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Reexamining INVESTMENTS FOR THE Future

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Maintenance Cost Growth in Aging Aircraft: Analysis of a New DHS Dataset

Nicholas J. Ross

This article finds that maintenance cost per flight hour increases by 8.0% as the average age of a fleet of aircraft increases by 1 year. The article is based on an examination of the impact of aircraft age on maintenance cost per flight hour by analyzing data from U.S. Customs and Border Protection Air and Marine Operations (CBP AMO), a component of the Department of Homeland Security (DHS).

CONTENTS | Featured Research

FROM THE CHAIRMAN AND EXECUTIVE EDITOR

Dr. Larrie D. Ferreiro

The theme for this issue is "Reexamining Investments for the Future." Issues such as education of military personnel, aging aircraft, and even contracting out services are examined, not merely as costs, but as means of improving efficiency and Warfighter readiness. With recent escalations in Europe and across the world, the need for the U.S. to reevaluate and modernize its military systems has come into even sharper focus. The book review in this issue also looks at the kinds of investments needed for the nation in the face of great power competition.

The first article, "Optimizing Warfighters' Intellectual Capability: Return on Investment of Military Education and Research," by Johnathan Mun, examines novel ways to value the monetary return on investment (ROI) of military education and research. The Department of Defense sends a large number of officers to various military universities to obtain graduate degrees or perform academic research, as well as to acquire highly valued technical skills and nontechnical competencies in their respective billets. This research indicates that such education brings overall government benefits valued at over five times the initial investment.

The second article, by Thomas Tincher and Tim Breitbach, "Fleet Sustainment and the Fiscal Impact of Contracting Red Air," uses qualitative analysis and quantitative modeling to determine when aggressor sorties should be contracted out in lieu of government-owned aircraft. This article shows that the government may benefit from contracting out aggressor sorties when organic resources are unavailable or more expensive to use than contractor aircraft. By utilizing contract aggressors more often, not only is direct demand on the sustainment base reduced, but training capacity and fiscal flexibility are increased, allowing for more efficient use of front-line aircraft and other resources.

The third article is “Maintenance Cost Growth in Aging Aircraft: Analysis of a New DHS Dataset” by Nicholas J. Ross. The author uses maintenance cost per flight hour data from Customs and Border Protection Air and Marine Operations to determine how maintenance costs increase with fleet age. The author shows that maintenance cost per flight hour increases by 8% for every year the fleet ages. These calculations pave the way for fleets that are both more effective in combat, and more cost-efficient on the balance sheet.

This issue’s Current Research Resources in Defense Acquisition focuses on Supply Chain Risk Management.

The featured work in the Defense Acquisition Reading List book review is *The Hundred Year Marathon: China’s Secret Strategy to Replace America as the Global Superpower* by Michael Pillsbury, reviewed by David Riel.

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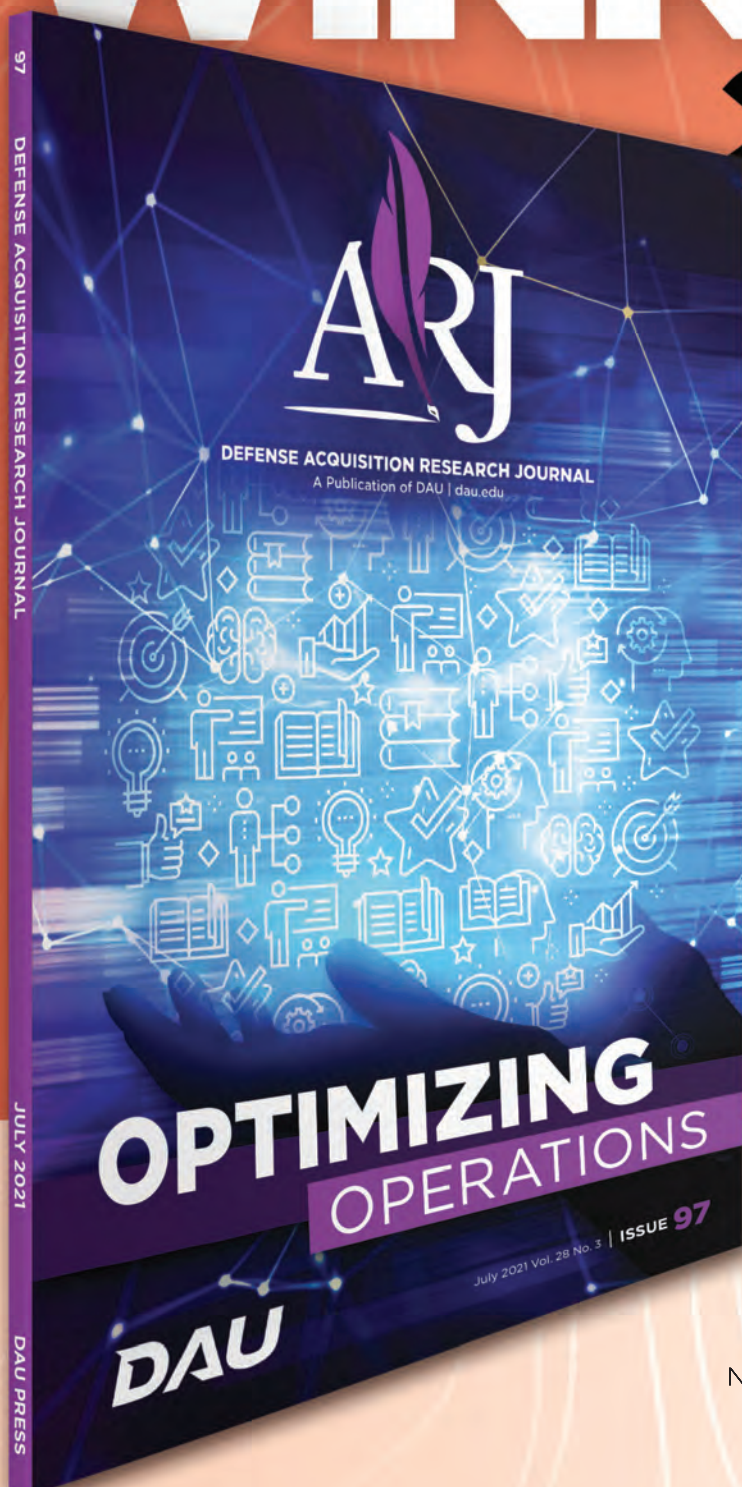

Norene Johnson, Emily Beliles, and Nicole Brate

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RESEARCH AGENDA 2022

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 return on investment (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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Optimizing WARFIGHTERS' INTELLECTUAL CAPABILITY: RETURN ON INVESTMENT OF Military Education AND RESEARCH

Johnathan Mun

The Department of Defense (DoD) sends a large number of officers to various military universities to obtain graduate degrees, perform academic research, and acquire the technical skills and nontechnical competencies highly valued in their respective billets. The cost of sending an officer to a 1.5- to 2-year program for a master's degree or doctorate may be upwards of $250,000–$500,000 per officer, plus the costs associated with temporary duty away from their billets for 3–4 years. The question is whether the benefits of such education and research are indeed greater than the cost incurred by the DoD. The proposed methodologies in this article apply theoretical constructs by using a systems approach to utilization; convolution methods to determine the frequency and quantity of use; and an analytical framework, empirical impact analysis, and work life-cycle approach.

