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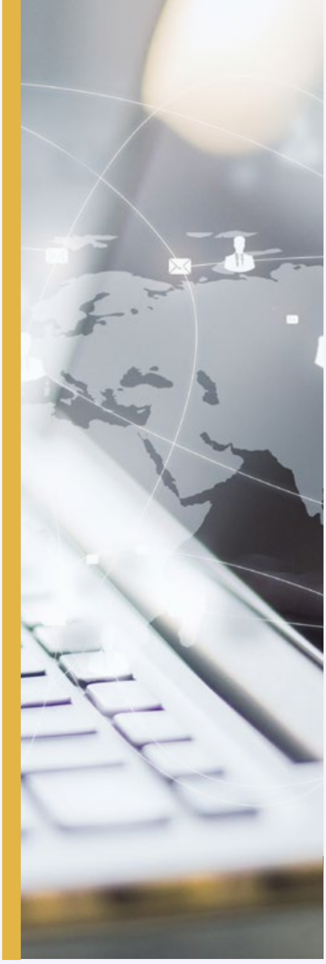

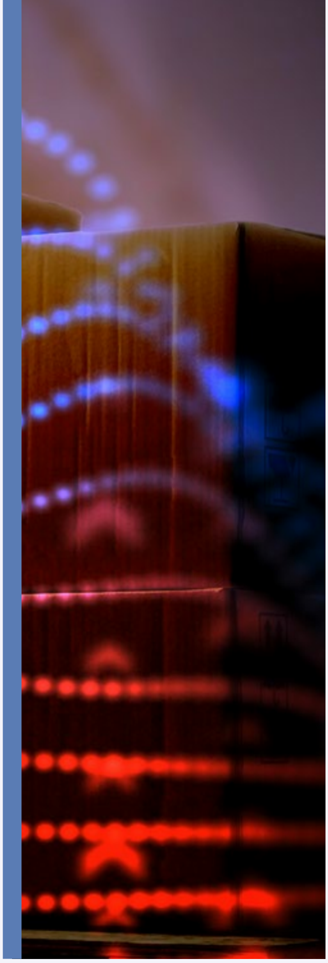

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"Extra!" Using the Newsvendor Model to Optimize War Reserve Storage

MAJ Minou Pak, USA, MAJ Joshua L. Peeples, USA, and Joseph T. Klamo

To support future troop surges, the U.S. military must make difficult decisions in advance concerning war materiel inventory levels in the face of uncertainty regarding the intensity and adversary of future conflicts. This research presents a method for selecting an optimal war reserve inventory level using expected marginal cost analysis.

CONTENTS | Featured Research

FROM THE CHAIRMAN AND EXECUTIVE EDITOR

Dr. Larrie D. Ferreiro

The theme for this issue is "Reimagining Program Management." The volume, velocity, and complexity of change, adversarial advances, emerging technologies, as well as new and adaptive acquisition policies, have upended previous business models and are shaping anew the way we live, think, work, learn, and lead. When it comes to acquisition, the program manager bears the brunt of change more often than most. As such, how might we reimagine the role of program managers to inspire and empower them to stay at the forefront and lead change rather than be forced to simply react to it?

The first paper, "Aligning Program Management Competencies to Industry Standards" by Jonathan L. Karnes and Robert F. Mortlock, examines DoD program management (PM) training standards by providing traceability between the DoD PM competencies and the Project Management Institute (PMI)'s standards for project, which were required by the 2020 National Defense Authorization Act.

The second paper, "Exploring Performance in Air Force Science and Technology Programs" by Eric A. Plack, Jonathan D. Ritschel, Edward D. White, Clay M. Koschnick, and Scott T. Drylie, examines Air Force science and technology programs, and assesses the linkages between technology maturation, cost/schedule growth, contract values, program type, and the contractor-government construct.

The third paper, "Extra! Using the Newsvendor Model to Optimize War Reserve Storage" by Minou Pak, Joshua L. Peeples, and Joseph T. Klamo, presents a method for selecting an optimal war reserve inventory level using expected marginal cost analysis, in support of future troop surges occurring in the face of uncertainty regarding the intensity and adversary of future conflicts.

This issue's Current Research Resources in Defense Acquisition focuses on Digital Engineering.

The featured work in the Defense Acquisition Professional Reading List book review is Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*, reviewed by Dr. John D. McCormack.

We welcome Dr. Marina Theodotou to the Editorial Board, whose ideas helped shape this issue's editorial remarks.

Dr. Larrie D. Ferreiro

Chairman and Executive Editor

Defense ARJ

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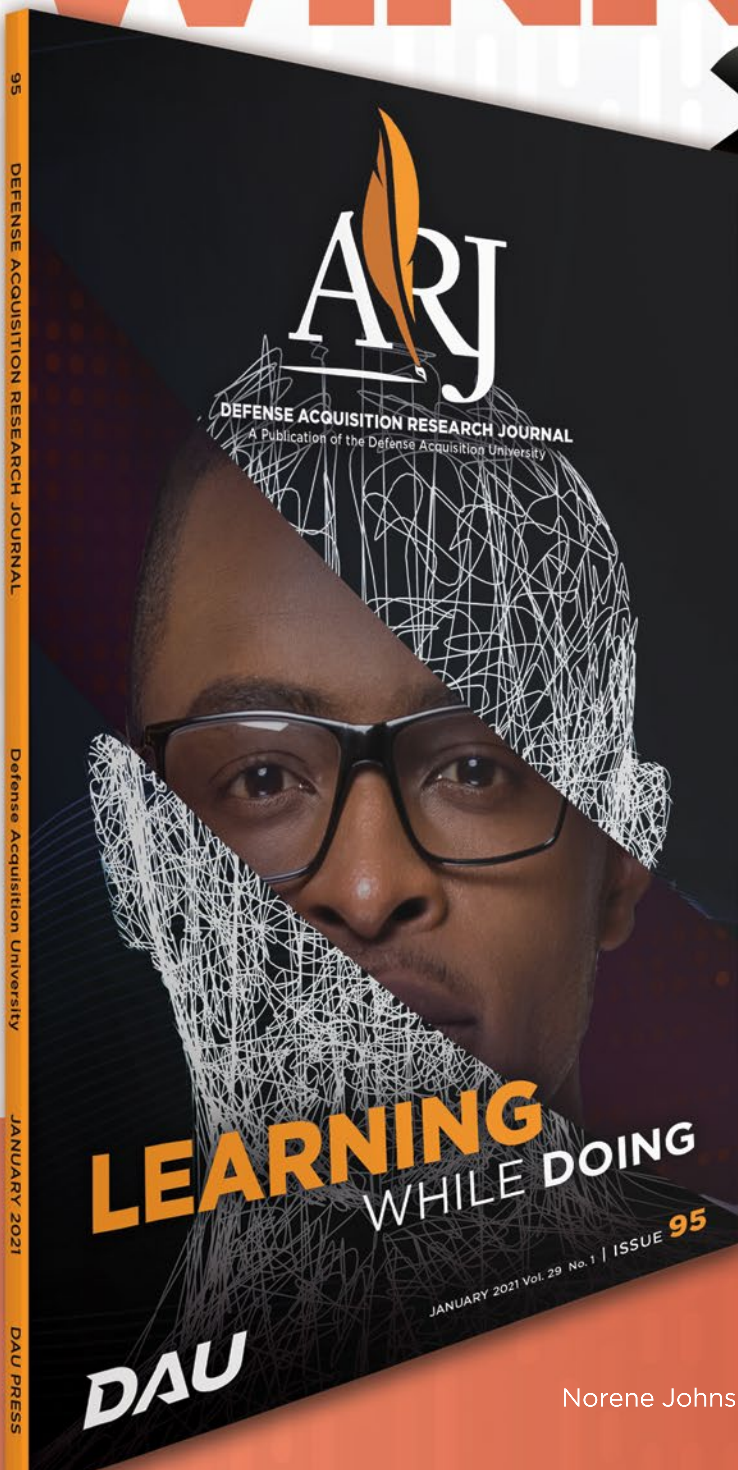

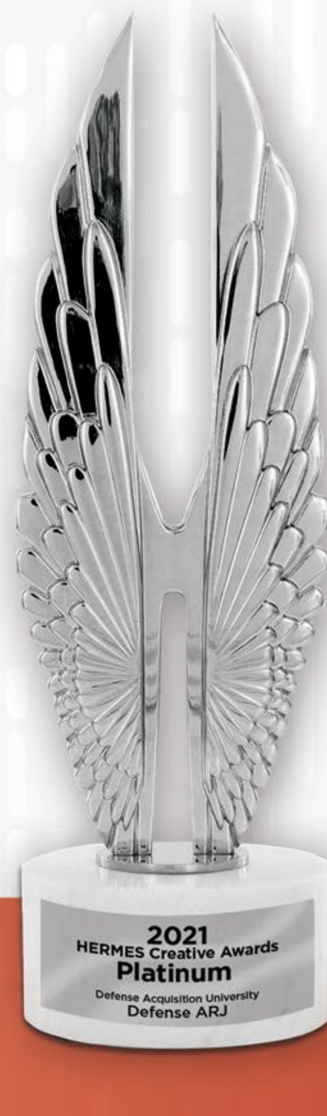

Norene Johnson, Emily Beliles, and Nicole Brate

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RESEARCH AGENDA 2021

This Research Agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broad defense acquisition community in the government, academic, and industrial sectors. It is compiled using inputs from subject matter experts (SMEs) across those sectors. These topics are periodically vetted and updated as needed to ensure they address current areas of strategic interest.

The purpose of conducting research in these areas is to provide solid, empirically based findings to create a broad body of knowledge that can inform the development of policies, procedures, and processes in defense acquisition, and to help shape the thought leadership for the acquisition community. These research topics should be considered guidelines to help investigators form their own research questions. Some questions may cross topics and thus appear in multiple research areas.

Potential researchers are encouraged to contact the DAU Director of Research (research@dau.edu) to suggest additional research questions and topics, or with any questions on the topics.

Affordability and Cost Growth

- Define or bound "affordability" in the defense portfolio. What is it? How will we know if something is affordable or unaffordable?

- What means are there (or can be developed) to measure, manage, and control "affordability" at the Program Office level? At the industry level? How do we determine their effectiveness?
- What means are there (or can be developed) to measure, manage, and control "Should Cost" estimates at the Service, Component, Program Executive, Program Office, and industry levels? How do we determine their effectiveness?
- What means are there (or can be developed) to evaluate and compare incentives for achieving "Should Cost" at the Service, Component, Program Executive, Program Office, and industry levels?
- Recent acquisition studies have noted the vast number of programs and projects that don't make it through the acquisition system and are subsequently cancelled. What would systematic root cause analyses reveal about the underlying reasons, whether and how these cancellations are detrimental, and how acquisition leaders might rectify problems?
- Do joint programs—at the inter-Service and international levels—result in cost growth or cost savings compared with single-Service (or single-nation) acquisition? What are the specific mechanisms for cost savings or growth at each stage of acquisition? Do the data lend support to "jointness" across the board, or only at specific stages of a program, e.g., only at Research and Development (R&D), or only with specific aspects, such as critical systems or logistics?
- Can we compare systems with significantly increased capability developed in the commercial market to Department of Defense (DoD)-developed systems of similar characteristics?
- Is there a misalignment between industry and government priorities that causes the cost of such systems to grow significantly faster than inflation?
- If so, can we identify why this misalignment arises? What relationship (if any) does it have to industry's required focus on shareholder value and/or profit, versus the government's charter to deliver specific capabilities for the least total ownership costs?

Industrial Productivity and Innovation

Industry insight and oversight

- What means are there (or can be developed) to measure the level of oversight and/or control that government has over subcontractors?
- What means are there (or can be developed) to measure costs of enforcement (e.g., auditors) versus actual savings from enforcement?
- What means are there (or can be developed) to evaluate and compare incentives for subcontractor/supply chain competition and efficiencies?
- What means are there (or can be developed) to evaluate and compare market-based incentives with regulatory incentives?
- How can we perform institutional analyses of the behaviors of acquisition organizations that incentivize productivity?
- What means are there (or can be developed) to evaluate and compare the barriers of entry for SMEs in defense acquisition versus other industrial sectors?
- Is there a way to measure how and where market incentives are more effective than regulation, and vice versa?
- Do we have (or can we develop) methods to measure the effect of government requirements on increased overhead costs, at both government and industrial levels?

- Examine the possibilities to rationalize and balance the portfolio of capabilities through buying larger quantities of common systems/subsystems/components across Defense Agencies and Services. Are there examples from commercial procurement and international defense acquisition that have produced positive outcomes?
- Can principal-agent theory be used to analyze defense procurement realities? How?
- What means are there (or can be developed) to measure the effect on defense acquisition costs of maintaining the industrial base in various sectors?
- What means are there (or can be developed) of measuring the effect of utilizing defense industrial infrastructure for commercial manufacture, particularly in growth industries? In other words, can we measure the effect of using defense manufacturing to expand the buyer base?
- What means are there (or can be developed) to measure the breadth and depth of the industrial base in various sectors that go beyond a simple head count of providers?
- Has change in the industrial base resulted in actual change in output? How is that measured?

Independent Research and Development

- What means do we require to measure the cost-effectiveness or Return on Investment (ROI) for DoD-reimbursed Independent Research and Development (IR&D)?
- Can we properly account for sales and revenues that are products of IR&D?
- Can we properly account for the barriers to entry for SMEs in terms of IR&D?
- Examine industry trends in IR&D, for example, percentage of revenue devoted to IR&D, collaboration with academia. How do they vary by industry sector—in particular, those associated with defense acquisition?
- What means are there (or can be developed) to measure the ROI for DoD-reimbursed IR&D versus directly funded defense R&D?
- What incentive structures will motivate industry to focus on and fund disruptive technologies?
- What has been the impact of IR&D on developing disruptive technologies?

Competition

Measuring the effects of competition

- What means are there (or can be developed) to measure the effect on defense acquisition costs of maintaining an industrial base in various sectors?
- What means are there (or can be developed) for measuring the effect of utilizing defense industrial infrastructure for commercial manufacture, particularly in growth industries? In other words, can we measure the effect of using defense manufacturing to expand the buyer base?
- What means are there (or can be developed) to determine the degree of openness that exists in competitive awards?
- What are the different effects of the two best value source selection processes (trade-off versus lowest price technically acceptable) on program cost, schedule, and performance?

Strategic competition

- Is there evidence that competition between system portfolios is an effective means of controlling price and costs?
- Does lack of competition automatically mean higher prices? For example, is there evidence that sole source can result in lower overall administrative costs at both the government and industry levels, to the effect of lowering total costs?
- What are long-term historical trends for competition guidance and practice in defense acquisition policies and practices?
- To what extent are contracts awarded noncompetitively by congressional mandate, for policy interest reasons? What is the effect on contract price and performance?
- What means are there (or can be developed) to determine the degree to which competitive program costs are negatively affected by laws and regulations such as the Berry Amendment, Buy American Act, etc.?
- The DoD should have enormous buying power and the ability to influence supplier prices. Is this the case? Examine the potential change in cost performance due to greater centralization of buying organizations or strategies.

Effects of industrial base

- What are the effects on program cost, schedule, and performance of having more or fewer competitors? What measures are there to determine these effects?
- What means are there (or can be developed) to measure the breadth and depth of the industrial base in various sectors, that go beyond a simple head count of providers?
- Has the change in industrial base resulted in actual change in output? How is that measured?

Competitive contracting

- Commercial industry often cultivates long-term, exclusive (noncompetitive) supply chain relationships. Does this model have any application to defense acquisition? Under what conditions/circumstances?
- What is the effect on program cost performance of awards based on varying levels of competition: (a) “Effective Competition” (two or more offers; (b) “Ineffective Competition” (only one offer received in response to competitive solicitation; (c) “Split Awards” versus winner take all; and (d) “Sole Source.”

Improve DoD outreach for technology and products from global markets

- How have militaries in the past benefitted from global technology development?
- How/why have militaries missed the largest technological advances?
- What are the key areas that require DoD focus and attention in the coming years to maintain or enhance the technological advantage of its weapons systems and equipment?
- What types of efforts should DoD consider pursuing to increase the breadth and depth of technology push efforts in DoD acquisition programs?
- How effectively are DoD’s global Science and Technology (S&T) investments transitioned into DoD acquisition programs?

- Are managers of DoD's applied R&D (i.e., acquisition program) investments effectively pursuing and using sources of global technology to affordably meet current and future DoD acquisition program requirements? If not, what steps could DoD take to improve its performance in these two areas?
- What are the strengths and weaknesses of DoD's global defense technology investment approach as compared to the approaches used by other nations?
- What are the strengths and weaknesses of DoD's global defense technology investment approach as compared to the approaches used by the private sector—both domestic and foreign entities (companies, universities, private-public partnerships, think tanks, etc.)?
- How does DoD currently assess the relative benefits and risks associated with global versus U.S. sourcing of key technologies used in DoD acquisition programs? How could DoD improve its policies and procedures in this area to enhance the benefits of global technology sourcing while minimizing potential risks?
- How could current DoD/U.S. Government Technology Security and Foreign Disclosure (TSFD) decision-making policies and processes be improved to help DoD better balance the benefits and risks associated with potential global sourcing of key technologies used in current and future DoD acquisition programs?
- How do DoD primes and key subcontractors currently assess the relative benefits and risks associated with global versus U.S. sourcing of key technologies used in DoD acquisition programs? How could they improve their contractor policies and procedures in this area to enhance the benefits of global technology sourcing while minimizing potential risks?
- How could current U.S. Government Export Control system decision-making policies and processes be improved to help DoD better balance the benefits and risks associated with potential global sourcing of key technologies used in current and future DoD acquisition programs?

Comparative studies

- Compare the industrial policies of military acquisition in different nations and the policy impacts on acquisition outcomes.
- Compare the cost and contract performance of highly regulated public utilities with nonregulated "natural monopolies" (e.g., military satellites, warship building).
- Compare contracting/competition practices of DoD with the commercial sector in regard to complex, custom-built products (e.g., offshore oil platforms).
- Compare program cost performance in various market sectors: highly competitive (multiple offerors), limited (two of three offerors), or monopoly?
- Compare the cost and contract performance of military acquisition programs in nations having single "purple" acquisition organizations with those having Service-level acquisition agencies.

Cybersecurity

General questions

- How can we perform analyses of the investment savings associated with institution of robust cybersecurity measures?

- How can we measure the cybersecurity benefits associated with using continuous integration and continuous deployment methodologies?
- How can we cost the discrete elements of cybersecurity that ensure system operational effectiveness within the categories of system functions, mission execution, system performance, and system resilience?
- How can we assess the most effective methodologies for identifying threats quickly, assessing system risk, and developing countermeasures?
- How can we establish a repeatable process for incorporating a continuous Authorization to Operate (ATO) construct for all software-centric acquisition programs?
- How can we articulate cyber risk versus operational risk so Combatant Commands (COCOMs) can be better informed when accepting new software?

Costs associated with cybersecurity

- What are the cost implications of (adding) cybersecurity to a program?
- What are reasonable benchmarks for cybersecurity cost as a percentage of Prime Mission Product (PMP)?
- What are the key cost drivers associated with cybersecurity?
- Is cybersecurity best estimated as a below-the-line common element (similar to Systems Engineering/Program Management or Training) or a PMP element?
- How are risks associated with not incorporating cybersecurity appropriately best quantified/monetized?

Acquisition of Services

Metrics

- What metrics are currently collected and available on services acquisition:
    - Within the DoD?
    - Within the U.S. Government?
    - Outside of the U.S. Government?
- What and how much do these metrics tell us about services acquisition in general and about the specific programs for which the metrics are collected?
- What are the possible metrics that could be used in evaluating services acquisition programs?
    - How many metrics should be used?
    - What is the efficacy of each metric?
    - What is the predictive power of each metric?
    - What is the interdependence (overlap) between metrics?
- How do we collect data for services acquisition metrics?
    - What is being done with the data currently being collected?
    - Are the data being collected on services acquisition reliable?
    - Is the collection process affecting the data collected for services acquisition?
- How do we measure the impact of different government requirements on overhead costs and rates on services contracts?

Industrial base

- What is the right amount of contracted services for government organizations?
    - What are the parameters that affect Make/Buy decisions in government services?
    - How do the different parameters interact and affect government force management and industry research availability?
- What are the advantages, disadvantages, and impacts of capping pass-through costs, and how do they change with the value of the pass-through costs?
- For Base Operations and Support (BOS) contracts, is there a best size? Should large BOS contracts be broken up? What are the parameters that should be considered?
- In the management of large service contracts, what is the best organization? Is the System Program Office a good model? What parameters should be used in evaluating the advantages and disadvantages of an organization to manage large service contracts?
- What effect does strategic sourcing and category management have on small business if the small business is a strategic source or whether the small business is not a strategic source?
- Do the on-ramping and off-ramping requirements of some service contracts have an effect on the industrial base? If so, what are the impacts?

Industry practices

- What private sector business practices, other than maximizing profit, can the government effectively use to incentivize performance and otherwise improve business relationships with vendors?
- What are the best methods for evaluating different incentives to encourage small businesses to participate in government services contracts?
- What potential benefits can the government achieve from long-term supply chain relationships? What are the disadvantages?
- What benefits does industry get from the use of category managers and functional domain experts, and can the government achieve the same benefits?
- How can the government best capture, validate, and use demand management strategies?
- Are current service acquisition taxonomies comprehensive, or can they be improved?

Make/Buy

- What methods can best be used to define the cost-value relationship in different classes of service contracts?
- Can we develop a method for determining the "should cost" of different services?
- Can we define and bound affordability of specific services?
- What are the characteristics of "inherently governmental" activities, and how can we evaluate the value of these services based on comparable characteristics in a competitive labor market?

- In service contracts, what are the inherent life-cycle costs, and how do we capture the life-cycle costs in Make/Buy decision making?
- In the case of government services contracting, what are the factors that contribute to less-than-optimum Make/Buy decision making?

Category management/strategic sourcing

- What effect does strategic sourcing/category management have on competition?
  - Effects on short term versus long term.
  - Effects on competition outside of the strategic sourcing/category management area of consideration.
- What metrics do different industries use for measuring the effectiveness of their supply chain management?
- Would the centralization of service acquisition contracts have measurable impacts on cost performance? Why or why not?
- What are the fundamental differences between the service taxonomy and the category management taxonomy, and are there means and good reasons to align the two taxonomies?

Contract management/efficacy

- What are the best ways to address the service parts of contracts that include both services and products (goods)?
- In the management of service contracts, what are the non-value-added tasks, and are there realistic ways to reduce the impact of these tasks on our process?
- When funds for services are provided via pass-throughs (i.e., from another organization), how are the requirements tracked, validated, and reviewed?
- Do Undefinitized Contract Actions have an effect on contractor pricing and willingness, or lack of willingness to provide support during proposal analysis?
- For multiaward, Indefinite-Delivery, Indefinite-Quantity (IDIQ)-type contracts, is there a method for optimizing the different characteristics (number of vendors, timelines, on-ramping, off-ramping, etc.) of these contracts?

Policy

- What current government policies inhibit alignment of contractors' approaches with the government's service acquisition programs?

Administrative Processes

- What means are there (or can be developed) to measure the efficiency and effectiveness of DoD oversight, at the Component, Service, and Office of the Secretary of Defense levels?
- What measures are there (or can be developed) to evaluate and compare the costs of oversight versus the cost savings from improved processes?
- What means are there (or can be developed) to empirically establish oversight process metrics as a basis for comparison? Can these be used to establish the relationship of oversight to cost/schedule/performance outcomes?
- What means are there (or can be developed) to study the organizational and governance frameworks, resulting in successful change management?

- To what extent (investment and performance) can scenario/simulation testing improve the delivery of complex projects?
- Is there a comparative statistical divergence between organizational honesty (reality) and contractual relationships (intent) in tendering?
- How does one formulate relational contracting frameworks to better account for and manage risk and liability in a collaborative environment?

Human Capital of Acquisition Workforce

- What means are there (or can be developed) to measure ROI for acquisition workforce training?
- What elements of the Professional Military Education framework can be applied to improve the professionalism of the civilian defense acquisition workforce?
- What factors contribute to the management and successful delivery of modern complex project management, including performance over the project life cycle?
- What behavioral leadership characteristics can be commonly observed in successful complex projects, contrasted against unsuccessful complex projects?
- What is the functional role of talent management in building organizational sustainability, performance, and leadership?
- How do we create incentives in the acquisition workforce (management, career, social, organizational) that provide real cost reductions?

Defense Business Systems

Organizational structure and culture in support of Agile software development methodologies

- At the beginning of the Business Capability Acquisition Cycle (BCAC) process, various steps are used to ensure accurate requirements are thoroughly documented and supported throughout the software development life cycle. How can these documentation requirements and processes be streamlined to support more direct-line communication between the end-user and software engineers? What are the hurdles to implementing these changes and how are they overcome? What are the effects of these changes on the organization or agency?
- Regarding new starts, how can the BCAC be modified specifically to support Agile development? How are these changes advantageous or disadvantageous to the customer and organization? Would these changes be helpful or detrimental to R&D versus a concurrent design and engineering software project?
- Generally, readiness review briefings within the BCAC are used to determine if a project is at an acceptable state to go to the next step in the process. If software is developed and released to production within a single sprint (potentially every 2 weeks), how are Test Readiness Reviews, Systems Requirements Reviews, and Production Readiness Reviews handled? How have the changes to these events made them more or less relevant?

- How are organizations and agencies structured to support concurrent software design and development? What organizational structure would support R&D and non-R&D information technology (IT) capabilities?
- What steps are used to choose Agile as the default software development process versus any other software development methodology (e.g., Waterfall, Spiral, or Incremental) for your organization? What are the effects on project cost, schedule, and performance?
- Within DoD agencies and military branches, has the adoption of Agile resulted in faster deployment of new IT capabilities to the customer? How is this determined and measured?
- Industry often produces software using Agile. The DoD's BCAC process can produce an abundance of bureaucracy counter to Agile principles. How does hiring a contractor to implement or maintain IT capabilities and introducing Agile software development methods within a BCAC non-Agile process create conflict? How are these conflicts resolved or reconciled?
- How is IT engineering investment and innovation supported throughout DoD? What organizational or cultural aspects of an agency are specific to that support?

Defense Acquisition and Society

- To what extent should the DoD use the defense acquisition process to effectuate various social policies? The existing procurement regime favors a dizzying array of private interests ranging from organized labor; domestic manufacturers and firms located in areas of high unemployment; small businesses, including disadvantaged and women-owned firms; blind, severely handicapped, and prison industries; and, most recently, environmentally friendly vendors. Affirmatively steering the government's business from the open marketplace to preferred providers adds complexity, thus increasing transaction costs throughout the procurement process, which absorbs scarce resources. (Source: IBM Center for the Business of Government, http://www.businessofgovernment.org)
- How significant are the transaction costs resulting from the administration's commitment to transparency (generally, and specifically in the context of stimulus or recovery spending)? In a representative democracy, transparency is critical. But transparency is expensive and time-consuming, and the additional resources required to comply with the recently enhanced disclosure standards remain an unfunded mandate. Thus, the existing acquisition workforce must devote scarce resources to an (admittedly legitimate) end other than the pursuit of value for money or customer satisfaction. Is there an optimal balance or a point of diminishing returns? In other words, at what point does the cost of developing transparent systems and measures exceed the benefits of that transparency? (Source: IBM Center for the Business of Government, http://www.businessofgovernment.org)

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Aligning Program MANAGEMENT COMPETENCIES to Industry Standards

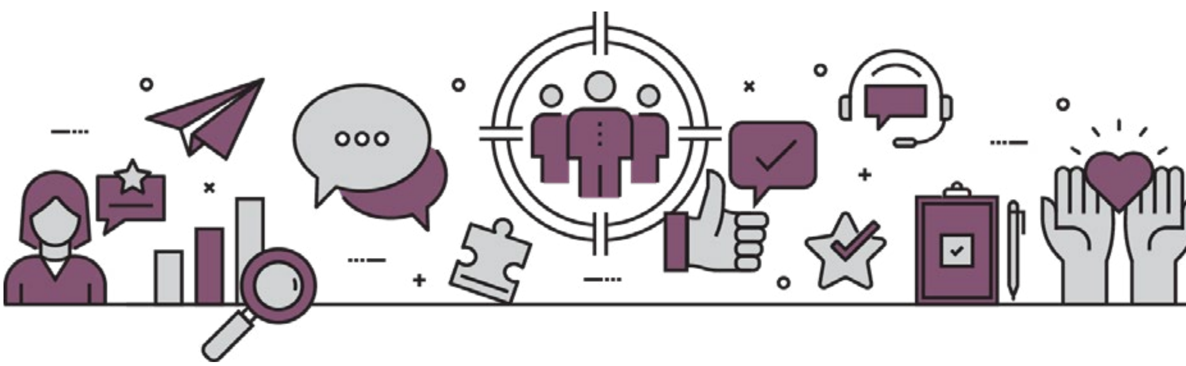
1st Lt Jonathan L. Karnes, USAF, and COL Robert F. Mortlock, USA (Ret.)

The 2020 National Defense Authorization Act mandated that acquisition career fields realign their certification requirements to be based on the nationally recognized standards of an accredited third party. This study offers recommendations for improving the DoD program management (PM) training standards by providing traceability between the DoD PM competencies and the Project Management Institute (PMI)'s standards for project, program, and portfolio management. The study elaborates on the extent of alignment, finding that 96% of the DoD PM competency elements align to PMI standards. Areas of misalignment identify opportunities to augment DoD PM training and highlight areas where DoD PM training deviates from industry standards.

DOI: https://doi.org/10.22594/dau.21-868.28.04
Keywords: *Project Management, Program Management, Portfolio Management, Defense Acquisition Workforce, Functional Career Field Competencies, Training, Industry Standards*

Image designed by Nicole Brate

The purpose of this research is to understand the extent to which the Department of Defense (DoD)'s program management (PM) functional career field competencies currently align with the internationally recognized standards for project, program, and portfolio management. This research will be used to make recommendations to the DoD on the best way to transition from its current PM certification requirements to certification requirements based on industry standards. We provide traceability between the DoD PM competencies and industry standards, and elaborate on the extent to which they are aligned. We also highlight inconsistencies and make recommendations for changes in DoD training and education standards and for potential policy changes.



Over decades, the DoD has been criticized for its inability to manage the various programs funded by U.S. taxpayers. These repeated failings in the realms of program cost, schedule, and performance have been documented in numerous reports from the Office of the Secretary of Defense (OSD) and the Government Accountability Office (GAO), and in a myriad of theses and dissertations (Bond et al., 2016; Choi, 2009; Defense Acquisition Workforce Improvement Act [DAWIA], 1990; GAO, 2019a, 2019b; Kupec, 2013; Pernin et al., 2012; President's Blue Ribbon Commission, 1986; Redshaw, 2011).

