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Is it Ready? Quantifying the Maturity of Emerging Technologies

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Abstract

The Department of Defense uses advanced technology to provide U.S. weapons systems superior operational capabilities. Technology Readiness Assessments establish the technological maturity level of emergent technologies. However, these assessments often rely upon subjective evaluations that depend upon measures indirectly associated with the actual readiness of a technology for use in a specific end-use application. The challenge of measuring the readiness of an emerging advanced technology for use in a new system remains subjective and a source of early program cost and schedule risk.

Prior bibliometric-based methods are sensitive to the search logic, keywords, and the specific corpus used. Visualization tools and larger datasets provide insights into the overall body of work and identify new patterns and associations. However, such methods have not been validated against independent assessments of actual maturity.

This paper presents novel methods, strategies, and results of using publicly available publication data to identify when specific technologies were mature enough to be used in programs approaching Milestone B. The method is calibrated using declarations from authoritative sources such as Selected Acquisition Reports and correlated against independent assessments from the Government Accountability Office.

Results statements: The method is predictive for the analyzed technologies and is shown to be appropriate for use in pre-Milestone B activities such as source selection and Milestone decision support.

Keywords: Acquisition, bibliometrics, technology maturity levels

Introduction

Independent technical risk assessments (ITRAs) are required by law and require either identification of critical technologies and manufacturing processes that need to be matured prior to program initiation (Milestone A) have not been successfully demonstrated in a relevant environment prior to start of engineering development (Milestone B; 10 U.S.C. § 4272, 2016). Their content is codified by regulation and guidance (Under Secretary of Defense for Research and Engineering [USD(R&E)], 2020b) and is intended to provide (as named) an independent assessment of technical risk.

Despite a mandated ITRA process, and mandatory demonstration of all technologies entering the engineering and manufacturing phase of acquisition be mature, the U.S. Department of Defense (DoD), in 2021, accumulated over $615.4 Billion (52%) in total cost growth since program start while simultaneously slipping schedule by 35% with an average delay of over 2 years (Oakley, 2021). Some of the blame for the cost and schedule growth can be firmly placed on lack of consistent knowledge-based acquisition practices, specifically on maturing critical technologies and conducting appropriate design reviews prior to starting product development (Sager, 2021).

This paper summarizes a novel a way to judge a technology's technical maturity based upon simple measurements of publication volumes. The results were calibrated to independent maturity assessments.

Literature Review

Technology Readiness

The DoD provides specific guidance on the technical risk assessment process that requires *subjective* evaluation of achievement of specific criteria (USD[R&E], 2020a). This method makes sense when the evaluators (experts) are familiar with the technology or are active in the technology development. However, for emergent or rapidly changing technologies, the assessment may be biased or incomplete and not capture the actual technical risk associated with trying to apply an emergent technology to a new use.

There is a subtle difference between technical risk and technology readiness. Technical risk is defined by NASA as "… the risk … affecting the level of *performance necessary to meet the stakeholder expectations and technical requirements*…." (NASA, 2022). Technology readiness characterizes whether a system (product) *performs as intended* (Persons & Sullivan, 2016). In this paper, the use of the terms "independent technical risk assessment," "technology risk assessment," and "technology readiness assessment" are treated as equivalent, consistent with current usage in the DoD.

There have been several methods developed to provide a simple answer to the program manager's question, "Is it ready for …?" Technology Readiness Levels (TRLs) are a common example. They are an ordinal scale, placing basic research discoveries in the lower levels (1 and 2), and in-use systems at the highest level (TRL 9; Mankins, 2009). They were created to help characterize the relative readiness of a component or system for use in a particular application (Olechowski et al., 2015). Azizian et al. (2009) noted that measuring "… *technology and system maturity is a multi-dimensional process that cannot be performed comprehensively by a one-dimensional metric*…." The point is that TRLs are by themselves insufficient to support technical readiness decisions. For example, technical maturity is defined as achieving TRL 6, when a model or prototype is demonstrated in a relevant environment (Persons et al., 2020). The problem is that TRLs are ordinal and are assigned based upon a subjective decision as to whether specific attributes related to a given TRL level are satisfied.

Bearden (1999) showed how for a complex system,[1] insertion of various technologies, although well understood at the component level, affect system cost and schedule due to unrecognized or underappreciated interdependencies. This is similar to the concept of architectural technical debt (Soliman et al., 2021).

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[1] Bearden's work was specific for small satellites.

There are other examples of how to measure technical maturity. Bailey et al. (2014) used a ratio of immature to total critical technologies[2] as a measure of technology maturity. Using attributes from a standards-based definition of software quality (ISO, 2001), Azizian et al. (2011) found that engineering activities related to improving system quality were strongly correlated with technology readiness and program performance.