Image designed by Nicole Brate

The research also includes an examination of three short case studies that deal with the value of military research: (1) a return on investment (ROI) case study on the Naval Postgraduate School Acquisition Research Program (NPS ARP); (2) an ROI case study on the ROI of NPS education; and (3) an ROI case study on Defense Acquisition University. The research findings indicate a statistically significant positive impact on the retention of graduating officers, lower attendance cost, and greater DoD control of the courses covered. Finally, the author concludes that the ROI of a training initiative might be intrinsic, unmeasurable, and subjective, rather than simple applications of specific knowledge or learned skill sets on the job.

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Keywords: *Return on Investment (ROI), Value of Military Education, Value of Military Research, Integrated Risk Management, Allocation of Resources*

The U.S. Navy is cutting its higher education funding according to the fiscal 2022 budget request released on May 28, 2021, which includes cuts in the U.S. Naval Academy (USNA), Naval Postgraduate School (NPS), and Naval War College (NWC) (Correll, 2021).

This research attempts to shed some light on the value propositions and return on investment (ROI) of military education and research. Education and research are inextricably linked in that both aspects contribute to the value of the Warfighter of the future. The intangible value of military education is significant in developing leadership skills; critical, creative, and strategic thinking skills; and quick tactical decision-making skills for junior and senior officers. In particular, as opposed to civilian universities, a military-oriented curriculum taught by faculty members with military-based academic and research backgrounds or knowledge allows the flow of institutional knowledge and expertise down to the students. And the strategic, tactical, and innovative changes and challenges of the future require continuous education of our joint forces to maintain a competitive advantage over our nation's current and future adversaries.

Background

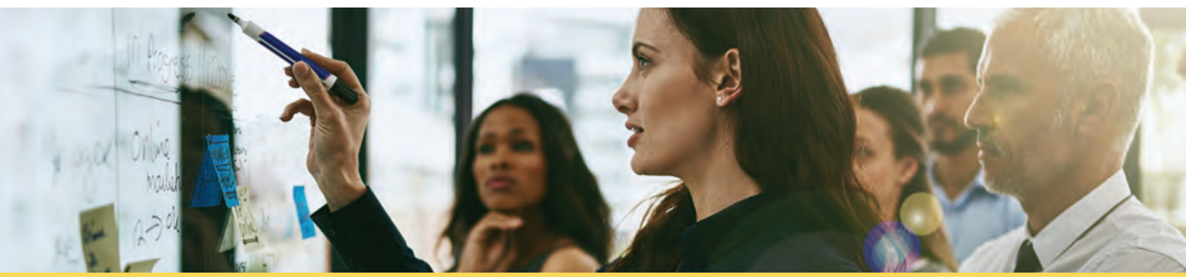
The value of education and research has always been a simple concept to understand but one that is fairly difficult to measure. We can generally agree that higher education adds significant value to the individual, both in terms of future economic returns through better and higher paying jobs, and in terms of incalculable and intangible values such as the deepening of one's knowledge and perspective and the enrichment of one's experience of the world. The literature is filled with descriptions of qualitative social benefits of higher education. However, the complete ROI for education is difficult to quantify economically and mathematically. And determining the value of highly specialized education such as military graduate education and research makes the value problem even more complex.

> **Education and research are inextricably linked in that both aspects contribute to the value of the Warfighter of the future.**

The various U.S. military services send a large number of their mid-level officers (mostly O-3 and O-4 levels) to graduate programs to obtain graduate and advanced degrees as well as technical skills and nontechnical competencies highly valued in their respective billets. Sending an officer to a 1.5- to 2-year graduate program costs upwards of $250,000 plus the opportunity cost of lost services (Ausink et al., 2016). A doctoral program costs upwards of $500,000 per officer, plus the respective soft opportunity costs of temporary duty away from their billets for 3–4 years (Department of the Navy, 2018). The question is whether the benefits of such education are indeed greater than the cost incurred by the U.S. Department of Defense (DoD). The current research looks at various novel ways to value the monetary ROI of these military education and research activities in sponsored DoD institutions.

The DoD Acquisition Workforce Development Fund (DAWDF) was created to provide "funds for the recruitment, training, and retention of acquisition personnel" (Ausink et al., 2016, p. ix). The purpose of the DAWDF is to "ensure the DoD Acquisition Workforce has the capacity, in both personnel and skills, to properly perform its mission; provide appropriate oversight of contractor performance; [and] ensure that DOD receives the best value for the expenditure of public resources" (Ausink et al., 2016, p. 1).

As mentioned, the value of education and research has always been a simple concept to understand but fairly difficult to measure, where higher education has value in terms of tangible economic and intangible values such as in-depth perspective and experience of the world. "The U.S. Navy invests over $3.3B across the FYDP [Future Years Defense Program] at NPS, NWC, and civilian schools" (Department of the Navy, 2018, p. 356); and in the past, the ROI in sending officers to such in-residence, on-campus education programs has been measured, to some degree, by retention or years of service beyond the education. The assumption is that these officers will apply the knowledge and skills learned in their respective billets or positions. Retaining our top warfighting talent and broadening their skill sets with the strategic and critical thinking attributes honed by these educational programs help build an officer corps that would be more capable of executing the DoD's strategy and enhancing our national security posture. Our future requires leaders who possess both the knowledge and the moral capacity to decide and act, and education is the key (Department of the Navy, 2018). Indeed, a 21st-century education for our military forces is vital to national security, and the Navy must change its evaluation and promotion system to value education (Kroger, 2019).



Research Motivation

Considering the importance of education and its associated costs, related research indicated that "the overall benefits in terms of ROI to the Navy from graduate education can be measured, given certain assumptions" (Kamarck et al., 2010, p. xv). But the report continues with a highly simplistic set of assumptions to generate said ROI. While most of the report analyzes the political landscape, military policies, and guidance on education, it includes only one paragraph explaining the potential benefits of an officer with a graduate degree. Using generalized and highly subjective, rough, order-magnitude estimates, it notes that "ROI can only be justified with an officer's long-continued service and reutilization post-education" (Kamarck et al., 2010). This indicates that even a detailed study performed by one of the world's most prestigious think tanks falls short of determining an adequately robust ROI measure for military education.