A debate continues as to whether the acquisition program failings are caused by the DoD's inherently complex acquisition system or the quality of its acquisition personnel. Eckerd and Snider (2017) claim that until the acquisition system and processes of the DoD are fixed, the training and education of program managers can be considered inconsequential to the success of defense programs. However, based on the recommendations in GAO-18-217, which was focused on improving program management, the DoD's program performance would improve if the DoD would "improve practices that do not align extensively with leading practices" (GAO, 2018a). This recommendation is further supported by the GAO's annual high-risk list, which highlights the DoD career fields that pose a great level of risk to the government if not improved or appropriately monitored. DoD weapon systems acquisition has consistently been on this list consistently since 1990 (General Accounting Office, 1995; GAO, 2019a). According to the most recent list developed in 2019, DoD program management was considered high risk because of the anticipated $1.66 trillion investments into its acquisition and procurement portfolio (GAO, 2019a). After decades of continuous defense acquisition reform initiatives, still no effort can guarantee resolution of the continued shortfalls in meeting cost, schedule, and performance goals for acquisition programs (GAO, 2019a). These three factors are commonly referred to as a program's triple constraint and form the acquisition program baseline for management.

"After decades of continuous defense acquisition reform initiatives, still no effort can guarantee resolution of the continued shortfalls in meeting cost, schedule, and performance goals for acquisition programs (GAO, 2019a). These three factors are commonly referred to as a program's triple constraint and form the acquisition program baseline for management.

The DoD has made many attempts to develop solutions meant to resolve continued issues with managing the nation's defense programs and their planned cost, schedule, and performance baselines. One such attempt was implemented under President Reagan's Blue Ribbon Commission, also commonly referred to as the Packard Commission. As it pertains to this research study, the Packard Commission's most relevant recommendation was to require business-related education and training for acquisition personnel (President's Blue Ribbon Commission, 1986). This recommendation led to the passing of the DAWIA, which then led to the establishment of the Defense Acquisition University (DAU). Since its inception in 1991, DAU has structured its acquisition curriculum in a way that would best prepare program managers (PM) to navigate the complexities of the Defense Acquisition System (DAS). The principal components of the DAS consist of the interoperation of management processes (the Adaptive Acquisition Framework), requirements processes (like the Joint Capabilities Integration and Development System [JCIDS] for formal programs of record), and a resourcing process (referred to as the planning, programming, budgeting, and execution [PPBE] system) (Office of the Under Secretary of Defense for Acquisition and Sustainment [OUSD(A&S)], 2020a, 2020b).

In 2016, the Office of the Assistant Secretary of Defense for Acquisition distributed the functional career field competencies for PMs and broke them down into the following DoD PM categories: Acquisition Management, Business Management, Technical Management, and Executive Leadership (MacStravic, 2016). From the DoD's perspective, these competencies serve as the standards that enable PMs to effectively "deliver mission-critical capabilities in terms of equipment and services" (MacStravic, 2016, p. 2). Further, this list of competencies serves as the basis for the PM DAWIA certification standards adopted by the Services.

The Project Management Institute (PMI) is an independent, private organization that has led the way in establishing the internationally recognized standards for project management, program management, and portfolio management across industries. They offer a variety of certifications to business and management professionals that are recognized globally. Since 1999, the American National Standards Institute (ANSI) has approved PMI's *Guide to the Project Management Body of Knowledge®* (*PMBOK Guide*) (PMI, 2017a) as the American national standard for project management (Holtzman, 1999). A contributing factor to the *PMBOK Guide*'s ANSI certification is its wide range of applicability across industries. The knowledge areas in PMI's *PMBOK Guide*, the performance domains of *The Standard for Portfolio Management* (*TSPfM*) (PMI, 2017b), and *The Standard for Program Management* (*TSPgM*) (PMI, 2017c) apply broadly.

"The Project Management Institute (PMI) is an independent, private organization that has led the way in establishing the internationally recognized standards for project management, program management, and portfolio management across industries.

In December 2019, Congress passed the National Defense Authorization Act for Fiscal Year 2020 (NDAA). The section of this Act that is relevant to this research is Section 861, "Defense Acquisition Workforce Certification, Education, and Career Fields," subsection (c), "Professional Certification." It states,

> The Secretary of Defense shall implement a certification program to provide for a professional certification requirement for all members of the acquisition workforce … the certification requirement for any

> acquisition workforce career field shall be based on standards developed by a third-party accredited program based on nationally or internationally recognized standards. (NDAA, 2019)

This subsection has mandated a refocusing of how the DoD trains its acquisition professionals. Per the NDAA, it is the role of the Office of the Secretary of Defense to produce the realigned certification program based on nationally or internationally recognized standards of an accredited third party (NDAA, 2019). Per the DAWIA (1990), it is DAU's role to provide the training that meets the requirements of the acquisition workforce.

Research Questions

This research will be used to make recommendations to the DoD on the best way to transition from its current PM certification requirements to certification requirements based on the PMI standards. This study answers the following research questions:

- To what extent are the DoD's program management competency elements at the basic, intermediate, and advanced DAWIA levels aligned with PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM*?
- To what extent are the knowledge areas and performance domains in PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM* aligned with the DoD's program management competency elements at the basic, intermediate, and advanced DAWIA levels?

The results of this study will enable decision-makers within the OSD to make informed decisions about modifying the PM certification requirements as mandated by the NDAA. This research focuses on a shift in the basis for DoD PM certification requirements. Specifically, this study pertains to the alignment of the DoD's PM functional career field competencies (MacStravic, 2016) to the PMI's 10 knowledge areas that comprise the *PMBOK Guide* (PMI, 2017a), the portfolio management performance domains of *TSPfM* (PMI, 2017b), and the program management performance domains of *TSPgM* (PMI, 2017c).

Background and Literature Review

The study of PM career field competencies can be linked to work and progress in other acquisition workforce career fields (Rendon, 2010). As Rendon (2019) discusses, it is important to make an organization auditable so that it will be better suited to achieve its mission goals and objectives. Auditability consists of three main components: capable processes, effective internal controls, and competent personnel. The DoD has robust processes within defense acquisition in the form of its acquisition management framework, requirements, and resourcing processes. The Department also has internal controls provided by the GAO, DoD's Office of Inspector General (DoD IG), congressional oversight, and adherence laws such as annual NDAAs and acquisition Acts like the Nunn–McCurdy Act (Schwartz, 2010). This research helps the DoD to improve the third component of auditability: competent personnel.

As previously discussed, defense acquisition has been criticized for failing to meet cost, schedule, and performance program baseline objectives. In response to the deficiencies in these three areas, the DoD has implemented multiple acquisition reform initiatives to improve its acquisition processes. The reform initiatives have also modified the acquisition reporting structure and used the power of government watchdogs such as the GAO and the DoD IG to implement effective internal controls. To improve the quality of its acquisition professionals, the DoD has made frequent modifications to the training and education requirements. This literature review covers former acquisition reform initiatives, internal and external findings on DoD acquisition performance, the standards published by the PMI, and scholarly articles that express support and opposition to modifying the alignment of the DoD competencies to the standards of a third party.

> **Auditability consists of three main components: capable processes, effective internal controls, and competent personnel.**

In 1985, the Reagan Administration appointed former U.S. Secretary of Defense David Packard as the head of its Blue Ribbon Commission, which was established to make recommendations on how to improve defense acquisition. The Packard Commission produced nine recommendations; the one recommendation addressed in this research study is to enhance the quality of acquisition personnel (President's Blue Ribbon Commission, 1986). This recommendation focused on improving the appointment criteria of senior-level personnel in order to run programs and portfolios more effectively, and called for business-related education for civilians (President's Blue Ribbon Commission, 1986). This recommendation was finally implemented via the passage of the DAWIA in 1990, which resulted in the development of DAU and the establishment of baseline education and training requirements for acquisition professionals. The DAWIA (1990) also outlined elevated requirements for personnel assigned to critical positions such as program executive officers and senior contracting officials.

DAU is the primary source of training for defense acquisition professionals, providing formal courses as well as continuous learning modules to promote continuing education and professional growth for thousands of students every year (Woolsey, 2019). To date, these courses are structured to accommodate DAWIA certification requirements and are broken down into three levels (DoD & DAU, n.d.):

- **Level I:** basic or entry level
- **Level II:** intermediate or journeyman level
- **Level III:** advanced or senior level. Additional training standards are required for unique positions, including program executive officers and PMs of major defense acquisition programs or major automated information systems.

The content of training requirements for PMs is based on the DoD PM functional career field competencies approved and published by the Office of the Assistant Secretary of Defense. The competencies are further separated into four overarching PM categories, which have served as the basis for developing the learning objectives and training materials for PMs (MacStravic, 2016):

- Acquisition Management
- Business Management
- Technical Management
- Executive Leadership (Level III education for unique positions)

In November 2019, the NDAA directed the Secretary of Defense to implement a certification program based on standards developed by a third party (NDAA, 2019). For the DoD's PM training curriculum, this requires adjusting the older training standards, which were based solely on DoD-unique functional career field competencies, to align with the "standards developed by a third-party accredited program based on nationally or internationally recognized standards" (NDAA, 2019, p. 778). This shift from DoD-centric competencies to the widely accepted standards of the private sector is an attempt to improve the quality of the Defense Acquisition Workforce by recruiting and growing an experienced and knowledgeable personnel base, thoroughly capable of working with defense industry partners throughout the acquisition process. Further, the purpose of this reform initiative is to change the mindset of PMs as well as to improve the quality of their performance.

As previously discussed, defense acquisition management has been on the GAO's high-risk list since 1990 because of failure to meet the five criteria for removal: leadership commitment, capacity, action plan, monitoring, and demonstrated progress (GAO, 2019b). Of those five, defense acquisition management meets the criteria for leadership commitment but only partially meets the other four. This continued pattern of insufficiency makes the DoD vulnerable to budget overruns, schedule slips, and underperformance—observed in major defense acquisition programs like the F-35 Joint Strike Fighter (GAO, 2018b) and the Army Future Combat Systems (Pernin et al., 2012). The poor returns on investment exhibited by these and other programs have led to the acquisition management career field remaining on the high-risk list (GAO, 2019b) and have created a continual demand for acquisition reform initiatives (Gansler et al., 2007).

> **"Defense acquisition management has been on the GAO's high-risk list since 1990 because of failure to meet the five criteria for removal: leadership commitment, capacity, action plan, monitoring, and demonstrated progress.**

While there is generally consensus among lawmakers and DoD senior leaders that room for improvement certainly exists in how DoD manages programs, the prevailing thought differs on how the DoD should work to improve the acquisition career field. Multiple GAO reports present contradictory views on what needs to change to remove defense acquisition from the high-risk list. Some reports recognize that certification training offered by the DAU is capable of providing adequate training to PMs (GAO, 2010), whereas others state that issues with PMs from the military services emanate from those very same training standards not aligning with leading practices (GAO, 2018a). The takeaway from these two findings is that DAU has the infrastructure and organizational alignment to provide effective training, but the current training can be more effective if aligned with more widely accepted standards. This issue could be addressed by incorporating the advisement provided by the GAO to the Office of Management and Budget (OMB) by adopting "an existing set of consensus-based standards, such as the widely accepted standards for program and project management from the Project Management Institute" (GAO, 2019a, p. 11).

The PMI is a not-for-profit association that publishes standards for certification programs, including the Project Management Professional (PMP), the Program Management Professional (PgMP), and the Portfolio Management Professional (PfMP). Earning these credentials certifies that one is qualified to lead a project, manage a program, and meet strategic objectives in overseeing one or more portfolios, respectively (PMI, 2020). The PMI certifications are recognized globally due to their widely applicable and highly detailed standards that have proven over time to improve the outcomes of projects, programs, and portfolios if applied and resourced appropriately.

> **"DAU has the infrastructure and organizational alignment to provide effective training, but the current training can be more effective if aligned with more widely accepted standards.**

In 1999, ANSI first approved PMI's *PMBOK Guide* (PMI, 2017a) as the American national standard for project management (Holtzman, 1999). To apply for PMI's PMP credential, candidates must have a high school diploma or associate degree, 5 years of experience in leading projects, and 35 hours of project management education/training. PMP candidates with a 4-year degree need only 3 years of experience in leading projects (PMI, 2020). This credential is ideal for individuals who lead cross-functional project teams and manage projects, which PMI defines as "temporary endeavors undertaken to create a unique product, service, or result" (PMI, 2017a, p. 4). The PMP credential is broken down into 10 knowledge areas, which are made up of 49 processes. Project management knowledge areas are categorized by their knowledge requirements and are described in terms of their various component processes, practices, inputs, outputs, tools, and techniques (PMI, 2017a). Project management processes are defined as "systematic activities directed toward causing an end result where one or more inputs will be acted upon to create one or more outputs" (PMI, 2017a, p. 18). Figure 1 includes a complete list of the 49 processes that fall under the 10 different knowledge areas in the *PMBOK Guide* (PMI, 2017a).

FIGURE 1. TEN KNOWLEDGE AREAS OF THE *PMBOK GUIDE*

Knowledge Areas	Project Management Process Groups				
	Initiating Process Group	Planning Process Group	Executing Process Group	Monitoring and Controlling Process Group	Closing Process Group
4. Project Integration Management	4.1 Develop Project Charter	4.2 Develop Project Management Plan	4.3 Direct and Manage Project Work 4.4 Manage Project Knowledge	4.5 Monitor and Control Work 4.6 Perform Integrated Change Control	4.7 Close Project or Phase
5. Project Scope Management		5.1 Plan Scope Management 5.2 Collect Requirements 5.3 Define Scope 5.4 Create WBS		5.5 Validate Scope 5.6 Control Scope	
6. Project Schedule Management		6.1 Plan Schedule Management 6.2 Define Management 6.3 Sequence Activities 6.4 Estimate Activity Durations 6.5 Develop Schedule		6.6 Control Schedule	
7.Project Cost Management		7.1 Plan Cost Management 7.2 Estimate Costs 7.3 Determine Budget		7.4 Control Costs	
8. Project Quality Management		8.1 Plan Quality Management	8.2 Manage Quality	8.3 Control Quality	

FIGURE 1. TEN KNOWLEDGE AREAS OF THE *PMBOK GUIDE* (CONTINUED)

Knowledge Areas	Project Management Process Groups				
	Initiating Process Group	Planning Process Group	Executing Process Group	Monitoring and Controlling Process Group	Closing Process Group
9. Project Resource Management		9.1 Plan Resource Management 9.2 Estimate Activity Resources	9.3 Acquire Resources 9.4 Develop Team 9.5 Manage Team	9.6 Control Resources	
10. Project Communications Management		10.1 Plan Communications Management	10.2 Manage Communications	10.3 Monitor Communications	
11. Project Risk Management		11.1 Plan Risk Management 11.2 Identify Risks 11.3 Perform Qualitative Risk Analysis 11.4 Perform Quantitative Risk Analysis 11.5 Plan Risk Responses	11.6 Implement Risk Responses	11.7 Monitor Risks	
12. Project Procurement Management		12.1 Plan Procurement Management	12.2 Conduct Procurements	12.3 Control Procurements	
13. Project Stakeholder Management	13.1 Identify Stakeholders	13.2 Plan Stakeholder Engagement	13.3 Manage Stakeholder Engagement	13.4 Monitor Stakeholder Engagement	

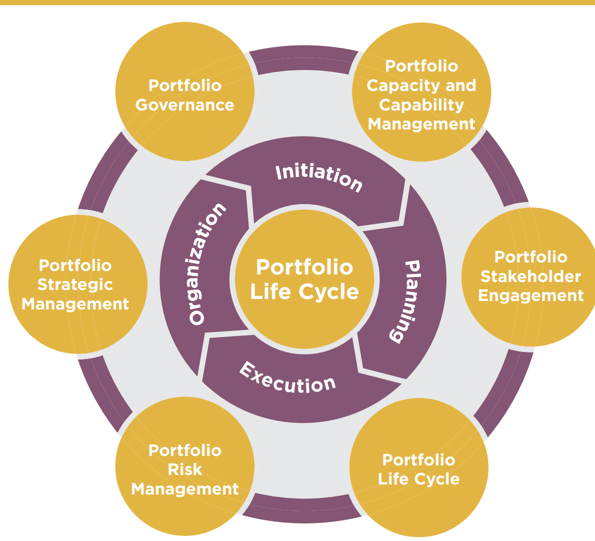
Note. Source: PMI (2017a). WBS = Work Breakdown Structure.

The PgMP certification is based on *The Standard for Program Management* (*TSPgM*) (PMI, 2017c). The purpose of *TSPgM* is to provide generally recognized guidance to support good program management practices, establish a common understanding of the role of a PM, and offer guidance for PMs' interactions with portfolio and project managers as well as any other program stakeholders (PMI, 2017c). According to PMI, a program is made up of "related projects, subsidiary programs, and program activities managed in a coordinated manner" (PMI, 2017c, p. 3). When programs are run effectively, they can deliver benefits that would not have been attainable had their subsidiary programs and projects been managed independently of one another. Similar to the *PMBOK Guide* (PMI, 2017a), *TSPgM* discusses five performance domains that are "complementary groupings of related areas of activity or function that uniquely characterize and differentiate the activities found in one performance domain from the others within the full scope of program management work" (PMI, 2017c, p. 23). The purpose of these domains is to provide PMs with a general checklist of tasks, analyses, and concepts to complete and consider throughout the life of the program. Figure 2 illustrates these domains.

FIGURE 2. PROGRAM MANAGEMENT PROFESSIONAL PERFORMANCE DOMAINS

Note. Source: PMI (2017c).

FIGURE 3. PORTFOLIO MANAGEMENT PROFESSIONAL PERFORMANCE DOMAINS



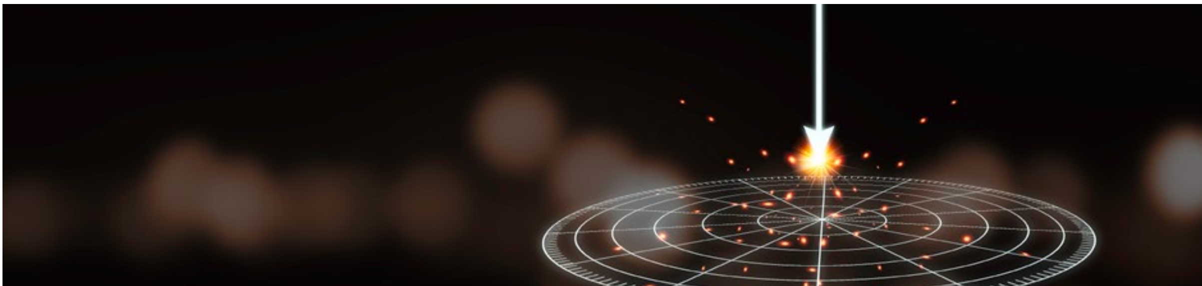
Note. Source: PMI (2017b).

The PfMP certification is based on *The Standard for Portfolio Management* (*TSPfM*) (PMI, 2017b), the purpose of which is to provide portfolio management principles and performance management domains that are considered to be good practices for organizations that manage complex programs and projects. Further, this standard is meant to provide a common understanding of the role of a portfolio manager as well as a unified vocabulary to use across industries (PMI, 2017b). According to PMI, "a portfolio is a collection of projects, programs, and subsidiary portfolios and operations managed as a group to achieve strategic objectives" (PMI, 2017b, p. 3). The purpose of managing a portfolio versus independent programs and projects is to achieve organizational objectives and strategies that could not be met otherwise. *TSPfM* is very similar to *TSPgM* in that it consists of seven performance domains and is supported by the *PMBOK Guide*. These seven performance domains, when followed and executed correctly, are what allow for the portfolio management plan to achieve its desired impact on strategy and performance (PMI, 2017b). For a complete list of these domains and their associated items, see Figure 3.

In the early 2000s, the DoD worked with PMI to develop the *U.S. Department of Defense Extension to: A Guide to the Project Management Body of Knowledge* (*PMBOK Guide*) (DoD & DAU, 2003). The purpose of the DoD and PMI collaboration was to identify defense applications of the *PMBOK Guide*'s knowledge areas and to meet the published objectives of the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD[AT&L]). These objectives focused on building credibility in acquisition and logistics support by improving cost estimation techniques and implementing evolutionary acquisition to deliver systems at a lower cost and on schedule (DoD & DAU, 2003). Despite this initiative, the *PMBOK Guide*'s extension was never implemented into the DAU certification curriculum (Kupec, 2013).

> **It is essential to base the new DAWIA certification requirements on all three of the PMI credentials.**

It has been well established that programs in the DoD have struggled for decades to effectively manage program cost, schedule, and performance (GAO, 2018a, 2018b, 2019a). The NDAA (2019) addresses this issue by mandating a modification to existing certification requirements to be based on the standards of an accredited third party with nationally recognized standards. Because of the high visibility and volatility of defense acquisition, many scholarly studies have been published on how the DoD could improve their training standards by mirroring an entity like PMI (Choi, 2009; Kupec,



2013; Redshaw, 2011). In comparison to the progressive complexity of PMI's certifications for project, program, and portfolio management, the DAWIA certifications for Level I (basic), Level II (intermediate), and Level III (advanced) "correlate to the complexity and responsibilities required for designated positions and different types of assignments in weapon systems, services, business management systems and information technology, and international acquisitions" (Redshaw, 2011, p. 55). Both Choi (2009) and Kupec (2013) concur with this analysis and elaborate further that modeling the new DAU standards after only one of the PMI credentialing standards—PMP for example—would not be sufficient. As mentioned above, the individuals who earn the PMP credential have proven themselves capable of effectively leading cross-functional project teams and managing a temporary project. While this credential is beneficial to earn and holds value in the program management industry, the body of knowledge that accompanies it would not be enough to equip an individual to run a complex decade-long program or portfolio. For these reasons, it is essential to base the new DAWIA certification requirements on all three of the PMI credentials.

According to auditability theory, in order for an organization, project team, program office, or portfolio executive officer to meet their specific objectives, it is critical that competent personnel are employed, effective internal controls are maintained, and capable processes are implemented (Rendon & Rendon, 2015). As it relates to defense acquisition reform, auditors have expressed divergent opinions as to which of the three components of auditability should be focused on to improve program metrics in cost, schedule, and performance. For example, Eckerd and Snider (2017) claim that the defense acquisition processes should be the focal point for reform due to their complexities. They add that the environmental politics that DoD PMs maneuver through daily prevent them from being effective, which nullifies any quality training they undergo. Other research comes to a similar conclusion that in order to make significant changes in federal acquisition, the reform needs to comprehensively consider changes to the management processes (acquisition framework), the resources processes (PPBE system), and the requirements processes (Bond et al., 2016). Mortlock (2020) asserts that providing DoD PMs with professional-level training and adopting internationally recognized industry standards (for example PMP, PgMP, and PfPM certifications) could help improve the effectiveness of PMs. Mortlock also maintains that these actions help gain acceptance for program management as a profession and help solidify the credibility of the defense acquisition workforce.

Methodology

This research involved a qualitative, lexicographic analysis of the descriptions of the DoD's PM competencies and the descriptions of PMI's knowledge areas and domains in the *PMBOK Guide* (PMI, 2017a), *TSPgM* (PMI, 2017c), *TSPfM* (PMI, 2017b), the NDAA for Fiscal Year 2020 (NDAA, 2019), and other key sources. In this analysis, we highlighted key words, phrases, and meaning from the description of each knowledge area, domain, and competency that allowed for an informed mapping of the DoD's PM competencies to PMI's standards.

The OUSD(AT&L) memorandum entitled *Program Management Functional Career Field Competencies* served as the primary DoD source used in analyzing the alignment between the DoD's PM competencies and PMI's standards (MacStravic, 2016). According to the memorandum, an integrated product team developed the updated competencies while considering the three certification levels: Level I (basic), Level II (intermediate), and Level III (advanced) (MacStravic, 2016). The memorandum includes the following information used in this research:

1. Program Management Competency Units and Competencies: The PM competencies are organized into the four program management categories and 18 units of competency. Figure 4 demonstrates the distribution of the competencies.
2. Program Management Functional Career Field Competencies: Descriptions of the 70 competencies are provided for each of the three DAU certification levels. The table data are

organized under the following column headings: unit #, unit of competency, unit of competency description, competency #, competency name, element #, basic competency element description, intermediate competency element, and advanced competency element description. Figures 5 and 6 provide excerpts to visualize the organization of the data.

FIGURE 4. DOD PROGRAM MANAGEMENT COMPETENCY UNITS AND COMPETENCIES

ACQUISITION MANAGEMENT

CAPABILITY INTEGRATION PLANNING
Requirements Management (Mgmt)
Acquisition Program Strategic Planning
Business Case Development

ACQUISITION LAW AND POLICY
Acquisition Policy and Best Practices
Contractual Laws, Regulations, and Obligations
Financial Mgmt Laws, Directives, and Policies
Program Support Laws, Directives, and Policies
Technical and Engineering Laws, Directives, and Policies
Information Technology Laws, Policy, Best Practices

INTERNATIONAL ACQUISITION AND EXPORTABILITY
International Cooperative Programs
Sales and Transfers
Technology Security and Foreign Disclosure
Defense Exportability Integration

STAKEHOLDER MGMT
Political Savvy
External Situational Awareness
Media Relationships

PROGRAM EXECUTION
Risk / Opportunity Mgmt
Program Planning
Teaming
Program Oversight
Resource Mgmt
Technology Mgmt

SERVICES ACQUISITION

BUSINESS MANAGEMENT

CONTRACT MANAGEMENT
Market Research
Presolicitation Planning and Execution
Source Selections and Negotiations
Contract Administration
Contract Closeout

FINANCIAL MGMT
Financial Planning
Programming
Budget Formulation
Budget Execution
Cost Estimates

TECHNICAL MANAGEMENT

ENGINEERING MANAGEMENT
Technical Planning
Requirements Decomposition
Technical Assessment
Decision Analysis
Configuration Mgmt
Technical Data Mgmt
Interface Mgmt

DEFENSE BUSINESS SYSTEMS
DBS Certification
DBS Acquisition Approach Preparation

TEST AND EVALUATION MGMT
Test Planning
Test Execution

MANUFACTURING MGMT
Manufacturing Planning and Transition
Manufacturing Shutdown

PRODUCT SUPPORT MGMT
Product Support Planning
Product Support Mgmt
Supply Chain Mgmt

EXECUTIVE LEADERSHIP

FOUNDATIONAL COMPETENCIES
Interpersonal Skills
Integrity / Honesty
Communicate Effectively
Continual Learning
Public Service Motivation
Technical Credibility

BUILDING COALITIONS
Influencing / Negotiating
Partnering

LEADING CHANGE
Creativity & Innovation
Vision
Flexibility
Resilience

LEADING PEOPLE
Conflict Management
Leveraging Diversity
Developing Others
Team Building

RESULTS DRIVEN
Accountability
Decisiveness
Entrepreneurship
Customer Service
Problem Solving

Note. Source: MacStravic (2016).

FIGURE 5. DOD'S PM FUNCTIONAL CAREER FIELD COMPETENCIES TABLE

Unit #	Unit of Competency	Unit of Competency Description	Comp #	Competency Name	Element #
AM1	Capability Integration Planning	Ability to develop both a short- and long-range, innovative acquisition plan/strategy that provides industry with the framework for creating functional activities essential to the development of a technology or system/product and manufacturing and fielding.	1.1	Requirements Management	1.1.1
AM1	Capability Integration Planning	Ability to develop both a short- and long-range, innovative acquisition plan/strategy that provides industry with the framework for creating functional activities essential to the development of a technology or system/product and manufacturing and fielding.	1.1	Requirements Management	1.1.2

Note. Source: MacStravic (2016).

FIGURE 6. DOD'S PM FUNCTIONAL CAREER-FIELD COMPETENCIES TABLE DESCRIPTIONS

Unit #	Basic Competency Element Description	Intermediate Competency Element Description	Advanced Competency Element Description
AM1	Understand that program and portfolio requirements are derived from capability needs statement and Concept of Operations (CONOPS) per the Joint Capabilities Integration and Development System (JCIDS) outputs or functional problem statements (for business systems) to establish the Acquisition Program Baseline (APB).	Derive or assist in deriving feasible program and portfolio requirements from the user capability needs statement and CONOPS per Joint Capabilities Integration and Development System (JCIDS) outputs or functional problem statements (for business systems) to establish the Acquisition Program Baseline (APB).	Derive, or supervise the effort to derive, feasible program and portfolio requirements from the user capability needs statement and CONOPS per Joint Capabilities Integration and Development System (JCIDS) outputs or functional problem statements (for business systems) to establish the Acquisition Program Baseline (APB).
AM1	Understand that there is a process in place that allows the management of the program's requirements baseline, to include interfaces across the program life cycle.	In coordination with the user, utilize a process to create and manage the program requirements baseline, to include interfaces across the program life cycle.	Implement a process, in coordination with the user, to create and manage the program requirements baseline (including interfaces) across the program life cycle.

Note. Source: MacStravic (2016).

The data sources used from PMI include the 6th edition of the *PMBOK Guide*, the 4th edition of *TSPgM*, and the 4th edition of *TSPfM*. Although the *PMBOK Guide* is the only ANSI-accredited standard of the three sources, the contents of *TSPgM* and *TSPfM* are recognized internationally as commercially accepted industry practices for program and portfolio managers, respectively. *TSPgM* and *TSPfM* define the standards for the application of their principles and practices, which enhances the likelihood of program and portfolio success (PMI, 2017b, 2017c).

The *PMBOK Guide* was developed to simplify and consolidate the vast body of knowledge that makes up the project management profession. It is an evolving standard due to the improving and ever-changing nature of the project management field. The *PMBOK Guide* consists of 10 knowledge areas: project integration management, scope management, schedule management, cost management, quality management, resource management, communications management, risk management, procurement management, and stakeholder management (PMI, 2017a). The 10 knowledge areas, the processes, and the three elements that are applicable across all knowledge areas were used as a source of comparison to the DoD's PM competencies. As an ANSI-approved standard, the *PMBOK Guide* meets the criteria of the NDAA (2019), as it is an accredited third-party program based on nationally recognized standards.

> **"Although the *PMBOK Guide* is the only ANSI-accredited standard of the three sources, the contents of *TSPgM* and *TSPfM* are recognized internationally as commercially accepted industry practices for program and portfolio managers, respectively.**

TSPgM was developed to provide "guidance on principles, practices, and activities of program management … [and to] provide a common understanding of the role of a program manager" (PMI, 2017c, p. 2). This standard both complements and aligns with PMI's *PMBOK Guide* (PMI, 2017a) and *TSPfM* (PMI, 2017b). The content of *TSPgM* is broader in scope than the *PMBOK Guide* and consists of five program management performance domains: program strategy alignment, program benefits management, program stakeholder engagement, program governance, and program life cycle management. These performance domains and various elements applicable across all program management domains serve as the source of comparison from *TSPgM* to the DoD's PM competencies. It is crucial to include *TSPgM* in this research because DoD's PMs do not only manage projects—their scope of responsibility ranges from participating on a project team to running large programs and portfolios.

