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A Comparative Analysis of the Value of Technology Readiness Assessments

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The U.S. Department of Defense endorsed and later mandated the use of Technology Readiness Assessments (TRAs) and knowledge-based practices in the early 2000s for use as a tool in the management of program acquisition risk. Unfortunately, implementing TRAs can be costly, especially when programs include knowledge-based practices such as prototyping, performance specifications, test plans, and technology maturity plans. What is the economic impact of these TRA practices on the past and present acquisition performance of the U.S. Army, Navy, and Air Force? The conundrum today is that no commonly accepted approach is in use to determine the economic value of TRAs. This article provides a model for the valuation of TRAs in assessing the risk of technical maturity.

« *Image designed by Diane Fleischer*

Background

The U.S. Government Accountability Office (GAO), formerly the General Accounting Office, has reported on the acquisition performance of major defense acquisition programs (MDAPs) since 1960 (U. S. General Accounting Office, 1988). From the inception of the GAO's mandate to report annually to Congress on its assessment findings, the ability of the U.S. Department of Defense (DoD) to consistently execute its acquisition plan for the purchase of major weapon systems has been erratic, seldom meeting cost, schedule, or original performance objectives. From 1997 to 2012, the DoD's budget grew by almost 200 percent to $529 billion, representing more than 20 percent of the total operating budget of the U.S. government (DoD, 2013b). Amazingly, 31 percent of all MDAPs since 1997 have incurred either a significant or critical Nunn-McCurdy cost breach (DoD, 2013c). In addition, during 1995–2013 each of the military services has experienced cancellation of several major programs without receiving any or very few operational units for the funds expended (DoD, 2013c). Specifically, the Army cancelled 14 MDAPs (Table 1):

TABLE 1. ARMY-CANCELLED MDAPs (1995–2013)

1	Aerial Common Sensor (ACS)	8	Joint Common Missile (JCM)
2	Armed Reconnaissance Helicopter (ARH)	9	Joint Tactical Radio System–Ground Mobile Radio (Army Portion) (JTRS-GMR)
3	Army Tactical Missile System–Brilliant Anti-armor Technology (ATACMS-BAT)	10	Land Warrior Integrated Soldier System
4	C-27J Military Transport Aircraft (Army Portion)	11	Net-Enabled Command Capability (NECC)
5	RAH-66 Comanche Reconnaissance Armed Helicopter	12	Non Line-of-Sight–Land Systems (NLOS-LS)
6	XM2001 Crusader Self-Propelled Howitzer	13	Patriot Medium Extended Air Defense System Combined Aggregate Program Fire Unit (Patriot MEADS CAP Fire Unit)
7	Future Combat System (FCS)	14	Surface Launched Advanced Medium Range Air-to-Air Missile (SLAMRAAM)

The Navy cancelled seven MDAPs (Table 2):

TABLE 2. NAVY-CANCELLED MDAPs (1995–2013)

1	Advanced Deployable System (ADS)	5	Extended Range Munition (ERM)
2	Advanced SEAL Delivery System (ASDS)	6	F-35 Alt Engine (Navy Portion)
3	Expeditionary Fighting Vehicle (EFV)	7	VH-71 Kestrel Presidential Helicopter
4	Electronic Patrol – X (EP-X)		

Finally, the Air Force cancelled 10 MDAPs (Table 3):

TABLE 3. AIR FORCE-CANCELLED MDAPs (1995–2013)

1	Third Generation Infrared System (3GIRS)	6	Expeditionary Combat Support System (ECSS)
2	C-130 Avionics Modernization Program (AMP)	7	F-35 F136 Engine
3	C-27J Joint Cargo Aircraft	8	National Polar-Orbiting Operational Environmental Satellite System (NPOESS)
4	Combat Search and Rescue (CSAR-X)	9	Space Based Space Surveillance (SBSS) Follow-on
5	E-10 Multi-Sensor Command and Control Aircraft (E-10 MC2A)	10	Transformational Satellite Communications System (TSAT)

In 1999 the U.S. General Accounting Office defined a framework of acquisition practices modeled after commercial best practices that emphasized knowledge-based decision making, and recommended its adoption by the DoD (U.S. General Accounting Office, 1999). The DoD adopted knowledge-based practices in 2001 with the issuance of DoD Directive (DoDD) 5000.1 and DoD Instruction (DoDI) 5000.2 (see DoD 2013e; 2013a, respectively). Starting in May 2003, and annually thereafter, the GAO has reported to Congress its assessment of the acquisition performance of MDAPs, emphasizing the DoD's use of mature technologies Technology Readiness Assessments (TRAs). Such assessment includes adherence to knowledge-based acquisition practices such as prototyping, performance specifications, test plans, and technology

