ROI of Technology Readiness Assessments Using Real Options: An Analysis of GAO Data from 62 U.S. DoD Programs

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Abstract

Based on data from 62 U.S. DoD programs, a method is described for estimating the return on investment (ROI) of performing technology readiness assessments (TRAs) using real options. ROI is a performance metric used for estimating the value of an investment and is expressed as the net economic benefits of the investment divided by the total economic cost of the investment. A TRA is a process of determining whether major U.S. DoD programs may proceed from early research stages into development and production if their key technologies are stable and mature. U.S. DoD programs based on key technologies that are stable and mature experience fewer cost and schedule overruns, save U.S. taxpayers trillions of dollars and increase production quantities. Real options is a strategy for estimating the ROI of delaying the development and production of U.S. DoD programs whose TRAs uncover key technologies that are unstable or immature.

Introduction

A TRA is a systematic, metrics-based process and accompanying report that is used to assess the maturity of certain technologies called critical technology elements (CTEs) for large systems. Technology elements are critical if the system being acquired depends on this technology to meet operational requirements within acceptable cost and schedule, and are considered new or novel. Created by NASA in the 1970s, TRAs were adopted by the U.S. DoD to curtail multi-billion cost and schedule overruns typically associated with major defense acquisition programs (MDAPs). MDAPs are U.S. DoD Acquisition Category (ACAT) I programs in excess of $300,000,000 per year in research and development costs and $1,800,000,000 in total procurement expenditures. Once an MDAP's CTEs have been identified, they must demonstrate a technology readiness level (TRL) of 6 for Milestone B and 7 for Milestone C in order to proceed to the next phase. TRLs are a sequence of nine carefully-defined levels of technology maturity intended to communicate the developmental status of technologies. Technology maturity is a measure of the degree to which critical technologies meet program objectives and is a principal element of risk.

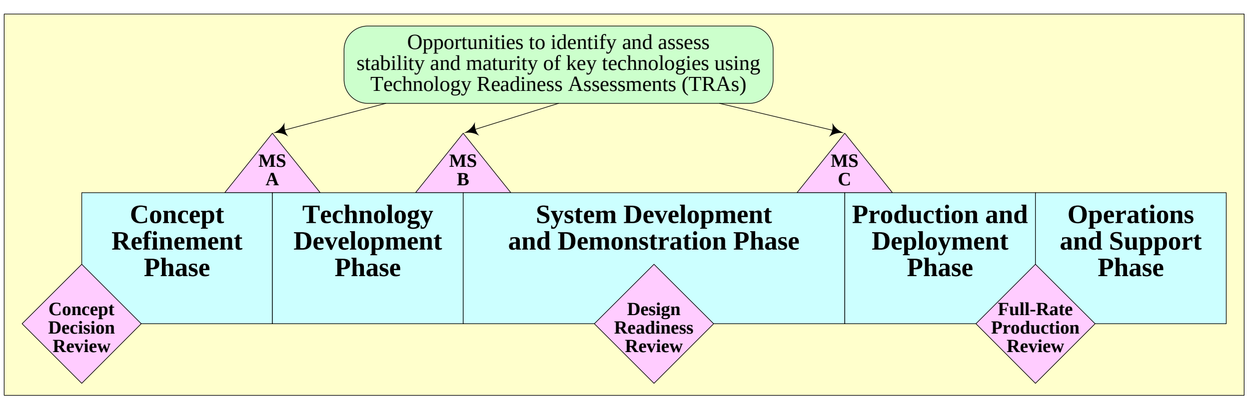

Figure 1. Integrated Defense Acquisition, Technology, & Logistics Life Cycle Management Framework.