TSPfM (PMI, 2017b) was developed to establish guiding principles for portfolio management practices and activities, and for defining the role of the portfolio manager (Ross & Shaltry, 2006). It was written to align with PMI's *PMBOK Guide* and *TSPgM*. Like *TSPgM*'s relationship to the *PMBOK Guide*, *TSPfM* is broader in scope than other standards. The scope differences are necessary because portfolios require a higher level of oversight than either programs or projects. Portfolios are ongoing ventures and may consist of other portfolios, programs, and projects. On the other hand, programs are made up only of other programs and projects; and projects, smaller still, are temporary and independent endeavors (PMI, 2017a, 2017b, 2017c). Seven portfolio management performance domains make up *TSPfM*: the portfolio life cycle, portfolio strategic management, portfolio governance, portfolio capacity and capability management, portfolio stakeholder engagement, portfolio value management, and portfolio risk management. These performance domains and the elements applicable across all portfolio management domains serve as the source of comparison to the DoD's PM competencies. As previously discussed, it is crucial to include *TSPfM* in this research because of the broad scope of responsibility assigned to DoD PMs.

The structure of the competency alignment map constructed mirrors the organization of the Office of the Assistant Secretary of Defense for Acquisition (OASD[A])'s PM functional career field competencies. The map was constructed in this manner for both ease of organization and for continuity. The headings of the OASD(A)'s table of competencies are shown in Figure 5 and are explained in the following list:

- **Unit #**: This is the coding of the four DoD PM categories (i.e., Acquisition Management [AM], Business Management [BM], Technical Management [TM], and Executive Leadership [EL]) and their successive units of competency. For example, the unit # for Capability Integration Planning is AM1 because it is the first unit of competency that falls under the AM management category.
- **Unit of Competency:** This heading consists of the competency units that make up the four DoD PM categories and is made up of multiple competencies.
- **Competency #**: This is the coding of each DoD PM competency. For example, the Capability Integration Planning competency is broken down into three sub-competencies: 1.1 – Requirements Management, 1.2 – Acquisition Program Strategic Planning, 1.3 – Business Case Development.

- **Competency Name**: This heading consists of the names for all 70 DoD PM competencies (i.e., Requirements Management, Acquisition Program Strategic Planning, Business Case Development, etc.).
- **Element #**: DoD PM competency elements are the lowest level to which the DoD PM competencies are broken down. Each element has a basic, intermediate, and advanced description. The PMI standards were mapped to each of the 190 elements at the basic, intermediate, and advanced level (570 total element descriptions) for a clear picture of the overall alignment. The Element #s are the coding of each element; for example, Element 1.1.1 = descriptor of the Requirements Management competency, which falls under the AM1 PM category and the Capability Integration Planning unit of competency.
- **Basic, Intermediate, and Advanced Competency Element Descriptions**: The three headings contain the descriptions for the basic (DAWIA Level I), intermediate (DAWIA Level II), and advanced (DAWIA Level III) elements.

FIGURE 7. COMPETENCY MAPPING TABLE EXCERPT WITH ADDED HEADINGS FOR BASIC COMPETENCY ELEMENTS

Competency Name	Element #	Basic Competency Element Description	Basic *PMBOK Guide* Equivalent
Requirements Management	1.1.4	Identify a rapid response situation and be aware of the uniquie documents and procedures needed to support urgent warfighter needs.	2.3 Organizational Process Assets 11.2 Identify Risks 11.6 Implement Risk Responses
Requirements Management	1.1.5	Understand how a system of systems architecture influences the decision-making process for requirements while meeting "customer needs."	Requirements Management
Requirements Management	1.1.6	Be aware of the best practices used in trade-off analysis and systems engineering that influence requirements-related program decisions.	2.4 Organizational Systems 5.2 Collect Requirements
Requirements Management	1.1.7	Be aware of the DoD Information Enterprise Architecture and the requirements for adherence to it.	2.2 Enterprise Environmental Factors 2.3 Organizational Process Assets 2.4 Organizational Systems
Acquisition Program Strategic Planning	1.2.1	Be aware of the requirement for an organizational mission, vision of success, and fundamental values as they relate to achieving successful acquisition outcomes.	2.2 Enterprise Environmental Factors 4.1 Develop Project Charter

Note. Adapted from MacStravic (2016). The color coding represents the PMI Standards' alignment with the DoD PM competencies (explained in Table 1).

FIGURE 8. COMPETENCY MAPPING TABLE EXCERPT WITH ADDED HEADINGS FOR INTERMEDIATE COMPETENCY ELEMENTS

Competency Name	Element #	Intermediate Competency Element Description	Intermediate *PMBOK Guide* Equivalent	Intermediate *TSPgM* Equivalent
Requirements Management	1.1.4	Identify and articulate rapid response situations and utilize the uniquie documents and procedures needed to support urgent warfighter needs.	2.3 Organizational Process Assets 4.6 Perform Integrated Change Control 10.2 Manage Communications 11.2 Identify Risks	6.1 Program Governance Practices 7.2 Program Activities and Integration Management 8.2 Program Delivery Phase Activities
Requirements Management	1.1.5	Utilize the requirements process with the user to make decisions in support of a system of systems architecture while meeting "customer needs".	Requirements Management	Requirements Management
Requirements Management	1.1.6	Identify and utilize best practices when conducting trade-off analysis and system engineering when making requirements-related decisions.	2.4 Organizational Systems 5.2 Collect Requirements	2.4 Organizational Systems 5.2 Collect Requirements
Requirements Management	1.1.7	Utilize the DoD Information Enterprise Architecture.	2.2 Enterprise Environmental Factors 2.3 Organizational Process Assets 2.4 Organizational Systems	8.1 Program Definition Phase Activities
Acquisition Program Strategic Planning	1.2.1	Utilize the organization's mission, vision of success, and fundamental values as they relate to achieving successful acquisition outcomes as guiding tools for decisions within a program.	2.2 Enterprise Environmental Factors	3.1 Program Business Case 3.2 Program Charter 6.1 Program Governance Practices

Note. Adapted from MacStravic (2016).

FIGURE 9. COMPETENCY MAPPING TABLE EXCERPT WITH ADDED HEADINGS FOR ADVANCED COMPETENCY ELEMENTS

Competency Name	Element #	Advanced Competency Element Description	Advanced *PMBOK Guide* Equivalent	Advanced *TSPgM* Equivalent	Advanced *TSPfM* Equivalent
Requirements Management	1.1.4	Supervise the identification and articulation of rapid response situations and ensure the use of the unique documents and procedures needed to support urgent warfighter needs.	2.3 Organizational Process Assets 4.6 Perform Integrated Change Control 10.2 Manage Communications 11.2 Identify Risks	6.1 Program Governance Practices 7.2 Program Activities and Integration Management 8.2 Program Delivery Phase Activities	2.3 Ongoing Life Cycle 2.4 Portfolio Management Information System 3.3 Portfolio Strategic Objectives 3.7 Portfolio Roadmap
Requirements Management	1.1.5	Guide the requirements process together with the user to meet "customer needs" and support decisions in the context of system of systems architecture.	5.2 Collect Requirements 12.3 Manage Stakeholder Engagement	5. Program Stakeholder Engagement 5.1 Program Stakeholder Identification 5.4 Program Stakeholder Engagement	6. Portfolio Stakeholder Engagement
Requirements Management	1.1.6	Identify and incorporate best practices when conducting trade-off analysis and systems engineering to make requirements-related decisions.	2.4 Organizational Systems 5.2 Collect Requirements	6.1 Program Governance Practices 6.3 Program Governance Design and Implementation	5.4 Capacity Planning 7.5 Negotiating Expected Value
Requirements Management	1.1.7	Ensure the DoD Information Enterprise Architecture is implemented.	2.2 Enterprise Environmental Factors 2.3 Organizational Process Assets 2.4 Organizational Systems	8.1 Program Definition Phase Activities	2.4 Portfolio Management Information System

FIGURE 9. COMPETENCY MAPPING TABLE EXCERPT WITH ADDED HEADINGS FOR ADVANCED COMPETENCY ELEMENTS (CONTINUED)

Competency Name	Element #	Advanced Competency Element Description	Advanced *PMBOK Guide* Equivalent	Advanced *TSPgM* Equivalent	Advanced *TSPfM* Equivalent
Acquisition Program Strategic Planning	1.2.1	Develop and document the organization's mission, vision of success, and fundamental values as they relate to achieving successful acquisition outcomes.	2.2 Enterprise Environmental Factors 4.1 Develop Project Charter	3.1 Program Business Case 3.2 Program Charter 6.1 Program Governance Practices	1.7 Principles of Portfolio Management 1.11 Other Roles in Portfolio Management 3.4 Developing Portfolio Strategic Objectives 3.6 Portfolio Charter

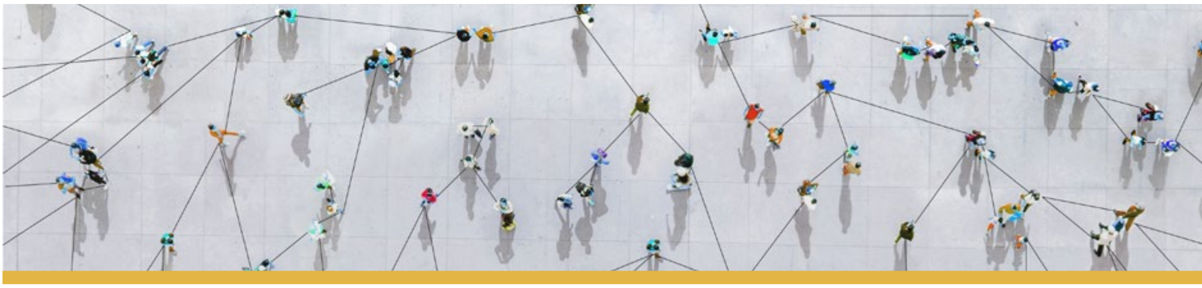
Note. Adapted from MacStravic (2016).

Six columns were added to the OASD(A)'s table of competencies to aid in the mapping process. These six columns and their placement are elaborated below and can be seen in Figures 7–9 to visualize the basic, intermediate, and advanced element mappings.

- **Basic *PMBOK Guide* Equivalent**: This column lists the *PMBOK Guide* knowledge areas that aligned with the DoD PM basic competency elements.
- **Intermediate *PMBOK Guide* Equivalent**: This column lists the *PMBOK Guide* knowledge areas that aligned with the DoD PM intermediate competency elements.
- **Intermediate *TSPgM* Equivalent**: This column lists the *TSPgM* performance domains that aligned with the DoD PM intermediate competency elements.
- **Advanced *PMBOK Guide* Equivalent**: This column lists the *PMBOK Guide* knowledge areas that aligned with the DoD PM advanced competency elements.
- **Advanced *TSPgM* Equivalent**: This column lists the *TSPgM* performance management domains that aligned with the DoD PM advanced competency elements.
- **Advanced *TSPfM* Equivalent**: This column lists the *TSPfM* performance management domains that aligned with the DoD PM advanced competency elements.

This research required the qualitative analysis of data—the data being the DoD's PM competency descriptions and the contents of PMI's knowledge areas and performance management domains, and the qualitative analysis being the alignment mapping. Six qualitative analyses of lexicographic comparisons were performed:

1. DoD's basic (DAWIA Level I) PM competencies to PMI's *PMBOK Guide* knowledge areas and processes
2. DoD's intermediate (DAWIA Level II) PM competencies to PMI's *PMBOK Guide* knowledge areas and processes
3. DoD's intermediate (DAWIA Level II) PM competencies to PMI's *TSPgM* program management domains
4. DoD's advanced (DAWIA Level III) PM competencies to PMI's *PMBOK Guide* knowledge areas and processes
5. DoD's advanced (DAWIA Level III) PM competencies to PMI's *TSPgM* program management domains
6. DoD's advanced (DAWIA Level III) PM competencies to PMI's *TSPfM* portfolio management domains



The purpose of performing these six iterations of comparison was to account for the increasing level of scope for both PMI's program and portfolio management and the DAWIA Level II and III certification requirements.

The sources used in the knowledge review for the DoD's PM competencies included the DoD 5000 series (Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD[A&S], 2020a, 2020b) and the competency descriptions provided by the OASD(A) (2016). Similarly, in mapping the DoD PM competency equivalents to the PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM*, additional PMI references were leveraged. PMI conference papers served as the primary source for additional information on PMI standards (Alie, 2016; Ross & Shaltry, 2006; Shenhar & Dvir, 2004).

The analysis resulted in the mapping of 1,085 DoD PM competency elements to PMI knowledge areas and domains. The next step in this research applied a quantitative analysis to the completed competency map. For a quantitative analysis, the qualitative data were transformed into a numeric, matrix format (Bernard, 1996). This transition to a matrix format was completed in conjunction with the more qualitative analysis by classifying each element mapping as either aligned, somewhat aligned, completely unaligned, or not applicable. These classifications were determined as follows:

- **Aligned (Green/"G")**: The description of the DoD PM competency element clearly aligned with one or more *PMBOK Guide* knowledge areas or one or more *TSPgM* or *TSPfM* performance domains. Indicators included exact, or synonymous, lexicon and application.
- **Somewhat Aligned (Yellow/"Y")**: The description of the DoD PM competency element was partially aligned with the processes of one or more *PMBOK Guide* knowledge areas or one or more *TSPgM* or *TSPfM* performance domains. Indicators included similar or related lexicon but dissimilar application of the concepts.
- **Completely Unaligned (Red/"RR")**: The description of the DoD PM competency element was not aligned with any of the *PMBOK Guide*'s knowledge areas or *TSPgM* or *TSPfM* performance domains. The only indicator was the absence of similar content and descriptors.
- **Not Applicable (Black/"N/A")**: Certain DoD PM competency elements were designated as not applicable at the basic and intermediate level because they only apply at the intermediate or advanced level of DoD program management.

A color-coding system was applied to this mapping process to signify the degree of alignment for each element mapping (green = aligned; yellow = somewhat aligned; red = completely unaligned; see Table 1). Green classifications were coded as "G"; yellow classifications were coded as "Y"; red classifications were coded as "RR"; black classifications were defined as "N/A." This coding system allowed the use of Microsoft Excel's = COUNTIF function to rapidly calculate the number of instances that DoD PM competency elements were aligned, somewhat aligned, completely unaligned, or not applicable with PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM*.

The next step in the analysis codified the PMI standards' knowledge areas and performance domains annotated in the element mapping as instances of alignment (see Tables 2–4). Several of the mapped elements aligned with multiple knowledge areas and performance management domains.

TABLE 1. CLASSIFYING AND CODIFYING ALIGNMENT

Classification	Code	DoD PM Competency Elements' Relationship with PMI	Indicators
Aligned	G	Clearly Aligned	Exact / Comparable Verbiage & Application
Somewhat Aligned	Y	Partially Aligned, or Interpreted as Such	Similar Verbiage / Dissimilar Application
Completely Unaligned	RR	Not Aligned	No Similarities
Not Applicable	N/A	Not Aligned	

TABLE 2. CODIFIED LABELING OF *PMBOK GUIDE* KNOWLEDGE AREAS

Knowledge Areas	Coded Label	Classifications
Introduction The Environment in Which Projects Operate The Role of the Project Manager	1 2 3	Elements Across All Knowledge Areas
Project Integration Management	4	Knowledge Area
Project Scope Management	5	Knowledge Area
Project Schedule Management	6	Knowledge Area
Project Cost Management	7	Knowledge Area
Project Quality Management	8	Knowledge Area
Project Resource Management	9	Knowledge Area
Project Communications Management	10	Knowledge Area
Project Risk Management	11	Knowledge Area
Project Procurement Management	12	Knowledge Area
Project Stakeholder Management	13	Knowledge Area

Note. Adapted from PMI (2017a).

TABLE 3. CODIFIED LABELING OF *TSPGM* PERFORMANCE DOMAINS

Knowledge Areas	Coded Label	Classifications
Introduction Program Management Performance Domains Program Activities	1 2 8	Elements Across All Domains
Program Strategy Alignment	3	Domain
Program Benefits Management	4	Domain
Program Stakeholder Engagement	5	Domain
Program Governance	6	Domain
Program Life Cycle Management	7	Domain

Note. Adapted from PMI (2017c).

TABLE 4. CODIFIED LABELING OF *TSPFM* PERFORMANCE DOMAINS

Knowledge Areas	Coded Label	Classifications
Introduction	1	Elements Across All Domains
The Portfolio Life Cycle	2	Domain
Portfolio Strategic Management	3	Domain
Portfolio Governance	4	Domain
Portfolio Capacity and Capability	5	Domain
Portfolio Stakeholder Engagement	6	Domain
Portfolio Value Management	7	Domain
Portfolio Risk Management	8	Domain

Note. Adapted from PMI (2017b).

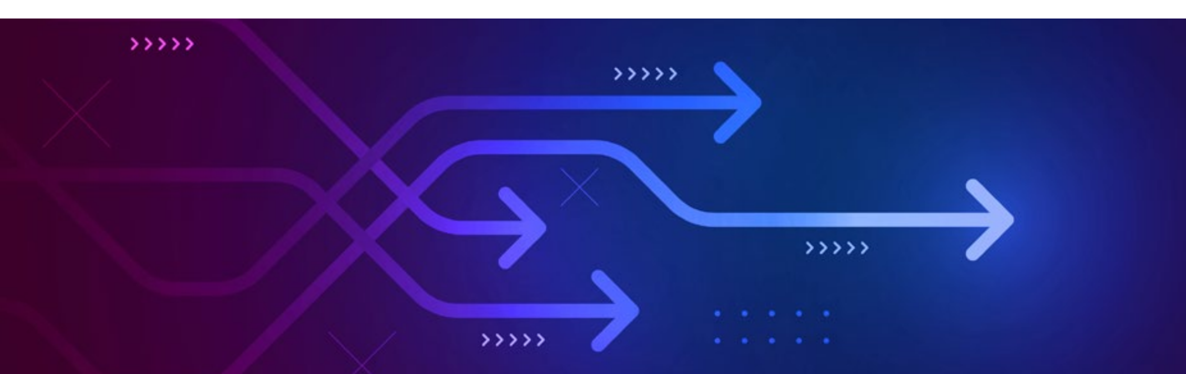


FIGURE 10. EXCERPT OF COMPETENCY MAP WITH CODIFIED ALIGNMENT AND KNOWLEDGE AREAS FOR BASIC ELEMENTS 3.3.3–3.4.2

Unit of Competency	Comp #	Competency Name	Element #	Basic Competency Element Description	KA	KA	KA	Alignment Code	Basic *PMBOK Guide* Equivalent
Program Execution	3.3	Teaming	3.3.3	Develop a basic understanding of how contractors develop and implement strategies for priming, subcontracting and teaming and how those strategies reflect a variety of desired outcomes.	12			Y	12.1 Plan Procurement Management
Program Execution	3.3	Teaming	3.3.4	Understand that there are internal and external customers and stakeholders with needs.	13			G	13.1 Identify Stakeholders 13.2 Plan Stakeholder Management
Program Execution	3.4	Program Oversight	3.4.1	Understand that program reviews and assessments evaluate the cost, schedule, and performance of the program.	6	7	8	G	6.6 Control Schedule 7.4 Control Costs 8.1 Plan Quality Management 8.2 Manage Quality Management 8.3 Control Quality
Program Execution	3.4	Program Oversight	3.4.2	Understand that the program is required to conduct technical assessments of prime and subcontractors.	8	11	12	Y	8.1 Plan Quality Management 11.1 Plan Risk Management 12.3 Plan Procurement Management

Note. Adapted from MacStravic (2016). KA = Knowledge Area. There are multiple rows because each DoD PM element may be covered by multiple knowledge areas.

After alignment of the DoD PM competencies to PMI knowledge areas and performance domains, the data were organized to ease interpretation. Six Microsoft Excel sheets were developed: one for every comparison made between the DoD PM competencies and PMI knowledge areas/domains (as shown in Figure 10). Each sheet tabulated the number of instances that PMI knowledge areas and domains mapped to each DoD PM unit of competency element; those mappings were then broken down into the different alignment categories. For example, the *PMBOK Guide* knowledge area Project Integration Management aligned with 24 of the DoD PM basic units of competency elements, somewhat aligned with 9, and was unaligned with 10.

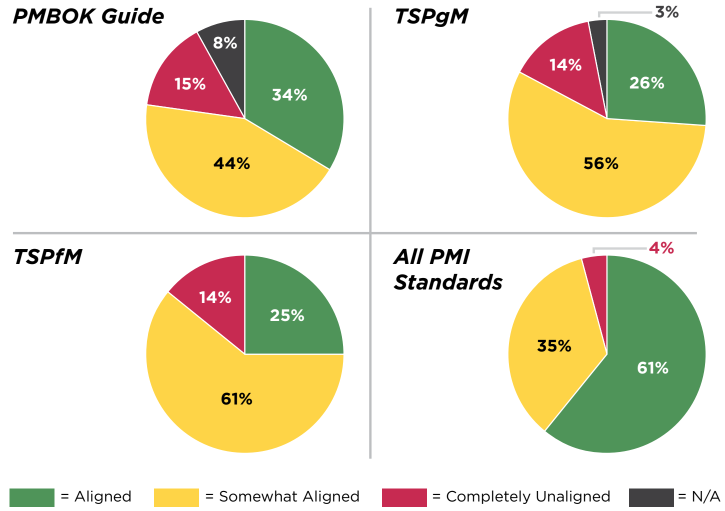
Data Analysis

This section addresses the extent to which the DoD's 2016 PM functional career field competencies are aligned with PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM*. The first step taken in the analysis was to count how many DoD competency elements were mapped to PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM* and were classified as *aligned, somewhat aligned, completely unaligned,* or *N/A* (refer to Table 5). Categories were created for the *PMBOK Guide*, *TSPgM*, and *TSPfM* by combining the basic, intermediate, and advanced elements that mapped to each standard. A fourth category was included that combined the findings across all three PMI standards to demonstrate the extent of alignment between the DoD PM competencies and the PMI standards when all PMI standards were applied. For example, if a single element was labeled as aligned under the *PMBOK Guide* but completely unaligned under *TSPgM* and *TSPfM*, it would be classified as aligned under the All PMI category. This method demonstrates the value of applying all three PMI standards in DoD PM training instead of the *PMBOK Guide* only. Finally, a fifth category was applied that shows the number of elements categorized as 100% aligned, somewhat aligned, or completely unaligned with the *PMBOK Guide*, *TSPgM*, and *TSPfM*. This category is significant because it shows that when all three PMI standards are applied, only eight of 190 DoD PM competency elements are completely unaligned with the PMI standards. According to the research, the DoD PM competencies align with the *PMBOK Guide*, *TSPgM*, and *TSPfM* as depicted in Figure 11.

TABLE 5. QUANTITY OF DOD PM COMPETENCY ELEMENTS MAPPED TO PMI'S STANDARDS (ORGANIZED BY LEVEL OF ALIGNMENT AND DAWIA LEVEL)

	Basic *PMBOK Guide*	Intermediate *PMBOK Guide*	Intermediate *TSPgM*	Advanced *PMBOK Guide*	Intermediate *TSPgM*	Advanced *TSPfM*
Aligned	73	65	52	56	47	47
Somewhat Aligned	66	83	98	99	115	116
Completely Unaligned	20	29	27	35	28	27
Not Applicable	31	13	13	0	0	0
	190	190	190	190	190	190

FIGURE 11. EXTENT TO WHICH THE DOD PM COMPETENCY ELEMENTS ALIGN TO THE PMI STANDARDS BY PIE CHART



Based on these findings, clearly, the *PMBOK Guide* is the PMI standard that is most aligned with the DoD PM competency elements. This is expected, as the *PMBOK Guide* serves as the building block for *TSPgM* and *TSPfM* and is the broadest of the three standards. However, by adding *TSPgM* and *TSPfM* standards to the standards of the *PMBOK Guide,* the alignment level of the PMI standards with the DoD PM competencies increases to 96% (61% completely aligned and 35% somewhat aligned). Further, the percentage of elements that are categorized as completely unaligned or not applicable decreased to 4% and 0%, respectively.

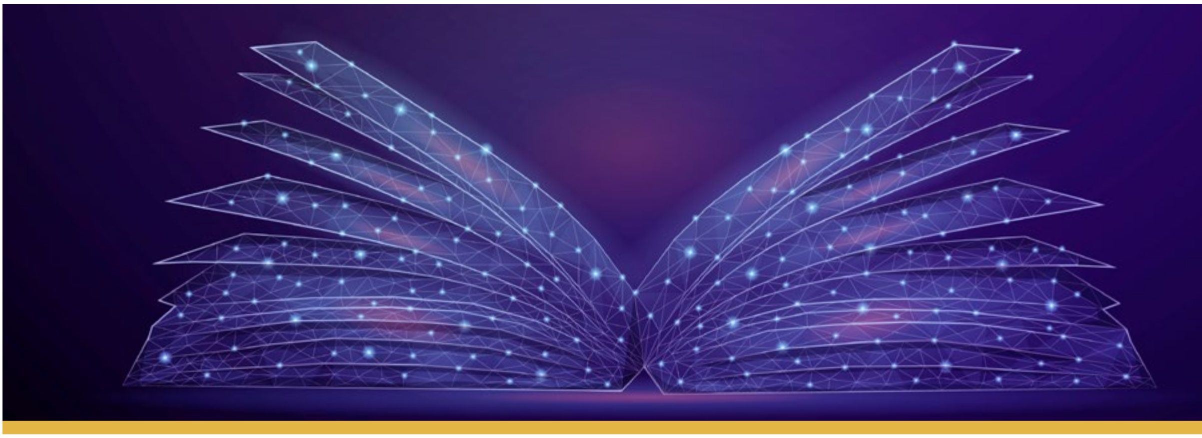


FIGURE 12. ALIGNMENT OF ACQUISITION MANAGEMENT DOD PM CATEGORY BY PMI

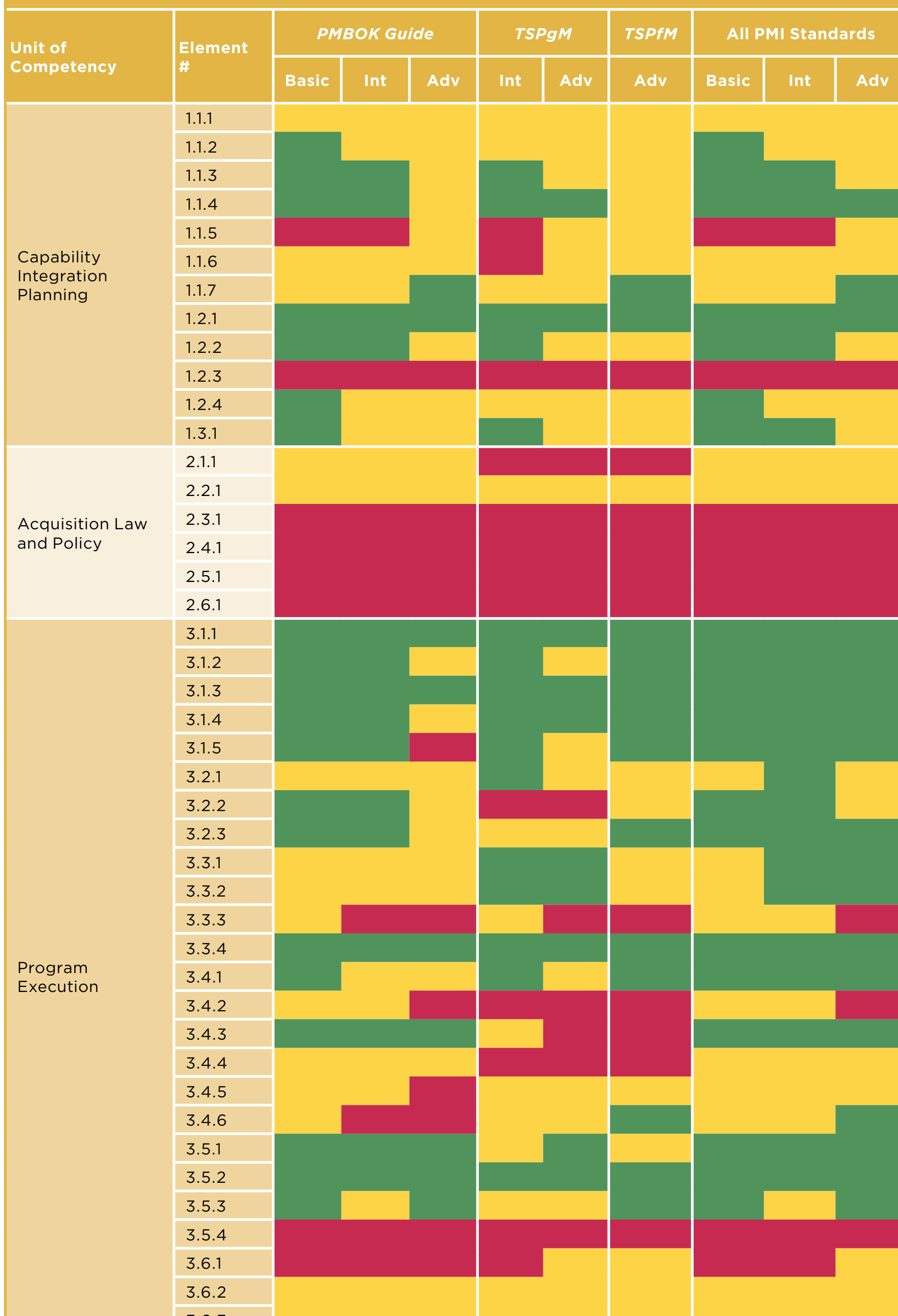


FIGURE 12. ALIGNMENT OF ACQUISITION MANAGEMENT DOD PM CATEGORY BY PMI (CONTINUED)

Unit of Competency	Element #	*PMBOK Guide*			*TSPgM*		*TSPfM*	All PMI Standards		
		Basic	Int	Adv	Int	Adv	Adv	Basic	Int	Adv
Stakeholder Management	4.1.1									
	4.2.1									
	4.3.1									
International Acquisition and Exportability (IA&E)	5.1.1									
	5.1.2									
	5.2.1									
	5.2.2									
	5.3.1									
	5.3.2									
	5.3.3									
	5.4.1									
	5.4.2									
Services Acquisition	6.1.1									
	6.1.1									
	6.1.1									