Such prior research reinforces the fact that ROI determination in military education is not an easy undertaking. Therefore, this current research will not evaluate the efficacy of the political status or policy deliberations but will focus on a singular goal: determining a set of potentially viable methodologies and techniques from which a robust ROI for military education and research can be ultimately determined. Computing the actual ROI requires a longer research project, necessitating the collection of actual data from current and former graduate students, and their current billets and performance, and hence falls outside the scope of the present research.

Research Objective and Problem Statement

The DoD's investment in education must be "fiscally disciplined focusing on the tenants [*sic*] of Warfighting First, Operate Forward, and Be Ready" (Department of the Navy, 2018, p. 120). Education resources need to be aligned with the highest priorities and ROI. The current research examines the challenges of determining the ROI of military education. The primary objective of the research is to provide a set of recommendations and methodologies, as well as additional insights and examples of how some of these methods can be applied.

Research Questions

The questions examined in this research follow:

1. How can ROI be defined and calculated within the realms of military education and research?
2. What is the ROI of military education and research within DoD-sponsored institutions such as the Naval Postgraduate School (NPS), U.S. Naval Academy (USNA), Naval War College (NWC), and Defense Acquisition University (DAU)?

> **Our future requires leaders who possess both the knowledge and the moral capacity to decide and act, and education is the key.**

Technical Approaches and Outcomes of the Research

Various technical approaches are proposed in this research to extract the valuation of an ROI for military education and research. Three main areas are (a) theoretical constructs, where various underlying theories in economics, finance, mathematics, data sciences, artificial intelligence methods, and decision sciences are brought to bear; (b) integrated risk management, where advanced Monte Carlo simulation of the life cycle of value-added benefits of education are run, and portfolio optimizations are executed to determine the ROI and benefit of military education; and (c) knowledge value-added, where intangible and noneconomic values can be monetized to generate quantifiable values to determine educational ROI. All three groups of methods are utilized in the case studies presented in this article.

Because they are very difficult to quantify and convert to a numerical ROI, this research dispenses with the detailed discussions of the soft benefits of graduate education (good judgment, better perception, risk management skills, common sense, presentation skills, leadership skills, etc.). Therefore, this current research focuses on more tangible skills that can be valued and modeled into an ROI measure.

Theoretical Constructs

Various theoretical approaches are examined in this research, from the Systems Approach with Utilization Metrics, Frequency-Quantity of Use, and Analytical Framework Approach to an Empirical Impact and Work Life-Cycle Approach. These methods will be combined with data science, artificial intelligence, and decision analytics approaches, such as Integrated Risk Management and Knowledge Value-Added, to determine the ROI of military education.

Integrated Risk Management (IRM)

IRM is a comprehensive methodology that is a forward-looking, risk-based decision support system incorporating various techniques such as Monte Carlo risk simulation, stochastic forecasting, portfolio optimization, strategic flexibility options, and economic business case modeling. Economic business cases using standard financial cash flows and cost estimates, as well as noneconomic variables such as Expected Military Value, Strategic Value, and other domain-specific Subject Matter Expert (SME) metrics (e.g., Innovation Index, Conversion Capability, Ability to Meet Future Threats, Force Structure, Modernization and Technical Sophistication, Combat Readiness, Sustainability, Future Readiness to Meet Threats) can be incorporated (Mun, 2016a). These metrics can be forecasted as well as risk simulated to account for their uncertainties and modeled to determine their return-to-education cost (e.g., ROI for innovation or return on sustainability). Capital investment and acquisition decisions within education portfolios can then be tentatively made, subject to any budgetary, billet requirement, and knowledge capability constraints. Portfolio management is often integrated with IRM methods to provide a more holistic view in terms of educational programs.

Knowledge Value-Added (KVA)

KVA identifies the actual cost and value of an organization's assets (human, educational, and technological), standard functional areas, or core processes. It identifies every process required to produce an output and the historical costs of those processes; the unit costs and unit values of products, processes, functions, or services can then be measured. By describing processes in common units, the methodology also permits market-comparable data to be generated. This ability is particularly important for nonprofits like the military and government organizations. Value is quantified using productivity metrics: return on knowledge (ROK) and return on knowledge investment (ROKI).[1]

Research Configuration

The research configuration described in this section begins with a literature survey on the state of the art, identifying the challenges in computing ROI in the military in general, military education, and military research. Following the survey is a detailed description of the proposed theoretical constructs used in the research (systems approach, frequency and use, analytical framework, empirical impact, work life cycle, and intrinsic-intangible value), KVA, and IRM (Monte Carlo simulation, strategic real options, portfolio optimization). Next are the proposed theoretical constructs: (a) an ROI case study on the NPS Acquisition Research Program (ARP); (b) an ROI case study on the ROI of NPS education; and (c) an ROI case study on the DAU. A summary of the key conclusions follows the case studies.

Literature Survey

In general, businesses have to question the value of their training and educational investments, as well as balance them against other investment opportunities that are more cut-and-dried. For instance, invest in a certain machine, and it generates a higher production output that can be measured; in turn, it generates additional revenue against the original investment. In such situations, ROI on the machine can be computed easily by performing a cost-benefit analysis. However, when evaluating the value added by education, the math becomes more complicated, if not intractable.

Challenges in Computing ROI in the Military

A decision maker's primary responsibility is to decide which investment alternatives provide the greatest return with the least risk of loss. In civilian organizations, numerous methods and models assist with these decisions (Mun, 2016b), but in military and government agencies, these methods often fall short because typical governmental and military investments do not provide for a monetary return. Instead, they provide "intangible returns such as national defense, public safety, goodwill, and other public goods that are difficult, but not impossible, to quantify" (MacLeod & Dinwoodie, 2015, p. 328).

Various economic models for calculating ROI exist, and most require only a few basic inputs such as costs, benefits, time horizon, and risks. The "benefit of calculating ROI of government investments is to save costs over other alternatives" (MacLeod & Dinwoodie, 2015, p. 328), but scholarly research into assessing the ROI of complete military systems is lacking or, at least at the time of writing, insufficient and unsatisfying. In MacLeod and Dinwoodie's (2015) article, they present "a method that efficiently compares equipment options using a composite index that generates a normalized measure of performance return. By objectively assessing the equipment's ROI, leaders can eliminate low-value and inefficient programs, ultimately saving U.S. taxpayer dollars" (p. 328).

For fully funded education, the Service must pay not only the cost of the education but the pay and allowances allocated for education associated with an officer's billet.

