of technology and vehicle development.

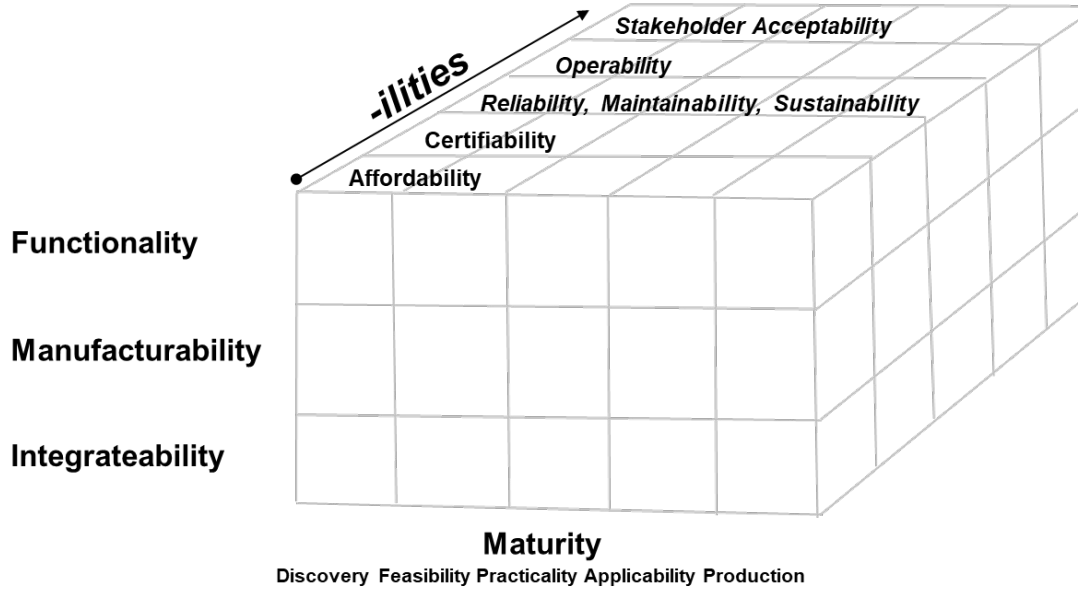


Fig. 10 -ilities create a 3-Dimensionality of Readiness

NASA and Boeing worked together post 2015 Active Flow Control flight testing to define other specific *-ilities* that are critical in commercial aircraft design readiness, including Affordability, Certifiability, Stakeholder Acceptability, and Sustainability. Figure 11 shows examples of definitions developed from the use cases in this study. Multiple perspectives were necessary to reach definitions that enable solution approaches from either the technology or vehicle design side. For instance, MRL addresses whether a technology can be manufactured, but it does not fully address the ability of technologies to be feathered into an ongoing production system. In the case of technologies targeted for integration into an airplane like the 737 with high production rates of up to 60 airplanes per month in 2019, *-ilities* definitions were jointly agreed to be Manufacturability Producibility of the vehicle effectively, at high quality and rate. Another timely example is that of Sustainability. As the industry grows, lifecycle considerations are included in decisions so that people, planet and profit are counterbalanced for a path to sustainable aviation.

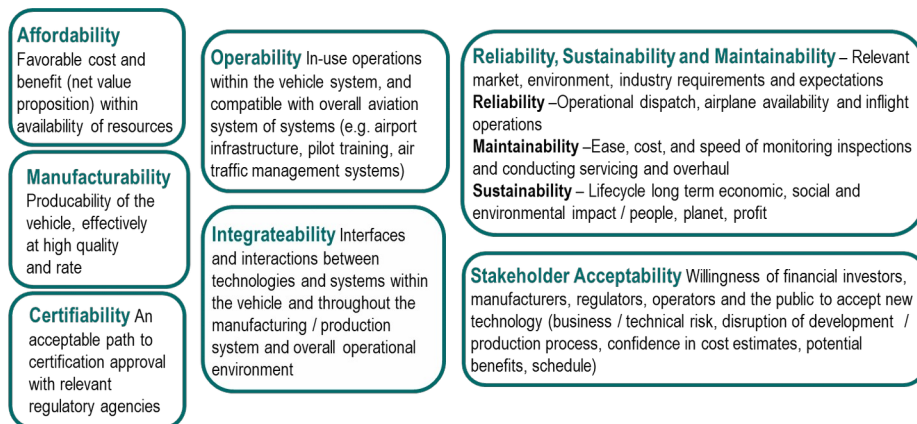


Fig. 11 Examples of Technologies / Aircraft Designer Co-developed -ilities Definitions