FIGURE 13. ALIGNMENT OF BUSINESS MANAGEMENT DOD PM CATEGORY BY PMI STANDARD

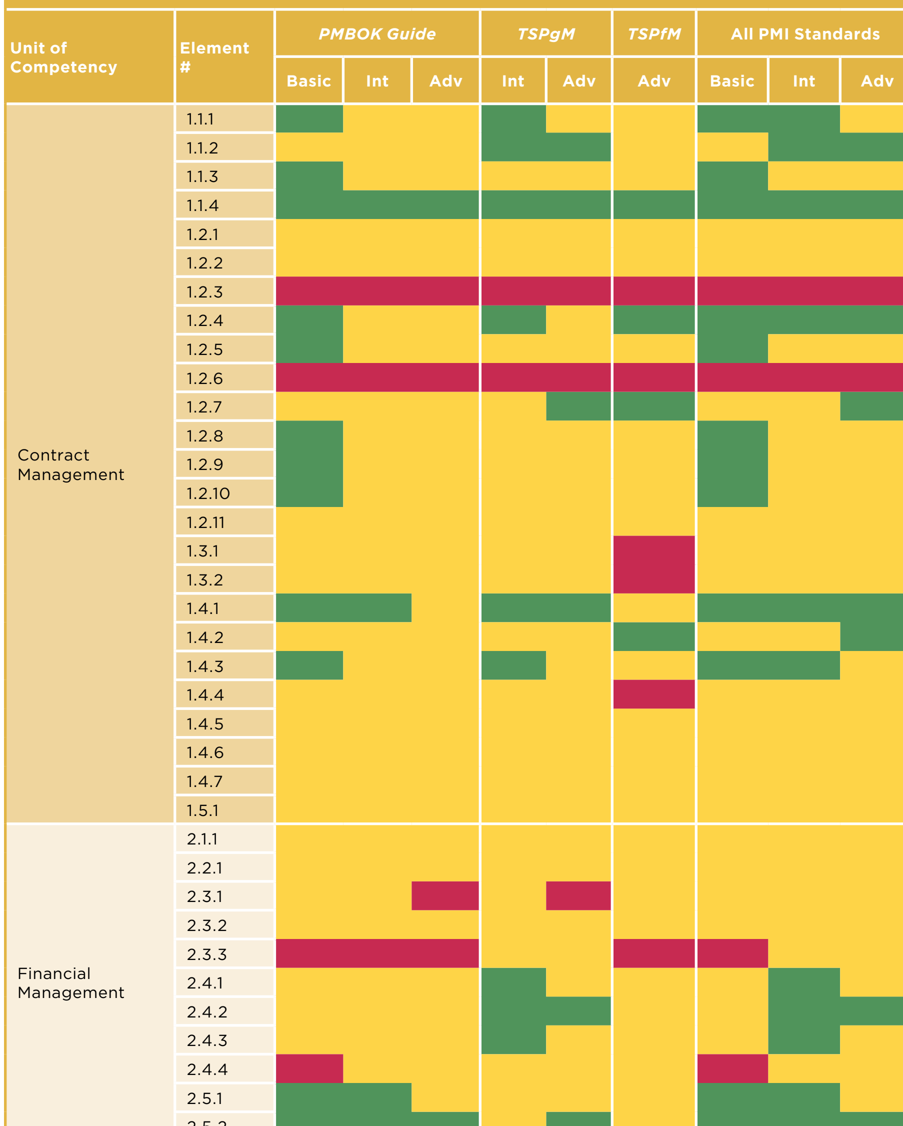


FIGURE 14. ALIGNMENT OF TECHNICAL MANAGEMENT DOD PM CATEGORY BY PMI STANDARD

FIGURE 14. ALIGNMENT OF TECHNICAL MANAGEMENT DOD PM CATEGORY BY PMI STANDARD (CONTINUED)

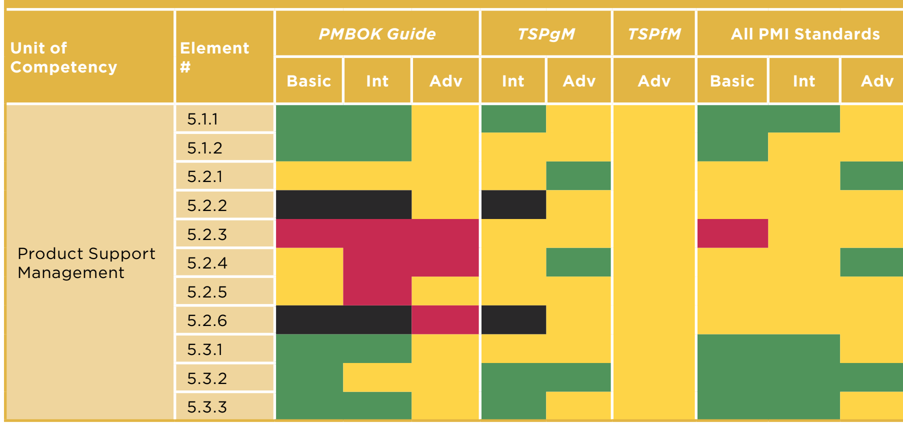


FIGURE 15. ALIGNMENT OF EXECUTIVE LEADERSHIP DOD PM CATEGORY BY PMI STANDARD

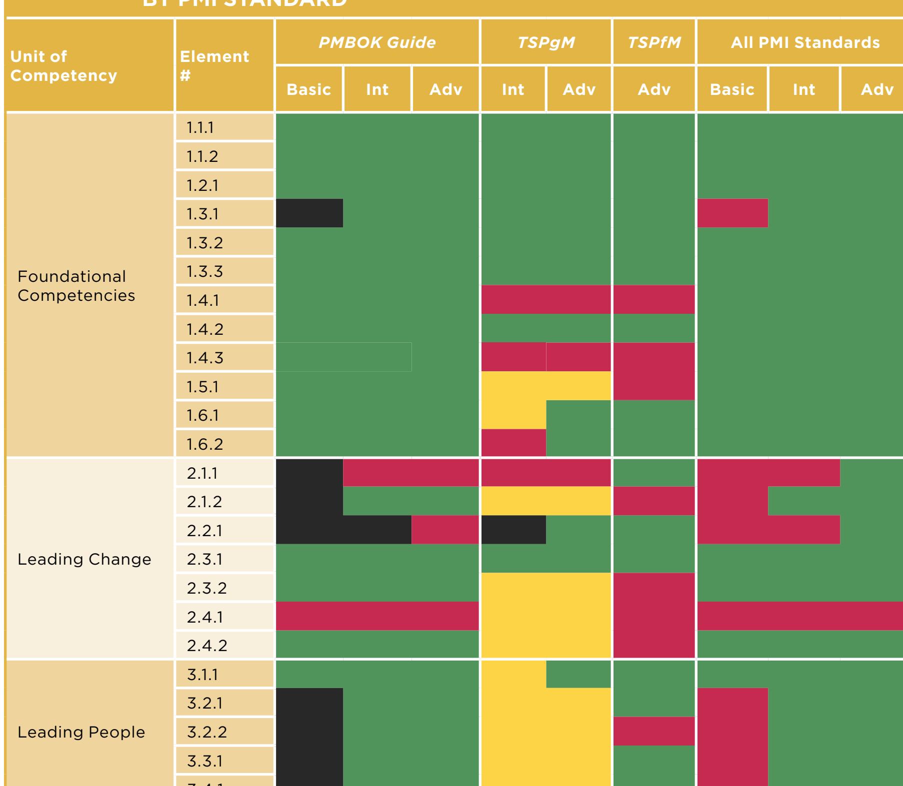
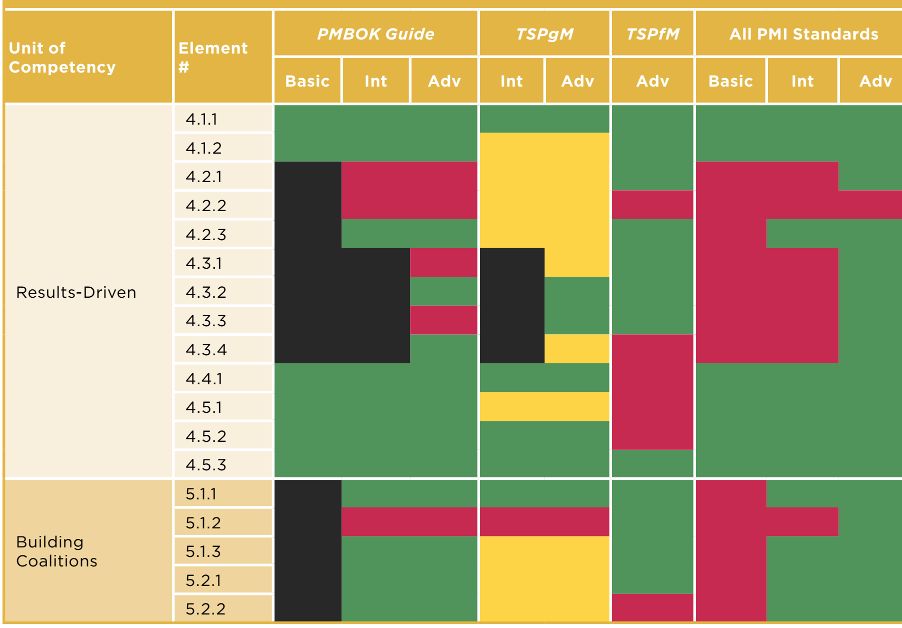


FIGURE 15. ALIGNMENT OF EXECUTIVE LEADERSHIP DOD PM CATEGORY BY PMI STANDARD



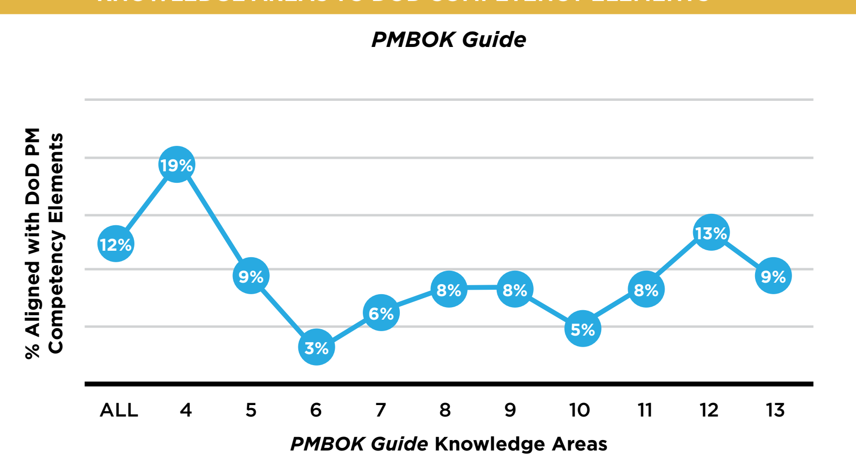
Figures 12–15 further elaborate on the impact achieved when applying all three PMI standards to DoD PM competencies in order to provide sufficient detail in determining which DoD PM competency elements need to be improved to ensure sufficient alignment with the PMI standards. These figures provide a visualization of the progressive improvement in alignment as all three PMI standards are applied. Figures 12–15 also demonstrate the different levels of alignment within the Acquisition Management, Business Management, Technical Management, and Executive Leadership DoD PM categories, respectively.

The visualizations in these figures demonstrate the alignment improvement of incorporating all three PMI standards to the DoD PM categories. By circumstance, the visualizations also provide a clear view of which DoD PM category is least aligned with the PMI standards. The Acquisition Management DoD PM category from Figure 12 contains the two DoD PM units of competency that are the least aligned across all three PMI standards. They include Acquisition Law and Policy (0% aligned, 33% somewhat aligned, and 67% completely unaligned) and the International Acquisition and Exportability (0% aligned, 74% somewhat aligned, and 26% completely unaligned) units of competency. This does not come as a surprise since these two units of competency are mostly exclusive to the DoD's nature of work and would not contain lexicon that would be commonplace in an industry-wide standard. Therefore, courses in these two units of competency would need to augment acquisition/PM training if the DoD adopted PMI certification standards.

This section provides a breakdown of the competency mapping by the *PMBOK Guide* project management knowledge areas, *TSPgM* program management performance domains, and *TSPfM* portfolio management performance domains to answer the question, *What PMI knowledge areas and performance domains are most aligned and least aligned with the DoD program management functional career field competency elements?* Analyzing the level of alignment between the DoD's PM functional career field competencies and the PMI standards at this level enables DoD officials to see which knowledge areas and domains are not being applied in the DoD's PM competencies.

This analysis required the approach of mapping the DoD's PM competency elements to the PMI knowledge areas and performance domains by determining the DoD PM competency elements that aligned (both completely and somewhat) with the PMI's knowledge areas and performance domains. This process enabled the tallying of each knowledge area and performance domain that aligned with the DoD PM competency elements. Figure 16 demonstrates the extent to which each of the *PMBOK Guide*'s 10 knowledge areas align with the DoD PM competency elements. This analysis enables DoD stakeholders such as DAU to adjust training and learning objectives to appropriately integrate the *PMBOK Guide* project management knowledge areas into PM certification curriculum.

FIGURE 16. ALIGNMENT OF THE *PMBOK GUIDE* PROJECT MANAGEMENT KNOWLEDGE AREAS TO DOD COMPETENCY ELEMENTS



The knowledge areas that exhibited the greatest level of alignment were 4 – Project Integration Management, 12 – Project Procurement Management, and All – Elements Across All Knowledge Areas.

- **4 – Project Integration Management**: This knowledge area made up 19% of all the aligned and somewhat aligned DoD PM competency elements—more than any other section. Project Integration Management includes the coordination of all processes that spread across every *PMBOK Guide* process group (initiating, planning, executing, monitoring and controlling, and closing) and thus unify a project/program's life cycle.
- **12 – Project Procurement Management**: This knowledge area made up 13% of all the aligned and somewhat aligned elements. Due to the high quantity of services and acquisition within the DoD that rely on contract management, this knowledge area could be considered critical to include in the training of DoD PMs. It should be noted that while this was the second most aligned knowledge area, it also mapped most to the Contract Management DoD PM unit of competency, which falls under the second most completely unaligned DoD PM category, Business Management.
- **All – Elements Across All Knowledge Areas**: This pseudo–knowledge area consists of *PMBOK Guide* Sections 1 – Introduction, 2 – The Environment in Which Projects Operate, and 3 – The Role of the Project Manager. While these sections are not *PMBOK Guide* project management knowledge areas, they contain a great deal of information regarding project management and should not be ignored in updating or developing new DoD PM standards. This section demonstrated 12% alignment with the basic, intermediate, and advanced elements of the DoD PM competencies.

> **This analysis enables DoD stakeholders such as DAU to adjust training and learning objectives to appropriately integrate the *PMBOK Guide* project management knowledge areas into PM certification curriculum.**

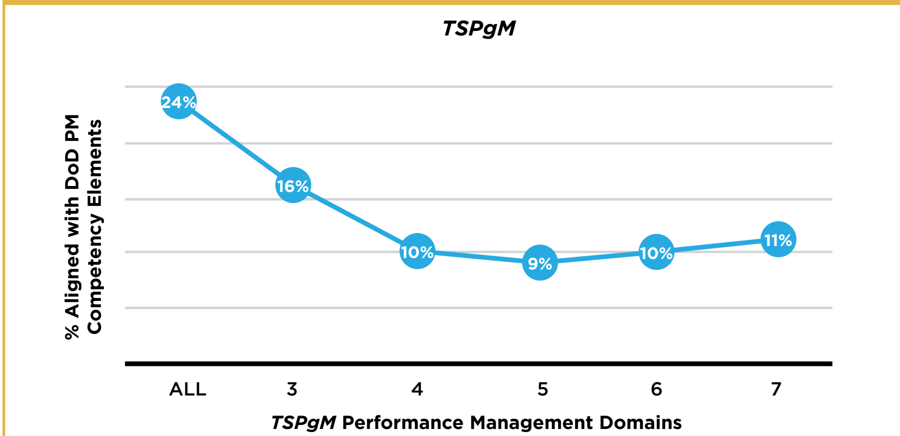
The knowledge areas that exhibited the lowest level of alignment were 6 – Project Schedule Management, 10 – Project Communications Management, and 7 – Project Cost Management.

- **6 – Project Schedule Management**: This knowledge area made up only 3% of the aligned and somewhat aligned DoD PM competency elements. This deficiency in alignment is concerning because managing schedule is one of the three project management tenets that make up the triple constraint of project management (Atkinson, 1999). The other two components of the triple constraint are cost management and scope/performance management. The concept behind the triple constraint is that if one of the three (cost, schedule, or scope/performance) changes, one or both of the other two will be impacted. Understanding how to manage the triple constraint is critical for project managers and PMs, for if the three components are not well planned, executed, monitored, or controlled, then the project's or program's acquisition baselines will be difficult to set and manage, jeopardizing the success of the project or program.
- **7 – Project Cost Management**: This knowledge area made up 6% of the aligned and somewhat aligned DoD PM competency elements. As stated, cost management is one of the three components of the triple constraint and is therefore critical in project management.
- **10 – Project Communications Management**: This knowledge area made up only 5% of the aligned and somewhat aligned DoD PM competency elements. The impact that communications management can have on a project cannot be overstated. Mortlock (2016) opined that including some form of communications document (e.g., a strategic communication [STRATCOM] plan) that conveys a project's or program's desired impact and synchronizes its implementation and execution plans has proven valuable to program success.

"Understanding how to manage the triple constraint is critical for project managers and PMs, for if the three components are not well planned, executed, monitored, or controlled, then the project's or program's acquisition baselines will be difficult to set and manage, jeopardizing the success of the project or program.

To summarize, the least aligned *PMBOK Guide* knowledge areas were project cost, schedule, and communications management. Two of these three are related to the triple constraint, which—if not professionally managed—can significantly impact project outcomes. The fact that the DoD PM competencies do not align well with these *PMBOK Guide* sections may be cause for concern because it is an indicator that the DoD is not adequately training their PMs on the importance of managing schedule, cost, and communications—at least in the realm of formal acquisition training.

FIGURE 17. ALIGNMENT OF *TSPgM* PROGRAM MANAGEMENT PERFORMANCE DOMAINS TO INTERMEDIATE AND ADVANCED DOD COMPETENCY ELEMENTS



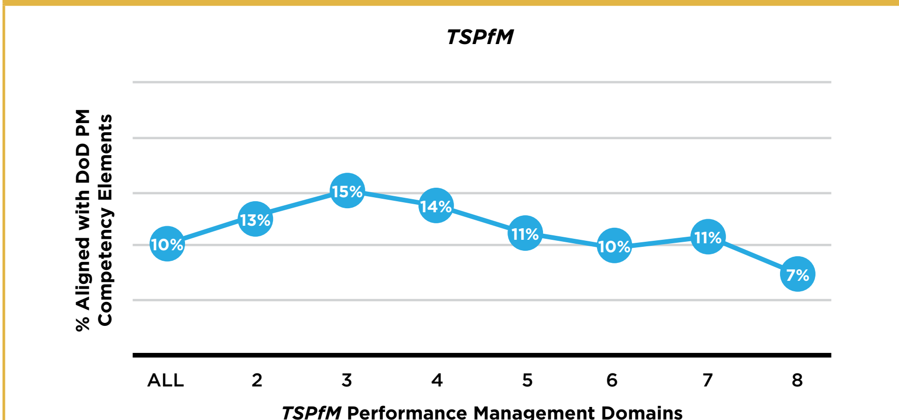
This section demonstrates the extent to which each of *TSPgM*'s program management performance domains—and elements across all domains—align with the intermediate and advanced DoD PM competency elements (see Figure 17). This analysis enables DoD stakeholders to focus on the most relevant *TSPgM* program management performance domains when restructuring their certification curriculum.

The program management performance domains that exhibited the greatest level of alignment include All – Elements Across All Knowledge Areas and 3 – Program Strategy Alignment. The remaining four performance domains exhibited mostly similar levels of alignment (9%–11%).

- **All – Elements Across All Program Management Performance Domains**: This pseudo domain consists of *TSPgM* Sections 1 – Introduction, 2 – Program Management Performance Domains, and 8 – Program Activities. While these sections are not *TSPgM* program management performance domains, they contain a great deal of information regarding program management and should not be ignored in updating or developing new DoD PM standards. This section makes up 24% of the DoD PM elements that were categorized as aligned or somewhat aligned.

- **3 – Program Strategy Alignment**: The contents of this performance domain identify "program outputs and outcomes to provide benefits aligned with the organization's strategic goals and objectives" (PMI, 2017c, p. 33). It is a good thing that the DoD PM competencies emphasize this performance domain because of the high number of portfolios and programs managed by the DoD. Providing training on organizational strategy and benefits management enables DoD PMs, portfolio managers, and other DoD acquisition leaders to effectively develop, align, and manage agency-wide acquisition and capability objectives.

FIGURE 18. ALIGNMENT OF *TSPfM* PORTFOLIO MANAGEMENT PERFORMANCE DOMAINS TO ADVANCED DOD COMPETENCY ELEMENTS



This section demonstrates the extent to which each of *TSPfM*'s portfolio management performance domains—and elements across all domains—align with the advanced DoD PM competency elements (see Figure 18). This analysis enables DoD stakeholders to focus on the most relevant *TSPfM* program management performance domains when restructuring their certification curriculum.

The portfolio management performance domains that exhibited the greatest level of alignment were 2 – The Portfolio Life Cycle, 3 – Program Strategic Management, and 4 – Portfolio Governance.

- **2 – The Portfolio Life Cycle**: Just as the *PMBOK Guide* Project Integration Management knowledge area was highly aligned with the DoD PM competencies, so too is this performance domain (13%). These two are comparable due to their ongoing nature. Project Integration Management and Portfolio Life Cycle Management heavily rely on information systems that enable effective communication and support seamless and timely transitions between project and life cycle phases (PMI, 2017a, 2017b). Due to the criticality of this performance domain, the DoD should continue to promote this as a highly aligned domain.
- **3 – Portfolio Strategic Management**: This performance domain makes up 15% of the aligned DoD PM competencies. Decisions relying on strategic alignment are made at the executive level.
- **4 – Portfolio Governance**: This performance domain makes up 14% of the aligned DoD PM competency elements. The effective implementation of Portfolio Governance aids an organization in becoming auditable (Rendon & Rendon, 2015). Implementing this domain into DoD PM training will offer guidance on ensuring portfolio oversight, effective reporting structures, and stakeholder management.

> **Project Integration Management and Portfolio Life Cycle Management heavily rely on information systems that enable effective communication and support seamless and timely transitions between project and life cycle phases.**

The performance domain that exhibited the lowest level of alignment was 8 – Portfolio Risk Management.

- **8 – Portfolio Risk Management**: This domain made up the lowest number of aligned DoD PM elements. This indicates that the current DoD PM competency elements do not include many elements related to risk management at the advanced level. The DoD should consider addressing this training gap to improve its PMs' ability to identify, analyze, and manage risks at the portfolio level. By successfully identifying and analyzing risks, the DoD will be able to develop more accurate cost and schedule management plans and estimates. This should lead to fewer cost overruns and schedule slips, and empower DoD PMs to develop more successful acquisition strategies that account for risks.

Conclusions

This research provided the DoD with information and insight necessary to respond effectively to the Fiscal Year 2020 NDAA's (2019) mandate to base acquisition workforce certification requirements on nationally or internationally recognized third-party standards. The goal of the NDAA's mandate is to improve the quality of the DoD's program management workforce through effective training. As globally recognized standards, PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM* serve as excellent foundations on which to base the DoD's program management certification requirements. The researchers investigated the degree to which the DoD's PM competencies align with the standards of the PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM*. Analyzing and defining the level of alignment between the two standards enables training organizations to provide the acquisition workforce with more comprehensive training that leverages internationally recognized PM standards.

From a high-level perspective, the *PMBOK Guide* proved to be the most aligned, *TSPgM* is the second most aligned, and *TSPfM* is the least aligned with DoD PM competencies (refer to Table 6). The knowledge areas and performance domains that were most aligned with the DoD's PM competency elements included concepts for strategic management, life cycle management, and overarching concepts as indicated by the "Elements Across all Knowledge Areas/Performance Domains" identifier. The most concerning finding from this research was the discovery of the relatively low level of alignment of the schedule and cost management knowledge areas across DoD PM competencies.

TABLE 6. SUMMARY RESEARCH FINDINGS

1. To what extent are the DoD's 2016 program management competency elements aligned with the PMI's *PMBOK Guide*, *TSPgM*, and *TSPfM*? Which PMI standard is most aligned?			
PMBOK Guide	***TSPgM***	***TSPfM***	**All PMI Standards**
34% Aligned (Most Aligned)	26% Aligned	25% Aligned	61% Aligned

2. What PMI knowledge areas and performance domains are most and least aligned with the DoD program management functional career field competency elements?	
***PMBOK Guide* Knowledge Areas**	
Most Aligned	**Least Aligned**
All - Elements Across All Knowledge Areas	6 - Project Schedule Management
4 - Project Integration Management	7 - Project Cost Management
13 - Project Stakeholder Management	10 - Project Communications Management
***TSPgM* Performance Domains**	
Most Aligned	**Least Aligned**
All - Elements Across All Performance Domains	N/A
3 - Program Strategy Alignment	
***TSPfM* Performance Domains**	
Most Aligned	**Least Aligned**
2 - The Portfolio Life Cycle	8 - Portfolio Risk Management
3 - Portfolio Strategic Management	4 - Portfolio Governance
4 - Portfolio Governance	

The following are recommendations based on analyses conducted throughout this research.

1. Base the new DAWIA PM training certification requirements on the *PMBOK Guide*, *TSPgM*, and *TSPfM*.

A review of the literature and the analysis of the mappings between the DoD's PM functional career field competencies and the PMI standards have led the researchers to believe that the DoD should base their new certification requirements on all three PMI standards. As discussed in the literature review, the progressive complexity and scope of the DAWIA certifications "correlate to the complexity and responsibilities required for designated positions and different types of assignments in weapon systems, services, business management systems and information technology, and international acquisitions" (Redshaw, 2011, p. 55). Because the *PMBOK Guide* is exclusively aimed towards individuals charged with managing temporary endeavors (projects), it would not suffice as the sole source of training for the DoD's program management workforce. For example, many PMs run programs that have existed for decades and manage portfolios that contain a multitude of different projects and programs. Such endeavors require a higher level managerial perspective and scope of control than the *PMBOK Guide* provides. Therefore, the *PMBOK Guide* would not be able to meet the progressive complexities of the DAWIA certifications and operational responsibilities that are reflected in the DoD's acquisition workforce. By adding *TSPgM* and *TSPfM* to the certification framework of their PMs, the DoD can account for the increase in managerial scope that PMs will see as they progress in their careers.

2. Maintain the three-tiered certification model.

The DAWIA three-tiered certification model consists of Level I (basic), Level II (intermediate), and Level III (advanced). This progressive education model enables PMs to be trained on relevant subject matter and prevents them from learning out-of-scope material too early. For example, it would not make sense for a DoD project manager to be trained on portfolio life-cycle management when the scope of their responsibilities is to manage small projects at the base level. Further, it would be a disservice to the DoD if program executive officers, who primarily manage portfolios, were not trained on basic project management practices, because those practices form the basis of portfolio governance and strategic alignment across projects, programs, and portfolios. To guide PMs from an introduction to project management to being capable of running vast programs and portfolios, the DoD must establish a training program that gradually increases in scope in correlation with the scope of the PM's current job responsibilities. This can be accomplished by establishing certification standards based on the following model:

- DAWIA Level I (basic/project managers) – *PMBOK Guide*
- DAWIA Level II (intermediate/PMs) – *TSPgM*
- DAWIA Level III (advanced/program and portfolio managers) – *TSPfM*

This would allow for a gradual increase in program management knowledge and application and align experience to training certifications. To improve upon this model, the DoD should enable cross-sectioning of the three PMI standards into each certification level. As mentioned, the *PMBOK Guide* serves as the foundation for both *TSPgM* and *TSPfM* and therefore holds valuable information that should be used in the training of managers of programs and portfolios. Likewise, including sections of *TSPgM* and *TSPfM* with the Level I education allows young DoD PMs to see the larger picture of their career and can help them to better understand the intricacies of the basic project management training.

> **"To guide PMs from an introduction to project management to being capable of running vast programs and portfolios, the DoD must establish a training program that gradually increases in scope in correlation with the scope of the PM's current job responsibilities.**

3. Augment professional certifications with DoD-specific PM training.

As this research has demonstrated, the three PMI standards alone do not cover all the DoD PM competencies. For example, if the PMP certification is adopted for DAWIA PM Level I (basic), *TSPgM* certification is adopted for DAWIA PM Level II (intermediate), and *TSPfM* certification is adopted for DAWAI PM Level III (advanced), additional DAU training courses would need to focus on the areas least aligned, like Acquisition Law and Policy and International Acquisition and Exportability. Additional DAU training would be required in the areas not covered by PMI standards sufficiently, including the following:

- Acquisition Management
    - Capability Integration Planning

        - Acquisition Program Strategic Planning: understanding, developing, and framing an acquisition strategy that addresses requirements, resourcing, risks, and opportunities
    - Acquisition Policy and Law
        - Financial Management Laws, Directives, and Policies
        - Program Support Laws, Directives, and Policies
        - Technical and Engineering Laws, Directives, and Policies
        - Information Technology Laws, Policy, and Best Practices
    - Program Execution
        - Resource Management: understanding, developing, and enabling business process reengineering efforts
    - International Acquisition and Exportability
        - International Cooperative Programs
        - Sales and Transfers
        - Technology Security and Foreign Disclosure
        - Defense Exportability Integration
- Business Management
    - Contract Management
        - Presolicitation Planning and Execution: understanding the use interagency acquisition
        - Presolicitation Planning and Execution: understanding the different levels of data rights including unlimited, government purpose, limited, and restricted
- Technical Management
    - Engineering Management
        - Technical Planning: understanding, applying, and ensuring program protection, cybersecurity, and counterintelligence

Considering that 190 DoD PM competencies exist, the fact that PMI standards aligned reasonably well to all but the 12 highlighted here reinforces the recommendation to adopt the PMI standards.

4. Consider all three components of auditability.

In conjunction with the modification to its PM certification requirements, the DoD should consider the research of Eckerd and Snider (2017) and Rendon and Rendon (2015). Both sets of research emphasize the importance of ensuring capable processes and effective internal controls. While this research exclusively considered the development of competent personnel through an analysis of training standards, the DoD should ensure that correct measures are being taken in modifying training certifications and in developing effective processes to transition the workforce and the training staff to the new standards.

5. Revitalize the *U.S. Department of Defense Extension to: A Guide to the Project Management Body of Knowledge*.

To fill competency gaps that are not covered by PMI standards, the DoD should look to the *U.S. Department of Defense Extension to: A Guide to the Project Management Body of Knowledge* (DoD & DAU, 2003; PMI, 2017a). We also recommend that the DoD consider publishing similar DoD extensions to both the *TSPgM* and the *TSPfM* to cover the training of PMs for programs and portfolios.

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Author Biographies

1st Lt Jonathan L. Karnes, USAF

is a contract specialist for the Air Force Life Cycle Management Center's Medium Altitude Unmanned Aircraft System Division. He holds an MBA in Acquisition Management from the Naval Postgraduate School, an MBA in Project Management from the University of Texas at San Antonio, and a BS in communication studies from the University of Texas at Austin.

(E-mail address: jonathan.karnes.3@us.af.mil)

Dr. Robert F. Mortlock

is a professor of the practice for defense acquisition and program management at the Graduate School of Defense Management, Naval Postgraduate School, Monterey, California. He holds a PhD in Chemical Engineering from the University of California, Berkeley; an MBA from Webster University; an MS in National Resource Strategy from Industrial College of the Armed Forces (now the Dwight D. Eisenhower School for National Security and Resource Strategy); and a BS in Chemical Engineering from Lehigh University.

(E-mail address: rfmortlo@nps.edu)

Image designed by Nicole Brate

Exploring PERFORMANCE IN AIR FORCE SCIENCE and Technology Programs

MSgt Eric A. Plack, USAF, Jonathan D. Ritschel, Edward D. White, Lt Col Clay M. Koschnick, USAF, & Lt Col Scott T. Drylie, USAF

Science and technology (S&T) programs serve an important function in the defense acquisition process as the initial phase leading to discovery and development of warfighting technology. The results of these programs impact the larger major defense acquisition programs, which integrate the technologies in subsequent phases of the life cycle. Despite this important role, little prior research has examined the performance of S&T programs. In this study, the authors investigate the impact of technological maturation as a critical success factor in Air Force S&T programs. The results suggest that S&T programs with mature technologies are more likely to experience above average cost growth and larger contract values while less likely to experience schedule growth. Additionally, the authors find the partnership method between the government and contractor matters for both technological maturation and schedule growth. Lastly, the nature of the S&T program is important, with aerospace programs more likely to technologically mature than human systems programs.