ROI in Military Education

The DoD sends its officers to graduate-level institutions each year to obtain advanced degrees, primarily to fill positions in their Services where duties require the knowledge and skills gained in graduate school. Furthermore, the benefits of a graduate education extend beyond the specific assignment for which the officer was educated, applying to subsequent assignments as well. For fully funded education, the Service must pay not only the cost of the education but the pay and allowances allocated for education associated with an officer's billet. The Service also assumes the opportunity cost of the officer's services while away on temporary duty, and that same officer will also have to forgo any experience that might have been gained while in school. Evaluating the qualitative effects of a graduate education poses several challenges. DoD educational policy suggests broader and more extensive use of graduate education than simply filling billets that have been determined to require it (Kamarck et al., 2010). The question, therefore, is whether the benefit gained from a graduate military education is worth the high cost.

ROI in Research

University research in the United States is world-class, and to continue such leadership requires major funding. Public and private sectors have risen to meet that financial need through increased support of university research. However, with this increased investment, greater accountability is needed. Bessette (2003) recommends that public funding agencies complete the following actions:

> Quantify and tabulate research outputs such that economic impacts are reported as a percent return on investment or ROI. With this model, multiple stakeholders can evaluate divergent research technologies using a measurement that is familiar to scientists, business leaders, elected officials, and the public. (p. 355)

Trewyn (2001) points out that

> Public research universities face many challenges ... , not the least of which involves documenting the value-added outcomes that derive from the teaching, research, and public service missions of the institution. Governing boards, accrediting bodies, funding agencies, state legislators, taxpayers, and the American citizenry in general want to know. (p. 71)

In fact, investment bankers and stockbrokers should not be the sole individuals interested in ROI; a university's prospective students and parents want to know what sort of ROI can be obtained from the education program.

However, estimating the ROI in scientific research proves to be elusive and difficult. According to Grant and Buxton (2018), valuing benefits in monetary terms is required because the time between investment and return is typically long. In addition, international research collaboration can make it difficult to attribute returns to national investments, where any ROI computations will require large amounts of data over long periods of time. But the problem is,

> A massive amount of intellectual capital gets created every day from $150 billion in annual research funding allocated to federal laboratories and universities in the United States. Unfortunately, most of that intellectual capital never makes it to the market and does not generate any return on investment. (Nag, 2018, para. 1)

Methodology–Proposed Theoretical Constructs

This section examines the following theoretical approaches:

- the *Systems Approach with Utilization Metrics*, where the ROI can be determined using production outputs
- the *Frequency and Quantity-of-Use Approach*, which looks at both the frequency and quantity of learned knowledge used to determine the value of the knowledge learned
- an *analytical framework approach* that is used if cross-sectional data can be gathered
- the *Empirical Impact Approach*, used to determine if, indeed, statistically significant added value exists in post-training compared to situations without any training
- the *Work Life-Cycle Approach*, which can be used to determine the life-cycle valuation of education

These methods will be combined into a single robust set of methods with modern data science and decision analytics approaches such as *IRM* and *KVA*, as discussed in more detail in the sections that follow, to simulate and triangulate the ROI of military education.

Systems Approach with Utilization Metrics

The standard utility model originally proposed by Schmidt et al. (1982) can be adapted to a more modern systems approach with the utilization model specified as:

$$\delta U = N[(\Phi_T - \Phi_{UT})\Omega\sigma - C] \qquad (1)$$

where δU is the net monetary value of training; N is the number of trained individuals; Φ is the output generated by trained, T, and untrained, UT, individuals; Ω is the duration of the training; C is the cost of the training;

and σ is the standard deviation of the performance output of the untrained group. Therefore,

$$ROI = \frac{\delta U}{C} \times 100\%$$

Frequency and Quantity-of-Use Approach

To quantify the value of the knowledge learned, this approach applies the frequency and quantity of learned knowledge used. The approach assumes a certain *frequency* that a specific type of learned knowledge is triggered or used and is further assumed to have a discrete Poisson distribution. Next, the *quantity* or amount of the learned knowledge that is used (this can be converted into monetary value or some other economic value or kept simply as an index of output or output ratios such as those computed using the KVA methodology discussed previously) and can be distributed from among a group of continuous distributions (e.g., Fréchet, Gamma, etc.). Specifically, let X, Y, and Z be real-valued random variables whereby X and Y are independently distributed with no correlations. Further, we define F_X, F_Y, and F_Z as their corresponding cumulative distribution functions (CDFs), and f_X, f_Y, f_Z as their corresponding probability density functions (PDFs). Next, we assume that X is a random variable denoting the *frequency* that a certain type of learned knowledge is triggered or used and is further assumed to have a discrete Poisson distribution. Y is a random variable denoting the *quantity* or amount of the learned knowledge that is used (this can be converted into monetary value or some other economic value or kept simply as an index of output or output ratios such as those computed using the KVA methodology) and can be distributed from among a group of continuous distributions (e.g., Fréchet, Gamma, Log Logistic, Lognormal, Pareto, Weibull, etc.).

Therefore, *Frequency* × *Quantity* equals the *Total Unit Quantified*, which we define as Z, where $Z = X \times Y$ (Mun, 2016a).

Then the Total Usage formula yields:

$$F_Z(t) = P(Z < t) = \sum_k P(XY < t | X = k) \times P(X = k)$$

$$F_Z(t) = P(Z < t) = \sum_k P(kY < t) \times P(X = k)$$

where the term with $X = 0$ is treated separately:

$$F_Z(t) = P(0 < t | X = 0) \times P(X = 0) + \sum_{k \neq 0} P(Y < \frac{t}{k}) \times P(X = k)$$

$$F_Z(t) = \sum_{k \neq 0} f_X(k)\, F_Y(\frac{t}{k}) + P(X = 0) \qquad (2)$$

The next step is the selection of the number of summands in Equation 2. As previously assumed, $f_X(k) = P(X = k)$ is a Poisson distribution where $P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}$ and the rate of convergence in the series depends solely on the rate of convergence to 0 of $\frac{\lambda^k}{k!}$ and not on t, whereas the second multiplier $P(Y < \frac{t}{k}) \leq 1!$. Therefore, for all values of t and an arbitrary $\delta > 0$, there is a value of n such that:

$$\sum_{k>n} \frac{\lambda^k e^{-\lambda}}{k!} F_Y\left(\frac{t}{k}\right) < \delta \tag{3}$$

In our case, δ can be set, for example, to 1/1000. Thus, instead of solving the quantile equation for t_p with an infinite series, on the left-hand side of the equation, we have:

$$F_Z(t) = P(Z < t) = \sum_k P\left(Y < \frac{t}{k}\right) \frac{\lambda^k e^{-\lambda}}{k!} = p \tag{4}$$

We can then solve the equation:

$$F_Z(t, n) = \sum_{k \leq n} \frac{\lambda^k e^{-\lambda}}{k!} F_Y\left(\frac{t}{k}\right) = p \tag{5}$$

with only n summands.