Scant literature addresses the time to progress between TRLs. El-Khoury and Kenley (2014) and Peisen and Schulz (1999) developed independent methods to forecast technology transition times between TRLs using existing program datasets. Reinhart and Schindler (2010) added a velocity measure to their estimation model. Ramirez-Marquez and Sauser (2009) developed System Readiness Levels to address the shortcomings of TRLs in addressing integration complexities, evidence that TRLs are insufficient to assess system maturity. Bailey et al. (2014) found TRAs have a positive return on investment for Major Defense Acquisition Programs. Peters et al. (2017) derived the confidence intervals for technology assessments and their effect on program execution. Olechowski et al. (2020) identified system complexity, planning and review, and validity of assessment as continuing challenges.

The Government Accountability Office (GAO) takes a different approach—they identified key knowledge practices and associated them with three key decision points—to invest in development, to demonstrate and test prototypes, and to proceed to production (Dodaro, 2021). They also created a technology readiness assessments (TRA) guide describing best practices to determine a technology's readiness (Persons et al., 2020). The GAO defines technical maturity when a system prototype or operational system is demonstrated in a relevant environment.[3]

Quantitative Technology Readiness Indicators

Commercial products typically will consider *commercialization potential*, which includes assessments of the market,[4] regulatory, legal, and intellectual property assessments, in addition to technical maturity (Mazurkiewicz et al., 2015). Radpour et al. (2021) found market penetration models based on *subjective* technology maturity estimates and market survey could be unreliable.

Scientometrics and bibliometrics are quantitative methods associated with publications and are commonly used to identify important research, using tools such as citation clustering, network analysis, and visualization (Chen, 2006). Early bibliometric methods used frequency charts, as shown in Figure 1.

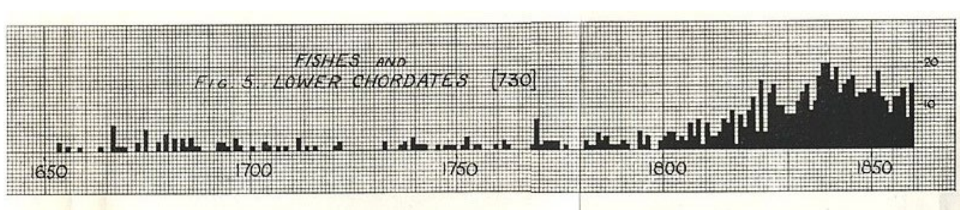

Figure 1. Example Publication Count Over Time
(Public Domain)

[2] Bailey et al. (2014) used the 2012 GAO weapon system assessment report for the count of immature and total critical technologies (Sullivan, 2012) to build their maturity estimates.

[3] This is a common definition of TRL 6.

[4] This may include market and economic assessments.

Figure 1 shows a growth in publications between 1825 and 1850. This indicates a surge of research activity in this domain and is related to the concept of a *research front.*[5]

Wiesner and Ladyman (2021) described complex systems as having 10 properties, with four as conditions for complexity,[6] and six are the results[7] of those first four. Modern systems fit this complex system description. Following Wiesner and Ladyman, we consider an electric vehicle as satisfying their definition of a complex system, as they have extensive sensing for electrical system function (numerosity), uncontrolled and unpredicted interactions between the vehicle and world (disorder and diversity), and dynamic vehicle response while driving (feedback and non-equilibrium).

Following Radpour et al. (2021), we assert that electric vehicles are of a system maturity allowing market introduction and early market acceptance. According to Bloomberg, electric vehicles are about 4% of the U.S. automotive market (Stock, 2022). A common indicator of technology maturity is patent issuance. Figure 2 shows electric vehicle patent activity.

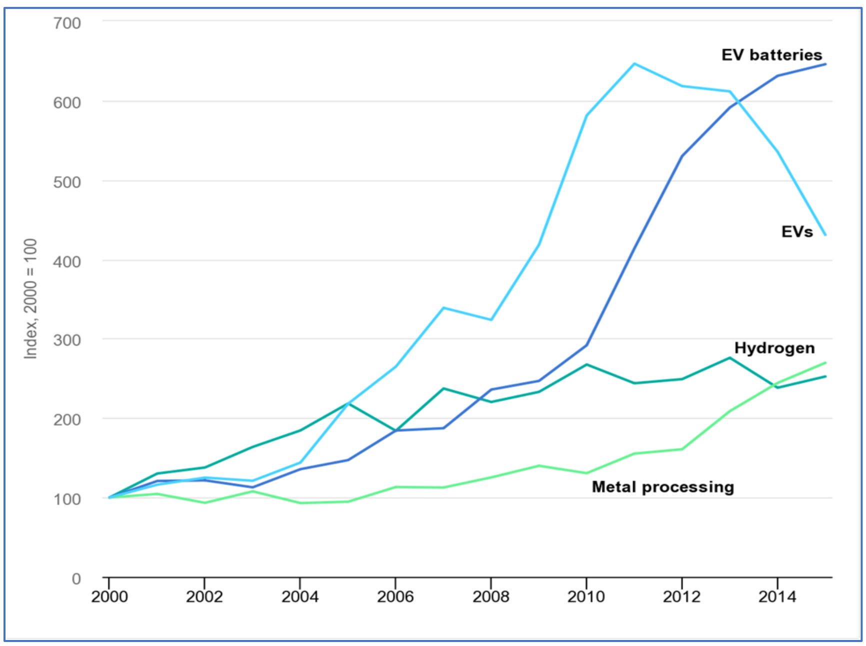

Figure 2. Electric Vehicle Related Patent Activity
(IEA, 2022)