-ilities consideration adds another layer early in the technology development process that if not considered may become a “show stopper” in a later business decision on whether a technology can transition or not. Solutions could take the shape of faster plug and play or airplane design solutions such as an integrated feature into an existing component that meet the quality and rate bar. This example also highlights another important point related to appropriate relevant environments that must be considered to transition a technology. Often when advancing

technology the vast majority of focus is on flight – quite reasonable and necessary. But in a situation requiring ongoing and continuously improving production, the factory floor and production system environment as a whole may require equal consideration to the operational/flight environment when considering technology readiness to transition. For example, a technology that reduces weight and saves fuel but limits production rates substantially may not be practical from a business standpoint and would point to the need for solutions to overcome the rate barrier.

The second step in considering *-ilities* development is identifying critical questions to be asked in each part of the TTRL process that enable early development for additional considerations that need to be taken into account for successful technology transition to application. For instance, Fig. 12 formulates the questions that technologists and vehicle designers agree should be addressed early and to what degree for particular technologies. This avoids the challenge often found in the field where detailed analysis is performed too early, before enough is known about the technology (discarding a technology prematurely), and the opposite issue where the challenge is not recognized and addressed soon enough (delays implementation unnecessarily). The early TRL 1-6 process benefits from these *-ilities* lenses through which to consider the technology, whereas once a technology proceeds to Practicality and Applicability, the vehicle design platform takes over and addresses these *-ilities* as part of the vehicle integration, often at the risk of cost overruns and schedule delays.

Again, note that *-ilities* readiness provides the development vector and is not overly prescriptive, but provides enough in terms of guiderails that the technologist and vehicle designer can co-develop solutions that may be embedded either in the approach to the technology and/or the approach to the vehicle design. With the visibility of these *-ilities*, there is then, language and agreement on strategic development items that must be kept in mind on the march to TRL 6 and real Practicality so the technology is better prepared for next steps towards graduation across the bridge to application. Furthermore, the flexible nature of *-ilities* enables tailoring and adaptation to different potential end applications that may guide the technologist (for example, a weight saving technology may have a different value proposition in a rotorcraft, than a transport category aircraft, but also in a different operational environment).

Further *-ilities* Readiness Development

	DISCOVERY	FEASIBILITY	PRACTICALITY <small>Generic Application</small>	APPLICABILITY <small>Specific Application</small>
CERTIFIABILITY	1. Certification implications identified (must be x reliable)	1. Certification requirements understood (path defined)	1. The vehicle integration process addresses <i>ilities</i> as part of design	1. New certification methodology required, must be x reliable, dependencies on certification development, etc.
Additional <i>-ilities</i>				
	Qualitative	Uncertainty / Low Fidelity		Quantitative

Fig. 12 *-ilities* Example – Certifiability

In each stage of Discovery, Feasibility and Applicability, the success of the Total Technology Readiness Level methodology will rely on identifying stakeholders and their roles and responsibilities at appropriate stages. Thus, the TTRL methodology study also emphasized the readiness research team formation with an effort to engage each stakeholder appropriately in the early stages. Figure 13 is an extract of stakeholders and to what degree they should be included early on, with the assumption that as the technology matures, more responsibility will fall on the design engineer.

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Phase	Who	Role / Ownership	Acceptability / Ownership Authority
Discovery	Researcher Designers	Owens / 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

Fig.

Stakeholder Collaboration and Coordination are Vital

In its future state an the *-ilities* catalog can provide the technologist and vehicle designer a set to select from potential “early” constraints that can shape the technology development beyond demonstrating a functional benefit including necessary adjacent technology development or policy to ensure technology transition success. This will form a stronger partnership between technologist and the vehicle designer to accelerate innovation and increase R&D yield.

C. Big Picture Perspective

Change is never as easy as it sounds or looks on paper. Using the civil aviation market as an example, the aircraft are complex, integrated marvels of modern technology providing an unmatched capability to transport people and goods safely and economically at high speed over long ranges relative to other modes of transportation.