For example, if we choose $p = 0.95$, $\delta = 1/1000$ and n such that Equation 3 takes place, then the solution $t_p(n)$ of Equation 4 is such that:

$$| F_Z(t_p(n)) - F_Z(t_p(n), n) | < \frac{1}{1000} \tag{6}$$

In other words, a quantile found from Equation 5 is almost the true value, with a resulting error precision in the probability of less than 0.1%.

The only outstanding issue that remains is to find an estimate for n given any level of δ. We have:

$$\sum_{k>n} \frac{\lambda^k e^{-\lambda}}{k!} F_Y\left(\frac{t}{k}\right) < e^{-\lambda} \sum_{k>n} \frac{\lambda^k}{k!} \tag{7}$$

The exponential series $R_n(\lambda) = \sum_{k>n} \frac{\lambda^k}{k!}$ in Equation 7 is bounded by $\frac{\lambda^{n+1}e^{\lambda}}{(n+1)!}$ by applying Taylor's Expansion Theorem, with the remainder of the function left for higher exponential function expansions. By substituting the upper bound for $R_n(\lambda)$ in Equation 7, we have:

$$\sum_{k>n} \frac{\lambda^k e^{-\lambda}}{k!} F_Y\left(\frac{t}{k}\right) < \frac{\lambda^{n+1}}{(n+1)!} \quad (8)$$

Now we need to find the lower bound in n for the solution of the inequality:

$$\frac{\lambda^{n+1}}{(n+1)!} < \delta \quad (9)$$

Consider the following two cases:

If $\lambda \leq 1$, then $\frac{\lambda^{n+1}}{(n+1)!} \leq \frac{1}{(n+1)!} \leq (n+1)^{-(n+1)} e^n$. Consequently, we can solve the inequality $(n+1)^{-(n+1)} e^n < \delta$. Since n^n grows quickly, we can simply take $n > -\ln\delta$. For example, for $= \frac{1}{1000}$, it is sufficient to set n=7 to satisfy Equation 9.

If $\lambda > 1$, then, in this case, using the same bounds for the factorial, we can choose n such that:

$$(n+1)\,(ln\,(n+1) - ln\lambda - 1) > -ln\delta\ -1 \quad (10)$$

To make the second multiplier greater than 1, we will need to choose $n > e^{2+ln\lambda} - 1$.

Approximation to the solution of the equation $F_Z(t) = p$ for a quantile value

From the previous considerations, we found that instead of solving $F_Z(t) = p$ for t, we can solve $F_Z(t,n) = \sum_{k \leq n} \frac{\lambda^k e^{-\lambda}}{k!} F_Y\left(\frac{t}{k}\right) = p$ with n set at the level indicated above. The value for t_p resulting from such a substitution will satisfy the inequality $|F_Z(t_p(n)) - F_Z(t_p(n),n)| < \delta$.

Solution of the equation $F_Z(t,n) = p$ given n and δ

By moving t to the left one unit at a time, we can find the first occurrence of the event $t = a$ such that $F_Z(a,n) \leq p$. Similarly, moving t to the right, we can find b such that $F_Z(b,n) \geq p$. Now we can use a simple Bisection Method or other search algorithms to find the optimal solution to $F_Z(t,n) = p$.

Analytical Framework Approach

An analytical framework approach is used if cross-sectional data can be gathered—specifically, data on measurable outputs such as those in a standard economic production function. Nonlinear regression and generalized linear models can be run, assuming continuous data variables, and Logit/Probit/Tobit models can be run on discrete and truncated limited dependent variables (Mun, 2021).

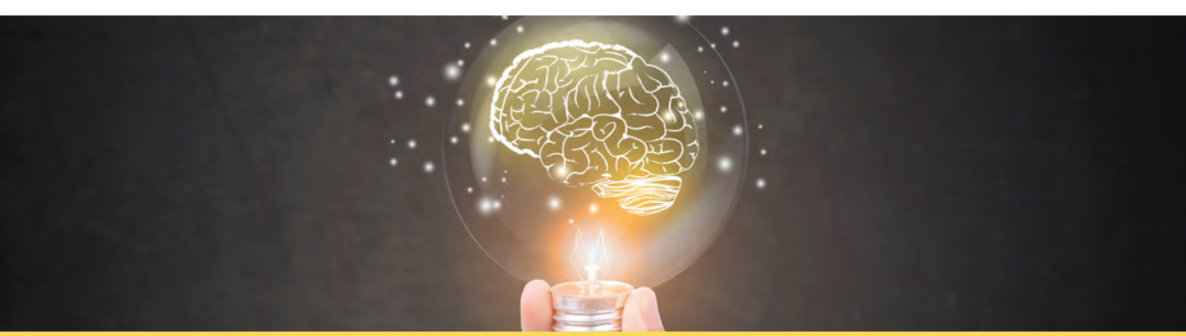
$$\text{Production function } Y = f(\epsilon, \tau, \varphi, \theta, \omega, \ldots, \varepsilon) \quad (11)$$

where Y is the measurable production output, ϵ is the education and training investment amount, τ is the technology supporting said production, φ is the capital investment, θ is the organizational design structure, ω is the environmental impacts, and ε is the forecast error in the model. Therefore, we can determine $\frac{\partial Y}{\partial \epsilon}$, and this will represent the expected change in the average value of production with respect to each unitary change in educational investment after accounting for all the other variables. In other words, this is the net effect of educational contribution to overall outcomes.

Performing some partial differentials, we obtain:

$$\frac{\partial Y}{\partial \epsilon} = \frac{\partial f}{\partial \tau}\frac{\partial \tau}{\partial \epsilon} + \frac{\partial f}{\partial \varphi}\frac{\partial \varphi}{\partial \epsilon} + \frac{\partial f}{\partial \theta}\frac{\partial \theta}{\partial \epsilon} + \frac{\partial f}{\partial \omega}\frac{\partial \omega}{\partial \epsilon} \quad (12)$$

A nonlinear regression can be run on Equation 12, assuming continuous data variables, or Logit, Probit, and Tobit models can be run on discrete and truncated limited dependent variables (Mun, 2016b).



Empirical Impact Approach

The Empirical Impact Approach can be used to determine if, indeed, a statistically significant added value exists in post-training compared to situations without any training (Mun, 2021). Multivariate, unequal variance, general linear models can be applied. If the standard deviations of these two sample datasets (with and without the requisite training and education) are still unknown but assumed to be different, combining them into a single pooled estimate as done previously would be inappropriate (Mun, 2016a). Therefore, the sample standard deviations (s) will be used independently to estimate the population standard deviations (σ). Nonetheless, normality of the underlying dataset is assumed, although this assumption becomes less important with larger datasets. The two-sample unequal variance t-test would be needed, and its specifications are described in Equation 13:

$$t=\frac{(\bar{x}_1-\bar{x}_2)-(\bar{\mu}_1-\bar{\mu}_2)}{\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}} \text{ and } df=\frac{\left(\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1-1}+\frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2-1}} \quad (13)$$

$H_0 : \mu_1 = \mu_2$, that is, the two samples' means are statistically similar.