One could argue from a qualitative perspective that the vehicle technology is mature on or after 2010, as patent issuances reduced. However, an electric vehicle is a system; what is to be made of the related patent activity? Is it correct to say that battery technology continued to mature and hydrogen power was behind? More importantly, these qualitative assessments do not answer when the various technologies were mature.

[5] This is a qualitative or quantitative visualization of a research field's state-of-the-art thinking.

[6] Specifically *numerosity, disorder and diversity, feedback,* and *non-equilibrium.*

[7] Wiesner and Ladyman (2021) argue a system is complex if it has one or more of the following properties: spontaneous order and self-organization, nonlinearity, robustness, nested structure and modularity, history and memory, and adaptive behavior.

Define Terms

This will compare a topic's research volume to that of all research conducted within online repositories. This is introduced as a relative research volume. Technologies for investigation are identified through declaration of technical maturity from authoritative government sources for Department of Defense Major Acquisition Programs. Investigation into the features of RRV, and changes in RRV (known in this praxis as ΔRRV), will be conducted in the Method chapter and proven through statistical testing in the Results chapter to find an objective measure of maturity that may be continuously updated and evaluated throughout a program's lifecycle. Any changes to the measure may indicate to the engineering manager to investigate or relook at specific maturation plans.

Method

Overview

The research used online repositories of publications such as IEEE, Wiley, SPIE, and arXiv. Search terms (keywords) are related to specific subject areas such as artificial intelligence (AI). In the case of the IEEE repository, an initial search with no keywords or search terms returns the total number of publications and breakdown of publications in six categories (Conference Papers, Journals, Magazines, Books, Standards, and Courses). An example search of IEEE Explore is shown in Figure 3.

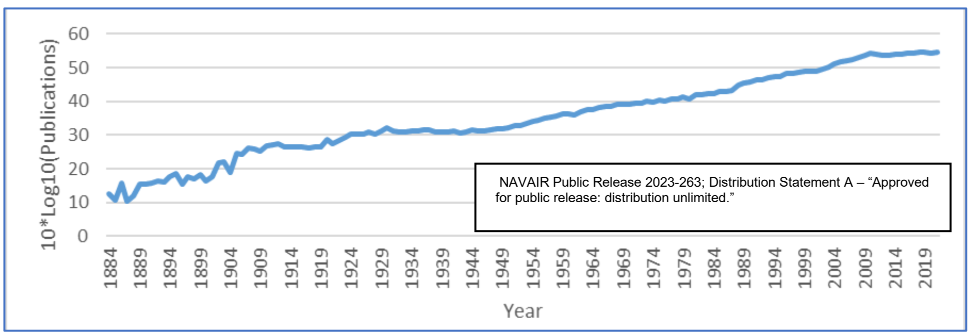

Figure 3. IEEE Publications
(Rea, 2022)

Figure 3 shows the increasing publication trend. A 10 dB rise in publications between any 2 years represents a tenfold increase in publications between years. However, the year-to-year change is noisy and is denoised by a moving average. The trend for a 5-year moving publication average is shown in Figure 4.

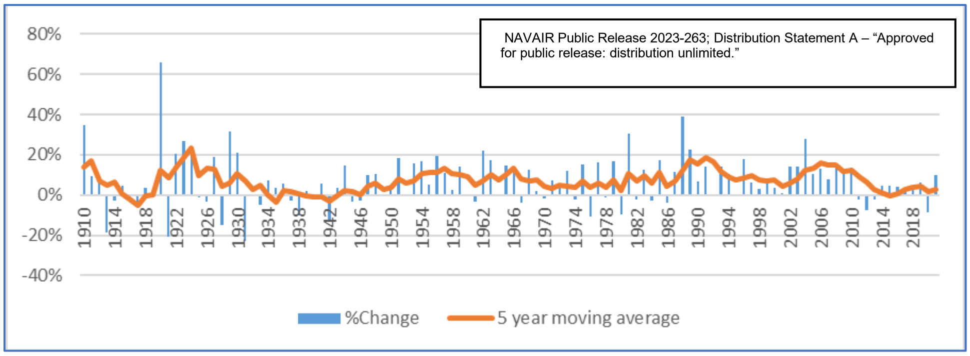

Figure 4. Percent Publication Volume 5 Year Moving Average
(Rea, 2022)

Figure 4 shows that trends in publication volumes over time reflect significant world events.[8] To demonstrate technology publication trends, we collected data from IEEE eXplore using the search term "Artificial Intelligence" and recoded total returned results were recorded for singular years, year over year, from 1956 to 2021 and shown in Figure 5 on a dB scale.