maturity plans (U. S. General Accountability Office, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012; U. S. General Accounting Office, 2003, 2004). The DoD attributes a significant proportion of poor acquisition performance to the incorporation of immature technologies into its weapon system acquisitions by DoD components, Defense agencies, and their suppliers. Associated with the DoD's yearly multibillion dollar budget for the procurement of military weapon systems is the expenditure of millions of dollars each year performing TRAs as one of the approaches to monitor and control the perceived risk of incorporating immature technology into the acquisition process. The DoD uses TRAs as a means of identifying key components, referred to as critical technologies (CT), and assessing their maturity using a nine-point Technology Readiness Level (TRL) scale (Mankins, 1995). As part of a TRA, an independent team of subject matter experts assists the program manager (PM) in the process of identifying CTs believed to be the major drivers of cost and schedule performance during the acquisition. The team also assists the PM in assessing component maturity and assigning TRLs. Their assessment is then documented in a TRA report prior to the major decision-making juncture in the overall acquisition life cycle (i.e., Milestone B). (Note that the TRA report is mandated by the Milestone Decision Authority [DoD, 2011a, 2011b].) Typically CTs are advanced or leading-edge technology that will push the performance envelope of the weapon system, thus providing a strategic military advantage (Petraeus, 2010). The DoD believes that identifying and mitigating the use of immature technologies (i.e., TRL < 6) early is the key to improving overall acquisition performance (i.e., reducing cost and schedule overruns, increasing delivery order quantities, successful weapon systems deployment, etc.)

(Cancian, 2010; DoD, 2009; U. S. General Accounting Office, 1998, 1999). Bailey, Mazzuchi, Sarkani, and Rico (2014) reported, however, that during 2003–2012 only slightly more than half—58.1 percent—of the CTs being used in development acquisitions were sufficiently matured (i.e., TRL ≥ 6) (see Table 4). This tendency to proceed into development or production with less knowledge than required has led to similar results experienced over the last five decades, with several programs failing to meet the original cost, schedule, and performance objectives (Bair, 1994; Fox, 2011; U. S. General Accounting Office, 1988).

TABLE 4. 2003–2012 DoD CT MATURITY ASSESSMENTS

Year	Critical Technologies		
	Immature	Total	Mature
2012	103	345	70.1%
2011	106	371	71.4%
2010	105	372	71.8%
2009	177	420	57.9%
2008	208	466	55.4%
2007	241	451	46.6%
2006	225	428	47.4%
2005	251	443	43.3%
2004	193	391	50.6%
2003	39	117	66.7%
Avg	**165**	**380**	**58.1%**

Sources: U.S. General Accounting Office, 2003, 2004; GAO 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012

Utilization of proven technologies that offer moderate performance improvements, yet are well understood in terms of meeting scope, cost, schedule, and performance constraints, is DoD's preferred acquisition approach. Currently, however, basic arguments favor applying the five-stage DoD acquisition life cycle defined by DoD (2013d). This life cycle includes up-front investments in large-scale system prototypes during the Technology Demonstration (TD) phase; and the performance of TRAs, along with identifying their associated CTs, assigning TRLs, and ensuring they reach sufficient maturity—all are qualitative at best and are based only on engineering judgment or face validity. Clausing and Holmes (2010) devised a structured technology readiness method

that added quantification measures in an attempt to remove perceived subjectivity within the National Aeronautics and Space Administration's TRL framework. However, little quantitative evidence has been collected on the actual economic benefits of technology maturity via TRAs for any of the military Services. Therefore, the purpose of this article is to examine the wealth of information emerging from government agencies such as the GAO, DoD, and others and apply economic models to begin examining the quantitative benefits of technology maturity for the major programs of each of the military Services. The results of this analysis should help members of the acquisition community determine whether TRA knowledge-based practices have a positive effect on acquisition outcomes. More important, in today's environment of fiscally austere federal budgets and after the impact of the sequester, such evidence may also be of benefit to military strategists if the use of TRAs helps reduce cost and schedule overruns and increases delivery order quantities (DoQs) for the Army, Navy, and Air Force (Petraeus, 2010).

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Problem

The DoD portfolio of MDAPs currently stands at 95, for fiscal year 2013, with an estimated cost for development and procurement of nearly $1.7 trillion (DoD, 2013b). Overall acquisition performance has been less than stellar, and a significant proportion of the programs suffer from excessive cost, schedule overruns, and dramatically reduced DoQs, while some have been cancelled outright. The DoD's position is that technology maturity, or lack thereof, is a primary measure of acquisition performance (GAO, 2008b). That is, weapon systems that use mature technologies will have better acquisition performance than those using immature technologies (Weapon Systems Acquisition Reform Act, 2009). Technical maturity (or knowledge-based practices as they are frequently called) such as the TD phase, full-scale system prototype, and