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Keywords: *Program Management, Defense Acquisition, Technology Readiness Level, Technological Maturity*

Program management focuses on cost, schedule, and performance as the three key measures of success (Meridith & Mantel, 2003; Pinto & Slevin, 1998). A large body of literature identifies critical factors that lead to program success in both private industry (Nasir & Sahibuddin, 2011; Pinto & Slevin, 1987; Zwikael & Globerson, 2006) and the public sector (Rendon, 2012; Rodriguez-Segura et al., 2016; Tishler et al., 1996). Prior analyses of program performance in defense programs, however, have focused almost exclusively on larger, more mature programs that have reached the Engineering and Manufacturing Development (EMD) phase of the life cycle or beyond. An abundance of studies exploring cost growth or schedule growth can be found for these major defense acquisition programs (MDAPs) (Bolten et al., 2008; Cancian, 2010; Smirnoff & Hicks, 2008). Missing from the literature is an exploration of smaller programs that feed basic science and technologies to subsequent acquisition programs or that develop new systems and technologies on a smaller scale. These are the science and technology (S&T) programs that are undertaken in defense research labs. This article seeks to bridge that gap through an exploratory analysis of program performance in Air Force S&T programs.

To the best of our knowledge, this study is the first to systematically analyze Air Force S&T program performance. While the contributions are novel, they are not intended to be the final word on the subject. Rather, this article seeks to ignite the spark that spawns the intellectual curiosity and research of others in S&T programs. Thus, the purpose of this article is to identify initial insights regarding relationships that may impact cost, schedule, and performance in S&T programs. By lighting the fire, we are optimistic that the findings articulated here will be further explored so that future S&T program decisions can be fully informed.

Importance of Science and Technology

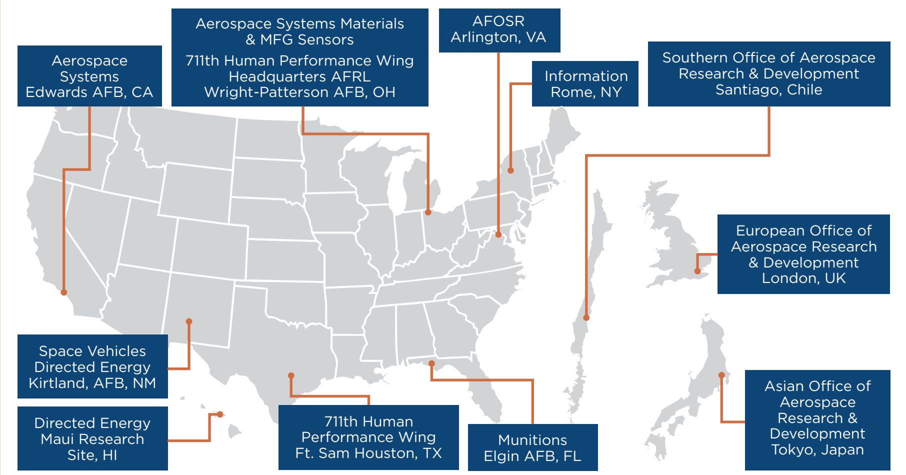
The vision to implement S&T as a centerpiece of our nation's airpower strategy has been around since 1945 (Duffner, 2000). General H. H. "Hap" Arnold, Commanding General of the Army Air Forces, enlisted the aid of top aeronautics scientist Dr. Theodore von Karman to lead the first of these efforts, recommending the creation of an agency devoted exclusively to aeronautical research and development (Gorn, 1988). Over time, that agency has evolved to what is known today as the Air Force Research Laboratory (AFRL) (Duffner, 2000).

S&T's enduring importance is demonstrated in the 2019 publication of the *U.S. Air Force 2030 Science and Technology Strategy*. The 2030 S&T strategy aligns with the National Defense Strategy to empower S&T programs to develop and deliver warfighting capabilities rapidly and effectively (United States Air Force, 2019). How does S&T fulfill this need? S&T functions as the initial phase of the acquisition process by which technologies are matured and, where appropriate, are transitioned for acquisition by the Air Force (Office of the Chief Scientist of the U.S. Air Force, 2010). Continual advancement in these cutting-edge technologies is crucial, as the Air Force faces ever-changing threats and adversarial advancements in technology.

The Anatomy of Air Force Research Labs

The S&T data analyzed in this article are from AFRL programs. A brief organizational description is provided for those unfamiliar with the laboratory. AFRL is headquartered at Wright-Patterson Air Force Base (AFB) in Ohio. It comprises nine technology directorates in the continental United States and four locations overseas in Hawaii, United Kingdom, Chile, and Japan, as shown in Figure 1.

FIGURE 1. AFRL LOCATIONS & MAJOR OFFICES



Note. AFOSR = Air Force Office of Scientific Research; AFRL = Air Force Research Laboratory; MFG = Manufacturing.

TABLE 1. AFRL TECHNOLOGY DIRECTORATES

Technology Directorate	Symbol	Program Descriptions
Air Force Office of Scientific Research	AFOSR	Basic Research Manager for AFRL
711th Human Performance Wing	RH	Aerospace Medicine S&T, Human Systems Integration
Directed Energy Directorate	RD	Laser, Electromagnetics, Electro-Optics

TABLE 1. AFRL TECHNOLOGY DIRECTORATES (CONTINUED)

Technology Directorate	Symbol	Program Descriptions
Information Directorate	RI	Information Fusion, Exploitation, Networking
Aerospace Systems Directorate	RQ	Aerodynamics, Flight Control, Engines, Propulsion
Space Vehicle Directorate	RV	Space-Based Surveillance, Capability Protection
Munitions Directorate	RW	Air-Launched Munitions
Materials & Manufacturing Directorate	RX	Aircraft, Spacecraft, Missiles, Rockets
Sensors Directorate	RY	Sensors for Reconnaissance, Surveillance

Each technology directorate focuses on the development and innovation of leading-edge technologies and is separated by technological capabilities. A list of AFRL's technology directorates, their office symbols, and program descriptions appears in Table 1. The analysis of individual technical directorates will be one of the ways this research segments the data.

Measures of Success: The Role of Technology Readiness Levels

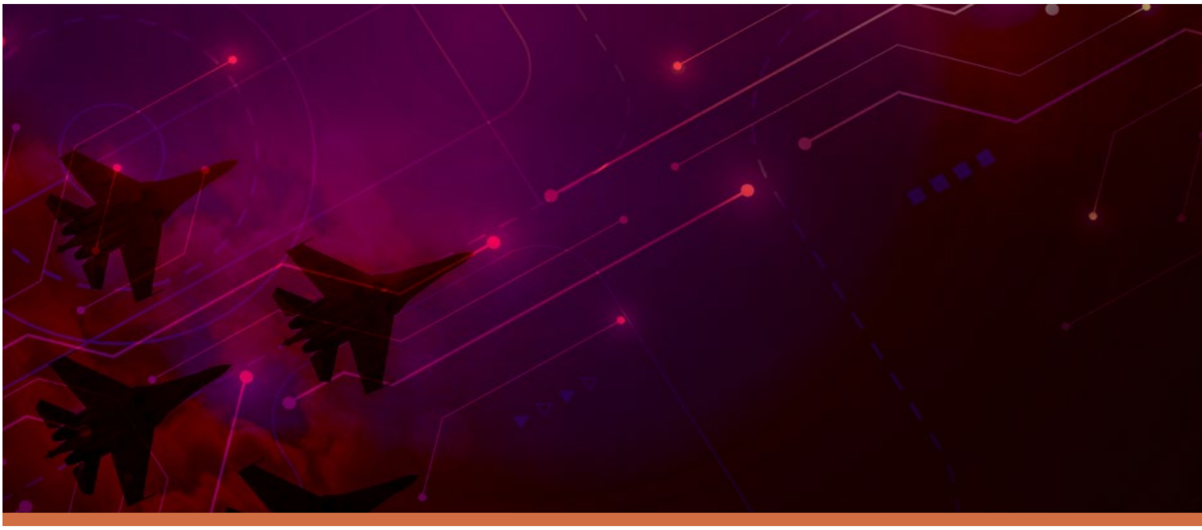
The General Accounting Office (GAO) has identified technology maturation as a critical success factor in product development (GAO, 1999). The DoD's approach to incorporate this critical success factor has been to emphasize Technology Readiness Levels (TRLs) as a measure for selecting mature technologies for inclusion in a program (Department of Defense [DoD], 2011). The TRL concept was developed by NASA (Sadin et al., 1989) and has subsequently been adopted by AFRL. A TRL is a tool to measure the technology maturity of a system or subsystem using a 9-level ordinal scale (DoD, 2011). Detailed TRL definitions and descriptions can be found in Appendix A.

It is believed that "programs that enter the Engineering and Manufacturing Development (EMD) phase of the Defense Acquisition System and have immature technologies will incur cost growth and schedule slippage" (DoD, 2009). To reduce the risk associated with entering the EMD phase of the acquisition life cycle at Milestone B, DoD Instruction 5000.02 requires technologies to be demonstrated in a relevant environment and obtain a TRL of at least 6 (DoD, 2011). AFRL, through the S&T programs they oversee, plays a key role in the creation and maturation of these technologies to reach those thresholds.

Despite TRLs being identified as a critical success factor, the literature has few empirical examinations. The dearth of analysis is particularly acute for S&T-type programs, but even MDAPs have relatively few studies examining TRLs. Dubos et al. (2008) analyzed the relationship between technology uncertainty and schedule slippage in the space industry. Their research resulted in the creation of TRL-schedule-risk curves that are intended to assist program managers in making informed decisions regarding the appropriate TRL to consider when confronted with schedule constraints. The findings suggested a close relationship between technology uncertainty and schedule risk where the more mature a technology is (the higher the TRL), the less potential schedule slippage.

“The findings suggested a close relationship between technology uncertainty and schedule risk where the more mature a technology is (the higher the TRL), the less potential schedule slippage.

Katz et al. (2015) specifically studied the relationship of TRLs to cost and schedule changes during the EMD phase. They found that weapon systems that achieved a TRL of 7 or greater at Milestone B had a lower probability of schedule slippage during the EMD phase than weapons systems that had a TRL of less than 7. While Katz et al. (2015) found evidence to suggest that technology maturity is related to schedule change, they found no relationship with cost changes.



Smoker and Smith (2007), however, found evidence that suggests costs vary exponentially across time as the system's technology progresses through each TRL. Similarly, Linick (2017) found that as the TRL increased throughout the development phase, the percentage of the development cost grew at an increasing rate. As shown by the literature, the extant TRL studies are primarily focused on programs once they reach the EMD stage. To the best of our knowledge, no studies focus solely on S&T programs—a gap this article is designed to fill.

Data

The data for this research were obtained from the AFRL cost and economics division. S&T programs typically fall below the dollar threshold for traditional standardized reporting such as Contract Performance Reports (CPRs). Instead, the S&T programs receive Funds and Man-Hour Expenditure Reports (FMERs). These FMERs provide the procuring activity visibility into the contractor's expenditures for labor, materials and parts, travel, subcontractors, and other charges. Like CPRs, these reports are required on a periodic basis from the contractor—usually monthly. Unlike CPRs, FMERs do not report standardized cost elements like the ones found in MIL-STD-881D. The initial AFRL dataset consisted of 165 S&T programs with contract start dates spanning from 2009 to 2017.

Research Summary Reports were also collected for these programs. These reports are generated at the start of the program (Initial), during the program (Periodic), and at the end of the program (Final). Research Summary Reports include general information such as the program title, lead technical directorate, and start/end dates. They also include DoD-required information such as performance type, joint capability area, Air Force technical capabilities, and TRLs. An example of a Research Summary Report can be found in Appendix B.

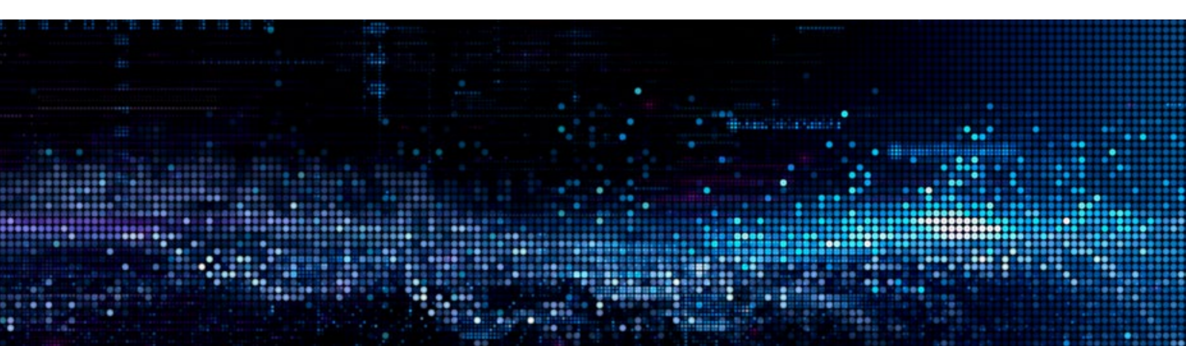


TABLE 2. DATASET EXCLUSIONS		
Category	**Number Removed**	**Remaining Programs**
Programs Obtained from AFRL		165
Missing Elements	64	101
Inadequate TD Sample Size	10	91
Less Than 92.5% Complete	48	43
Final Dataset for Analysis		43

Of the 165 programs obtained from AFRL, 43 are included in the final dataset. Table 2 provides the exclusion criteria and associated number of programs remaining in the analysis.

> **“S&T programs typically fall below the dollar threshold for traditional standardized reporting such as Contract Performance Reports (CPRs). Instead, the S&T programs receive Funds and Man-Hour Expenditure Reports (FMERs).**

As shown in Table 2, programs that had missing elements are excluded. These 64 programs had their costs reported on the FMER in unique ways, including cost burn rates, earned value management graphs, total costs in phases, or simply an overall total cost or labor hours spent. These reporting methods lack the specific elements needed in this analysis to compute percentages of total cost, which are used to observe the program's behavior. Of the 101 remaining programs, 10 programs fall under four different technical directorates (RD, RI, RX, and RY). Each technical directorate represents unique programs with different characteristics, which precluded aggregation above the technical directorate level. Therefore, the small sample size in these directorates would likely skew the analysis results, especially when observing how these programs behave at the technical directorate level. For these reasons, the programs are excluded from the analysis. Finally, programs with a completion percentage of less than 92.5% are excluded from the dataset. A program's completion percentage is computed using the total cost from the last available FMER to the program's contract value at that time. Previous research determined that a program with a completion percentage of 92.5% or greater accurately predicts the final cost of the program (Tracy & White, 2011). The final number of programs in the dataset is 43, which is sufficient to conduct a robust analysis. See Appendix C for details on the 43 individual programs.

Methods: Contingency Table Analysis

The dataset consists largely of qualitative variables. Therefore, the methodological approach employed is a two-way contingency table analysis. (See McClave et al. [2018, pp. 608–632] for more details on contingency tables.) This type of analysis is used to summarize the relationship between two categorical variables based on the data observed. The contingency table analysis uses a 2 x 2 table to test for independence. For each test, the same type of hypothesis test will be implemented, as shown in Equation 1:

H_o: The two classifications are independent

H_a: The two classifications are dependent (1)

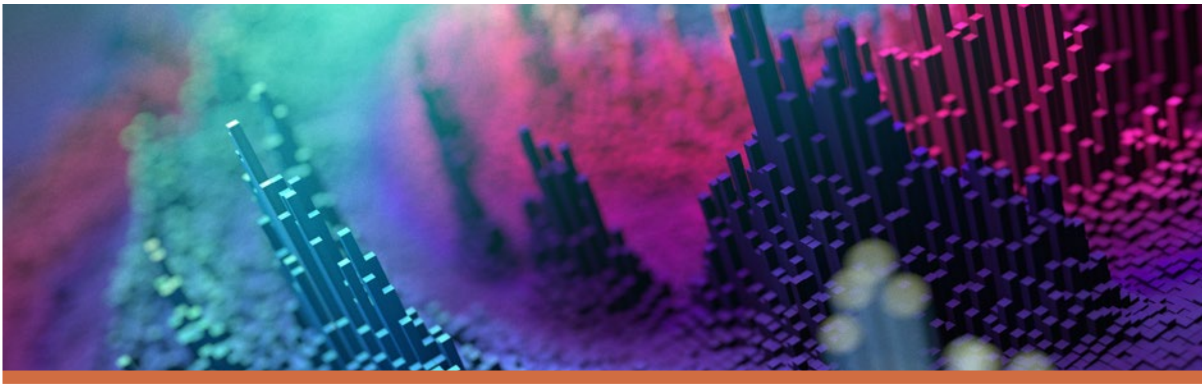
The chi-square distribution is the test statistic used for considering inferences about the category probabilities. If there is a failure to reject the null, the two variables are independent and are not statistically related to one another. If the null is rejected, then the variables are dependent, and a statistical relationship exists between them. The two-way contingency analysis examines the categorical variables (Table 3) with subsequent discussion on the rationale behind variable selection and categorization.

TABLE 3. CATEGORICAL VARIABLES USED IN CONTINGENCY TABLE ANALYSIS

Categorical Variables	
Technical Directorate	Cost Growth > 0%
Performance Type	Cost Growth > 33.7%
TRL Increase	Cost Growth > 44.1%
Last Known TRL ≥ 6	Cost Growth > 56.5%
Final TRL ≥ 6	Cost Growth > 60.5%
TRL 1 - 3	Cost Growth > 68%
TRL 4 - 5	Contract Value > $1M
TRL 6 - 7	Contract Value > $3M
TRL 8 - 9	
Schedule Growth > 0%	
Schedule Growth > 33%	
Schedule Growth > 63%	

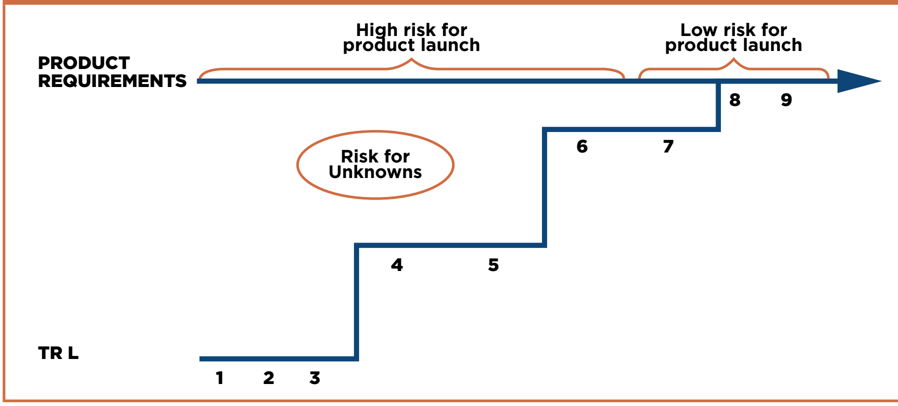
An underlying assumption of the chi-square contingency table test is that the sample size should be large enough so that the estimated expected cell count will be equal to five or more. If this assumption is violated, the Fisher's Exact Test can be utilized. The Fisher's Exact Test is based on hypergeometric probabilities, and no statistical assumptions are needed except for computational ability and time. (For more details regarding the use of Fisher's Exact Test, see McDonald [2014, pp. 77–85] or Mehta and Patel [1983].)

When highly significant results are found, one of the benefits of a contingency table is that odds ratios and their associated confidence intervals can be produced. An odds ratio is a measure of association for a two-way contingency table. The ratio is the odds of an event occurring in one group to the odds of the same event occurring in another group. In other words, the odds ratio is the ratio of the probability of a property being present compared to the probability of it being absent. If the odds ratio is 1, the two events are independent.



Categorical variables for the Technical Directorate (TD), Performance Type, and TRLs are obtained from the Research Summary Reports. The TD variable denotes which AFRL directorate is the lead on the program. Such a variable may capture organizational/managerial/technological differences. For this dataset, the TD variable is either RH (Airman/Human Systems) or RQ (Aerospace Systems). (This limitation is due to the sample size of the other TDs as previously discussed.) The performance type represents the partnership method between AFRL and the contractor. This variable consists of Research, Development, Test and Evaluation (RDT&E) and Small Business Innovative Research (SBIR) relationships. This type of variable may capture differences due to the size, skills, or knowledge of the company types (e.g., small vs. large companies). TRL data for the S&T programs are used in seven different categorical variables. TRL Increase indicates whether the TRL increases at any point during the program's life cycle. Last Known TRL $\geq$ 6 denotes the last reported TRL of the program, while Final TRL $\geq$ 6 only analyzes programs that have a Final Research Summary Report. The decision to categorize based on TRL level 6 is due to the role this TRL level fulfills in the defense acquisition process. Specifically, a TRL of 6 is equivalent to demonstration in a relevant environment, which is needed for a program to enter Milestone B (DoD, 2011). Four variables were created by grouping TRLs (Figure 2) based on the maturity of the technology and the product's requirements, as determined in the literature (GAO, 1999).

FIGURE 2. USING TRL'S TO MATCH TECHNOLOGY WITH REQUIREMENTS



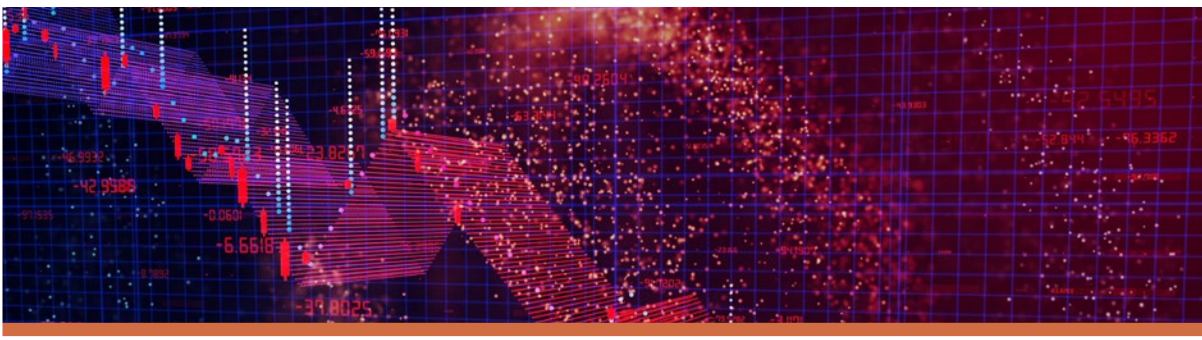
Note. Adapted from GAO (1999).

TABLE 4. BREAK POINT SUMMARY

Category	Break Point	Reason	Source
Schedule Growth	0% 33% 63%	Any growth Median Mean	Dataset Dataset Dataset
Cost Growth	0% 33.7% 44.1% 56.5% 60.5% 68%	Any growth DoD Development - Median Air Force Development - Median DoD Development - Mean Air Force Development - Mean Mean	Dataset Bolten et al. (2008) Bolten et al. (2008) Bolten et al. (2008) Bolten et al. (2008) Dataset
Contract Value	$1M $3M	Median Mean	Dataset Dataset

Additional variables of interest created from the Research Summary Report contract information include schedule growth, cost growth, and contract value. These attributes are commonly studied for acquisition programs at all phases of their life cycles.

The variables for cost growth, schedule growth, and contract value have been converted from continuous variables to categorical variables for inclusion in the contingency table analysis. Binary (or dummy) variables with methodical break points were created to test the relationships at different locations. These breakpoints were derived either from the literature review or from descriptive statistics of the variable itself in the dataset with its mean and/or median. For example, the mean cost growth of the dataset was 68%, which led to the creation of a dummy variable (Cost Growth > 68%), separating programs that are above and below the sample mean. Likewise, Bolten et al. (2008) distinguished mean and median percentages of total DoD and Air Force acquisition program development cost percentages. These thresholds from Bolten et al. (2008) are also examined. A summary of the break points can be seen in Table 4.



Results and Discussion

The contingency table results are organized into four sections: technical directorate, performance type, TRL, and growth relationships. Using the chi-square distribution as the test statistic, relationships are identified when Pearson's chi-squared test is significant at a p-value of less than 0.10. For highly significant results (p-value < 0.01), the odds ratio and its associated confidence interval are analyzed. It is important to note the possibility of spurious relationships. Spurious relationships occur when the two variables are associated, but not causally related, possibly due to an unknown mediating variable. With the sheer number of 2 x 2 tables generated in this analysis, spurious relationships are possible. Therefore, only highly statistically significant results (p-value < 0.01) will be studied in detail (i.e., full contingency table shown) while the other significant variables are observed solely as potential findings.

Technical Directorate

The Technical Directorate (TD) categorical variable denotes which AFRL directorate is the lead on the respective program: either RH (Airman/Human Systems) or RQ (Aerospace Systems). Analyzing the TD variable resulted in 19 contingency tables to be tested for significance. Two variables were significant at an alpha of 0.10 and two were significant at an alpha of 0.05. The full set of test results is provided in Table 5, where the more likely TD is annotated with a + and its name (e.g., +RQ).

TABLE 5. CONTINGENCY TABLE RESULTS FOR TECHNICAL DIRECTORATE

Variable	TD
Performance Type	
TRL Increase	** (+RQ)
Last Known TRL ≥ 6	
Final TRL ≥ 6	
TRL 1-3	
TRL 4-5	
TRL 6-7	
TRL 8-9	
Schedule Growth > 0%	
Schedule Growth > 33% (Median)	** (+RQ)
Schedule Growth > 63% (Mean)	* (+RQ)
Contract Value > $1.0M (Median)	
Contract Value > $3.0M (Mean)	
Cost Growth > 0%	* (+RQ)
Cost Growth > 33.7% (DoD Dev - Median)	
Cost Growth > 44.1% (AF Dev - Median)	
Cost Growth > 56.5% (DoD Dev - Mean)	
Cost Growth > 60.5% (AF Dev - Mean)	
Cost Growth > 68% (Mean)	
Total Significant Contingency Tables:	**4**

Note.
* *p*-value <0.10
** *p*-value <0.05
*** *p*-value <0.01

TRL Increase is the only TRL variable with a statistically significant relationship to TD. This test suggests that it is more probable to have a program's TRL increase with RQ (Aerospace Systems) programs compared to RH (Airman/Human Systems) programs. The RQ (Aerospace Systems) programs are composed primarily of engine and propulsion (hardware) system technologies. The ability to transition RQ (Aerospace Systems) through TRL levels may be due to the relationship of hardware versus software

(human systems interactions). It is likely easier to make advancements in hardware technologies as the testing, failures, and efficiencies may be more conclusive.

Similarly, the contingency table results suggest that RQ (Aerospace Systems) programs are more probable to have cost growth as well as schedule growth that is greater than 33% (the dataset's median) and 63% (the dataset's mean). This could be related to the maturing technology (increasing the TRL) of RQ (Aerospace Systems) programs. If the technology is maturing, a program office may be more likely to increase funding and schedule to keep the maturation on track. If the technologies do not mature, it could be that the agile nature of S&T programs allows for an early decision to cancel programs. In summary, the TD results suggest that RQ (Aerospace Systems) programs are more likely to technologically mature, have cost growth, and have schedule growth (greater than the dataset mean and median) when compared to RH (Airman/Human Systems) programs.

Performance Type

The performance type variable represents the partnership method between AFRL and the contractor: either Research, Development, Test & Evaluation (RDT&E) or Small Business Innovative Research (SBIR) relationships. This variable formed 19 contingency tables to be tested for significance. One variable was significant at an alpha of 0.10, two variables were significant at an alpha of 0.05, and one variable was significant at an alpha of 0.01. The full set of test results is provided in Table 6 where the more likely performance-type variable is annotated with a + and its name (e.g., +RDT&E).

TABLE 6. CONTINGENCY TABLE RESULTS FOR PERFORMANCE TYPE

Variable	Performance Type
TD	
TRL Increase	
Last Known TRL ≥ 6	** (+RDT&E)
Final TRL ≥ 6	** (+RDT&E)
TRL 1-3	
TRL 4-5	
TRL 6-7	
TRL 8-9	
Schedule Growth > 0%	* (+SBIR)
Schedule Growth > 33% (Median)	
Schedule Growth > 63% (Mean)	
Contract Value > $1.0M (Median)	*** (+RDT&E)

TABLE 6. CONTINGENCY TABLE RESULTS FOR PERFORMANCE TYPE (CONTINUED)

Variable	Performance Type
Cost Growth > 0%	
Cost Growth > 33.7% (DoD Dev - Median)	
Cost Growth > 44.1% (AF Dev - Median)	
Cost Growth > 56.5% (DoD Dev - Mean)	
Cost Growth > 60.5% (AF Dev - Mean)	
Cost Growth > 68% (Mean)	
Total Significant Contingency Tables:	**5**

Note.
* p-value <0.10
** p-value <0.05
*** p-value <0.01

Table 6 test results suggest that an S&T program with an RDT&E performance type is more likely to have or end with a TRL of at least 6 than an SBIR-type program. SBIR programs are developed by small domestic businesses, which potentially provide an agile way to stimulate high-tech innovation. But RDT&E programs are dominated by the larger, more experienced defense contractors. These results suggest that the larger defense contractors may obtain contracts with more mature technologies due to their capacity and ability to develop these technologies when compared to SBIR businesses.