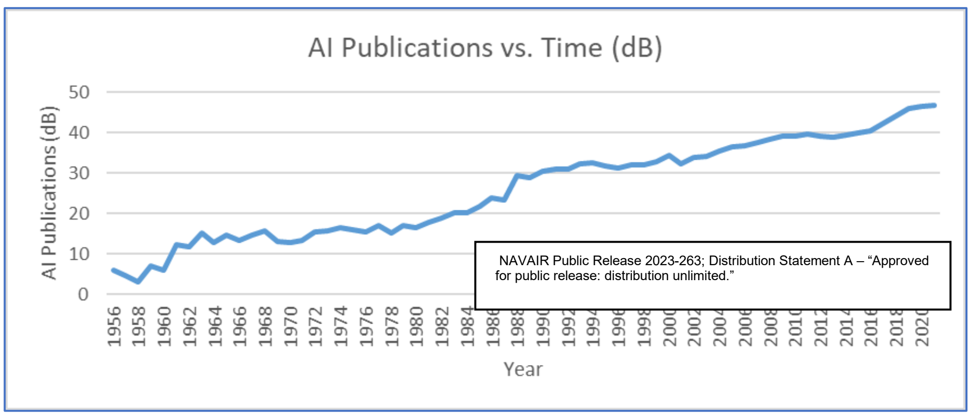

Figure 5. AI Publications Over Time, dB
(Rea, 2022)

Figure 5 shows increasing AI research volume. We define relative research volume (RRV_n) as the log of the fraction of all publications in a given repository in year n. For example, if AI_n is the total research publications containing the term "Artificial Intelligence" in year n in the IEEE eXplore repository and $IEEE_n$ is the total publications in the IEEE eXplore repository in year n, then RRV_n is

$$RRV_n = 10\log_{10}\left(\frac{AI_n}{IEEE_n}\right) \tag{1}$$

[8] For example, World War I, the Great Depression, World War II, the Gulf War, and the 2008 Global Recession. During SARS-COV-2 there was a -9% change in publication volume from 2019 to 2020.

In this equation, a value of 0 means all research within a given year, or 100% of publications, contained the search keywords. A value of -10 dB means that the search term was found in 10% of all research for the given year.[9]

Artificial intelligence went through several growth periods from initial discovery; growth periods are recognizable by the upward trend in publication volume of AI relative to all publication data on IEEE 1956–1962, 1978–1987, and 2013–current. Plateaus are areas where there were few publications, such as during the "AI winter" during 1992–2012. This growth and fallback of relative research volume (RRV) is shown in Figure 6.

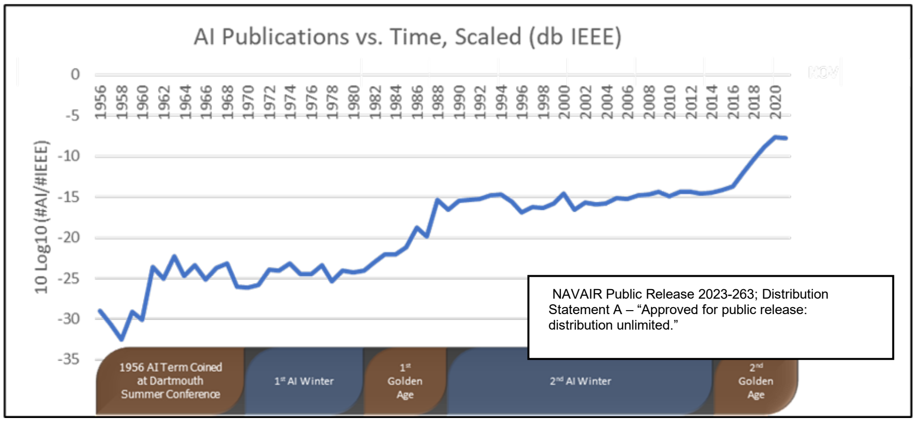

Figure 6. AI Publications RRV
(Rea, 2022)

This methodology was repeated with a second technical repository (Wiley); the results are shown in Figure 7.

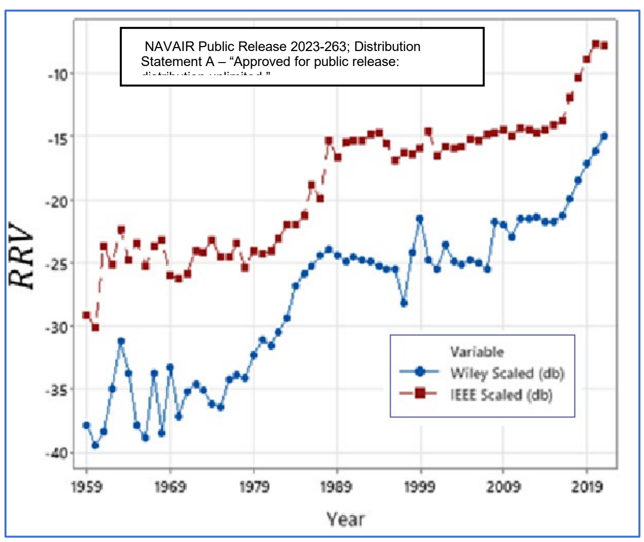

Figure 7. Comparison of Wiley and IEEE RRVs
(Rea, 2022)

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[9] About 17.5% of all published research in IEEE eXplore was related to AI as of 2021.