the TRA process together may cost up to 10 percent of the acquisition budget through the manufacturing phase. The fundamental concept is that these up-front technology maturity investments will head off downstream manufacturing, operating, and maintenance costs (Assessment Panel, 2006; DoD, 2008; Olagbemiro, Mun, & Shing, 2011). Each of the military Services has incurred costs implementing the TRA process as mandated by the DoD and have assumed the advertised benefits would lead to a successful acquisition. However, little data are available on the economic benefits of performing TRAs. Even the most avid supporters of TRAs want to quantify their economic benefits (Dubos, Saleh, & Braun, 2008; Kenley & El-Khoury, 2012). The use of economic valuation is experiencing a revival of sorts throughout the project management, engineering, information technology, and acquisition communities (Honour, 2004; Reinertsen, 2009). Among these, the most commonly cited measure of business value is the concept of return on investment or ROI (Morgan, 2005). That is, cumulative economic benefits less costs, divided by costs. Today, however, economists promote a suite of other, more valid measures, such as net present value (NPV), internal rate of return, real options analysis (ROA), and numerous other measures of project performance (Tockey, 2004). The majority of these methods are what is known as top-down parametric models, which require only a few basic inputs such as costs, benefits, interest rate, time horizon, or even risk. Costs and benefits are the key inputs. Cost data are being collected with increasing frequency, and soft, nonquantifiable benefits are sometimes collected as well. It's only when the latter are converted into economic terms, or monetized, that the portfolio of economic equations and models may be applied. In spite of the myriad complex economic methods, three basic forms seem to be standing the test of time (i.e., ROI, NPV, and ROA). Therefore, the basic research problem or question, given the DoD mandate requiring TRAs for all MDAPs, is this: What are the economic benefits of applying TRAs for each military Service? More specifically, what is the associated cost, benefit, ROI, NPV, and ROA of TRAs? Consequently, the fundamental goal and objective of this article is to collect and analyze MDAP acquisition data, apply some of these basic economic models, and explore the economic value of applying TRAs to acquisitions of each military Service.

Research Method

The research method developed for this article involved collecting measurements, which were used to analyze the value of TRAs for each military Service. It was used to help determine the costs and benefits of technology maturity and whether it translates to improved acquisition performance. First, a spreadsheet model was constructed consisting of basic attributes, such as government agency, program type, program name, acquisition costs, and technology maturity. Then other fundamental valuation drivers were added to derive key indicators of value, such as acquisition risks, TRA costs, and TRA benefits. Using the basic acquisition attributes and derived data, metrics and models were then added to help determine the value of TRAs. These included benefit/cost ratio (B/CR), ROI, NPV, breakeven point (BEP), and ROA. The cost-and-benefit spreadsheet was then populated with acquisition data from GAO reports of the major programs from each military Service covering a 10-year period—2003 to 2012—for further analysis. These seven metrics were originally outlined by Rico (2007) as follows:

1. Costs = Total amount of money spent on technology readiness

2. Benefits = Total amount of money gained from technology readiness

3. B/CR = Ratio of technology readiness benefits to costs

4. ROI percent = Ratio of adjusted technology readiness benefits to costs

5. NPV = Discounted cash flows of technology readiness

6. BEP = Point when benefits exceed costs of technology readiness

7. ROA = Business value realized from strategic delay due to risk

ROA attempts to estimate the value of the flexibility a PM has to change direction of a project as new data and information emerge to help remove uncertainty about the viability of a chosen or desired path (de Weck, de Neufville, & Chaize, 2004). Trigeorgis (1993) asserted that managerial flexibility is a set of real options that may consist of options to defer, abandon, contract, expand, or switch investment. Each of these

options may result in a different valuation. The Black-Scholes method for determining real option value was chosen for this study as it provides the most accurate valuation available today. As suggested earlier, parametric forms of ROA have emerged making it possible to analyze acquisition performance (Black & Scholes, 1973; Kodukula & Papudesu, 2006).

Data Analysis and Results

A recent report by the GAO provided detailed cost data of 47 DoD programs from the 2012 MDAP portfolio, which is the first required input for determining the ROI of TRAs (GAO, 2012). Risk is the second required input for determining ROI of TRAs. Management of risk is a key element in the operational planning of any major system development. Identifying and quantifying the technological risk of a program may have been challenging in the past; however, the GAO report on the 2012 MDAP portfolio provided the necessary information for estimating risks: (a) total cost, and (b) technology maturity (GAO, 2012). Technology maturity is the ratio of immature to total critical technologies (equally weighted), which allows us to determine technology risk as the normalized rank of technology maturity. Cost risk is the normalized rank of total costs, which when combined with technology risk gives a combined risk. Finally, we determine an overall risk percentage as the normalized combined risk. Armed with these measures, we are able to unlock the benefits of technology stability and maturity, and reveal the third input—the economic benefits of performing TRAs. The GAO report on 2012 MDAPs provided three data points for determining the benefits of TRAs: (a) total costs, (b) technology maturity, and (c) the average cost savings from technology stability and maturity. Benefits are a product of total costs, risk, and an average reported benefit of 29.7 percent (GAO, 2007). Based on a sensitivity analysis, benefits were moderated and smoothed by the normalized costs. The following discussion utilizes these measures in analyzing the value of TRAs for each military Service.

Value Analysis of TRAs for Army, Navy, and Air Force MDAPs

A multitude of economic equations–such as cost, benefit, B/CR, ROI percent, NPV, BEP, and ROA–many of which were first introduced during the industrial revolution, help determine the business value of an investment such as cost, benefit, B/CR, ROI percent, NPV, BEP, and

ROA (Rico, 2007). ROI percent, which is a ratio of benefits to costs less the costs, is one of the oldest measures used to estimate business value (Phillips, 1997). Although having some similarity with ROI percent, NPV additionally takes into account the time-value of money (e.g., devaluation due to inflation) and is considered more realistic and economically responsible. During the 1970s, ROA emerged as a measurement approach to estimate the value of investments as a strategy of delaying investments due to risk presence (Black & Scholes, 1973; Kodukula & Papudesu, 2006). Rico (2007) posits that ROI percent is used for determining near-term benefits, NPV for mid-term benefits, and ROA for longer term benefits in the presence of risk. Our study utilizes all three vantage points in analyzing the acquisition data for the Army, Navy, and Air Force: (a) ROI percent, (b) NPV, and (c) ROA (see Tables 5–7, respectively).