FIGURE 3. CONTINGENCY TABLE OF PERFORMANCE TYPE BY CONTRACT VALUE > $1M

Contingency Table

Last Contract Value > $1M (Med)

Performance Type	0	1	Total
Count Expected			
RDT&E	3 7.69231	12 7.30769	15
SBIR	17 12.3077	7 11.6923	24
Total	20	19	39

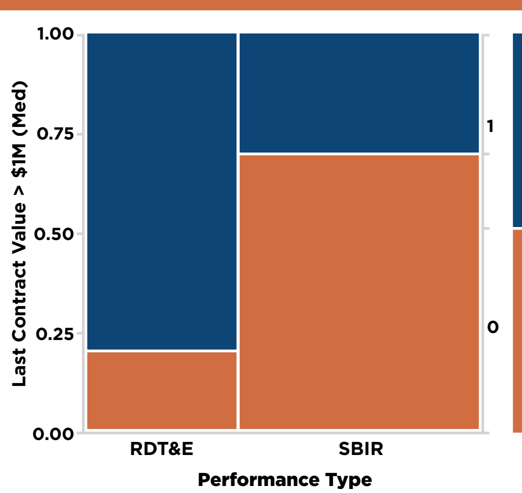
Tests

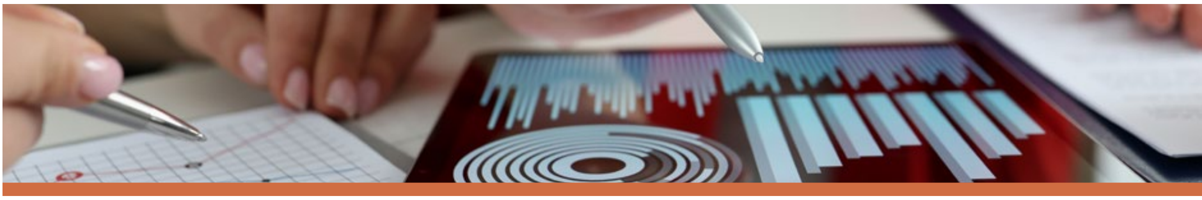
N	DF	-LogLike	RSquare (U)
39	1	5.0265877	0.1860

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	10.053	0.0015*
Pearson	9.547	0.0020*

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.102941	0.022042	0.480764





Further, as a potential indication of RDT&E and SBIR working different kinds of programs from the start, one can observe that contract values greater than $1 million (the dataset's median) are more probable with RDT&E performance types, as seen in Figure 3. This result may be an artifact of the policy constraints on SBIR programs. A phase II SBIR contract cannot exceed $1.73 million without a waiver from the U.S. Small Business Administration. Due to this limitation, one might question the appropriateness of comparing RDT&E and SBIR programs by contract value. But in the dataset analyzed, the average SBIR contract was $977 thousand, with only one program nearing the waiver cap (Appendix C). At the same time, RDT&E programs have no lower dollar limit, and six of the 17 RDT&E programs are below the $1.73 million SBIR waiver threshold. Therefore, while comparisons of larger contract values are likely inappropriate, the $1 million threshold compared here may suggest that the differences are not conclusively a result of the policy limitation, but rather may be highlighting differences in the types of contractors involved in RDT&E and SBIR programs. SBIR programs may target uncertain and risky technologies that small businesses research so that AFRL can evaluate which programs have the potential to develop into mature technologies. The scale of these uncertain programs may contribute to lower contract values. In fact, the odds ratio indicates that given the program has an SBIR performance type, the odds of the contract value being less than $1 million are 9.7 times higher than when the program has an RDT&E performance type.

> **SBIR programs may target uncertain and risky technologies that small businesses research so that AFRL can evaluate which programs have the potential to develop into mature technologies.**

The Table 6 contingency test results also suggest that a program with an SBIR performance type is more likely to have schedule growth. While test results indicate that RDT&E programs are more likely to have higher TRL levels, the opposite could be said that SBIR programs are more likely to have lower TRL levels. Less is known about these immature technologies (where immature is defined as TRL 1–5), which could lead these small businesses to spend more time developing them, leading to schedule slippage. This result is consistent with the literature findings of Dubos et al. (2008).

In summary, the results suggest that a program that has a performance type of RDT&E is more likely to have a TRL of 6. Furthermore, highly significant results point to evidence that a program that has a performance type of RDT&E is more likely to have a contract value greater than $1 million. Lastly, the results suggest that SBIR programs are more likely to experience schedule growth.

> **“As technologies mature, investments are made, which allow costs to grow over their initial estimates. As the technology integrates into a demonstration effort (TRL 6–8), the program is often met with new and unexpected challenges, which tends to increase costs.**

Technology Readiness Level

TRL data were used to create seven different binary variables as previously discussed. These seven TRL variables were tested for significance against the 11 performance variables to produce 77 contingency tables. Seven variables were significant at an alpha of 0.10, four variables were significant at an alpha of 0.05, and one variable was significant at an alpha of 0.01. Despite registering significant Pearson *p*-values, the contingency table results for the seven significant variables at an alpha of 0.10 were found to be invalid. For all seven tests, the expected counts of two of the four cells were less than five. This violates an assumption for a valid chi-squared contingency table test, which states the sample size should be large enough so that the estimated expected count will be equal to five or more. As a further check, Fisher’s Exact Test—which is a nonparametric test for small samples—found all seven tests to be nonsignificant. This result was largely due to the small number of programs with a TRL of 6–7 (5) and a Final TRL of ≥ 6 (4). The full set of test results is provided in Table 7, with special subscript designators on those test results deemed invalid.

TABLE 7. SIGNIFICANT CONTINGENCY TABLE FOR TECHNOLOGY READINESS LEVEL

Variable	TRL Increase	Last Known TRL ≥ 6	Final TRL ≥ 6	TRL 1-3	TRL 4-5	TRL 6-7	TRL 8-9
Schedule Growth > 0%		**	$*_1$			$*_1$	
Schedule Growth > 33% (Median)							
Schedule Growth > 63% (Mean)							
Contract Value > $1.0M (Median)				**			
Contract Value > $3.0M (Mean)		**				***	
Cost Growth > 0%						$*_1$	
Cost Growth > 33.7% (DoD Dev - Median)						$*_1$	
Cost Growth > 44.1% (AF Dev - Median)						$*_1$	
Cost Growth > 56.5% (DoD Dev - Mean)						$*_1$	
Cost Growth > 60.5% (AF Dev - Mean)						$*_1$	
Cost Growth > 68% (Mean)						**	
Total Significant Contingency Tables:	0	2	1	1	0	8	0

Note.

$*_1$ *p*-value <0.10, 50% of Expected Counts <5, Non-significant Fisher's Exact Test

* *p*-value <0.10

** *p*-value <0.05

*** *p*-value <0.01

FIGURE 4. CONTINGENCY TABLE OF TRL 6–7 BY CONTRACT VALUE > $3M

Contingency Table

TRL 6-7	Count / Expected	Last Contract Value > $3M (Mean): 0	1	Total
	0	29 / 26.4286	8 / 10.5714	37
	1	1 / 3.57143	4 / 1.42857	5
	Total	30	12	42

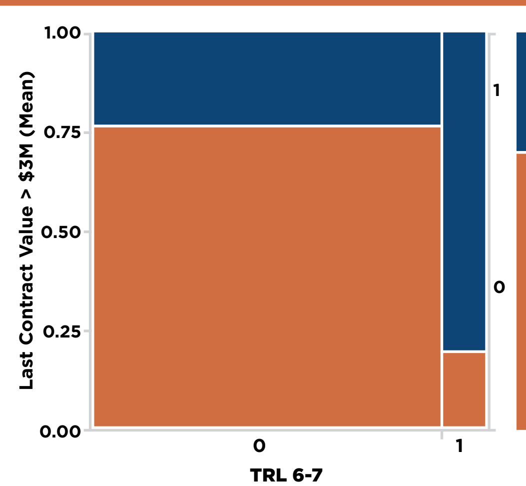
Tests

N	DF	-LogLike	RSquare (U)
42	1	3.3084592	0.1317

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	6.617	0.0101*
Pearson	7.356	0.0067*

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
14.5	1.415167	148.5691



The contingency table results suggest that an S&T program is *more* likely to have cost growth greater than 68% (the dataset's mean) with a TRL of 6 or 7 but *less* likely to have schedule growth with a TRL ≥ 6. Such a finding, perhaps unusual for a development program, is both intuitive and precedent in an S&T context. With an early TRL (1–5), there is little knowledge of how the technology will mature. This poses a problem to program managers and cost estimators. As technologies mature, investments are made, which allow costs to grow over their initial estimates. As the technology integrates into a demonstration effort (TRL 6–8), the program is often met with new and unexpected challenges, which tends to increase costs. These results support previous research conducted on Air Force programs, which concluded that estimated costs vary exponentially across time with the progression through the various TRLs (Smoker & Smith, 2007). However, for more mature technologies, a broader knowledge base is available for the technology's development due to more completed research. With a higher TRL, and thus more knowledge of the technology available, the better the chance of meeting schedule requirements (Dubos et al., 2008). This literature finding is also consistent with the results found here.

Table 7 results also suggest that an S&T program with a TRL of 6 or greater is *more* likely to have contract values greater than $3 million (the dataset's mean). An S&T program with a TRL of 1 through 3 is *less* likely to have contract values greater than $1 million (the dataset's median). The explanation is consistent with the aforementioned cost growth finding. As the program's technology matures, additional investments are made, as shown in the contingency analysis results in Figure 4. In fact, the odds ratio indicates that given the program has a TRL of 6 or 7, the odds of the contract value being greater than $3 million are 14.5 times higher than a program with a TRL other than 6 or 7.

In summary, the TRL results suggest that programs with mature technologies are more likely to experience larger than average cost growth and larger contract values. Additionally, these programs are less likely to experience schedule growth. Further, the results suggest that programs with immature technologies are less likely to have larger contract values.

Growth Relationships

As previously shown, variables for TD, performance type, and TRL were tested for their relationships with cost growth, schedule growth, and contract value. An analysis was also conducted among these latter variables to analyze their relationships to each other; a total of 63 relationships were tested for significance. Eight tests were significant at an alpha of 0.10, 11 tests were significant at an alpha of 0.05, and 22 tests were significant at an alpha of 0.01. The full set of test results appears in Table 8.

TABLE 8. SIGNIFICANT CONTINGENCY TABLES FOR GROWTH RELATIONSHIPS

Variable	Schedule Growth > 0%	Schedule Growth > 33% (Med)	Schedule Growth > 63% (Mean)	Contract Value > $0.9M	Contract Value > $1.0M (Med)	Contract Value > $3.0M (Mean)	Contract Value > $4.0M	Contract Value > $5.0M	Total Significant Contingency Tables
Contract Value > $0.9M		**	**						2
Contract Value > $1.0M (Median)									0
Contract Value > $3.0M (Mean)									0
Contract Value > $4.0M									0
Contract Value > $5.0M									0
Cost Growth > 0%	**	***	***	***	***	**	**	*	8
Cost Growth > 33.7% (DoD Dev - Median)	*	*	***		***	***	***	**	7
Cost Growth > 44.1% (AF Dev - Median)	*	*	***		***	***	***	**	7
Cost Growth > 56.5% (DoD Dev - Mean)	*	**	***			***	***	**	6
Cost Growth > 60.5% (AF Dev - Mean)	*	**	***			***	***	**	6
Cost Growth > 68% (Mean)		*	***			***	***	***	5
Total Significant Contingency Tables:	**5**	**7**	**7**	**1**	**3**	**6**	**6**	**6**	**41**

Note.
* *p*-value <0.10
** *p*-value <0.05
*** *p*-value <0.01

The contingency table results suggest that it is more probable for S&T programs with larger contract values to experience cost growth. Observing cost growth relationships with the original two contract value variables (using the mean and median of the dataset) provided highly significant results. To explore the sensitivity of these relationships relative to the threshold used to define the binary variables, additional contract value variables were created with lower and higher breakpoints. This additional analysis found contract values greater than $0.9 million to be the lowest threshold for which a statistically significant relationship could be found with an amount of cost growth (i.e., cost growth > 0%). As the contract value threshold increased, additional cost growth variables displayed statistical significance until all were significant at a contract value of $3.0 million. The progression is illustrated by the cells with light green shading, as shown in Table 8. This suggests that cost growth and contract value have a positive correlation with each other.

Table 8 results also suggest that it is more probable for S&T programs with contract values greater than $0.9 million to experience schedule growth above the median and mean (i.e., greater than 33% and 63%, respectively). This was the only contract value variable to result in significant *p*-values when tested with schedule growth variables (see light blue shaded cells in Table 8). These results imply that programs with contract values less than $0.9 million are less likely to experience schedule growth.

"Analyzing the relationship between cost and schedule growth suggests that programs with schedule growth are more likely to have cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.

Finally, the results suggest that if S&T programs are experiencing schedule growth, then it is more likely that they're also experiencing cost growth. This seems to contradict the findings that programs with mature technologies are more likely to experience cost growth and less likely to experience schedule growth. But closer analysis of these results suggests that programs with large schedule growth percentages are even more likely to experience cost growth at all amounts. Thus, when this cost and schedule growth relationship is found, it is not in the mature technology programs, but rather in those programs with *immature* technologies.

In summary, the results suggest that S&T programs with larger contract values experience cost growth, while programs with smaller contract values (< $0.9 million) are less likely to experience schedule growth. Finally, analyzing the relationship between cost and schedule growth suggests that programs with schedule growth are more likely to have cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.

Conclusions

S&T programs serve an important role in the defense acquisition process. They constitute the initial phase of the acquisition process through discovery and development of warfighting technology. The results of these programs impact the larger MDAPs, which integrate the technologies in subsequent phases of the life cycle. Despite this important role, little prior research has examined the performance of S&T programs. Thus, the overarching goal of this article was to discern new insights from an analysis of Air Force S&T program characteristics in relation to their program's performance.

The literature review identified technological maturity as a critical success factor in product development (GAO, 1999). One measure that defense programs use for technological maturity is TRL levels. TRLs, therefore, were an integral component under investigation in this analysis. The objective was to understand how TRLs affect S&T program performance. Several key findings emerged from this analysis.

First, the results suggest that aerospace programs are more likely to technologically mature when compared to human system programs. In other words, the AFRL aerospace programs are more likely to progress through the TRLs in their programs. To the extent that technological maturity is a measure of success, the aerospace programs outperform. However, this technical performance comes at a cost as the aerospace programs were also more likely to experience cost and schedule growth. Intuitively, these results are compatible; with proven success in technology maturation, increases in funding and schedule are likely to keep the maturation on track.

Second, the partnership method between the government and contractor may matter. The partnerships for S&T programs consist of SBIR and RDT&E relationships. The RDT&E programs are more likely to have—and end—with a TRL of 6 or more in comparison to SBIR programs. The result is not entirely surprising because, by definition, the larger defense companies constitute the RDT&E category. These larger companies have the capacity and resources to mature technology that the smaller SBIR companies may not possess. Additionally, the purpose and limitations of SBIR programs must be acknowledged. SBIR programs are intended to increase private-sector commercialization of innovation and stimulate technology innovation. Funding limits are associated with these programs and, depending on the objectives of the specific SBIR program, they may eventually transition to a funded R&D or procurement contract. These differences are important when comparing SBIR to RDT&E programs.

> **"Further analysis of the relationship between cost and schedule growth suggests that if programs have larger schedule growth, then they are more likely to have larger cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.**

Third, TRLs and program performance are linked. The relationships with TRLs suggest that programs with mature technologies are more likely to experience above average cost growth and larger contract values while less likely to experience schedule growth. Additionally, the results suggest that programs with immature technologies are less likely to have larger contract values. As technologies mature, additional funds for investments are made, which increases costs over their initial contract values. From a practical standpoint, these additional investments may occur due to the need for an increased performance outcome and are not an indictment on the management effort. This is likely to happen when the program is met with new and unexpected challenges as the technology integrates into a demonstration effort (TRLs 6–8). Linick (2017) found that as the TRL increased throughout the development phase, the percentage of the development cost increased at an increasing rate. This literature finding is in agreement with these results. Conversely, as these technologies mature, a broader knowledge base is gained for its development, which increases the chance of meeting schedule requirements.

Lastly, the analysis of "growth" variables (cost growth, schedule growth, and contract value) provides additional insights on S&T programs. Specifically, the analysis suggests that S&T programs with larger contract values experience larger cost growth at the same time programs with smaller contract values (< $0.9 million) are less likely to experience schedule growth. Further analysis of the relationship between cost and schedule growth suggests that if programs have larger schedule growth, then they are more likely to have larger cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.

When interpreting the results of this article, it is important to remember that S&T programs are different than MDAPs. As a result, the risk tolerance manifested in cost and schedule performance standards between the two should not be conflated. The research nature of an S&T program inherently makes it more risky. The subtext is that technical failure, or growth in cost and schedule, is often a normal part of the research process and may not be viewed in the same manner as MDAP performance. Rather, the benefit of the current study is the new understanding that arises from depicting the relationship between S&T program characteristics and their performance.

Prior examinations of S&T programs are scarce. Thus, the possibilities for future research are vast. The exploratory analysis conducted here focused solely on AFRL programs. S&T programs in the other military services warrant examination. Additionally, one of the more surprising aspects of the data obtained from S&T programs was the reported TRL at various stages of the program's life cycle. In order for a program to advance past Milestone B into the EMD phase, a program must have a TRL of 6 or greater. Further research into those S&T programs whose technology matured (TRL increased) could identify common characteristics, which indicates a higher probability of technological maturation. Lastly, future research should investigate the reasons or root causes behind the correlations found in this article. The aim of that research would be to expound upon the interpretation of the data. The contribution from that research is important to arming leadership with the necessary information upon which to base decisions. The exploratory analysis provided here was just the first step of the journey. Through future research and discoveries, we can gain the knowledge needed to increase the odds of successful S&T programs.

Appendix A

TRL Definitions, Descriptions, and Supporting Information

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?

TRL	Definition	Description	Supporting Information
6	System/ subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	

Note. Adapted from DoD (2011).

Appendix B

Sample Research Summary Report

Research Summary Report

General Information

Work Unit Title:	Program Title		
Work Unit (WU) #:		Accession #:	XXXXX
Start Date:	MM/DD/YYYY	End Date:	MM/DD/YYYY
Lead TD:	RQ	Effort Security:	Unclassified
Literature Search Order #:	XXXXX	Lit Search Date:	MM/DD/YYYY
Work Phase Code:		WU Category:	
Responsible Organization:	Aerospace Systems Directorate (AFRL/RQ) WRIGHT-PATTERSON AFB, OH		
Parent Program:	Parent Program Title		

Work Unit Manager

Name:	XXXX XXXX	Phone:	(XXX) XXX-XXXX
Office Symbol:	RQTE	Email:	xxxx.xxxx@us.af.mil

DoD Required Information

Performance Method:	PROCUREMENT/ACQUISITION AWARD - Contract,	Lab Core Technical Competency:	Power, Propulsion, Energy & Alternative Fuels
Performance Type:	RDTE - Research, Development, Test, & Evaluation Work Unit	Technology Readiness Level:	2 Technology Concept
Fields of Science & Engineering:		Data Management Plan Exist:	No
Joint Capability Area:	Force Application		
Communities of Interest:	1.1 Aircraft Propulsion, Power and Thermal		
Technology Transition Opportunities:	None at this time. Follow on contract will progress TRL of key components to enable future transition.		

Principal Investigator

Name:	XXXX XXXXXX	Phone:	XXX-XXX-XXXX
Office Symbol:	XX	Email:	xxxx.xxxxx@xxx.com

Performing Mechanism

Contract #:	FAXXXX-XX-X-XXXX-XXXX	Contract Status:	Complete
Contract Face Value	$XX,XXX,XXX	TR Due DTIC Date:	MM/DD/YYYY
Award Date:	MM/DD/YYYY	TR Draft Due Date:	MM/DD/YYYY
Tech End Date:	MM/DD/YYYY	Terminate Date:	
End Date:	MM/DD/YYYY	WAWF /DD250Z Date:	MM/DD/YYYY

Performing Organization

Performer:	NAME OF COMPANY	Address:
Division:	XX	
CAGE Code:	XXXXXX	
Performing Org Type:	Industrial Firm	

WU Funding ($K)

PE / BPAC	Source	Funding	Prior	FY18	FY19	FY20	FY21	FY22	FY23	To Complete	Total
		Appropriated									
		Obligations									
		Appropriated									
		Obligations									

Descriptive and Progress/Status

Objective/Restricted

MMM DD, YYYY
12:00:00 AM

Page 1

Appendix C

Dataset

Last Performance					Last Performance				
Program ID	TD	TRL	Type	Total Cost	Program ID	TD	TRL	Type	Total Cost
Program 1	RH	7	RDT&E	$2,660,154	Program 22	RQ	4	CRDA*	$5,648,405
Program 2	RH	5	RDT&E	$1,224,259	Program 23	RQ	4	CRDA*	$3,595,076
Program 3	RH	6	RDT&E	$4,815,251	Program 24	RQ	2	CSAE*	$7,166,910
Program 4	RH	5	RDT&E	$1,640,552	Program 25	RQ	6	RDT&E	$4,428,565
Program 5	RH	4	RDT&E	$2,424,100	Program 26	RQ	2	RDT&E	$974,340
Program 6	RH	6	RDT&E	$4,856,299	Program 27	RQ	5	RDT&E	$10,086,064
Program 7	RH	4	RDT&E	$747,541	Program 28	RQ	3	RDT&E	$4,781,200
Program 8	RH	3	RDT&E	$8,437,990	Program 29	RQ	6	RDT&E	$892,110
Program 9	RH	4	SBIR	$705,525	Program 30	RQ	5	RDT&E	$749,489
Program 10	RH	4	SBIR	$719,187	Program 31	RQ	3	RDT&E	$18,922,869
Program 11	RH	3	SBIR	$1,475,528	Program 32	RQ	6	RDT&E	$14,897,568
Program 12	RH	5	SBIR	$728,021	Program 33	RQ	5	RDT&E	$5,236,777
Program 13	RH	4	SBIR	$727,783	Program 34	RQ	5	SBIR	$1,698,117
Program 14	RH	3	SBIR	$737,907	Program 35	RQ	4	SBIR	$742,919
Program 15	RH	3	SBIR	$733,454	Program 36	RQ	8	SBIR	$1,234,988
Program 16	RH	2	SBIR	$1,110,133	Program 37	RQ	3	SBIR	$747,185
Program 17	RH	5	SBIR	$1,442,603	Program 38	RQ	3	SBIR	$758,161
Program 18	RH	4	SBIR	$1,428,715	Program 39	RQ	2	SBIR	$748,685
Program 19	RH	4	SBIR	$1,246,712	Program 40	RQ	4	SBIR	$748,172
Program 20	RH	4	SBIR	$739,001	Program 41	RQ	3	SBIR	$998,582
Program 21	RH			$5,958,377	Program 42	RQ	2	SBIR	$941,116
					Program 43	RQ	2	SBIR	$1,085,073

Note. *Not included in TD analysis due to small sample size

Performance Type	
CRDA	Cooperative Research and Development Agreements
CSAE	Contracted Studies, Analysis and Evaluations
RDT&E	Research, Development, Test and Evaluation
SBIR	Small Business Innovative Research

Technical Directorate	
RH	Aerospace Medicine, Human Systems Integration
RQ	Aerodynamics, Flight Control, Engines, Propulsion

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Author Biographies

MSgt Eric A. Plack, USAF

is an Operations and Support Cost Analyst at the Air Force Cost Analysis Agency (AFCAA). He received his BA in Mathematics and Statistics from Miami University and an MS in Cost Analysis from the Air Force Institute of Technology (AFIT). MSgt Plack is also a certified Professional Cost Estimator Analyst (PCEA).

(E-mail address: Eric.Plack@us.af.mil)

Dr. Jonathan D. Ritschel

is an Assistant Professor of Cost Analysis in the Department of Systems Engineering and Management at AFIT. He received his BBA in Accountancy from the University of Notre Dame, his MS in Cost Analysis from AFIT, and his PhD in Economics from George Mason University. Dr. Ritschel's research interests include public choice, the effects of acquisition reforms on cost growth in DoD weapon systems, and economic institutional analysis.

(E-mail address: Jonathan.Ritschel@@afit.edu)

Dr. Edward D. White

is a Professor of Statistics in the Department of Mathematics and Statistics at AFIT. He received his BS in Mathematics from the University of Tampa, MAS from The Ohio State University, and PhD in Statistics from Texas A&M University. His primary research interests include statistical modeling, simulation, and data analytics.

(E-mail address: Edward.White@@afit.edu)

Lt Col Clay M. Koschnick, USAF

is an Assistant Professor of Systems Engineering in the Department of Systems Engineering and Management at AFIT. Lt Col Koschnick holds a PhD in Industrial and Systems Engineering from the University of Florida, a BS in Operations Research from the United States Air Force Academy, and an MS in Operations Research from the Georgia Institute of Technology. His research interests include engineering economics, decision analysis, and econometrics.

(E-mail address: Clay.Koschnick@afit.edu)

Lt Col Scott T. Drylie, USAF

is an Assistant Professor of Cost Analysis in the Department of Systems Engineering and Management at AFIT. He received his BS in Economics from Montana State University, his MS in Cost Analysis from AFIT, and his PhD in Economics from George Mason University. His research interests include institutional economics, the economics of education, software costs, and aircraft sustainment costs.

(E-mail address: scott.drylie@afit.edu)

Image designed by Nicole Brate

"EXTRA!" USING THE Newsvendor Model TO OPTIMIZE WAR RESERVE STORAGE

MAJ Minou Pak, USA, MAJ Joshua L. Peeples, USA, and Joseph T. Klamo

The United States Marine Corps (USMC) Installation and Logistics Command requested a study for determining appropriate inventory levels of war reserve materiel to meet future operational needs under surge demands in uncertain environments. This study sought to explore a potential approach by using the common newsvendor model, but modified for a military scenario. The authors' novel version of this core concept considers the purchase and storage costs of an item and proposes an intangible cost function to capture the consequences of a shortage. Further, they show a sample application of the model using a ubiquitous military item—the BA-5590/U battery. The output of the model provides USMC with a new tool to optimize inventory levels of a given item of interest, depending on scenario inputs.

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Keywords: *Inventory Level, Newsvendor Model, Military Cost of Shortage, War Reserve Materiel*

The objective of this study was to support recent United States Marine Corps (USMC) efforts to modernize approaches used to decide the optimal levels within their War Reserve Materiel (WRM). The acquisition of materiel for the WRM is unique compared to other acquisition conditions since it is not buy-as-you-need. Instead, enough inventory must already exist so that surged troops are not experiencing a shortage of items needed during combat. On the other hand, unused and discarded items erode the overall benefit of having the WRM. Although we focused on the specific requirements of the USMC and their typical deployment units and timelines, we presented an approach in a general framework that could be adjusted to meet the WRM storage requirements of other branches of military service as well. This expository piece explores a new method—the newsvendor model—that has not yet been fully evaluated for military applications. The primary research focus was to determine appropriate modifications to the newsvendor model for adaptation to military scenarios for predicting an appropriate WRM inventory level.

How Much Supply Is Enough Without Buying Excess Capacity?

Marine Air-Ground Task Forces (MAGTFs) are typically employed by the USMC to serve as a unified arms organization for military operation missions. They consist of air, ground, command, and logistics elements and come in battalion, brigade, and larger force sizes. In the event of a surge deployment requiring supplies beyond the stock on hand, the Marine Corps will need additional supplies from the WRM inventory, with immediate availability to support theater operations of MAGTFs until the expected long-term sustainment is established.

To make optimized decisions on WRM levels, the USMC must consider logistical capabilities and capacity for theater-level sustainment. It must also identify items that may have limited suppliers, lengthy production lead times, or both. However, the definitive features of the USMC WRM problem are uncertainties surrounding such issues as no restock opportunity, seemingly random demand, and the ultimate discarding of any unused expendable items. While multiple purchases may be made to stock the WRM, the no-restocking constraint refers to the fact that during the typical 60-day mission surge window, the USMC will be unable to replenish the WRM when inventory runs low. The demand has large uncertainty because, while surges have occurred before, databases tracking required demand were not kept until recently. Even now, the method used for estimating the WRM is lacking tracking systems to measure the materiel demand during conflicts and a process for keeping track of changes made to storage levels during peacetime. Given these circumstances, the USMC has significant concerns regarding its ability to accurately predict and store appropriate levels of WRM inventory that can support its next surge demand. This is likely not a problem confined to the USMC, but extends to rapid-deploying units of the other Services as well.

> **“Few demand-tracking systems exist, and logisticians struggle to account for item additions, deletions, and usage over many past years. Given these circumstances, the USMC has significant concerns regarding its ability to accurately predict and store appropriate levels of WRM inventory that can support its next surge demand.**

Department of Defense Instruction 3110.06 War Reserve Materiel (2019) establishes policy and provides guidance to Military Departments for computing WRM levels of inventory. However, this policy guidance provides the military services a great deal of latitude without specifying what methods should be used to determine the appropriate WRM inventory level. Currently, the Marine Corps utilizes the legacy War Reserve System (WRS) software program to aid in WRM decisions. WRS uses inputs such as unit size, operational plans, temperature zone, tempo of combat, estimated number of days for the mission plan, classes of supply requirements, and several other factors. The USMC WRS approach has had issues in the past though, highlighted by the fact that some critically important items were understocked during the opening days of Operation Iraqi Freedom in 2003. For example, BA-5590/U batteries were severely understocked. Navy

CAPT Clark Driscoll, liaison to the Joint Staff for the Defense Contract Management Agency said, "We literally [came] within days of running out of these batteries—where major combat operations would either have ceased or changed in their character because of the lack of battery support" (Fein 2003). Although 180,000 batteries were maintained as a reserve in the period leading up to the beginning of the conflict, initial demand for the batteries was nearly 620,000—far exceeding the ability of the reserve inventory to supply them (Government Accountability Office, 2005).

Numerous other approaches exist to achieve optimized inventory levels. One such approach is Economic Order Quantity (EOQ), which determines the number of items that should be purchased given the demand, cost to place an order, and the cost of holding the items. The method balances the costs of placing orders and storing the items in conditions of constant usage rates. Although useful in some applications, this approach is not applicable to WRM planning for two reasons. First, the EOQ model simply assumes restocking will take place when an item inventory level decreases and does not capture the consequences of running out of an item. Second, the EOQ model assumes a constant demand, but for WRM inventory the demand is uncertain.

Our Approach: Adopting the Newsvendor Model Framework

The newsvendor model is based on assumptions that are consistent with WRM modeling constraints. Porteus (2008) noted that the newsvendor model provides a methodology for solving the problem of how much inventory to purchase for the economical storage of a perishable item. Other considerations include solving the problem within an applicable time frame when the actual demand of the item is unknown, and when the economic consequences of having "too much" and "too little" are known. Moreover, our interest in the newsvendor model is motivated by the fact that many others experiencing similar inventory-level problems, where the items in inventory are not sold for profit, have used the model. Olivares et al. (2008) applied the newsvendor model to estimate how many operating rooms should be reserved for cardiac surgery cases. Arikan and Deshpande (2012) used the approach in airline flight scheduling to estimate the impact that airport operational factors have on airline block-time scheduling. Hadas and Herbon (2014) applied a generalized newsvendor model to a public transportation operation to estimate the balance between the physical size of the fleet and the frequency of certain routes taken. Chen et al. (2017) used the same approach to estimate purchasing humanitarian relief items as a secondary sourcing option to monetary donations. Likewise, Mallidis et al. (2018) estimated the amount of perishable inventory that should be donated in humanitarian efforts to achieve an ethical goal to reduce food waste to best assist those in need of food. Thus, the newsvendor model as a core concept appealed to us as a potentially viable new approach to the USMC's problem.

> **"The EOQ model simply assumes restocking will take place when an item inventory level decreases and does not capture the consequences of running out of an item.**

Newsvendor Model Explained

The newsvendor model optimizes the inventory level by balancing the expected marginal costs of both excess and shortage. The expected marginal cost of excess at a particular inventory level is simply the product of the marginal cost of excess and the probability of demand being less than that level. Similarly, the expected marginal cost of shortage is the product of the marginal cost of shortage and the probability of demand being greater than that level. The basic idea is that when the expected marginal cost of excess is less than the expected marginal cost of shortage, the inventory level should be increased. The optimal inventory level occurs when these two expected marginal costs are equal. Adelman et al. (1999) demonstrated the process of determining the optimal inventory level in detail for the nonmilitary applications of a fashion store and an individual selling newspapers.