In addition, if the collected data are limited and categorical or ordinal in nature, or if there are significant biases in the data, we can apply the Kruskal–Wallis (KW) test, which is an extension of the Wilcoxon Signed-Rank test by comparing more than two independent samples. The corresponding parametric test is the One-Way Analysis of Variance (ANOVA), but unlike the ANOVA, the KW does not require that the dataset be randomly sampled from normally distributed populations with equal variances. The KW test is a two-tailed hypothesis test where the null hypothesis is such that the population medians of each treatment are statistically identical to the rest of the group; that is, no effect is evident among the different treatment groups. Similar to the ANOVA method, the KW tests the following hypothesis:

$H_0 : m_1 = m_2 = \ldots = m_k$ for $i = 1$ to k
(population medians are identical)

The method starts off with k variables to be tested. For each variable, the data are ranked from smallest to largest, with the smallest value receiving the rank of 1, and all tied ranks are assigned their average values. Then, all the ranks are summed for each variable, yielding a list of summed ranks $\Sigma(R1), \Sigma(R2), \ldots, \Sigma(RK)$. Then, the H statistic is computed using:

$$H=\frac{12}{N(N+1)}\left[\frac{(\Sigma R_1)^2}{n_1}+\frac{(\Sigma R_2)^2}{n_2}+\cdots+\frac{(\Sigma R_k)^2}{n_k}\right]-3(N+1) \quad (14)$$

The calculated H is compared to critical H values computed using a chi-square distribution with degrees of freedom $df = k - 1$.

Work Life-Cycle Approach

Finally, the Work Life-Cycle Approach can be used to determine the life-cycle valuation of education. According to Kamarck et al. (2010), several past studies of individuals with privately funded education such as an MBA or other technical master's degree show that they earn an average rate of return of at least 46% more than a bachelor's degree in a 2008 study, and the ROI ranges between 27% to 36% for an MBA.

However, the application of a similar methodology might not work well within the DoD because the U.S. military's human resource environment is such that it is a closed internal and hierarchical structure. For instance, an officer's pay is based on his or her rank and years of service, regardless of educational background. It can be argued that higher education may result in higher efficiency and productivity, thereby increasing the speed of promotions, but these are fairly difficult to quantify. An alternate approach might be to consider the years of service beyond the time the education was received. This amounts to the value of retention—in other words, how much the military can save in costs by having a higher retention and reutilization rate than by having to train a new officer to replace a billet due to attrition. Using comparables, traditional financial metrics can be applied to determine the ROI. The Work Life-Cycle Approach model might look something like:

$$ROI = \frac{\Psi[f(h, \tau_t, o_t) + \delta P_t(V_t)] - C_0}{C_0}$$

where Ψ is the years of service; C_0 is the cost of education; δP_t is the change in productivity due to the new knowledge gained (with a nonlinear depreciation over time); V_t is the salary and overhead cost of the billet; τ_t is the learning curve measured in time to train a new officer to adequately replace the outgoing officer; and o_t is the opportunity cost of lower retention rate or cost of attrition. With the proper experimental approach, these variables can be adequately measured to provide a robust ROI measure.

As a matter of comparison, for privately funded educational programs, one can much more easily model the ROI where we can use a traditional NPV to determine the ROI such as:

$$NPV = \sum_{i=n+j}^{k-j-n} [S_e \pi_{e_t} - S_0 \pi_{0_t}] e^{-rt} - \sum_{i=1}^{j} C_t e^{-rt}$$

$$ROI = \frac{\Sigma_{i=n+j}^{k-j-n} [S_e \pi_{e_t} - S_0 \pi_{0_t}] e^{-rt} - \Sigma_{i=1}^{j} C_t e^{-rt}}{\Sigma_{i=1}^{j} C_t e^{-rt}}$$

where S_e is the salary with the education; S_0 is the presumably lower salary without the requisite education; π is the inflationary and natural growth rate of the salary over the time period t, each with a different acceleration slope for educated e and uneducated 0 rates; r is the reinvestment rate or opportunity cost of the cost of education C_t that changes over time, over the course of the education j; and the analysis is performed on the life cycle of the individual's working life, starting from the current age n to the retirement age k (the age of natural attrition, retirement age, or the average age of leaving the employment market). These inputs can be Monte Carlo risk-simulated using the IRM Approach.

> **Creative thinking, leadership, strategic thought, and quick tactical decision-making skills can be honed through education, especially when taught by a faculty with military-based academic and research backgrounds.**

Intrinsic and Intangible Value Propositions

Intangible and intrinsic value exists in both military education and research but cannot be readily quantified in standard ROI calculations. In nonmilitary college education in the private sector, higher education brings with it various intangible added value, such as value to society (Blagg & Blom, 2018) through diversification and innovation of the nation's economy, encourages graduates to be more civic-minded, increases wages and lowers crime rate, increases tax receipts of the country, increases productivity and output, lowers expenditures on policing due to lower crime, and lowers dependencies on social welfare programs. However, the intangible value of military education is different. The military is a closed vertical society. A survey of past naval students at NPS, NWC, and USNA indicated that approximately 96% agreed that formal education was extremely useful or very useful in their naval careers. The study found that military personnel have more positive perceptions of their institutions than civilian personnel.

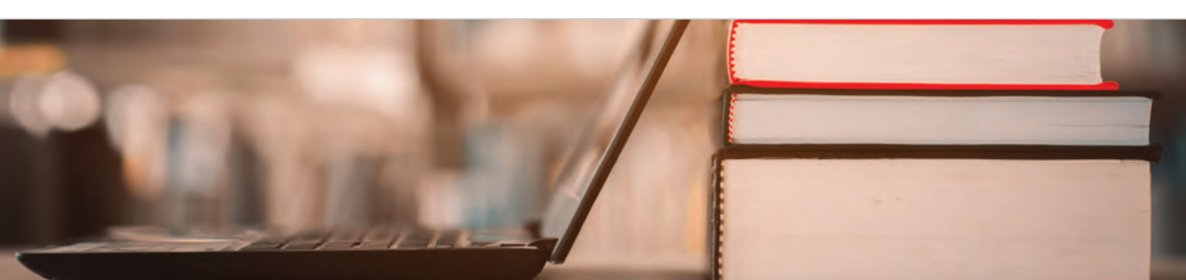
We can certainly conclude that the intangible value of military education is significant in developing leadership and critical thinking skills for junior as well as senior officers. The military-oriented curriculum taught by faculty members with former military experience or knowledge allows the flow of institutional knowledge down to the students. Although these intangible and qualitative aspects of military education are significant, this current research focuses on the more quantitative measure of ROI. Nonetheless, creative thinking, leadership, strategic thought, and quick tactical decision-making skills can be honed through education, especially when taught by a faculty with military-based academic and research backgrounds. And the strategic, tactical, and innovative changes and challenges of the future require continuous education of our joint forces to maintain a competitive advantage over our current and future adversaries.