TABLE 5. ILLUSTRATIVE ARMY ROI DATA FROM 2012 MDAP PORTFOLIO

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
17	Excalibur	$178.1	$472.5	2.7:1	165.4%	$231.1	3.9 Years	$333.8
28	JHSV	$367.4	$851.5	2.3:1	131.7%	$369.9	5 Years	$567.6
23	Gray Eagle	$515.9	$983.3	1.9:1	90.6%	$335.5	7.7 Years	$624.8
4	IAMD	$552.9	$963	1.7:1	74.2%	$280.9	9.8 Years	$608.2
31	JTRS AMF	$816.1	$1,039.9	1.3:1	27.4%	$84.4	48.4 Years	$660.8
32	JTRS HMS	$835.8	$1,035.8	1.2:1	23.9%	$61.1	68.4 Years	$658.8
3	AH-64D Block IIIa	$1,073.7	$1,141.4	1.1:1	6.3%	-$85.3	-62.9 Years	$729.7

Note. All costs and benefits are in millions of dollars. IAMD = Integrated Air and Missile Defense; JHSV = Joint High Speed Vessel; JTRS AMF = Joint Tactical Radio System Airborne & Maritime/Fixed Station; JTRS HMS = Joint Tactical Radio System Handheld, Manpack, and Small Form Fit.
Source: GAO, 2012

TABLE 6. ILLUSTRATIVE NAVY ROI DATA FROM 2012 MDAP PORTFOLIO

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
25	IDECM	$82.2	$239	2.9:1	190.9%	$124.8	3.3 Years	$175
38	NMT	$188.1	$532.2	2.8:1	183.0%	$272.7	3.4 Years	$385.7
45	VTUAV	$261.5	$725.7	2.8:1	177.5%	$366.9	3.6 Years	$522
41	SSC	$441.3	$1,165.3	2.6:1	164.1%	$567.8	3.9 Years	$821.7
37	MUOS	$697.8	$1,709.2	2.4:1	144.9%	$782.2	4.5 Years	$1,166.3
11	BAMS	$1,305.2	$2,605.4	2.0:1	99.6%	$950.8	6.9 Years	$1,666
16	E - 2 D AHE	$1,774.7	$2,920.8	1.6:1	64.6%	$754.4	11.8 Years	$1,843.1

Note. All costs and benefits are in millions of dollars. BAMS = Broad Area Maritime Surveillance; E-2D AHE = Advanced Hawkeye; IDECM = Integrated Defensive Electronic Countermeasures; MUOS = Mobile User Objective System; NMT = Navy Multiband Terminal; ROA = Real Options Analysis; ROI = Return on Investment; SSC = Ship-to-Shore; VTUAV = Vertical Take-Off and Landing Tactical Unmanned Aerial Vehicle.
Source: GAO, 2012

TABLE 7. ILLUSTRATIVE AIR FORCE ROI DATA FROM 2012 MDAP PORTFOLIO

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
27	JASSM-ER	$373	$1,097	2.9:1	194.1%	$576.9	3.2 Years	$806.5
21	GPS III	$421.1	$1,236.7	2.9:1	193.7%	$649.8	3.2 Years	$908.8
19	FAB-T	$468.8	$1,375.3	2.9:1	193.3%	$722	3.2 Years	$1,010.2
12	C-130 AMP	$620.4	$1,812.7	2.9:1	192.2%	$949.2	3.3 Years	$1,329.5
40	MQ-9	$1,191.9	$3,429.1	2.9:1	187.7%	$1,777.4	3.4 Years	$2,500.9
43	SBIRS High	$1,826.7	$5,165.1	2.8:1	182.8%	$2,645.7	3.5 Years	$3,742.5
33	KC-46	$4,412.7	$10,464.4	2.4:1	137.1%	$4,648.3	4.7 Years	$7,041.1

Note. All costs and benefits are in millions of dollars. C-130 AMP = C-130 Avionics Modernization Program; FAB-T = Family of Advanced Beyond-Line-of-Site Terminals; GPS III = Global Positioning System III; JASSM-ER = Joint Air-to-Surface standoff Missile-Extended Range; KC-46 = KC-46 Pegasus Military Aerial Refueling and Strategic Transport Aircraft; MQ-9 = MQ-9 Reaper Unmanned Aerial Vehicle; ROA = Real Options Analysis; ROI = Return on Investment; SBIRS High = Space-Based Infrared System High.
Source: GAO, 2012