A point generally overlooked by many is that performance is guaranteed and aircraft to initial operators before detailed design, build, or certification. The risk of a go-ahead decision requires critical questions that must be asked are: When do you launch a product? Can you confidently meet operator and society requirements? How much risk are you willing to take? And for what potential reward? These are business decisions made by business leaders in a complex, high technology marketplace. Figure 14 shows a simplified view of the business decision for a new or derivative product and how it is based on the convergence of technology readiness, market and regulatory requirements, resource availability and financial viability. If one dimension is missed, then there is no product opportunity. Note that pure technology readiness is but one of the key elements necessary and that “*-ilities*” permeate all dimensions. If the benefits or associated risks are substantially under-estimated, the consequence is a potential loss that can threaten the company’s future. So TTRL is necessary and it is useful for the technologist and vehicle designer to keep this appropriately in mind as they identify *-ilities* that will fill the technology gaps on the way to design, production and ultimately the market.



Fig. 14 The Whole Context for Opportunity

IV. Conclusion

A Total Technology Readiness Level (TTRL) approach is introduced to improve the productivity of successfully bringing technologies into application. This productivity is vital, as it is largely realized that it is technology opportunities that fuel the progress of our industry towards more sustainable, safer, more efficient and capable aircraft. Through case studies and understanding current practices, a framework has been proposed that can facilitate the early stages work of the technologist and vehicle designer together for successful, timely transitions to application. Doing so will require greater communication and understanding of all involved parties that work along the technology development chain, from the initial technologists with their early inspirations, to the vehicle designers tasked with bringing a product to market. Some may perceive this as simply doing more work earlier. In fact, it may result in less development effort overall, as identification of potential “show stopping” issues will allow earlier technology or application configuration adaptations, when there is usually more available time and risk tolerance to do so. Furthermore, the flexible nature of *-ilities* enables tailoring and adaptation to different potential end applications.

The TTRL framework aims to improve the aerospace community’s ability to better bridge technologies over the TRL 6 Practicality stage where so often technologies stall out. Successful technology transitions enhance research and development yield, maximizing the use of available resources, and ensures that industry programs are able to implement with reduced risk and improved readiness. When the TTRL framework is successfully implemented, commercial operators benefit with improved products, and the public benefits from aviation advancements at an accelerated pace to meet the challenges and opportunity of the 21st century.

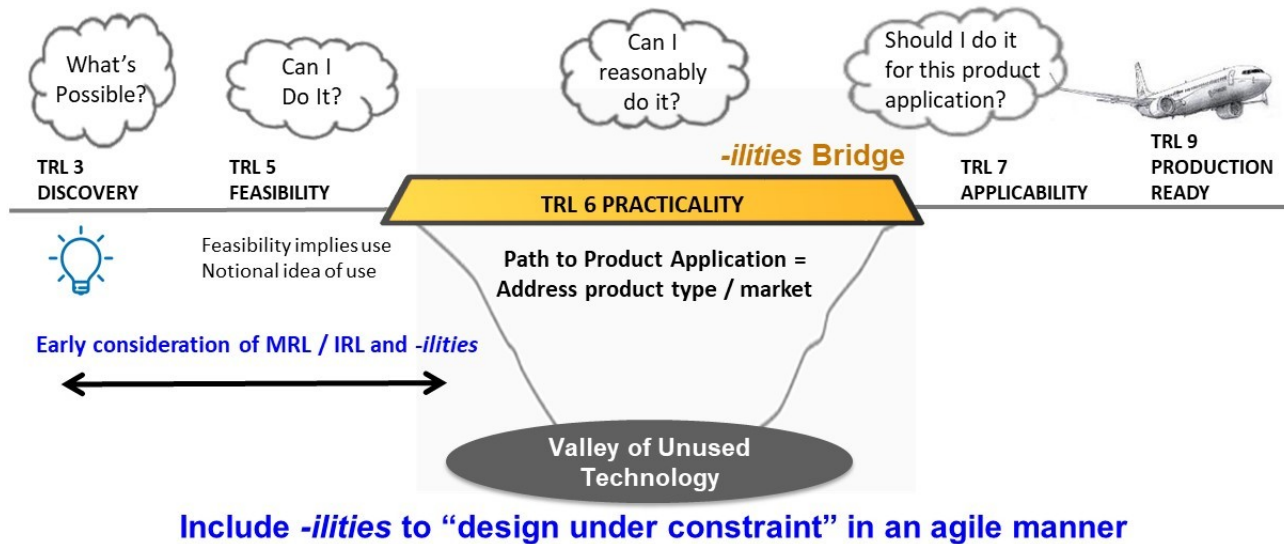


Fig. 15 TTRL Accelerates More Successful Technology Transitions

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