Marginal Cost of Excess and Shortage Formulation

To perform this optimization, we must first determine the marginal cost of excess and the marginal cost of shortage. The marginal cost of excess is simply the additional cost incurred if we were to have one more item in our inventory and it ended up not being used. The marginal cost of shortage is the additional cost that we would incur if we had decided not to stock that extra item in our inventory, even though it would have been used if available. The formulation to estimate the marginal cost of excess is usually straightforward. Since it captures the cost of increasing our inventory by one additional item, the marginal cost of excess, ΔC_e, is calculated as

$$\Delta C_e(Q) = P(Q) + H(Q) - R_u \tag{1}$$

where $P(Q)$ is the unit cost to purchase one additional item when purchasing a total of Q items for a given inventory, $H(Q)$ is the unit holding, or storage, cost of that one additional item, and R_u is the unit resale value of that one item. Since items are typically sold individually or in batches much smaller than one's inventory size, we consider this value to be a constant independent of the inventory level, and therefore it is not a function of Q. Certain items, while stored, could create additional costs, such as maintenance.

"In our military application, where the inventory level is quite large, it is possible that as more items are produced, the supplier can produce them more cheaply. This is the concept of a learning curve. These savings could be partially passed on to the buyer by lowering the purchase price accordingly as more items are produced.

These costs would need to be captured as well, most naturally as part of the holding term. Although the formulation is straightforward, the actual estimation of the value of each term could be difficult and, in some situations, require best engineering judgments to be made.

In the typical newsvendor problem, the unit cost to purchase an additional item is not a function of the quantity. However, in our military application, where the inventory level is quite large, it is possible that as more items are produced, the supplier can produce them more cheaply. This is the concept of a learning curve. These savings could be partially passed on to the buyer by lowering the purchase price accordingly as more items are produced. In that case the purchase price of an additional item would depend on quantity.

The analysis also requires that the marginal cost of shortage be estimated. To properly capture it, we need to take into account that not incurring the cost of purchasing and storing an item in the first place partially offsets the cost of revenue lost from being unable to sell the item. Therefore, the cost of shortage, ΔC_s, for an item is expressed as

$$\Delta C_s(Q) = S_u + \Delta I(Q) - P(Q) - H(Q) \quad (2)$$

where S_u is the sale price of a single item and $\Delta I(Q)$ is the marginal intangible costs that result from not having the additional item. Like Equation (1), the sale price is assumed independent of the quantity in inventory. The marginal intangible cost attempts to quantify, in monetary terms, the future costs that will occur due to not having an additional item available for a customer. In typical newsvendor applications, this is normally the loss of future revenue from customers that do not return after being unable to purchase the item the first time.

Occasionally, newsvendor models contain an alternative source term to capture the situation, where the vendor quickly obtains additional items from a back-up source when item demand exceeds the inventory level purchased from the original source. However, since we assume that logisticians have no option to quickly procure additional items from an alternate source during the surge, we do not include an alternative source term in our formulation. If alternative sourcing were considered, it could be from a domestic producer of the item or an allied nation.

Expected Marginal Cost Analysis

The optimal inventory level is determined by increasing the inventory level, Q, while the expected marginal cost of excess is less than the expected marginal cost of shortage. This condition, where the inventory should be increased, is shown mathematically as

$$\Delta C_e(Q)\, P[d \leq Q] < \Delta C_s(Q)\, P[d > Q] \tag{3}$$

where d is the unknown future demand and $P[.]$ is the probability that the condition inside [.] is true. The inventory level should be increased until the expected marginal cost from excess is greater than the expected marginal cost of shortage. Therefore, we can define the optimal inventory quantity, Q^*, that occurs when the following expression is satisfied

$$\Delta C_e(Q)\, P[d \leq Q^*] = \Delta C_s(Q)\, (1 - P[d \leq Q^*]) \tag{4}$$

while acknowledging that due to the discrete nature of inventory levels, the equality may not be realized, in which case the difference between the two expected marginal costs should be minimized.

Military Application of the Newsvendor Model

To develop our model, we focused on the unique aspects of military operations. Our analysis considered a Marine Expeditionary Brigade (MEB) as a typical force that would need to be supported by supplies from the WRM. Our results could be scaled to account for a different force size, for instance a Marine Expeditionary Force that planners wish to support with their WRM. Our model was based on the expectation of a 60-day surge deployment. After that time, we assumed the USMC units would be re-supplied through theater sustainment operations. We also assumed a useful shelf life of 10 years for the military item. This contributes to the cost of excess by establishing the total holding cost of the item. Finally, we only considered materiel from the inventory control stocks, which consists of materiel stored centrally at the wholesale level using USMC logistics bases, held within the DoD supply system, or positioned around the globe.

In military inventory scenarios, the possibility of revenue does not exist since the inventory item is never intended to be sold. Instead, the item is stored for the sole purpose of using it to achieve military objectives. This situation simplifies the cost of excess so that Equation (1) reduces to

$$\Delta C_e(Q) = P(Q) + H(Q) \tag{5}$$

since $R_u = 0$ because the item has no resale value. This expression becomes our military scenario marginal cost of excess function.

Similarly, in the marginal cost of shortage expression, the item has no sale price. Unlike the typical newsvendor problem, where the cost of an inventory shortage is lost profit, in a military application the cost of a shortage must be captured by quantifying the intangible cost of not achieving the objectives of the operation due to the shortage. The resultant marginal cost of shortage expression from Equation 2 becomes

$$\Delta C_s(Q) = \Delta I(Q) - P(Q) - H(Q) \tag{6}$$

since there is no sale of the item. The lack of revenue makes the intangible cost portion of the marginal cost of shortage critical for the analysis. If no marginal intangible cost component can be determined, then the cost of shortage is negatively valued. This negative cost represents a *benefit* to being short of inventory. In such a situation, since it would be beneficial to have a shortage, the analysis would provide $Q^* = 0$ as the optimized inventory. Therefore, the intangible cost term creates a penalty for being short and an incentive to hold a certain minimum inventory level.

To construct our marginal intangible cost function, we first note that for a military scenario, the marginal intangible cost of shortage depends on how many items were available in inventory. This is because the ability to achieve the objectives of the operation will depend on the warfighting capability of the unit. As the warfighting capability increases, the ability to achieve a larger number of the mission objectives increases and therefore the intangible cost of not having an additional item should decrease.

> **"Our model was based on the expectation of a 60-day surge deployment. After that time, we assumed the USMC units would be re-supplied through theater sustainment operations.**

To better illustrate this, consider a small unit in an isolated engagement with only one battery. The soldiers would have to choose between using it to fire a weapons system to defend themselves or to power a radio to call for support or an evacuation. In such a situation, having an additional battery would have allowed the soldiers to do both, greatly increasing the soldier's warfighting capability. On the other hand, consider the same situation but with enough batteries to power primary weapons and communications systems as well as multiple back-up systems with corresponding batteries. If the soldiers are short one battery, due to doctrine that requires back-up systems to be powered and available, then the main consequence is that one of multiple back-up systems cannot be operated. But since the primary systems, and at least one back-up system, are operational, little, if any, of the unit's warfighting capability decreases.

Mathematically, this behavior translates to a function that has a larger value for small inventory levels, monotonically decreases, and approaches zero for large inventory levels. The exponential function with a negative argument has those characteristics. Further, through the use of two coefficients, which we will call the value-to-cost ratio and the inverse rate, we can control how large the initial cost is for small inventory levels and the rate at which the penalty for being short decreases. The use of these two coefficients provides a large amount of freedom to specify the shape of the exponential function.

We define our marginal intangible cost function, $\Delta I(Q)$, found in Equation (6), as

$$\Delta I(Q) = \alpha P(Q)\, e^{-\left(\frac{Q}{\gamma}\right)} \tag{7}$$

where α is the value-to-cost ratio coefficient and γ is the inverse rate coefficient. Since we were interested in only the first 60 days of a surge deployment, we assumed that the capability, or value, of the item would not decrease over this timeframe. We also assumed that the value of the item would not decrease while in storage.

> **"As the warfighting capability increases, the ability to achieve a larger number of the mission objectives increases and therefore the intangible cost of not having an additional item should decrease.**

The value-to-cost ratio coefficient, α, can be used to adjust the procurement cost to better reflect the value of a single item in terms of achieving military objectives. Figure 1(a) shows how changing the value-to-cost ratio coefficient alters the marginal intangible cost function when the inverse rate coefficient is held fixed. In the figure, the inverse rate coefficient is set at 500,000. As the value-to-cost ratio coefficient increases, the marginal intangible cost increases for a given inventory level. Since no single value can be determined for all the items that might be stored in WRM, the appropriate value for the value-to-cost ratio coefficient will depend on the item of interest.

FIGURE 1(A). DEPENDENCE OF THE PROPOSED MARGINAL INTANGIBLE COST FUNCTION ON THE VALUE-TO-COST RATIO COEFFICIENT, α, FOR AN INVERSE RATE COEFFICIENT, γ, OF 500,000

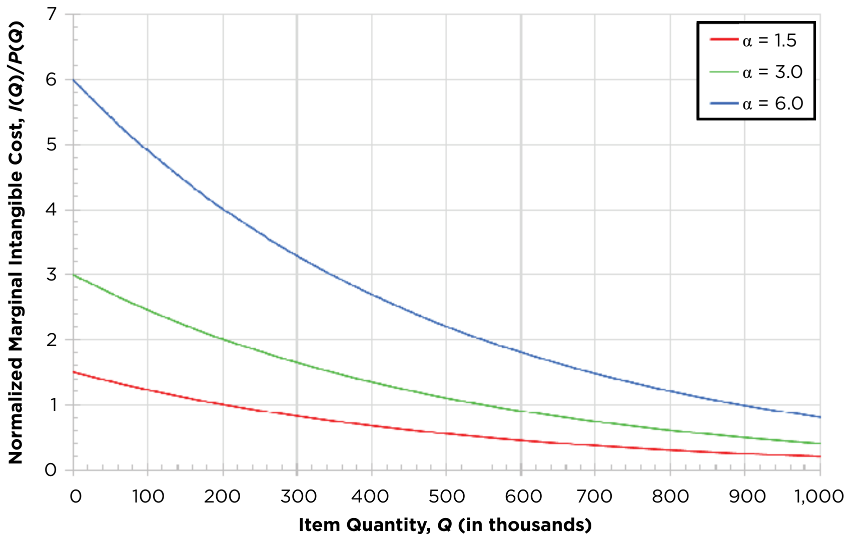
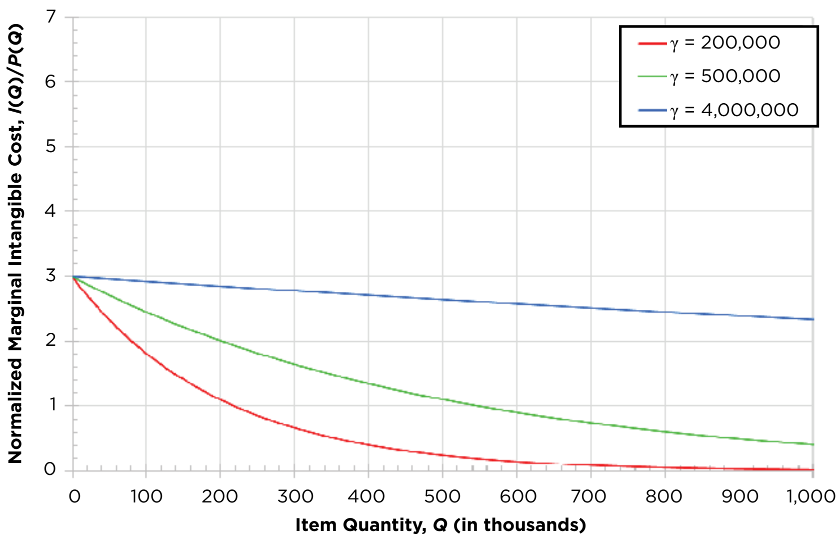


FIGURE 1(B). DEPENDENCE OF THE PROPOSED MARGINAL INTANGIBLE COST FUNCTION ON THE INVERSE RATE COEFFICIENT, γ, FOR A VALUE-TO-COST RATIO COEFFICIENT, α, OF 3.0



The inverse rate coefficient, γ, can be described as the rate at which the intangible cost function penalty decreases as the inventory level increases. We named it the inverse rate because as its value gets larger, the rate at which the intangible cost function approaches zero decreases. Figure 1(b) shows how changing the inverse rate coefficient alters the marginal intangible cost function when the value-to-cost ratio is held fixed. At a given inventory level, as the inverse rate coefficient is decreased, the marginal intangible cost decreases. Mathematically, when the inventory level is equal to the value of the inverse rate coefficient, the marginal intangible cost will be 36.8% of its value at zero inventory. Therefore, the value of the inverse rate coefficient should typically be on the order of the median from the expected item demand curve or larger. If the value is too small, then the marginal intangible cost function goes to zero too rapidly, before even reaching the average demand for the batteries. Like the value-to-cost ratio coefficient, the appropriate value for the inverse rate coefficient will also depend on the item of interest.

"The item quantity needed for future conflicts of various intensities should, in theory, be able to be estimated with some degree of accuracy, especially if a database of the required quantities of each item during a given conflict is maintained.

Even though the marginal intangible cost portion of Equation (6) is critical, logisticians have no straightforward way to capture the monetary value of the intangible costs of an item shortage. Our model is but one possible way to estimate an intangible cost component. We recognize that many different functional relationships, other than exponential, could be used to characterize the intangible cost. For example, Hadas and Herbon (2014) used a polynomial to capture their cost of shortage. A number of approaches are available, other than scaling the procurement cost, to quantify the cost of shortage. For example, linking increased casualty rates in battle with equipment nonavailability could potentially serve as a powerful method. However, we were not able to find the required data to determine the form of such a relationship. Finally, the value-to-cost ratio coefficient of the item could be allowed to decrease over time as it is stored. One such example of valuation changes over time is Hildebrandt (1985), which describes military assets in monetary terms.

Characterizing the demand distribution is also required to conduct the expected marginal cost analysis. In military applications, both the conflict intensity and the variance in the inherent service life of the item affect how

many of the items are needed and therefore influence the overall demand curve. Depending on the item, the demand curve could be influenced more by one of these factors versus the other.

The dependence on conflict intensity requires that we estimate how much more of the item would be consumed as the intensity increases. It also requires that we estimate how likely the various battle intensities are. Although the demand undoubtedly increases for an item as the battle intensity increases, the likelihood of such battle protraction should likely decrease. The balance between these two factors creates the overall item demand. Szayna (2017) sought to understand what the trends in conflict have been, why they have changed, and what type of conflicts we can expect in the future. The item quantity needed for future conflicts of various intensities should, in theory, be able to be estimated with some degree of accuracy, especially if a database of the required quantities of each item during a given conflict is maintained. However, accurately estimating the *likelihood* of each such conflict is much more difficult.

The dependence on service life is typically easier to estimate since data usually exist to support its determination. The distribution of the service life of the item can be estimated from manufacturers' data or from historical maintenance data. Depending on the amount of data available, an assumption about the shape of the distribution might have to be made.

Sample Application: The BA-5590/U Battery

The BA-5590/U is a nonrechargeable lithium-sulfur-dioxide ($LiSO_2$) battery that has been in service since the early 1990s (U.S. Marine Corps, 2011, pp. F2–F21). These high-energy batteries are the most widely used battery within the DoD. They power a wide range of the electronic equipment used by the USMC. Though often associated with radios and other communications equipment, this battery is also essential for weapon systems such as the Javelin and Tube-Launched, Optically Tracked, Wire-Guided missile systems.

The expressions for both the marginal cost of excess and shortage require the unit purchase cost for the battery to be determined. Based on economies of scale that the government has achieved through bulk purchases, the approximate current purchase cost is $75 for each battery. The expressions for the marginal cost of excess and shortage also require the unit holding cost for the batteries to be determined. The BA-5590/U battery has specific storage requirements due to its classification as hazardous materiel and benefits from refrigeration. Based on a table of storage costs per square foot and considering a 10-year storage period, the unit holding cost of an additional battery is $10.84. The required square footage of storage space was determined by assuming we stacked the batteries vertically on a standard pallet up to the weight handling limits of each pallet. By knowing the size of the batteries, we were then able to determine how many pallets and how much floor space was needed.

From Equation (5), the marginal cost of excess for BA-5590/U batteries is given by

$$\Delta C_e = 75.00 + 10.84 = 85.84 \tag{8}$$

which is simply a constant value independent of the quantity in inventory. From Equations (6) and (7), the marginal cost of shortage for the batteries is expressed as

$$\Delta C_s\,(Q) = 75.00\alpha\, e^{-\left(\frac{Q}{\gamma}\right)} - 85.84 \tag{9}$$

where the value does depend on the quantity, due to the marginal intangible cost portion.

The final required component of the model is an estimate of the BA-5590/U battery demand curve. Ideally, battery usage during past conflicts would be used to generate the demand curve. Unfortunately, such a detailed database of battery usage during previous conflicts does not exist. The most relevant databases show how the number of batteries stored at various locations changed over time, but the reason for the change is not included. Sometimes the batteries were used during conflicts; however, many other times they were used for other purposes such as training. Therefore, another approach was required to estimate the battery demand.

> **"The simulation user must specify the conflict duration and is also able to select from several predefined scenarios that capture the tempo and intensity of the operation.**

We used an existing simulation that models the power and energy consumption of various units in the U.S. military to estimate the battery demand curve. The simulation used was the MAGTF Power and Energy Model (MPEM) tool (T. Hagen, personal communication, February 11, 2020). The MPEM tool provides an estimate of the required quantity of many types of batteries used by the military, one of which is the BA-5590/U. The tool considers all the equipment used by each of the various units that make up an MEB. The simulation user must specify the conflict duration and is also able to select from several predefined scenarios that capture the tempo and intensity of the operation. For all other inputs being held fixed, a higher intensity scenario results in the tool predicting a larger number of batteries being needed.

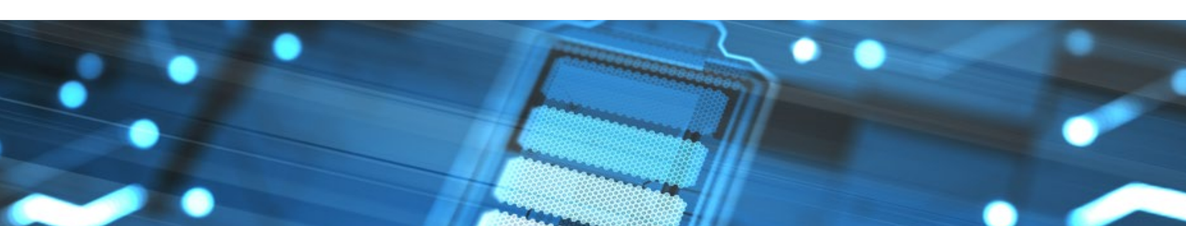
We considered five different combinations of maximum and minimum battery usage days when spanning the 60-day surge. The maximum battery usage days involved all units of the MEB and a high usage predefined scenario in the tool. The minimum battery usage days involved only a limited number of units and a low usage predefined scenario in the tool. To represent a range of conflict intensities, we varied the number of maximum and minimum battery usage days within the 60 days. For instance, our lowest intensity conflict considered 5 days of maximum battery usage and 55 days of minimum battery usage. Our middle intensity conflict assumed 30 days of each situation. Overall, we considered five conflicts with different intensities. For each of them, we also had to estimate the likelihood that future conflicts would require *less* than the number of estimated batteries from each one.

TABLE 1. DATA USED TO CONSTRUCT THE CUMULATIVE DISTRIBUTION FUNCTION OF THE BA-5590/U BATTERY DEMAND CURVE

Days of maximum battery usage by all units	Days of minimum battery usage by selected units	Estimated number of batteries needed	Likelihood of future conflicts requiring fewer batteries
5	55	58,086	0.05
15	45	121,731	0.25
30	30	182,356	0.50
45	15	224,476	0.75
55	5	237,210	0.95

Table 1 lists the number of batteries that the MPEM tool predicted were needed for each of our five conflicts, along with our estimate for the likelihood of a future conflict requiring more batteries than listed in each row. The battery results highlight that to estimate the required number of batteries, the MPEM tool does not use an average daily battery usage rate approach that would linearly scale to any length of conflict. Instead, it uses historical battery usage data, from both combat and field tests, the actual duration itself, and several other factors to estimate the batteries required. The conflict duration is important because in longer duration conflicts and field tests, batteries tend to be utilized more efficiently rather than replaced frequently with new batteries, which tends to happen in short-duration situations. From our results, we estimated that the median of the battery demand curve is 182,356 batteries. We denote this battery quantity as Q_0 and will scale it to set our inverse rate coefficient value.

We also looked at the effect that the battery service life would have on the number of required batteries in our demand distribution. A previous battery study conducted at Naval Postgraduate School (Vroom et al., 2019) determined that the average battery life of the BA-5590/U was 8.60 hours with a standard deviation of 1.52 hours. The estimated total required battery hours is the product of this average battery life and the estimated number of batteries. To determine the variability in the number of batteries needed due to variance in the service life, we created a simulation. The simulation



predicted how many batteries were needed to reach the required total battery hours if the service life of any given battery followed a normal distribution with a mean and standard deviation given from the Vroom study. By running 1,000 simulations, we determined that the standard deviation on the number of required batteries to reach our total battery hours was insignificant compared to the variability due to changing the MPEM tool input parameters. For example, the 30-30 day conflict scenario that requires 1,568,261.6 battery hours resulted in a standard deviation of only 75 batteries due to the variability of battery service life. This rather small variance revealed that the effects of consumption during battle are more important than the variability in battery service life when estimating the number of required batteries.

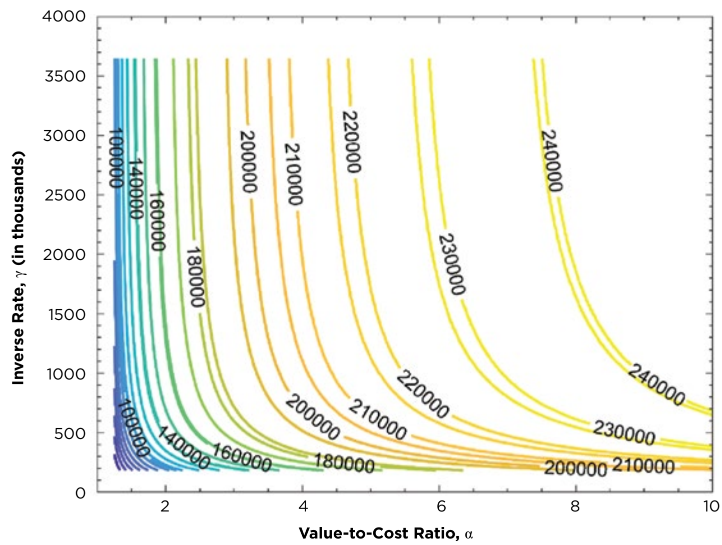
Results and Discussion

Sensitivity to Intangible Cost

The most subjective aspect of our expected marginal cost analysis was the marginal intangible cost component. Therefore, we explored the sensitivity of our model to the value-to-cost ratio and inverse rate coefficients. The purpose of our sensitivity study is not only to determine how changes to the value-to-cost ratio or inverse rate coefficients can change the calculated optimal inventory level, but also how much that level changes when the shape of the marginal intangible cost function is altered. Since the marginal intangible cost function is subjective, it is quite possible that different analysts could value the intangible costs significantly different when putting them in monetary terms. Therefore, we selected value-to-cost ratio and inverse rate coefficient values that would result in intangible cost curves that had significantly different values while keeping the coefficient values reasonable.

Figure 1(a) showed that as the value-to-cost ratio increases, the cost of not having an additional item at any inventory level increases. The smallest value-to-cost ratio coefficient that is realistic is something slightly greater than 1.0 since anything smaller means that the value of the item is less than its purchase cost. Therefore, we used a value of 1.5 for our smallest value. For our largest value-to-cost ratio, we settled on 6.0—a value four times larger than our smaller value—but we show results for up to a value of 10.0 in Figure 2. We decided that a value-to-cost ratio, larger than an order of magnitude, would be more appropriate when considering two different items.

FIGURE 2. OPTIMAL INVENTORY STORAGE LEVELS FOR THE BA-5590/U BATTERY FOR A RANGE OF VALUE-TO-COST RATIO COEFFICIENT AND INVERSE RATE COEFFICIENT VALUES



As explained above, the inverse rate, to be realistic, should be set by scaling up the pre-analysis estimated median demand of the item from the demand curve. The smallest reasonable scaling up would be to just use the median demand itself, so we used $1.0Q_0$ as our smallest coefficient value. The largest scaling-up value would be one that makes the curve locally appear linear. This clearly happens when the inverse rate takes on a value near $20Q_0$, since the blue line in Figure 1(b) corresponds to an inverse rate coefficient of $21.9Q_0$.

When exploring the sensitivity of one coefficient, we held the other one fixed to isolate the sensitivity of each coefficient. Besides the smallest and largest coefficient values previously discussed, we also selected a third, middle value for both coefficients. This middle value was selected to cause the marginal intangible cost function to have a shape that was between the two shapes created by the smallest and largest coefficient values. Since the value-to-cost ratio linearly scales the marginal intangible cost function, we simply selected the middle value of 3.0. The inverse rate coefficient is part of the argument of the exponential function, so it does not linearly scale the shape like the value-to-cost coefficient. We found that a value of $2.5Q_0$ created a shape that visually appeared approximately halfway between the two shapes when using the smallest and largest values. Figure 1(b) shows that the green curve, which is $2.7Q_0$ (roughly $2.5Q_0$), is not nearly as steep as the red curve nor nearly as flat as the blue curve.

When examining the sensitivity of the value-to-cost ratio coefficient, we fixed the inverse rate coefficient at $2.5Q_0$. We fixed the value-to-cost ratio coefficient at 3.0 when looking at the sensitivity of the inverse rate coefficient. Table 2 shows the optimal inventory level for the five cases corresponding to the different combinations of our coefficient values. The top row contains the three value-to-cost ratio coefficients we considered, while the first column has the three inverse rate coefficients considered.

TABLE 2. OPTIMAL INVENTORY LEVELS OF BA-5590/U BATTERIES FOR VARIOUS VALUE-TO-COST RATIO AND INVERSE RATE COEFFICIENTS

γ \ α	1.5	3.0	6.0
$1.0Q_0$	---	134,000	---
$2.5Q_0$	93,250	173,750	212,500
$20.0Q_0$	---	196,750	---

We observed that as the value-to-cost ratio coefficient increases, the optimal inventory level increases as well. A significant difference in optimal inventory levels was also observed between the smallest and largest value-to-cost ratio coefficients considered. These two values produce a difference in optimal inventory levels of nearly 119,250 batteries, or just over a factor of 2.28 between the smallest and largest value-to-cost ratio coefficients. The optimal inventory level is very sensitive to the value-to-cost ratio coefficients, relying upon the subjective judgment of planner inputs.

The results also show that as the inverse rate coefficient values increase, the optimal battery inventory level also increases. The optimal inventory level changes by about 62,750 batteries, or a factor of 1.47, between the smallest and largest inverse rate coefficients. Although the inverse rate coefficient influences the optimal storage level, it appears to be less sensitive than the value-to-cost ratio coefficient. This is most apparent when considering that the inverse rate was varied by a factor of 20 in this sensitivity study, while the value-to-cost ratio was only varied by a factor of 4.

A contour map of the optimal inventory storage levels over a range of value-to-cost ratio and inverse rate coefficients provides a complete picture of the inventory level sensitivity plane. Figure 2 shows contour lines of constant optimal inventory levels with the value-to-cost ratio coefficients ranging from 1.25 to 10 and the inverse rate coefficients ranging from Q_0 to $20Q_0$, where Q_0 = 182,356 for this battery study. The contour map clearly shows that the optimal inventory storage level is less sensitive to, and in fact almost independent of, the inverse rate coefficient when it is larger than about a value of $5Q_0$. Conversely, the optimal storage level is sensitive to the value-to-cost ratio coefficient across its entire range, but especially when the inverse rate coefficient is larger than roughly $3Q_0$.

Sensitivity to Demand Distribution

Since we used a normal distribution as an expedient for the battery distribution, we also examined the sensitivity to the form of the demand distribution. One could argue that the battery demand distribution might be somewhat skewed toward lower quantities since a minimum number of batteries is consumed for even the lowest intensity conflict. So, we also created a Weibull distribution to model the battery demand to use in our expected marginal cost analysis. The scale and shape parameters of the Weibull distribution allow it to capture skewness. Figure 3 shows the cumulative distribution function of the Weibull distribution that we created as the blue curve, and the normal distribution that we used previously as the red curve. The scale and shape parameter values were selected by minimizing the error, in a least-squares sense, to the MPEM tool data. It has a 25th-percentile quantity of 131,294 batteries, a median quantity of 172,878 batteries, and a 75th-percentile quantity of 214,748 batteries. For our normal distributions, these percentiles were 142,818, 182,356, and 221,894 batteries, respectively. Therefore, the largest difference is with the left tail skewness of the distributions, which is also evident in Figure 3.

FIGURE 3. NORMAL AND WEIBULL CUMULATIVE DISTRIBUTION FUNCTIONS USED IN THE ANALYSIS ALONG WITH THE MPEM TOOL GENERATED DATA

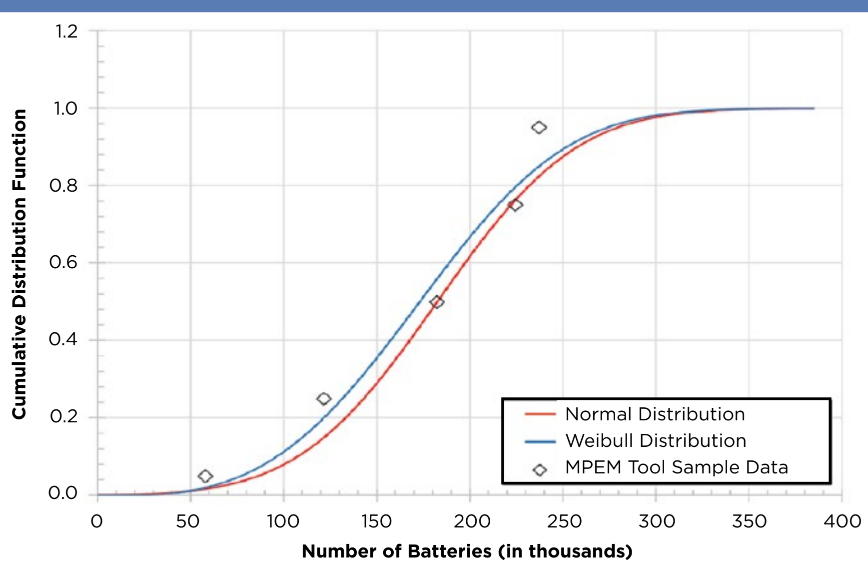


TABLE 3. COMPARISON OF OPTIMAL INVENTORY STORAGE LEVELS OF BA-5590/U BATTERIES USING A WEIBULL DISTRIBUTION DEMAND COMPARED TO A NORMAL DISTRIBUTION DEMAND

γ \ α	1.5	3.0	6.0
$1.0Q_o$	---	127,750 (0.95)	---
$2.5Q_o$	87,500 (0.94)	165,500 (0.95)	205,500 (0.97)
$20.0Q_o$	---	188,500 (0.96)	---

To examine the sensitivity to this demand distribution, the optimal inventory level was determined using the same value-to-cost ratio and inverse rate coefficients as in the previous section but now using the Weibull distribution for battery demand. Table 3 shows the optimal inventory levels for the five different combinations of coefficients considered previously. The optimal inventory level for the five cases using the Weibull distribution is the first number shown, while the second number (shown in parentheses) is the ratio of this inventory level to the previously determined normal distribution demand inventory level. The second number being only slightly less than 1 shows that the optimal inventory level is not very sensitive to the actual distribution shape when the range of the distributions is similar. Since the optimal inventory level must fall within the range of the demand distribution, it will only change significantly if the range of the distribution is significantly changed.