We examined the model results for each of the military Service portfolios. The Army's acquisition performance, as reported in its 2012 portfolio of MDAPs, exhibited a wide range of performance. For example, the B/CR performance estimate ranged from 1.1:1 to 2.7:1, and the BEP from -62.9 years to 3.9 years. Conversely, the Navy's B/CR ranged from 1.6:1 to 2.9:1, and the BEP from 11.8 years to 3.3 years, while the Air Force's B/CR ranged from 2.4:1 to 2.9:1, and the BEP from 4.7 years to 3.2 years. This performance may indicate a lack of consistent institutional adherence to DoDI 5000.02 by the Army, although further detailed analysis is required. The Navy's acquisition performance, as reported in its 2012 portfolio of MDAPs, appears to exhibit more consistency within its portfolio of programs in reaping the benefits of TRA knowledge-based practices than the Army. In particular, a higher percentage of its programs had an ROI greater than 100 percent, which may indicate a more effective CT selection process that leverages sufficiently matured technology for incorporation into development programs, although less than that accomplished by the Air Force. The Air Force's acquisition performance, as reported in its 2012 portfolio of MDAPs, appears to exhibit even more consistency within its portfolio of programs in reaping the benefits of TRA knowledge-based practices than the Army or Navy. Of particular note is that a higher percentage of the Air Force programs had a B/CR measurement of 2.8:1 or higher; additionally, the Service reached its BEP sooner (< 3.5 years). This performance may indicate a greater efficiency in program acquisition and operation due to greater adherence to knowledge-based practices.

A sampling of the case study analysis performed for each portfolio is provided in the following discussion. Each case provides additional insight into the potential economic risk associated either with or without sufficiently mature critical technology.

Analysis of AH-64D Block IIIa. The Army's Apache Block IIIa program (AB3A) is an upgrade of the "AH-64D Longbow helicopters to improve performance, situational awareness, lethality, survivability, and interoperability, and to prevent friendly fire incidents" (GAO, 2012, p. 45). The program acquisition state for this study was in the early stages of the Production and Deployment (P&D) phase. Upon determination of costs and benefit of TRAs for the AH-64D Block IIIa, our model estimates values for the other five metrics (i.e., B/CR, ROI percent, NPV, BEP, and ROA). Our analysis of the B/CR metric reflects a less-than-favorable valuation. It indicates, for every dollar expended, only a relatively small

percent (i.e., 10 percent) is returned as benefit. The ROI percent valuation, which also reflects a simple cost-benefit ratio, less the costs, without consideration for the time value of money, shows only a 6.3 percent return on the program's investment in TRA practices, or $.063 saved for every dollar invested. The NPV valuation incorporates the time value of money in the economic evaluation and provides the present value of the estimated return. In a traditional business decision-making scenario, a positive difference between NPV and cost provides justification to proceed with the program or investment. The NPV valuation here reflects a significant negative valuation of -$85.3 million, and may provide sufficient justification to halt the program or investment. The BEP valuation reflects being unable to recoup the full initial cost of investment in TRA practices due to the remaining immaturity of critical technologies and unstable requirements. Finally, the ROA valuation results in an estimated return of $729.7 million, which is $674.4 million more than the NPV estimate, and is an estimated $344.7 million less than the cost of implementing TRA practices. In this example of the AB3A program, several of the key ROI metrics suggest an unstable technology base and cost risk, and that the program risk in proceeding into the next phase is high.

Analysis of Mobile User Objective System (MUOS). The Navy's MUOS is "a satellite communications system that is expected to provide a worldwide, multi-Service population of mobile and fixed-site terminal users with increased narrowband communications capacity and improved availability for small terminal users" (GAO, 2012, p. 111). The program acquisition state for this study was in the early stages of

the P&D phase. The B/CR valuation reflects an impressive value added between the cost of implementing TRA and knowledge-based practices, and the potentially derived benefits. About $2.40 of benefit is gained or saved for every dollar expended (i.e., efficiency). The ROI percent valuation indicates an approximate return of 144.9 percent on the program's investment in TRA practices, or approximately $1.44 saved for every dollar invested. The NPV valuation result is approximately $782.2 million. The BEP valuation reflects being able to recoup (in efficiency gains) the full initial cost of the investment in TRA practices in approximately 4.5 years. Finally, the ROA valuation results in an estimated return of $1,166.3 million, which is $384.1 million more value than the NPV estimate, and an estimated return of $468.5 million above the cost of implementing TRA practices. In this example of the MUOS program, all of the key ROI metrics suggest a sufficiently mature technology base. Furthermore, it indicates the technological risk of proceeding into the next development phase is low.