Knowledge Value-Added

KVA is an objective, quantifiable method for measuring the value associated with a system and the subprocesses within the system. The value measurements of each process are ratio-scale numbers, allowing analysts to compare them with the values from other subprocesses to determine their relative effectiveness. Productivity ratios such as ROK—the output of a process divided by the process cost—can be adapted for use in KVA. The ROKs and ROIs, which are always 100% correlated, give managers information about the amount of value a process generates compared to the amount of money spent to create the value.

Integrated Risk Management

IRM is a system developed by the author and designed to provide management with the ability to analyze the risk associated with the development of projects or initiatives. It combines several commonly accepted analytical procedures—such as predictive modeling with Monte Carlo simulation, real options analysis, and portfolio optimization—into a single, comprehensive methodology. The methodology uses existing techniques and metrics such as discounted cash flow, ROI, and other metrics within the analytical processes to improve the traditional manner of evaluating potential projects within a company or in an organization like the DoD. In contrast to the other methodologies, IRM focuses on the risk involved with a decision. It seeks to mitigate negative effects from risk while maximizing rewards from potential outcomes. At its core, IRM is a technique to provide decision makers with the best analytic information available to use during the real options process. All of these methods can be combined in various ways to create a robust set of methodologies to determine the true ROI of military education and research.[2]



Case Study: NPS Acquisition Research Program

The DoD Acquisition Workforce Development Fund was created to provide "funds for the recruitment, training, and retention of acquisition personnel of DOD" (Ausink et al., 2016, p. 1). The purpose of the DAWDF is "to ensure the DoD Acquisition Workforce has the capacity, in both personnel and skills, to properly perform its mission; provide appropriate oversight of contractor performance; [and] ensure that DOD receives the best value for the expenditure of public resources" (Ausink et al., 2016, p. 1). Within this context, NPS graduate students have been collaborators in multiple research opportunities in the NPS ARP and can now bring these analytical skills to the acquisition workforce (AWF).

The NPS ARP should be seen as a research and development (R&D) organization that generates innovations from research that may take years to bear fruit. ARP research is focused on possible scenarios that might *add value, reduce cost, provide savings, add capabilities,* and *provide value-added insights* that will make acquisition processes more productive and efficient. It should also be recognized that typical R&D organizations yield a small number of breakthrough products and services, and ARP research output should be viewed the same way. ARP research studies provide estimates of the future increases in the ROI of technologies to support core U.S. Navy processes such as shipbuilding and ship maintenance. Many DoD leaders see ROI as a measure of cost savings, often without reference to the value created by an asset, intellectual capital, or other forms of value production. In a nonprofit or governmental organization, an ROI ratio requires a revenue surrogate in common units, and establishing such units is what KVA does. In the following summaries of the ROI on ship maintenance and shipbuilding core processes, the Housel and Mun ARP studies used market comparables to establish an estimate of the price per common unit of output of core processes to provide a monetized revenue surrogate. The cost of doing this kind of research, performed by SMEs and professionals at NPS, compared to the cost of doing such studies by a comparable consulting company (e.g., McKinsey) would likely be at least three times as much due to the steep learning curve by non-SMEs (Ford et al., 2017; Housel et al., 2015; Majchrzak et al., 2017).

Research-based ROI

Naval research and education are not separate tasks but tend to coexist alongside the innovation engines of the country. Several ARP studies provided estimates of the potential ROI increases in Navy ship maintenance and shipbuilding core processes. The following tables summarize the results of the ship maintenance and shipbuilding ROI increase estimates from incorporating three technologies into core processes. Table 1 shows that the detailed design and outfitting phases of shipbuilding benefit the most from the use of the technologies and that the sea trials and postshakedown maintenance benefit the least. Even if several orders of magnitude off, the ROI would still yield a highly significant percentage. We would maintain that the ARP research's contribution to this specific project (even with a highly conservative estimate that it is worth 1/1000 of ROI) is above **240%**.[3]

TABLE 1. ROI PROJECTIONS FOR SHIPBUILDING USING PLM, 3DP, AND 3D LST TECHNOLOGIES

Item	Process or Phase	As-Is ROI	To-Be ROI	Change in ROI	Automation Tools
1	Concept Design	-2%	94%	96%	AM, PLM
2	Detailed Design	561%	1826%	1265%	AM, PLM
3	Preconstruction Planning	218%	244%	25%	PLM
4	Block Fabrication	-67%	-31%	36%	3DLS, AM, PLM
5	Block Assembly and Outfitting	-17%	116%	133%	3DLS, AM, PLM
6	Keel Laying and Block Erection	-63%	1%	64%	3DLS, AM, PLM
7	Predelivery Outfitting	505%	1270%	764%	3DLS, AM, PLM
8	System Testing	280%	582%	301%	3DLS, PLM
9	Sea Trials	1018%	961%	-57%	PLM
10	Postdelivery Outfitting	476%	1243%	767%	3DLS, AM, PLM
11	Postdelivery Tests	239%	282%	42%	PLM
12	Postshakedown Maintenance	221%	201%	-20%	PLM
	Totals	**135%**	**464%**	**329%**	

Note. 3DLS = 3D Laser Scanning; 3DP = 3D Printing; 3DLS = 3D Landing Ship, Tank; AM = Aviation Structural Mechanics; PLM = Precision Landing Mode.