Analysis of Technology Readiness

NASA's 32-year old TRA process was standardized by the U.S. DoD to ensure that technology used in major weapon systems is stable and mature before development begins (to save money). The TRA process was used by General Dynamics in 1975 for a NASA Space Shuttle study, used in 1976 on NASA's Jupiter probe, and was used again in 1977 to evaluate NASA's solar sail.[1] Today, the U.S. DoD's TRA process is comprised of six major steps: (a) identify CTEs, (b) collect CTE data, (c) finalize CTEs, (d) perform TRA, (e) submit TRA, and (f) approve TRA.[2] Program managers are responsible for identifying CTEs, independent panels are responsible for finalizing CTEs and performing the TRA itself, and U.S. DoD representatives approve TRAs.

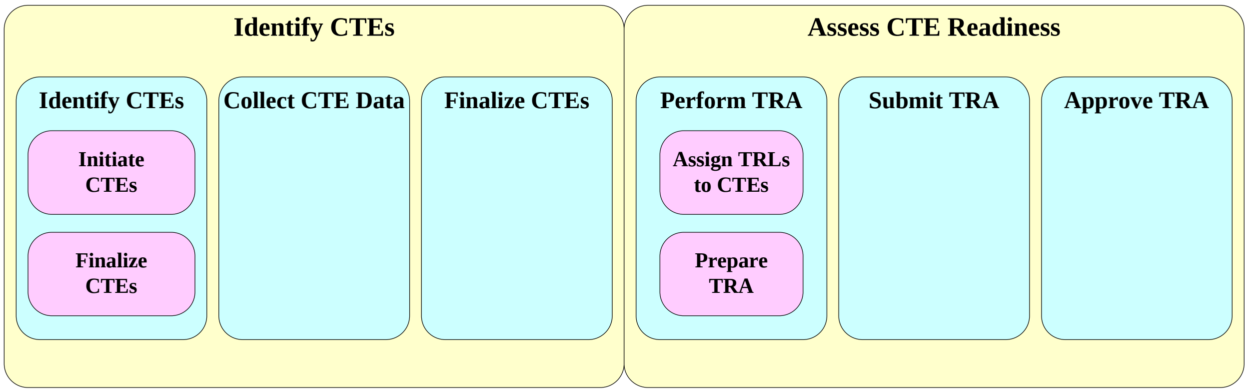

Figure 2. TRA Readiness Assessment (TRA) Process.

Levels of Technology Readiness

TRLs are nine measures used to describe the technology maturity of CTEs, where technology maturity is defined as a measure of the degree to which proposed CTEs meet program objectives. There were only seven TRLs in the 1970s, but today there nine TRLs for hardware, software, and manufacturing, and there are TRLs for industries such as medicines and biomedical devices. CTEs should satisfy TRL 3 by Milestone A, TRL 6 by Milestone B, and TRL 7 by Milestone C, where relevant environment is simulated and operational environment is real-world conditions. CTEs must be demonstrated in a relevant environment for system development/demonstration phases and demonstrated in an operational environment for production/deployment phases. The notion of TRLs is that unstable or immature technologies cause cost and schedule overruns.

Table 1. Technology Readiness Level (TRL) Definitions for Hardware.

Milestone	Level	Description
MS A	1	Basic principles observed and reported
	2	Technology concept and/or application formulated
	3	Analytical and experimental critical function and/or characteristic proof of concept
MS B	4	Component and/or breadboard validation in a laboratory environment
	5	Component and/or breadboard validation in a relevant environment
	6	System/subsystem model or prototype demonstration in a relevant environment
MS C	7	System prototype demonstration in an operational environment
FRP	8	Actual system completed and qualified through test and demonstration
IOC & FOC	9	Actual system proven through successful mission operations

MS—Milestone, FRP—Full-rate production, IOC—Initial operational capability, FOC—Full operational capability

ROI Metrics for Technology Readiness

Value of TRAs may be measured with seven metrics: (a) costs, (b) benefits, (c) benefit-to-cost-ratio, (d) return-on-investment, (e) net-present-value, (f) breakeven-point, and (g) real-options.[3-6] Costs are expenses, such as developing principles, concepts, experiments, and prototypes, and benefits are associated savings from technology stability and maturity after Milestones B and C. The costs and benefits of TRAs are the basic inputs to the formulas and equations for benefit-to-cost-ratio, return-on-investment, net-present-value, breakeven-point, and real-options.