There is over a 94% correlation between these two results.[10] In summary, researchers may create RRV data sets using the following steps:

- Identify technologies of interest.
- Identify related Repository to investigate technology publications over time.
- Formulate search term in accordance with best practices to return relevant publications.
- Record the volume of publications per year for time window of interest.
- Record the total volume of publications in the repository for the same time window.
- Calculate Relative Research Volume according to Equation 5.
- Plot the results and identify trends.

Change in Relative Research Volume (ΔRRV)

We define the change in relative research volume over time as

$$\Delta RRV_n = RRV_x - RRV_{x-n-1} \tag{2}$$

where x is the year of interest and n is the length of the moving time average window. Figure 8 is an annotated example of ΔRRV_{10} for software defined radio technology.

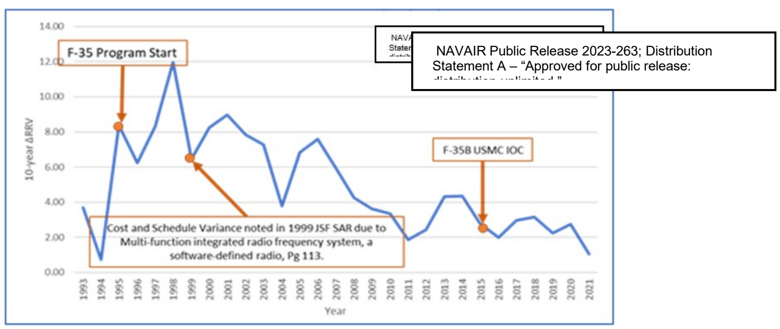

Figure 8. Example ΔRRV_{10}
(Rea, 2022)

Method Calibration

Relative research volumes over time for specific technologies were calibrated using independent technology maturity declarations. GAO *Defense Acquisitions: Assessments of Selected Weapon Programs* reports from 2003 to 2021 were reviewed to identify technical, design, and manufacturing risks to programs of record in the DoD. The year column in the following table represents either a significant event such as program start, the first report year of maturity, or Initial Operational Capability (IOC). All *No* declarations were researched for either program IOC, a GAO declaration of *Yes*, or technology was replacement with a mature substitute.[11] There are a total of 60 data points—31 declared mature and 29 not mature. Table 1 summarizes the systems, critical technologies and binary[12] technology maturity declarations (Rea, 2022).

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[10] Using a zero lag cross correlation.

[11] Such as the Multi-Mission Maritime Aircraft Data Fusion (MMA, later known as P-8)

[12] If there is a clear "Mature" declaration, the technology is treated as mature. Any other adjectives, such as not mature, near (-ly, -ing) maturity are treated as not mature.

Table 1. Technology Maturity Declarations
(Rea, 2022)

#	Technology	Year	Mature?	Notes
1	F-35 Software Defined Radio	1995	No	Program Start,
		1999	No	1999 JSF SAR Pg 113
		2015	Yes	USMC IOC
2	F-35 Sensor and Data Fusion	1995	No	Program Start
		2015	Yes	USMC IOC
3	F-35 Organic Light Emitting Diode	2019	Yes	Gen III HMDS Fielding
4	F-35 Agile Engineering	2017	Yes	C2D2 (Block 4) start
5	2004 DARPA Grand Challenge - Autonomous Driving	2002	No	Announced in 2002
	Autonomous Driving	2021	No	Current research volume
6	FCS - Network Intrusion Detection	2008	No	GAO Report on FCS
7	FCS - Mobile Ad Hoc Networking	2008	No	GAO Report on FCS
8	FCS - Distributed Fusion Management	2008	No	GAO Report on FCS
9	GAO - Quantum Cryptography	2021	No	GAO Report on Quantum Technol
10	GAO - Quantum Communication	2021	No	GAO Report on Quantum Technol
11	GAO - Quantum Key Distribution	2021	No	GAO Report on Quantum Technol
12	GAO - Quantum Computing	2021	No	GAO Report on Quantum Technol
13	GAO - Quantum Random Number Generation	2021	No	GAO Report on Quantum Technol
14	USPS - Optical Character Recognition	2021	Yes	USPS Deployed OCR
15	CVN 78 Dual Band Radar System	2001	No	2004 GAO Report, CVN-21 Progr
	CVN 78 Dual Band Radar System	2021	Yes	CVN 78 IOC
16	E-2D AHE Space Time Adaptive Processing Algorithms	1999	No	2004 GAO Defense Report
		2008	Yes	2008 GAO Defense Report
17	E-2D AHE SiC Power Transistor	2001	No	2004 GAO Report - 2001 program
		2007	Yes	2009 GAO Report
18	GAO - Gait Recognition	2002	No	2002 GAO Report on Biometrics T
	Commercial Gait Recognition	2018	Yes	1st Commercial Availability
19	Space qualified atomic frequency standards	2008	Yes	2008 GAO Page 153
20	MMA Data Fusion	2008	No	2008 GAO Page 157
21	Space Radar - SAR Moving Target Indication	2008	No	2008 GAO Page 167
22	TSAT Program - Dynamic Bandwidth and Resource Allocation	2008	Yes	2008 GAO Page 172
23	VH-71 Voice-over Internet Protocol Security	2008	No	2008 GAO Page 177
24	WGS - Phased Array Radar	2000	Yes	2008 GAO Page 181
25	AMDR - Digital Beamforming	2017	No	2017 GAO Page 98
26	G/ATOR Program - Gallium Nitride Power Amplifier	2016	Yes	2017 GAO Page 108
27	F-22 Geolocation Algorithm	2017	Yes	2017 GAO Page 150
28	F-22 Open Systems Architecture	2020	Yes	2021 GAP Page 130
29	MGUE Anti-Spoof	2017	No	2017 GAO Page 158
30	WSF-M Polarimetric Receiver	2017	No	2017 GAO Page 162
		2019	Yes	2021 GAP Page 114
31	ITEP Additive Manufacturing	2019	No	2019 GAO Page 97