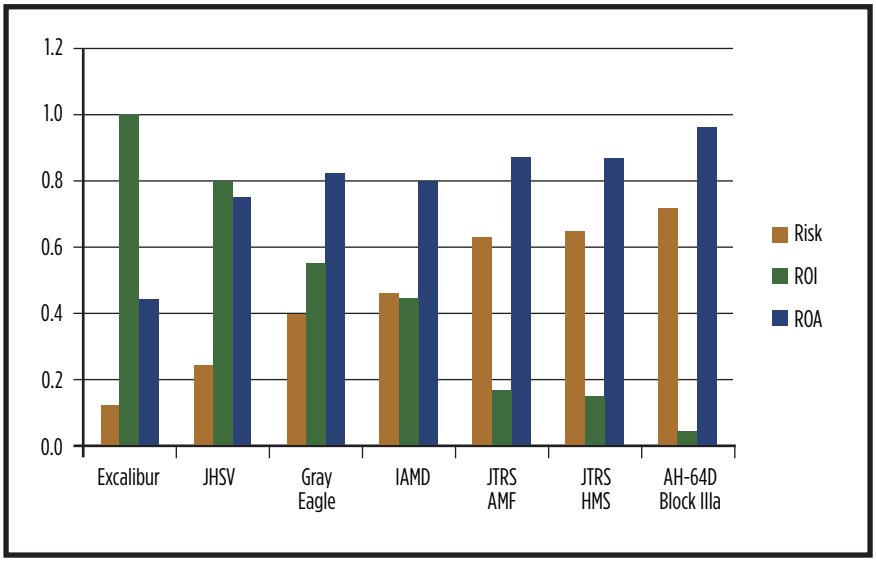
Analysis of JASSM-ER. The Air Force's Joint Air-to-Surface Standoff Missile–Extended Range (JASSM-ER) program will "field a next-generation cruise missile capable of destroying the enemy's war-sustaining capability from outside its air defenses. The JASSM-ER missiles are low-observable, subsonic, and have a range greater than 500 miles" (GAO, 2012, p. 91). The program acquisition state for this study was in the early stages of the P&D phase. Similar to the MUOS program, the resultant economic valuations are equally impressive. Of particular note here, the ROA valuation results in an estimated return of $806.5 million, which is $229.6 million more value than the NPV estimate, and an estimated return of $432.9 million above the cost of implementing TRA practices. Similar to the MUOS program, all of the JASSM-ER program key ROI metrics suggest a sufficiently mature technology base. It also indicates the technological risk of proceeding into the next development phase is low.

Summary of Data Analysis

Using our model, the data from the GAO (2012) report on the 2012 MDAP portfolio were first sorted by risk percent in ascending order. The data were then filtered by military Service. Figures 1, 2, and 3 provide illustrative histograms of each of the Services' programs that have been highlighted in this article. The first major finding revealed by this analysis, and consistent across the portfolios of the military Services, was that ROI percent decreases as program risk and cost increase. This

coincides with results from other studies: larger programs are inherently more complex and risk-prone than smaller, shorter duration programs, which have exhibited as much as a 90 percent success rate (Benediktsson & Dalcher, 2005). In addition, increasing risk percent indicates decreasing technology maturity; consequently, programs with a larger number of unstable and immature technologies will have a larger risk and lower ROI. The most significant finding is that ROA increases as risk increases and ROI percent decreases, especially if risk-reducing acquisition practices are used, such as evolutionary acquisition, dividing acquisitions into smaller increments, and spiral development (Benediktsson & Dalcher, 2005; Reagan & Rico, 2010). Delaying a program due to size and technology instability and immaturity by dividing the scope into numerous smaller increments, spirals, and iterations across the entire acquisition life cycle may result in greater economic benefits for each military Service. This supports the concept provided by other studies, which reflect that when there is heightened risk, the flexibility to delay a decision or investment can be quite valuable (Dixit & Pindyck, 1995; Fichman, Keil, & Tiwana, 2005; Luehrman, 1995; Trigeorgis, 1993).

FIGURE 1. ILLUSTRATIVE ARMY RISK, ROI, AND ROA DATA FROM 2012 MDAP PORTFOLIO

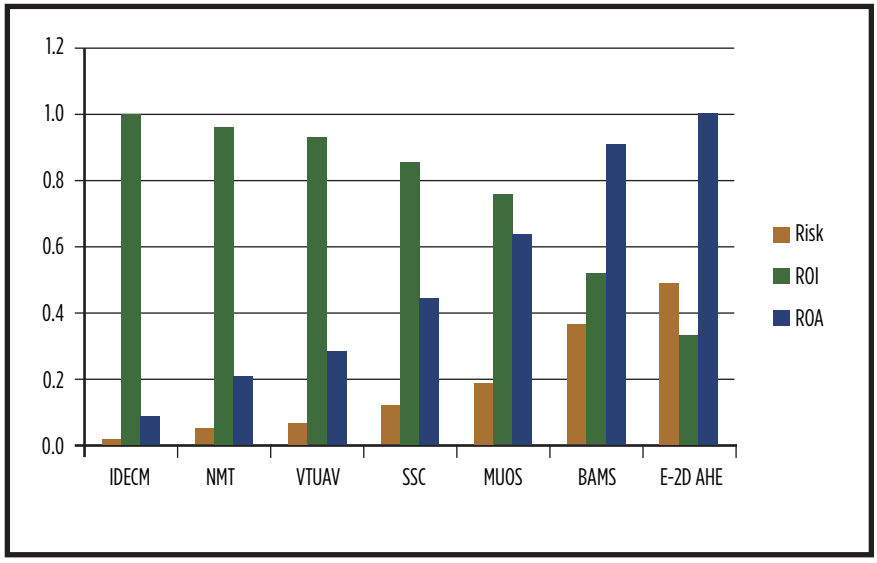


Source: GAO, 2012

It can be seen from the earlier examples that the use of classical economic valuation methods may provide useful management insight into the state of an acquisition program. In addition, ROA may provide each

military Service a useful estimate of the value of deferring a program until its technologies are sufficiently mature, even when NPV indicates no further investment may be warranted, hence our motivation for including ROA in our process framework (Kodukula & Papudesu, 2006).