Table 2. A suite of simple of metrics and models for measuring the ROI of TRAs.

Costs	Total amount of money spent on technology readiness	$\sum_{i=1}^{n} Cost_i$
Benefits	Total amount of money gained from technology readiness	$\sum_{i=1}^{n} Benefit_i$
B/CR	Ratio of technology readiness benefits to costs	$\frac{Benefits}{Costs}$
ROI%	Ratio of adjusted technology readiness benefits to costs	$\frac{Benefits - Costs}{Costs} \times 100\%$
NPV	Discounted cash flows of technology readiness	$\sum_{i=1}^{Years} \frac{Benefits_i}{(1 + Discount\ Rate)^{Years}} - Costs_0$
BEP	Point when benefits exceed costs of technology readiness	$\frac{Costs}{NPV} \times 60\, Months$
ROA	Business value realized from strategic delay due to risk	$N(d_1) \times Benefits - N(d_2) \times Costs \times e^{-Rate \times Years}$

d1 = [ln(Benefits ÷ Costs) + (Rate + 0.5 × Risk²) × Years] ÷ Risk × √Years, d2 = d1 − Risk × √Years

Cost Analysis of Technology Readiness

A recent study by the U.S. Government Accountability Office (GAO) provided detailed cost data of 62 U.S. DoD programs, which is the first required input for determining the ROI of TRAs.[7-8] The study provided detailed examples of research and development (R&D) and total costs, but analysis of the data revealed gross inconsistencies in the R&D data not present in the total costs. While the U.S. DoD has funding categories to distinguish between activities such as R&D and operations and maintenance (O&M), funding is often blurred when it comes to program survival. Though the R&D stage of the acquisition lifecycle is ideal for achieving technology stability and maturity, and should be used for studies on technology maturity, total costs were used instead. When the programs were sorted by total costs, the larger programs did not have larger R&D costs, but appeared arbitrary. Therefore, total costs were used as the basis for cost estimation.

Table 3. Illustrative Cost Data from 62 Major U.S. DoD Weapon System Programs.

No.	Service	Type	Acronym	Program Name	R&D Cost	Total Cost
1	Air Force	Laser	ABL	Airborne Laser	$5,449.2	$5,449.2
2	Army	Sensors	ACS	Aerial Common Sensor	$1,158.9	$1,170.9
3	Navy	Missile	ABMD	Aegis Ballistic Missile Defense	$9,038.8	$9,038.8
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60	Army	UAV	UAS	Warrior Unmanned Aircraft System	$384.8	$1,825.0
61	Joint	Satellite	WGS	Wideband Global SATCOM	$332.7	$2,013.2
62	Army	C^2	WIN-T	Warfighter Information Network-Tactical	$1,260.5	$11,601.6

Note. All costs are in millions of dollars.

Benefit Analysis of Technology Readiness

Historically, cost data was rarely collected and difficult to obtain, but is now becoming common and identifying benefit data is the largest challenge for performing ROI studies in any discipline. However, the GAO's study of 62 U.S. DoD programs provided the key to unlocking the benefits of technology stability and maturity, thus revealing the benefits of determining the ROI of TRAs. The GAO study provided three data points for determining the ROI of TRAs: (a) total costs, (b) technology maturity, and (c) the average cost savings from technology stability and maturity. Technology maturity is a simple ratio of immature to total technologies. Cost risk is the normalized rank of total costs. Technology risk is the normalized rank of technology maturity. Combined risk is a composite of cost and moderated technology risk. Risk% is the normalized combined risk. Benefits are a product of total costs, risk, and a benefit constant of 29.7%.

Table 4. Illustrative Benefit Data from 62 Major U.S. DoD Weapon System Programs.