The Table 1 dataset represents systems or technologies or systems with known technologies corresponding to search terms available in the IEEE or Wiley online repositories. There may be cases where specific technology search terms for military specific technologies *do not* match terms used in publicly available literature.

Results

Difference Between ΔRRV of Mature and Not Mature Technologies

Figure 9 shows histograms of 5-, 7-, and 10-year ΔRRVs of Table 1 data overlaid with 3-parameter Weibull distributions.

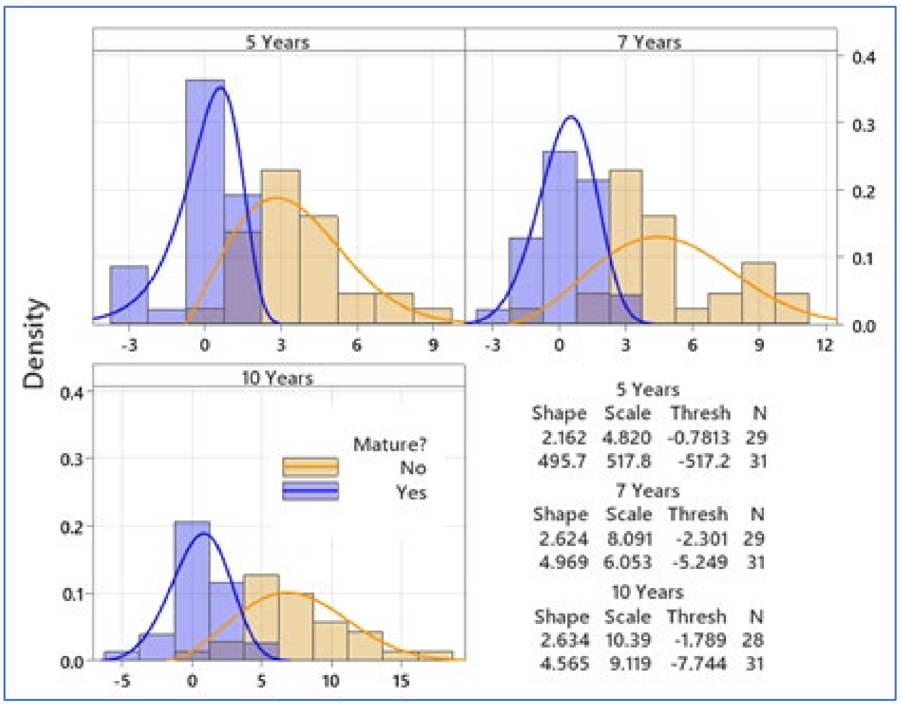

Figure 9. Histograms of Mature vs. Not Mature Declarations for ΔRRV
(Rea, 2022)

Figure 9 clearly shows separation between the mature and not mature declarations. To prove this, an analysis of variance and means is used. For 5-, 7-, and 10-year ΔRRVs (n={5,7,10}), p=0.000 for the ANOVA between mature and not mature populations; the mature and not mature samples come from statistically significant different populations. Figure 10 visually summarizes a one-way ANOVA for $n = \{5,7,10\}$ between mature and not mature declarations.