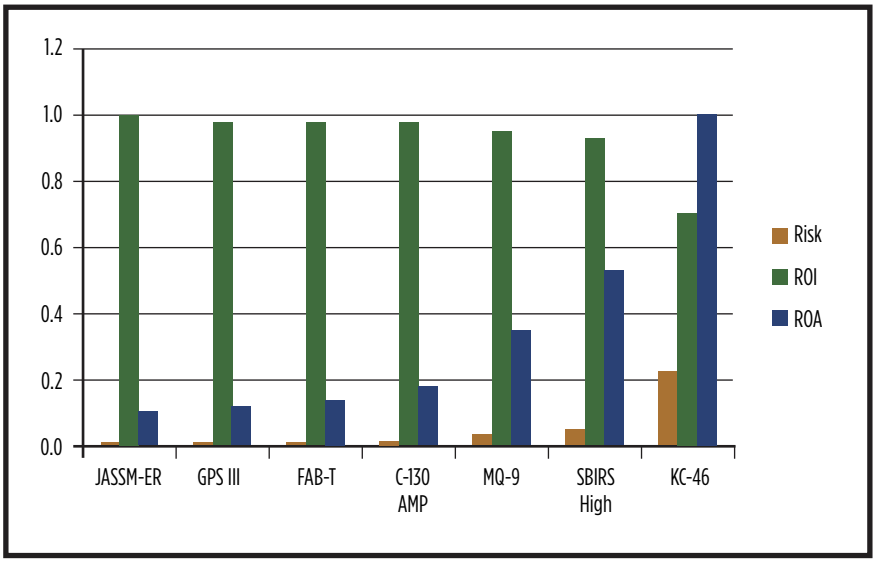
FIGURE 2. ILLUSTRATIVE NAVY RISK, ROI, AND ROA DATA FROM 2012 MDAP PORTFOLIO



Source: GAO, 2012

Delaying a program due to size and technology instability and immaturity by dividing the scope into numerous smaller increments, spirals, and iterations across the entire acquisition life cycle may result in greater economic benefits for each of the military services.

FIGURE 3. ILLUSTRATIVE AIR FORCE RISK, ROI, AND ROA DATA FROM 2012 MDAP PORTFOLIO



Source: GAO, 2012

Trend Analysis (2003–2012)

As we extended our study of the GAO data to encompass the 2003–2012 period, our analysis indicated what appears to be inconsistency in the level of adherence and commitment by the individual military Services in their execution of knowledge-based acquisition practices mandated by Congress and the DoD (U. S. General Accounting Office, 2003, 2004; GAO, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012). Specifically, as reflected in Table 8, we found, on average, taht 40 percent of the Army's MDAP CTs rated as sufficiently mature, compared to 57 percent for the Navy and 67 percent for the Air Force. Perhaps even more telling is that the commitment level of adherence to TRA knowledge-based practices appears to have carried through to the level of acquisition performance success realized during this decade. This seems to be consistent with results from other studies by the GAO and DoD, showing that technology maturity, or lack thereof, is a predictor of acquisition performance (DoD, 2008; GAO, 2008b). Moreover, weapon systems that use mature technologies will have better acquisition performance than those using immature technologies.

TABLE 8. 2003–2012 DoD MILITARY SERVICES CT MATURITY ASSESSMENTS

Year	Army Critical Technologies			Navy Critical Tehnologies			Air Force Critical Technologies		
	Immature	Total	Mature	Immature	Total	Mature	Immature	Total	Mature
2012	35	83	57.8%	34	109	68.8%	25	74	66.2%
2011	44	122	63.9%	31	102	69.6%	29	82	64.6%
2010	43	106	59.4%	35	104	66.3%	8	72	88.9%
2009	83	124	33.1%	40	100	60%	18	82	78%
2008	81	128	36.7%	48	117	59%	30	96	68.8%
2007	91	125	27.2%	71	160	55.6%	44	108	59.3%
2006	99	140	29.3%	63	103	38.8%	44	98	55.1%
2005	104	118	11.9%	76	130	41.5%	47	105	55.2%
2004	85	109	22%	60	102	41.2%	30	102	70.6%
2003	7	19	63.2%	10	33	69.7%	11	37	70.3%
Avg	**67**	**107**	**40.451%**	**47**	**106**	**57.061%**	**29**	**86**	**67.7%**

Source: U.S. General Accounting Office, 2003, 2004; GAO, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012

For each of the military Services, and the DoD overall—including the Marines and Missile Defense Agency—a few trends seemingly emerge as reflected in Table 9: (a) an overall lowering of risk percent in the weapon system portfolio, which indicates an overall reduction in the incorporation of immature technology into development programs; (b) an overall improvement in B/CR, indicating growth in execution efficiency; (c) overall growth in ROI percent, indicating a trend of maximizing return on technology choices; (d) improvement in BEP, indicating less time needed before the benefits of technology readiness exceed costs; and (e) an overall lowering of ROA valuation as risk percent is lowered, indicating more programs are waiting for critical technologies to mature before entering into development. The trends seem to suggest that the incorporation of TRAs and knowledge-based practices into the acquisition programs of each military Service may indeed improve cost, schedule, and technical performance of those programs, and consequently of the overall DoD weapon systems portfolio.