No.	Program	Cost	Maturity	Cost Risk	Tech. Risk	Com. Risk	Risk%	Benefit
1	ABL	$5,449.2	0.0%	0.02	1.00	0.12	11.6%	$1,449.9
2	ACS	$1,170.9	16.7%	0.01	0.83	0.09	8.2%	$322.0
3	ABMD	$9,038.8	33.3%	0.04	0.67	0.11	10.0%	$2,443.9
↯	↯	↯	↯	↯	↯	↯	↯	↯
60	UAS	$1,825.0	50.0%	0.01	0.50	0.06	5.4%	$515.6
61	WGS	$2,013.2	100.0%	0.01	0.00	0.01	0.8%	$593.4
62	WIN-T	$11,601.6	0.0%	0.05	1.00	0.15	14.1%	$3,007.7

Note. All costs and benefits are in millions of dollars.

Cost and Benefit Analysis of Technology Readiness

Numerous economic equations have evolved since the industrial revolution to help quantify the business value of an investment such as cost, benefit, B/CR, ROI%, NPV, breakeven, and ROA. One of the oldest, yet least understood and seldom-used, methods of quantifying the business value of investments is ROI%, which is a simple ratio of benefits to costs less the costs of course. NPV was considered more sophisticated, realistic, and economically responsible than ROI%, because it took the time-value of money into consideration (e.g., devaluation due to inflation). Like the TRA process itself, ROA emerged in the 1970s to estimate the business value of one or more investments as a sophisticated strategy of delaying investments due to the presence of risk. In simple terms, ROI% is used for determining near-term benefits, NPV is used for determining mid-term benefits, and ROA is used for determining longer term benefits in the presence of risk. Since TRAs are all about estimating the risks of implementing large-scale U.S. DoD programs, we have taken advantage of all three of these vantage points: (a) ROI%, (b) NPV, and (c) ROA.

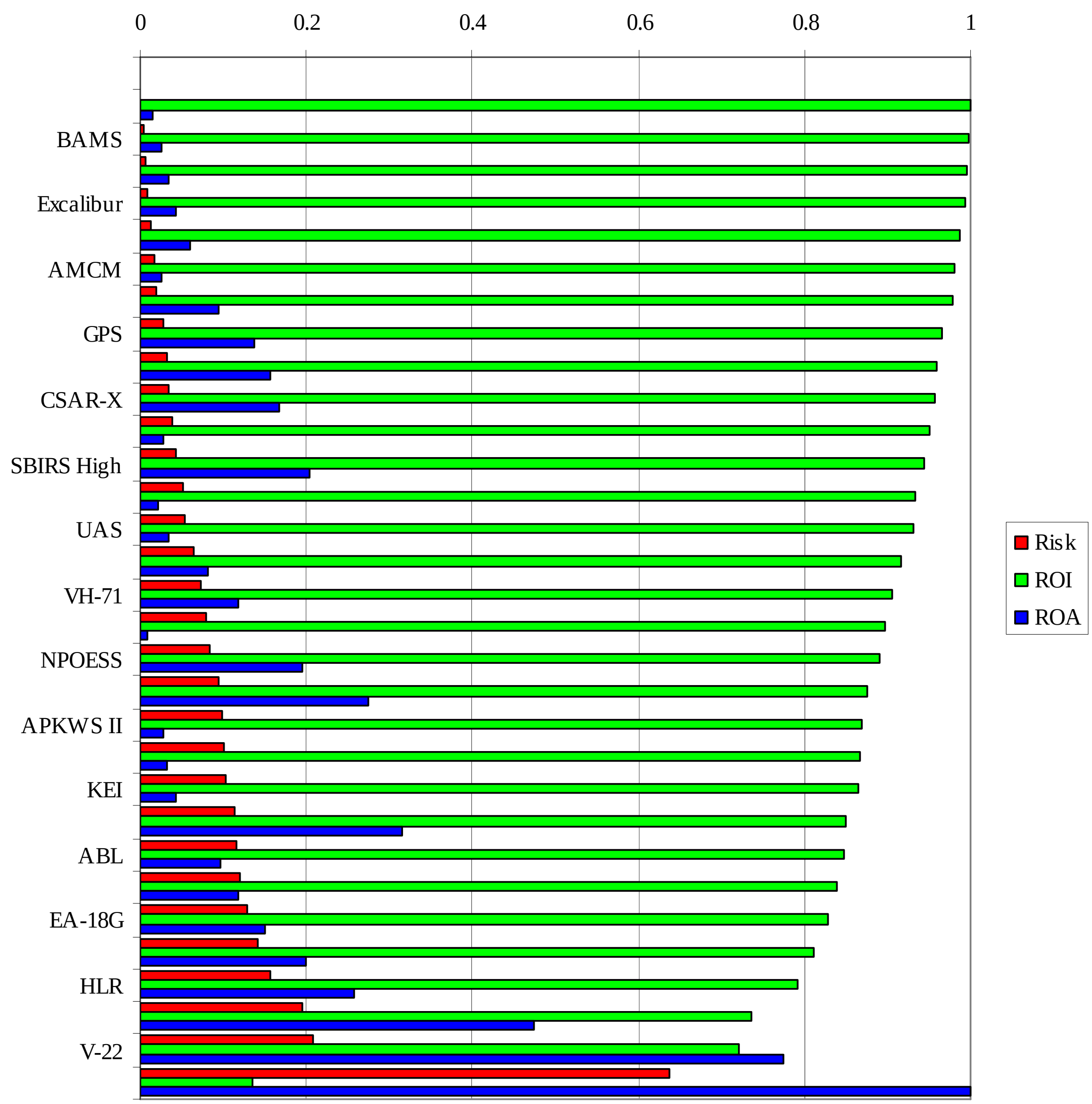
Table 5. Illustrative ROI Data from 62 Major U.S. DoD Weapon System Programs.