Sensitivity to Purchase and Holding Costs

Although considerably less subjective than the intangible cost component or the demand distribution, we also looked at the sensitivity of the optimal inventory level to the purchase and holding costs in our model. To do this, we determined the optimal inventory level using low- and high-purchase and holding costs. However, when conducting this sensitivity analysis, we had to address the fact that our formula for the intangible cost function (Equation 7) contains the purchase cost as well. The purpose of multiplying the value-to-cost ratio coefficient and the purchase cost is to capture the true military value of the item. Therefore, for this sensitivity analysis, we held the value of the purchase cost variable used in Equation (7) fixed at $130. The value-to-cost ratio coefficient was also fixed at 3.0 for all cases. This allowed us to vary the purchase and holding costs but not the intrinsic military value of the item.

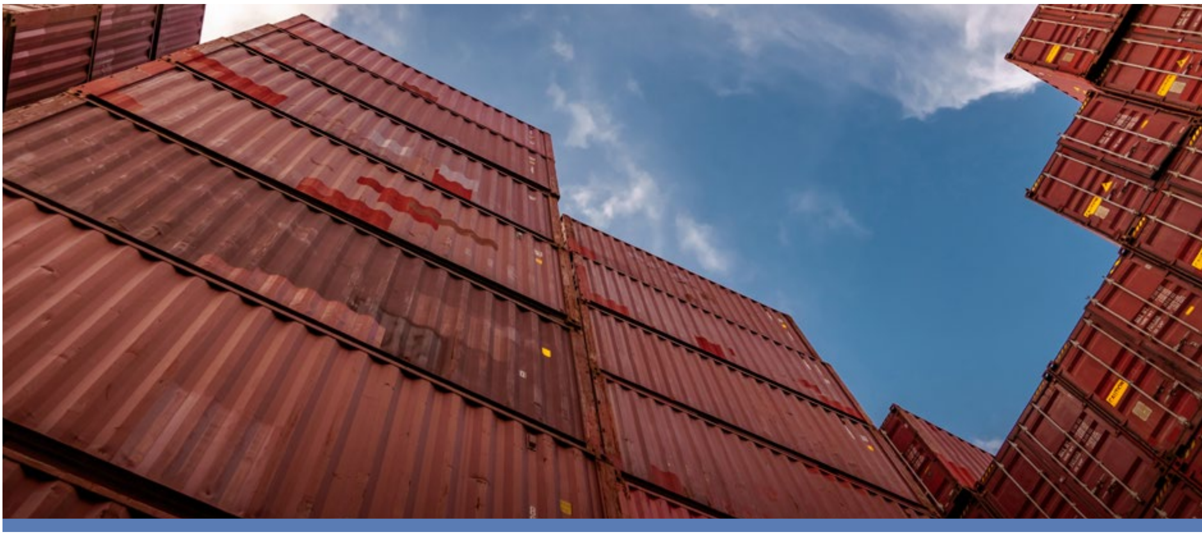
To perform this sensitivity analysis, we used the following ranges of purchase and holding costs. For the low end, we used a unit purchase cost of $75 and a monthly battery pallet holding cost of $50 ($5.40 per battery assuming 10 years of storage). These values represent realistic low-end values that we identified considering economies of scale from buying in large quantities and nonrefrigerated storage. For the high end, we used a unit purchase cost of $185 and a monthly battery pallet holding cost of $100 ($10.80 per battery for 10 years). These values correspond to the purchase cost of a single commercially available battery, ignoring the benefits of economies of scale, and including refrigerated storage. When calculating the optimal inventory level, the value-to-cost ratio coefficient for all cases was 3.0 and the inverse rate coefficient was $2.5Q_0$.

> **"The purpose of multiplying the value-to-cost ratio coefficient and the purchase cost is to capture the true military value of the item.**

For an item with a fixed military value, when the purchase and holding costs increase, the optimal inventory storage level decreases. For the low-end costs, the optimal inventory storage level was 208,750 batteries, while for the high-end costs, the optimal storage level was 151,500 batteries. This results in a range of 57,250 batteries, or a factor of 1.38, between the optimal storage levels considering the low- and high-end cases. This level of sensitivity is similar to that of the inverse rate coefficient and much less than that of the value-to-cost ratio coefficient.

Conclusions and Future Research

Like any optimization problem, expected marginal cost analysis finds a balance between two competing factors—in this case, the expected costs incurred from having too many of an item and having too few. The cost of having too many is usually straightforward. However, the cost of shortage in a military scenario must be captured using an intangible cost function. This is inherently a subjective determination. Through our sensitivity analysis, we have shown that the most important aspect of our modified newsvendor approach is the value-to-cost ratio coefficient. The results of the analysis will be meaningful only if one accurately captures the "costs" incurred when additional items are needed but not available. Since quantifying this will always be conjectural and vary widely, depending on the modeler's input, so too will the optimal inventory levels for the WRM. The span of the demand distribution is another important aspect of our approach because the optimized inventory level is forced to occur within the bounds of the demand distribution. Thus, if the estimated demand distribution covers



the wrong quantity range, then the optimized inventory level will also be wrong. Therefore, the two biggest shortfalls of the newsvendor model in a military context are the uncertainty surrounding the intangible cost of item shortage and the distribution of demand.

The formulation of our model is general enough that it can be applied to any item that is part of the WRM and to the other branches of military service. However, each branch would need to adjust the parameter values to reflect the supported unit size and surge duration that the WRM needs to supply. This would most clearly show up in the demand distribution used for the analysis. Our model is also general enough that it can be applied to other scenarios where the cost of shortage is due to intangible costs rather than lost profits, such as humanitarian aid and disaster relief efforts.

Our model has neglected factors such as reuse of items while in theater, maintenance of items in storage, and waste in transport and use. These factors, presumed to be less significant, would undoubtedly make the model more realistic, but would also make the determination of parameter values more difficult. This is an area for further research that could leverage and refine our work.

Feedback given to us by our research sponsors at the USMC Installation and Logistics Command was enthusiastic about how our methods could be used to better convey stockage levels in a more realistic context for sustainment preparations.

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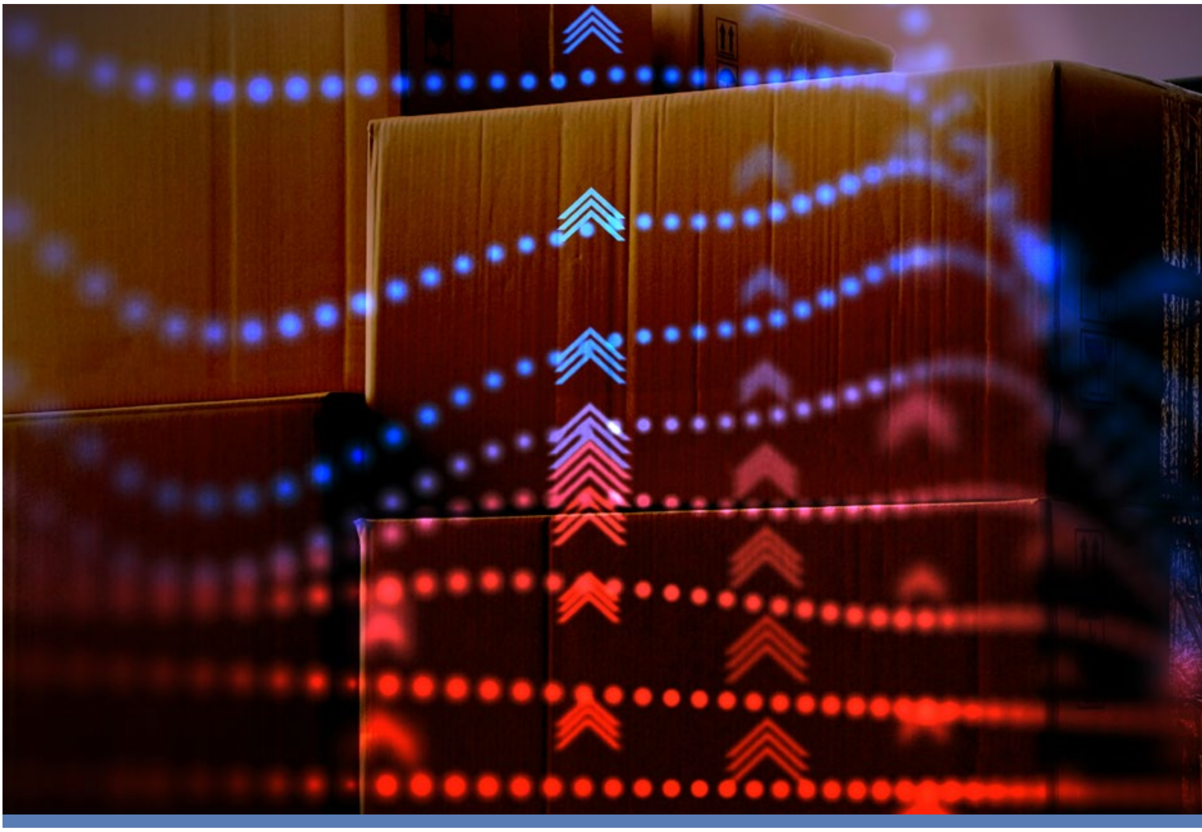
Acknowledgments

The authors would like to thank Terry Hagen and Tim Kibben of USMC Installation and Logistics Command, Logistics Plans and Operations (Maritime and Geo-Prepositioning Programs) (LPO-2), for their sponsorship of our study and for their frank and timely feedback in guiding our research to aid them in estimating optimal USMC WRM inventory. We also wish to thank the faculty and staff of the Systems Engineering Department at the Naval Postgraduate School for their mentorship of our study, especially Senior Lecturer COL John T. Dillard, USA (Ret.) for his insights and guidance to make this effort relevant for the acquisition community; and Associate Professor COL Alejandro S. Hernandez, USA (Ret.) for his counsel. This study originated from a Naval Postgraduate School Program 522 Capstone Project, where our colleagues MAJ Alexandre W. Anderson, USA, MAJ Casey B. Close, USA, and MAJ Chad S. Frizzell, USA, combined their operational logistical and contracting experiences, contributing immensely to the level of military analysis required.



Author Biographies

MAJ Minou Pak, USA

is an Army Acquisition Corps Officer currently assigned to the Army Research Laboratory, Adelphi, Maryland, as a Science and Technology Military Advisor. He holds a Master's in Systems Engineering Management from Naval Postgraduate School (NPS) and a BS in Mechanical Engineering from United States Military Academy.

(E-mail address: minou.pak.mil@mail.mil)

MAJ Joshua L. Peeples, USA

is an Army Acquisition Corps Officer currently assigned to the Missile Defense Agency, Huntsville, Alabama, as an Assistant Product Manager. He holds a Master's in Systems Engineering Management from NPS, a Masters in Logistics Management from Florida Institute of Technology, and a BA in Sociology/Criminal Justice from University of Tennessee, Knoxville.

(E-mail address: joshua.l.peeples.mil@mail.mil)

Dr. Joseph T. Klamo

is an Assistant Professor in the Systems Engineering Department at NPS. He holds a PhD and MS in Mechanical Engineering from California Institute of Technology and a BS in Mechanical Engineering from University of Michigan. Prior to NPS, Dr. Klamo was head of the Captive Model Testing Group in the Submarine Maneuvering and Control Division at Naval Surface Warfare Center, Carderock Division.

(E-mail address: jklamo@nps.edu)

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PROFESSIONAL READING LIST

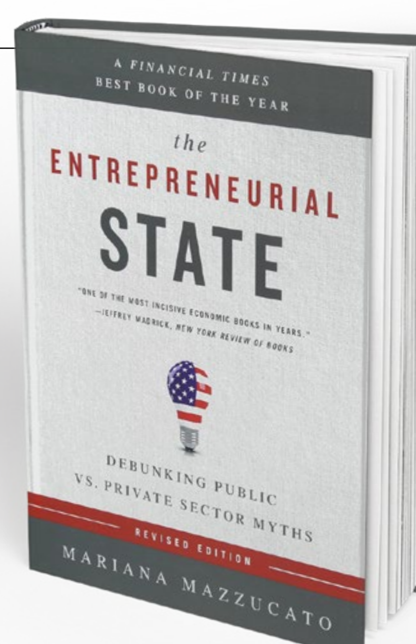
The Defense Acquisition Professional Reading List is intended to enrich the knowledge and understanding of the civilian, military, contractor, and industrial workforce who participate in the entire defense acquisition enterprise. These book recommendations are designed to complement the education and training vital to developing essential competencies and skills of the acquisition workforce. Each issue of the *Defense Acquisition Research Journal* will include one or more reviews of suggested books, with more available on our website: http://dau.edu/library.

We encourage our readers to submit book reviews they believe should be required reading for the defense acquisition professional. The books themselves should be in print or generally available to a wide audience; address subjects and themes that have broad applicability to defense acquisition professionals; and provide context for the reader, not prescriptive practices. Book reviews should be 450 words or fewer, describe the book and its major ideas, and explain its relevance to defense acquisition. Please send your reviews to the managing editor, *Defense Acquisition Research Journal* at DefenseARJ@dau.edu.

Featured Book

The Entrepreneurial State: Debunking Public vs. Private Sector Myths

Author: Mariana Mazzucato
Publisher: PublicAffairs
Copyright Date: 2015
Hard/Softcover/Digital: Softcover, 288 pages
ISBN-13: 9781610396141
Reviewed by: Dr. John D. McCormack, Senior Lecturer, Cardiff School of Management, Cardiff Metropolitan University



Review:

The Entrepreneurial State: Debunking Public vs. Private Sector Myths was written by Mariana Mazzucato in 2011 (revised edition 2015). This work expands upon a 2006 paper discussing the perception of the role of states in promoting the scientific and technological innovation powering much of the high-growth elements of the modern economy. Using a carefully researched series of case examples, Mazzucato seeks to contribute to the often divisive and partisan debate over the role of the state in promoting innovation and risk-taking throughout the economy. She challenges a perceived wisdom that governments lack the competence and capabilities required to effectively identify and nurture the nascent technologies that drive the modern economy, and that only the private actors—specifically venture capitalists—are the primary facilitators of industrial innovation.

Mazzucato looks at instances from across industrial sectors such as biotechnology, nanotechnology, and the emergence of the internet to provide examples where governments were more willing and able to take risks and provide support at key moments than their private sector partners. Further, she examines instances where developments would not have happened—specifically at the early stages of development—and casts light on the tendency of venture capitalists to avoid the high-risk early phases of research and development (R&D) projects without government backing. By applying innovations and putting them into practice once they are demonstrated as viable, Mazzucato describes how such innovations add more value in the later stages of their development. Apple is reviewed in detail, with a chapter dedicated to articulating the role of public research funding in the development of several of the firm's blockbuster products.

The author shows that government agencies around the world—for example, DARPA (Defense Advanced Research Projects Agency) and ARPA-E (Advanced Research Projects Agency-Energy) in the United States, the German state-owned investment and development bank KfW, the National Development Bank of Brazil, and the Chinese Development Bank—have all played active roles in promoting key elements in technological development. The success of these international agencies illustrates the competencies that state agencies have in promoting promising new sectors and enabling private engagement, which would not have been possible without public sector encouragement. Mazzucato seeks to present positive examples of where innovation is the direct result of interventions.

The author clearly sides with engaged public industrial strategies and structured systems for state interventions in support of R&D projects, especially those which might be categorized as high risk. She further makes a clear, well thought-out, and thorough critique of many of the assumptions of the schools of policy economics such as New Public Management. Such schools typically argue that the state is ineffective in this area, and she goes on to dedicate two chapters to looking at how emerging areas such as the Green Economy—which she posits as the next big thing after the Internet—can be better facilitated by state engagement.

Since the underlying approach of the book is anecdotal, in that it presents a series of case studies and examples, it is limited in its ability to make broad claims about its controversial theory. However, it is not really attempting to construct an argument to demonstrate causality, but rather to point out that the role of the state in driving innovation tends to be overlooked, and that policy makers who ignore the ability of the public sector to drive innovation do so at their peril. As a work grounded in selective anecdotes, Mazzucato presents its argument's best examples and doesn't make a really representative presentation of the range of poor choices that public agencies have also made over the years. As such, it is not designed to be a handbook for policy makers, but rather an instrument to inform the broader debate about the role of public involvement in R&D activities.

The fact that the work is a decade old at this point does not detract from its relevance today. In fact, many examples at the heart of her narrative are just as salient today as they were at the time of writing. The work is extremely well researched, thought-provoking, and engaging. It is a worthwhile read, not only for defense acquisition professionals, but also for those interested in the broader debate about the role of industrial policies and state involvement in economic development.

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Current Research Resources in DEFENSE ACQUISITION

Digital Engineering

Each issue of the *Defense Acquisition Research Journal* will bring to the attention of the defense acquisition community a topic of current research, which has been undertaken by the DAU Virtual Research Library team in collaboration with DAU's Director of Research. Both government civilian and military Defense Acquisition Workforce readers will be able to access papers publicly and from licensed resources on the DAU Virtual Research Library Website: https://dau.libguides.com/daukr.

Nongovernment Defense Acquisition Workforce readers should be able to use their local knowledge management centers/libraries to download, borrow, or obtain copies. We regret that DAU cannot furnish downloads or copies.

Defense Acquisition Research Journal readers are encouraged to submit proposed topics for future research by the DAU Virtual Research Library team. Please send your suggestion with a short write-up (less than 100 words) explaining the topic's relevance to current defense acquisition to: Managing Editor, *Defense Acquisition Research Journal*, DefenseARJ@dau.edu.

Digital Transformation for Defense Acquisition: Digital Engineering Competency Framework (DECF)

Nicole Hutchison

Summary:

Digital engineering (DE) is "an integrated digital approach that uses authoritative sources of systems data and models as a continuum across disciplines to support life-cycle activities from concept through disposal. A DE ecosystem is an interconnected infrastructure, environment, and methodology that enables the exchange of digital artifacts from an authoritative source of truth" (Office of the Deputy Assistant Secretary of Defense [Systems Engineering], 2017). The purpose of the Digital Engineering Competency Framework is to provide clear guidance for the DoD acquisition workforce, in particular the engineering acquisition workforce, through clearly defined competencies that illuminate the knowledge, skills, abilities, and behaviors required for DE professionals.

APA Citation:

Hutchison, N. (2021, May). *Digital transformation for defense acquisition: Digital engineering competency framework (DECF)*. Naval Postgraduate School. https://dair.nps.edu/bitstream/123456789/4376/1/SYM-AM-21-069.pdf

A Framework to Categorize the Benefits and Value of Digital Engineering

Tom McDermott

Summary:

This research sought to define a comprehensive framework for DE benefits and expected value linked to the ongoing development of DE enterprise capabilities and experienced transformation "pain points," enablers, obstacles, and change strategies. Using a combination of literature review, broad surveys, and government program office visits, the author found that the DE and Model-Based Systems Engineering communities, across government, industry, and academia, are not sufficiently mature at this point in their DE transformations to standardize on best practices and formal success metrics. Pockets of excellence exist, but experience and maturity vary widely. The author also found that government lags industry in maturity and should look to both their industry partners and the broader swath of commercial industry for best practices.

APA Citation:

McDermott, T. (2021, May). *A framework to categorize the benefits and value of digital engineering*. Naval Postgraduate School. https://dair.nps.edu/bitstream/123456789/4375/1/SYM-AM-21-068.pdf

A Project-Oriented Model-Based Systems Engineering (MBSE) Approach for Naval Decision Support

Z. I. Jenkins

Summary:

Systems engineering projects in the Navy require the use of a singular engineering method that lacks tailorability, and while this method works for large-scale projects, it has also caused small-scale projects (those with less than 1,000 function points) implementing MBSE to fall behind schedule in the technology maturation phase. This study describes the design and implementation of a Decision Support Tool, which fills the gap in guidance while improving schedule performance for small-scale MBSE projects.

APA Citation:

Jenkins, Z. I. (2021, January) *A project-oriented Model-Based Systems Engineering (MBSE) approach for naval decision support* (Publication No. 28259498) [Doctoral dissertation, The George Washington University]. ProQuest Dissertations & Theses Global. https://www.proquest.com/dissertations-theses/project-oriented-model-based-systems-engineering/docview/2470415232/se-2?accountid=40390

Using Model-Based Systems Engineering Methods to Capture a Department of Defense Acquisition Life Cycle

Ronald J. Torok

Summary:

The Office of the Deputy Assistant Secretary of Defense for Systems Engineering is pushing Model-Based Systems Engineering (MBSE) methods to increase efficiencies and technical rigor in Department of Defense engineering practices. MBSE methods might also aid in the planning of an acquisition process. An MBSE process is proposed for capturing the acquisition life cycle, the structure that implements the life-cycle processes, and the developed information artifacts using an SysML model.

APA Citation:

Torok, R. J. (2020, December). *Using Model-Based Systems Engineering methods to capture a Department of Defense acquisition life cycle*. Naval Postgraduate School. http://hdl.handle.net/10945/66736

Bending the Spoon: Guidebook for Digital Engineering and e-Series

Will Roper

Summary:

I do indeed know why you're here. Whether by direct experience, online research, or extrapolating from *The Matrix*, you've glimpsed what digital acquisition might achieve. You've read *There is No Spoon* and tried applying its digital trinity—agile software, digital engineering, and open

architecture—inside your programs. But remaining questions still drive you: What is digital engineering and an e-Series, really? Do we need them? What are their criteria? And how far must we go to effect a digital transformation for the Air Force and Space Force? … This companion guide to *There is No Spoon* will equip you for those value judgments and help you pursue spoon-bending results for both digital engineering and e-Series. Specifically, it goes deeper on the modeling and infrastructure requirements to effect several tenets of *There is No Spoon: eCreating before Aviating*, and owning and furnishing the tech stack. Though written to stand alone, its insights will make more sense if read as a sequel.

APA Citation:

Roper, W. (2021, January). *Bending the spoon: Guidebook for digital engineering and e-series*. United States Air Force. https://www.af.mil/Portals/1/documents/2021SAF/01_Jan/Bending_the_Spoon.pdf

There is No Spoon: The New Digital Acquisition Reality

Will Roper

Summary:

This is indeed your last chance. Should you continue reading, your defense acquisition training—no matter what life-cycle facet, function, or operational domain—becomes a dream from which to wake up…to something new. Digital Engineering and Management, combined with Agile Software and Open Architecture, truly is the "rabbit hole" to escape traditional defense acquisition. I am excited to share more about this trinity of digital design technologies, why their digital Wonderland excites me, and how they foretell a faster, more agile, and more competitive weapons-buying process our nation needs to succeed long term. This *Matrix*-inspired guide is designed to reboot outdated approaches—and analog thinking—to a new spoon-bending, digital acquisition reality. It will illuminate terms and provide insights, best practices, and litmus tests for success (as best we know them) from commercial industry and bellwether Air Force programs.

APA Citation:

Roper, W. (2020, October). *There is no spoon: The new digital acquisition reality*. United States Air Force. Retrieved from https://software.af.mil/wp-content/uploads/2020/10/There-Is-No-Spoon-Digital-Acquisition-7-Oct-2020-digital-version.pdf

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WINNER 2020

Norene Johnson, Emily Beliles, and Michael Krukowski

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Defense ARJ Guidelines **FOR CONTRIBUTORS**

The *Defense Acquisition Research Journal (ARJ)* is a scholarly peer-reviewed journal published by DAU. All submissions receive a double-blind review to ensure impartial evaluation.

IN GENERAL

We welcome submissions describing original research or case histories from anyone involved in the defense acquisition process. Defense acquisition is broadly defined as any actions, processes, or techniques relevant to as the conceptualization, initiation, design, development, testing, contracting, production, deployment, logistics support, modification, and disposal of weapons and other systems, supplies, or services needed for a nation's defense and security, or intended for use to support military missions.

Research involves the creation of new knowledge. This generally requires either original analysis of material from primary sources, including program documents, policy papers, memoranda, surveys, interviews, etc.; or analysis of new data collected by the researcher. Articles are characterized by a systematic inquiry into a subject to establish facts or test theories that have implications for the development of acquisition policy and/or process.

The *Defense ARJ* also welcomes case history submissions from anyone involved in the defense acquisition process. Case histories differ from case studies, which are primarily intended for classroom and pedagogical use. Case histories must be based on defense acquisition programs or efforts. Cases from all acquisition career fields and/or phases of the acquisition life cycle will be considered. They may be decision-based, descriptive or explanatory in nature. Cases must be sufficiently focused and complete (i.e., not open-ended like classroom case studies) with relevant analysis and conclusions. All cases must be factual and authentic. Fictional cases will not be considered.

We encourage prospective writers to coauthor, adding depth to manuscripts. We recommend that junior researchers select a mentor who has been previously published or has expertise in the manuscript's subject. Authors should be familiar with the style and format of previous *Defense ARJs* and adhere to the use of endnotes versus footnotes, formatting of reference lists, and the use of designated style guides. It is also the responsibility of the corresponding author to furnish any required government agency/employer clearances with each submission.

MANUSCRIPTS

Manuscripts should reflect research of empirically supported experience in one or more of the areas of acquisition discussed above. The *Defense ARJ* is a scholarly research journal and as such does not publish position papers, essays, or other writings not supported by research firmly based in empirical data. Authors should clearly state in their submission whether they are submitting a research article or a case history. The requirements for each are outlined below.

Research Articles

Empirical research findings are based on acquired knowledge and experience versus results founded on theory and belief. Critical characteristics of empirical research articles:

- clearly state the question,
- define the research methodology,

- describe the research instruments (e.g., program documentation, surveys, interviews),
- describe the limitations of the research (e.g., access to data, sample size),
- summarize protocols to protect human subjects (e.g., in surveys and interviews), if applicable,
- ensure results are clearly described, both quantitatively and qualitatively,
- determine if results are generalizable to the defense acquisition community
- determine if the study can be replicated, and
- discuss suggestions for future research (if applicable).

Research articles may be published either in print and online, or as a Web-only version. Articles that are 5,000 words or fewer (excluding abstracts, references, and endnotes) will be considered for print as well as Web publication. Articles between 5,000 and 10,000 words will be considered for Web only publication, with a two sentence summary included in the print version of the *Defense ARJ*. In no case should article submissions exceed 10,000 words.

Case Histories

Care should be taken not to disclose any personally identifiable information regarding research participants or organizations involved unless written consent has been obtained. If names of the involved organization and participants are changed for confidentiality, this should be highlighted in an endnote. Authors are required to state in writing that they have complied with APA ethical standards. A copy of the APA Ethical Principles may be obtained at http://www.apa.org/ethics/.

All case histories, if accepted, will receive a double-blind review as do all manuscripts submitted to the *Defense ARJ*.

Each case history should contain the following components:

- Introduction
- Background
- Characters
- Situation/problem
- Analysis
- Conclusions
- References

Book Reviews

Defense ARJ readers are encouraged to submit book reviews they believe should be required reading for the defense acquisition professional. The reviews should be 500 words or fewer describing the book and its major ideas, and explaining why it is relevant to defense acquisition. In general, book reviews should reflect specific in-depth knowledge and understanding that is uniquely applicable to the acquisition and life cycle of large complex defense systems and services. Please include the title, ISBN number, and all necessary identifying information for the book that you are reviewing as well as your current title or position for the byline.

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The readers of the *Defense ARJ* are primarily practitioners within the defense acquisition community. Authors should therefore strive to demonstrate, clearly and concisely, how their work affects this community. At the same time, do not take an overly scholarly approach in either content or language.

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Please submit your manuscript according to the submissions guidelines below, with references in APA format (author date-page number form of citation) as outlined in the latest edition of the *Publication Manual of the American Psychological Association.* References should include Digital Object Identifier (DOI) numbers when available. The author(s) should not use automatic reference/bibliography fields in text or references as they can be error-prone. Any fields should be converted to static text before submission, and the document should be stripped of any outline formatting. All headings should conform to APA style. For all other style questions, please refer to the latest edition of the *Chicago Manual of Style.*

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The author (or corresponding author in cases of multiple authors) should attach a cover letter to the manuscript that provides all of the authors' names, mailing and e-mail addresses, as well as telephone numbers. The letter should verify that (1) the submission is an original product of the author(s); (2) all the named authors materially contributed to the research and writing of the paper; (3) the submission has not been previously published in another journal (monographs and conference proceedings serve as exceptions to this policy and are eligible for consideration for publication in the *Defense ARJ*); (4) it is not under consideration by another journal for publication. If the manuscript is a case history, the author must state that they have complied with APA ethical standards in conducting their work. A copy of the APA Ethical Principles may be obtained at http://www.apa.org/ethics/. Finally, the corresponding author as well as each coauthor is required to sign the copyright release form available at our website: www.dau.edu/library/arj.

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All manuscript submissions should include the following:

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- Cover letter containing the complete mailing address, e-mail address, and telephone number for each author
- Biographical sketch for each author (70 words or fewer)
- Headshot for each author saved as a 300 dpi (dots per inch) high resolution JPEG or Tiff file no smaller than 5x7 inches with a plain background in business dress for men (shirt, tie, and jacket) and business appropriate attire for women. All active duty military should submit headshots in Class A uniforms. Please note: low-resolution images from Web, PowerPoint, or Word will not be accepted due to low image quality.
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The manuscript should be submitted in Microsoft Word (please do not send PDFs), double-spaced Times New Roman, 12-point font size (5,000 words or fewer for the printed edition and 10,000 words or fewer for online-only content excluding abstracts, figures, tables, and references).

Figures or tables should not be inserted or embedded into the text, but submitted as separate files in the original software format in which they were created. For additional information on the preparation of figures or tables, refer to the Scientific Illustration Committee, 1988, Illustrating Science: Standards for Publication, Bethesda, MD: Council of Biology Editors, Inc. Restructure briefing charts and slides to look similar to those in previous issues of the *Defense ARJ*.

All forms are available at our website: www.dau.edu/library/arj. Submissions should be sent electronically, as appropriately labeled files, to the *Defense ARJ* managing editor at: DefenseARJ@dau.edu.

Defense ARJ
PRINT SCHEDULE

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All submissions are due by the first day of the month. See print schedule below.

Author Deadline	Issue
July	January
October	April
January	July
April	October

In most cases, the author will be notified that the submission has been received within 48 hours of its arrival. Following an initial review, submissions will be referred to peer reviewers and for subsequent consideration by the Executive Editor, ***Defense ARJ***.

Contributors may direct their questions to the Managing Editor, *Defense ARJ*, at the address shown below, or by calling 703-805-3801, or via the Internet at norene.johnson@dau.edu.

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