TABLE 9. SUMMARY ROI OF TRA ANALYSIS OF U.S. GAO MDAP DATA FROM 2003–2012

Yr.	No. Pgms	Critical Technologies			Risk %	Cost	Benefit	B/CR	ROI	NPV	BEP (Yrs)	ROA
		Immature	Tot	Mature								
2012	47	103	345	70.1%	8.0%	$82,935.8	$228,547.6	2.8:1	175.6%	$114,962.5	3.6	$163,957.1
2011	49	106	371	71.4%	8.7%	$83,456.8	$228,483.7	2.7:1	173.8%	$114,386.1	3.6	$163,487.4
2010	55	105	372	71.8%	9.6%	$87,909.6	$238,416.2	2.7:1	171.2%	$118,533.9	3.7	$169,952.1
2009	59	177	420	57.9%	10.2%	$97,444.3	$262,715.5	2.7:1	169.6%	$130,039.9	3.7	$186,825.9
2008	72	208	466	55.4%	8.7%	$106,304.8	$291,048.4	2.7:1	173.8%	$145,712.6	3.6	$208,258.1
2007	62	241	451	46.6%	10.0%	$87,997.8	$237,794.1	2.7:1	170.2%	$117,907.0	3.7	$169,261.4
2006	51	225	428	47.4%	11.2%	$84,425.8	$225,533.7	2.7:1	167.1%	$110,862.8	3.8	$159,782.8
2005	54	251	443	43.3%	11.3%	$80,422.3	$214,634.1	2.7:1	166.9%	$105,428.4	3.8	$152,001.2
2004	51	193	391	50.6%	10.9%	$67,429.3	$180,664.2	2.7:1	167.9%	$89,007.0	3.8	$128,150.2
2003	26	39	117	66.7%	12.0%	$47,702.0	$126,332.6	2.6:1	164.8%	$61,688.8	3.9	$89,182.2

Note. All costs and benefits are in millions of dollars.
Source: U.S. General Accounting Office, 2003, 2004; GAO, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012

Conclusions

For several decades the DoD and Congress have endeavored to institute, revamp, refine, tweak, overhaul, and reform the Defense Acquisition System in attempts to structure a system of procuring major weapon systems as efficiently, effectively, and affordably as possible, but unfortunately, without achieving significant sustained improvement (Bair, 1994; DoD, 2013b; Fox, 2011; U. S. General Accounting Office, 1988). Acquisition performance continues to struggle and manifest itself in the form of cost and schedule overages, and reduced DoQs. Economic evidence, however, is starting to emerge indicating that investments in knowledge-based practices, especially TRAs as a means of achieving technology maturity, are beginning to pay off. In this article, we have introduced a model to evaluate the costs and benefits of the current MDAP portfolios of the U.S. Army, Navy, and Air Force using classic economic techniques such as ROI, NPV, and ROA. We have shown there is added ROI valuation due to the use of TRAs for MDAPs. We have also shown that the ability to delay a decision to move into development/production until CTs (and associated risk) are sufficiently matured (mitigated) may provide significant cost benefit to a program. We have defined a set of valuation metrics for ROI of TRAs that includes costs,

benefits, B/CR, ROI percent, NPV, BEP, and ROA. Indeed, used along with traditional discounted cash-flow methods, real options analysis provides additional insight for the decision maker into the cost and technology risk for MDAPs. In addition, use of the TRA framework enhances opportunities to maximize ROI from new, complex technologies targeted for MDAPs. The ROA measure supports (a) valuation of the decision to delay, (b) identification and quantification of risk associated with CTs, and (c) prioritization of program development and mitigation of risks.

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Acquisition performance continues to struggle and manifest itself in the form of cost and schedule overages and reduced DoQs. Economic evidence, however, is starting to emerge indicating that investments in knowledge-based practices, especially TRAs as a means of achieving technology maturity, are beginning to pay off.

Our study has also revealed an inconsistency between the military Services in their commitment level of adherence to knowledge-based practices as mandated by DoDI 5000.02 (DoD, 2013e). In particular, although the evidence continues to mount indicating that programs with immature technology experience cost, schedule, and performance shortfalls, the military Services appear to discount this risk, continuing to allow immature technology into their development programs. Table 8 speaks clearly to this issue, showing that, on average over the past decade, 40 percent of the Army's MDAP CTs rated as sufficiently mature, compared to 57 percent for the Navy and 67 percent for the Air Force.

This article is designed to help decision makers within the Army, Navy, and Air Force, as well as the DoD overall, in understanding the economic impact of the use or nonuse of TRA knowledge-based practices. Through objective, quantifiable measures of performance such as those discussed in this article, we can begin making significant strides toward improving the outcome of our investments in major weapon systems acquisition (Weapon Systems Acquisition Reform Act, 2009).

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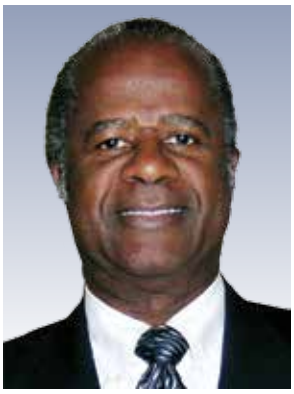

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