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
1	ABL	$544.9	$1,449.9	2.7:1	166.1%	$710.6	3.8 Years	$1,025.5
2	ACS	$117.1	$322.0	2.7:1	175.0%	$161.7	3.6 Years	$230.8
3	ABMD	$903.9	$2,443.9	2.7:1	170.4%	$1,212.3	3.7 Years	$1,740.0
↯	↯	↯	↯	↯	↯	↯	↯	↯
60	UAS	$182.5	$515.6	2.8:1	182.5%	$264.0	3.5 Years	$373.5
61	WGS	$201.3	$593.4	2.9:1	194.8%	$312.5	3.2 Years	$436.6
62	WIN-T	$1,160.2	$3,007.7	2.6:1	159.2%	$1,444.2	4.0 Years	$2,104.1

Note. All costs and benefits are in millions of dollars.

ROI Analysis of Technology Readiness

The data from the GAO study of 62 DoD programs was first sorted by Risk% in ascending order, which is represented by the red bar (e.g., programs were sorted by least to greatest risk and size). The first major finding revealed by this analysis was that ROI% decreases as program risk and cost increase, which is logical since larger programs are inherently more complex and risk prone. Increasing Risk% also includes decreasing technology maturity; that is, programs with a larger number of unstable and immature technologies will have a larger red bar and a smaller green bar. The most important finding is that ROA increases as risk increases and ROI% decreases. That is, delaying a program due to size and technology instability and immaturity results in greater ROI. Another method of delaying a program is incremental and iterative development, which involves smaller initial investments in releases or spirals until technologies become stable and mature.



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Principles for Technology Readiness

Technology readiness is a very old and commonsense approach to systems and software engineering that involves proof-of-concepts as a means of risk reduction and system success. There is value in traditional and classical approaches to systems engineering that involve basic analytical principles such as mathematical analyses, architectural drawings, and plastic models. However, there comes a time when we have to push the fledgling idea out of the nest of science and into the fuzzy and complex world of people, process, and technology—the earlier, the better.