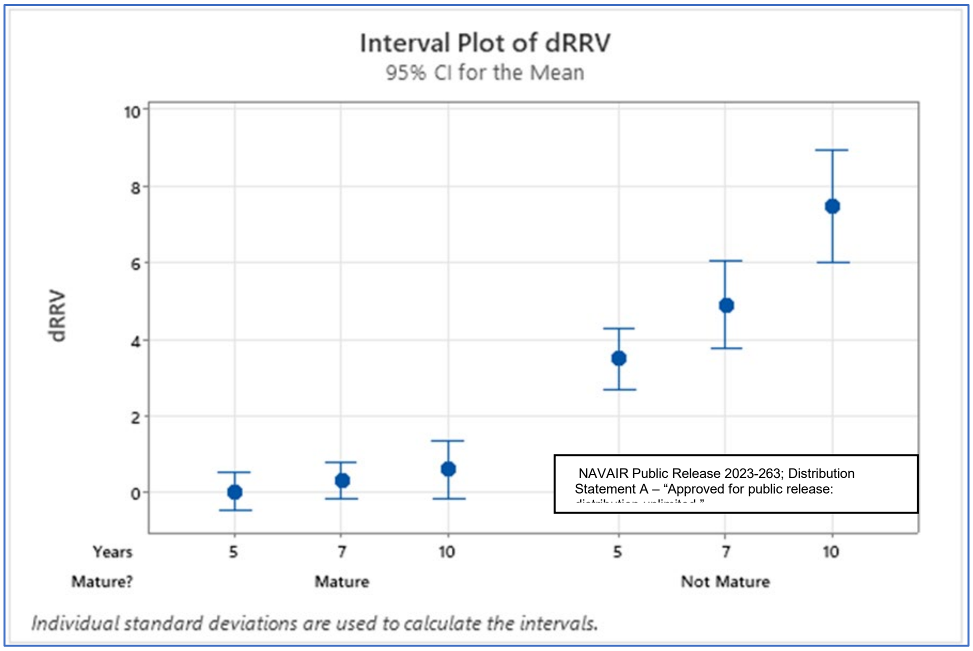

Figure 10. Interval Plot of ΔRRV Mature/Not Mature Declarations
(Rea, 2022)

Figure 10 clearly shows the difference between mature and not mature declarations and the existence of a threshold ΔRRV of approximately 2 between mature and not mature declarations. This is shown visually in Figure 11, where t = 2.

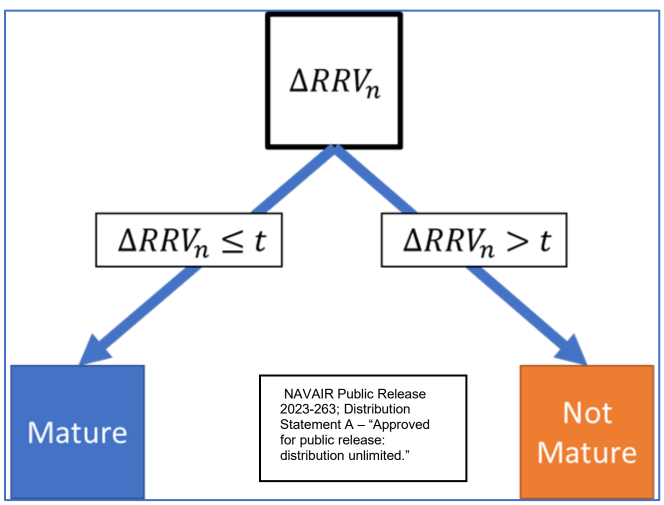

Figure 11. Example ΔRRV Maturity Classification
(Rea, 2022)

Given the separation between ΔRRVn for n={5,7,10} does not support the data being from separate populations, decision tree depth is a maximum of 1.

Conclusions

ΔRRV_n is shown to be a relevant measure of technology maturity. This will greatly enhance a program manager's ability to get quick looks at potential solutions' technology risk, increase ability for non-experts to have insight into critical technology identification, and empower engineering managers to utilize the technology maturation planning process across a broader range of technologies assessed.

The calculation of ΔRRV is simple, and a program or engineering manager could use it as a quick first look at potential critical technology element candidates before subject matter experts have independently reviewed proposals for new or novel uses of technologies. The data for any given technology takes minutes to generate across multiple public repositories.

Research Limitations/Implications

This research used publicly available data from budget submissions, program-related reporting, contractor annual reports, and contemporaneous press releases. The findings are specific to the analyzed technologies and programs.

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References

Azizian, N., Mazzuchi, T., Sarkani, S., & Rico, D. F. (2011). A framework for evaluating technology readiness, system quality, and program performance of U.S. DoD acquisitions. *Systems Engineering*, *14*(4), 410–426. https://doi.org/10.1002/sys.20186

Azizian, N., Sarkani, S., & Mazzuchi, T. (2009, October 20). A comprehensive review and analysis of maturity assessment approaches for improved decision support to achieve efficient defense acquisition. *Proceedings of the World Congress on Engineering and Computer Science 2009 Vol. II*. World Congress on Engineering and Computer Science, San Francisco, CA. www.iaeng.org/publication/WCECS2009/WCECS2009_pp1150-1157.pdf

Bailey, R. U., Mazzuchi, T. A., Sarkani, S., & Rico, D. F. (2014). A comparative analysis of the value of technology readiness assessments. *Defense Acquisition Research Journal: A Publication of the Defense Acquisition University*, *21*(4), 825–850. a9h.