- **Design your system for technology readiness**. Use the principles of technology readiness as a project management tool. You've heard of the old adage, "Design for cost, schedule, and quality." What this means is optimizing your system based on one of these variables, i.e., optimal cost, time, or quality efficiency and effectiveness. Now it's time to add one more variable to the equation, "Optimize your system for technology readiness."
- **Identify a short-list of key technologies**. Identify, select, and evaluate a small list of key technologies upon which to focus. Common mistakes include selecting two or three key technologies for a multi-billion dollar system, or selecting dozens or even hundreds of key technologies for a multi-million dollar system. Seven to fifteen key technologies are about right for a large system and two or three technologies are about right for a medium-sized one.
- **Identify the right list of key technologies**. Identify key technologies that define and differentiate your system from the rest-of-the-pack. That's the reason you're building this system isn't it? You're building this system because no one has ever made one of these before and you're attempting to use state-of-the-art technologies for a very special purpose. Don't identify a laundry-list of hardware and software technologies, but differentiating ones.
- **Develop risk-reduction prototypes early**. The goal of technology readiness is to prove your short-list of key, differentiating technologies is feasible through breadboards, prototypes, and scale-models of your system in both a relevant and operational environment. A relevant environment is kin to a wind-tunnel, static radar range, or other simulated conditions. An operational environment is more of a flight test, live-fire test, or other real-world scenario.
- **Develop holistic prototypes if necessary**. While there is value in prototyping individual technologies, skeletal, end to end prototypes may be necessary to evaluate the entire system. Oftentimes, the whole is more important than the sum of the parts. It is commonplace to evaluate an engine, airframe, or heads-up display, but it is less common to evaluate an entire avionics design. This is the type of mistake that causes major cost and schedule overruns.
- **Use iterative and incremental development**. Develop your system in phases or stages rather than all-at-once and then allowing it to come crashing down during big-bang integration tests. This is called iterative and incremental development in the popular vernacular of the day. For software, this may mean developing operational software in 14 to 30 day increments. For hardware, this may mean developing operational hardware in 30, 60, or 90-day increments.
- **Focus on high-risk technologies early**. Focus on prototyping your highest-risk technologies at the earliest possible opportunity, rather than saving the worst technological risks for last. This is all part of the science of front-loading your program resources in order to head off risk rather than saving all of your risk for the last minute when it costs more time and resources. Simply front-load your human resources, quality engineering, and technology readiness.

Conclusions

The goal of this article was to introduce technology readiness, the TRA process, TRLs, and a metrics suite to evaluate the ROI of TRAs, and then to analyze data from 62 U.S. DoD programs. TRAs were used by NASA in the 1970s, the purpose of TRAs is to ensure key technologies are mature and stable, and technology maturity must be achieved at key points early in the lifecycle. With costs and benefits as basic inputs, benefit-to-cost ratio, return-on-investment, net-present-value, breakeven-point, and real-options could be used to determine the business value of TRAs. Finally, we illustrated the ROI of TRAs using real-world data from 62 U.S. DoD programs.

The secret to unlocking the ROI of TRAs is determining their benefits, and this article outlined a simple, but effective methodology for translating technology maturity into measurable benefits. Cost and technology risk were converted into a single risk factor to account for both program complexity and technology maturity as a method of determining the economic benefits of TRAs. Once the costs and benefits data were determined from a GAO study of 62 U.S. DoD programs, we were able to perform a detailed cost and benefit analysis of TRAs using five simple metrics. This revealed that U.S. DoD programs with stable and mature technologies exhibit higher ROI.

Using real options, this article also illustrated that greater benefits may be obtained by delaying U.S. DoD programs with unstable and immature technologies, rather than continuing with them. This is known as a "strategic delay"—That is, delaying investments in U.S. DoD programs in order to maximize the business value of one or more investments because of technological risk. However, it's important not to confuse the strategic delay associated with using real options and the process of front-loading risk management by creating early prototypes of key technologies. The order of events should be: (a) identify key technologies, (b) prototype key technologies, and (c) delay further investments if key technologies prove infeasible (not vice versa).

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