Bearden, D. A. (1999). *A methodology for spacecraft technology insertion analysis balancing benefit, cost and risk* [PhD]. University of Southern California.

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, *57*(3), 359–377. https://doi.org/10.1002/asi.20317

Dodaro, G. L. (2021). *Weapon systems annual assessment updated program oversight approach needed* (GAO-21-222). https://www.gao.gov/assets/gao-21-222.pdf

El-Khoury, B., & Kenley, C. R. (2014). An assumptions-based framework for TRL-based cost and schedule models. *Journal of Cost Analysis and Parametrics*, *7*(3), 160–179. https://doi.org/10.1080/1941658X.2014.982232

IEA. (2022). *Counts of global patents for related applications of electric mobility, 2000-2015 IEA, Paris. License CC-BY-4.0*. IEA.Org. https://www.iea.org/data-and-statistics/charts/counts-of-global-patents-for-related-applications-of-electric-mobility-2000-2015

ISO. (2001). *Quality model*. International Organization for Standardization. https://www.iso.org/standard/22749.html

Mankins, J. C. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica*, *65*(9), 1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058

NASA. (2022, January). *Systems engineering handbook*. https://www.nasa.gov/seh/

Oakley, S. S. (2021). *DOD acquisition reform: Increased focus on knowledge needed to achieve intended performance and innovation outcomes* (GAO-21-511T). GAO. https://www.gao.gov/products/gao-21-511t

Olechowski, A. L., Eppinger, S. D., & Joglekar, N. (2015). Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2588524

Olechowski, A. L., Eppinger, S. D., Joglekar, N., & Tomaschek, K. (2020). Technology readiness levels: Shortcomings and improvement opportunities. *Systems Engineering*, *23*(4), 395–408. https://doi.org/10.1002/sys.21533

Peisen, D. J., & Schulz, C. L. (1999). *Task order 221 case studies: Time required to mature aeronautic technologies to operational.*

Persons, T. M., Mackin, M., Bothjwell, B., Schwenn, R., & Ortiz, J., Jr. (2020). *Technology readiness assessment guide: Best practices for evaluating the readiness of technology for use in acquisition programs and projects [Reissued with revisions on Feb. 11, 2020.]* (GAO-20-48G). GAO. https://www.gao.gov/products/gao-20-48g

Persons, T. M., & Sullivan, M. J. (2016). *Technology readiness assessment guide: Best practices for evaluating the readiness of technology for use in acquisition programs and projects*.

Radpour, S., Mondal, M. A. H., Paramashivan, D., & Kumar, A. (2021). The development of a novel framework based on a review of market penetration models for energy technologies. *Energy Strategy Reviews*, *38*, 100704. https://doi.org/10.1016/j.esr.2021.100704

Ramirez-Marquez, J. E., & Sauser, B. J. (2009). System development planning via system maturity optimization. *IEEE Transactions on Engineering Management*, *56*(3), 533–548. https://doi.org/10.1109/TEM.2009.2013830

Rea, C. A. (2022). *Using relative research volume as a measure of technology maturity*. ProQuest Dissertations Publishing.

Sager, M. (2021). *High-risk series: Dedicated leadership needed to address limited progress in most high-risk areas* (GAO-21-119SP). GAO. https://www.gao.gov/products/GAO-21-119SP

Soliman, M., Avgeriou, P., & Li, Y. (2021). Architectural design decisions that incur technical debt—An industrial case study. *Information and Software Technology*, *139*. https://doi.org/10.1016/j.infsof.2021.106669

Stock, K. (2022, September 27). *Just 4% of North American car production is electric*. Bloomberg. https://www.bloomberg.com/news/articles/2022-09-27/just-4-of-north-american-car-production-is-electric#xj4y7vzkg

Sullivan, M. J. (2012). *2012 defense acquisitions: Assessments of selected weapon programs*.

10 U.S.C. § 4272, Pub. L. No. 114–283 (2016). https://www.law.cornell.edu/uscode/text/10/4272

Under Secretary of Defense for Research and Engineering. (2020a). *Defense technical risk assessment methodology (DTRAM)-0-1*. DoD. https://ac.cto.mil/wp-content/uploads/2021/01/DTRAM-0-1.pdf

Under Secretary of Defense for Research and Engineering. (2020b). *Department of Defense independent technical risk assessment guidance*. DoD. https://ac.cto.mil/wp-content/uploads/2021/01/DTRAM-0-1.pdf

Wiesner, K., & Ladyman, J. (2021). Complex systems are always correlated but rarely information processing. *Journal of Physics: Complexity*, *2*(4). https://doi.org/10.1088/2632-072X/ac371c

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