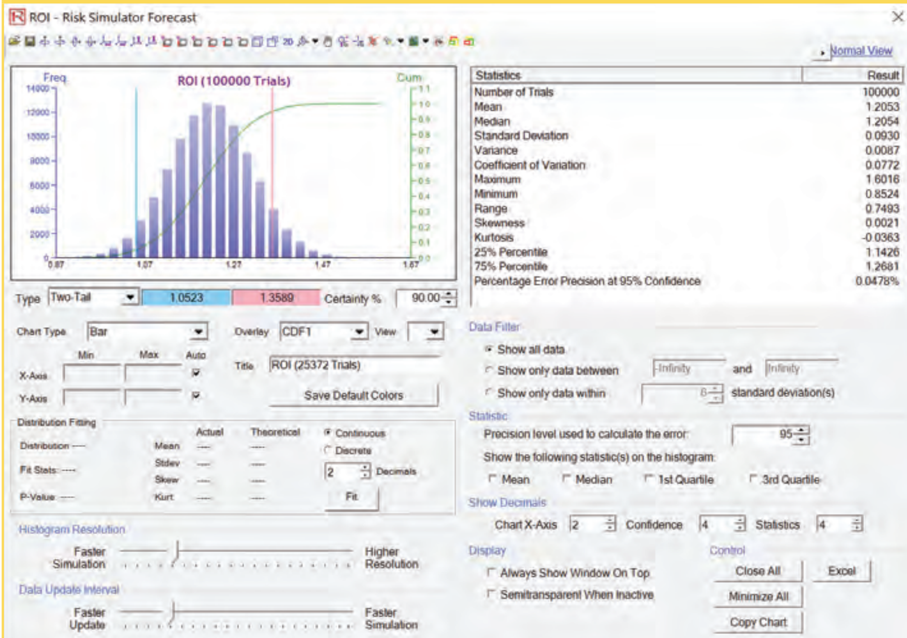
TABLE 2. ROI PROJECTIONS FOR SHIPBUILDING BY PART COMPLEXITY							
Part Complexity (% of total parts)		**High (25%)**		**Medium (50%)**		**Low (25%)**	
Part Manufacturer		**Industry**	**Navy**	**Industry**	**Navy**	**Industry**	**Navy**
% Made by Navy	0	573%	n/a	151%	n/a	12%	n/a
	25	n/a	1120%	151%	n/a	12%	n/a
	50	n/a	1120%	236%	510%	12%	n/a
	75	n/a	1120%	n/a	358%	12%	n/a
	100	n/a	1120%	n/a	358%	n/a	103%

Table 2 shows research on a Make or Buy analysis of the impacts of whether the Navy should execute 3D printing operations, 3D laser scanning technology, and collaborative product life-cycle management on ship maintenance and modernization cost savings that had ROI of the common unit of output (high-, medium-, or low-complexity parts) ranging from **103%** to **1,120%** in ROI per year per ship, averaging at 600%. These ROI values can be multiplied by a factor of 100 over the next 10 years when more ships implement the recommendations. Again, we would maintain that the ARP research's contribution to this specific project is above **600%**. Even if the ARP study cost savings estimates were off by several orders of magnitude, they would well have been large enough to justify the overall investments in the ARP research studies.

TABLE 3. A STANDARD PWC OR MCKINSEY RESEARCH PROGRAM COST		
	Hourly (2022 Levels)	**% Utilization**
Partner	$800	2%
Manager	$600	5%
Senior Consultant	$500	10%
Analyst	$400	15%
	Total Cost	**$312,000**

Note. PWC = PricewaterhouseCoopers.

FIGURE 1. ROI PROJECTIONS WORST-CASE SCENARIO



Worst-Case Scenario ROI

Next, we can show the absolute worst-case scenario ROI in Table 3 and Figure 1. The annual ARP cost is $1.7 million, with 15 research projects on average. If done similarly by a third-party consulting company such as PricewaterhouseCoopers or McKinsey, the research usually runs around $250,000–$350,000 over the course of 1 year. For instance, the standard research takes 12 months, and a standard project requires a partner, manager, and, at the very least, a senior consultant and analyst. Even with the assumption that only 2% to 15% of their hours are used for the project, the average cost is $312,000 per research project. Table 3 illustrates the computations.

A risk-based Monte Carlo simulation of 100,000 trials was run, and we see from Figure 1 that the average ROI, even in the worst-case scenario, is **120.5%**, with a 100% probability that the ROI of the ARP program returns a positive value. In other words, assuming that we separate and put aside for the moment the actual and significant value of the actionable intelligence from the research programs and focus solely on the cost savings of the research, we generate a value of $3.75 million for the investment of $1.7 million for research and operating expenses. This creates an ROI of **120.5%** in this worst-case scenario (the 95% confidence interval has the ROI between 105% and 136%).

Value of Knowledge and ROI

The ARP researchers use graduate students to assist in their work. These MS, MBA, and PhD students are active-duty Navy and Marine officers who will return to their commands armed with valuable hands-on practical research knowledge and experience that are second to none. We quantify these knowledge value-added learnings from the ARP research they have conducted and monetize them using the KVA approach, as seen in Table 4. The ROI on a single ARP research program is calculated to be 253%.

TABLE 4. VALUE OF KNOWLEDGE

	Experiential Graduate ARP Research	Graduate Student (ARP Cases)	ARP Symposium Participant Learner
Number of Days per Year	200	200	200
Normalized Total Knowledge Units	100	100	100
Accumulated Knowledge Used	10%	5%	1%
Hours/Day Used	4	4	4
Units of Knowledge Used/Hour	10	5	1
Total Knowledge Units	8000	4000	800
Consultant Annual Salary	$150,000	$150,000	$150,000
Comp Price Per Unit of Knowledge	$18.75	$18.75	$18.75
Daily Value	$750	$375	$75
Value/Year Per Student	$150,000	$75,000	$15,000
Average Students Exposed	10	50	50
Valuation for Each Category	$1,500,000	$3,750,000	$750,000
Total Valuation of Knowledge	$6,000,000	$6,000,000	
ARP Total Cost (Research Only)	$1,700,000		
ROI of ARP in Knowledge Terms	**252.94%**		

The calculations assume that the graduate students will populate the future AWF. We also assume that the acquisition case studies that have been developed from ARP research and are used to teach a wide variety of acquisition, business, public policy, and information science classes provide important lessons that translate into future acquisition workforce knowledge. We have normalized the knowledge into common units of learning time and assumed that the graduate students would apply their acquisition knowledge to acquisition challenges and opportunities for adding value to the core acquisition processes. Those students who attend the annual Acquisition Symposium are also likely to pick up some valuable key lessons that they can then apply to future acquisition decision-making situations. The opportunities to obtain acquisition knowledge in these three learning contexts are summarized in Table 4. These estimates are very conservative and represent 1 year of learning opportunities. The central assumption in this analysis, as in most educational value analyses, is that the students will be able to apply their knowledge once they leave NPS. As it is put to use, it will generate value for the acquisition workforce.

In summary, we can quantify that the ARP's ROI, based on an annual investment of $1.7 million, will range from the absolute worst case of 121% to an average of 240–600% for each specific program (Table 5). The KVA method pegs the ROI at 253%. Therefore, using standard industry best practices, we conclude the average conservative ROI for the entire ARP program to be around 304% for the approximate annual $1.7 million total investment for research and operating expenses. These ROI estimates should be seen as the minimum value because a significant intangible value exists when we run research programs with uniformed graduate students and when we hold the annual Acquisition Symposium.

TABLE 5. SUMMARY ROI FOR MILITARY RESEARCH AND DEVELOPMENT

ROI for Military Research and Development (e.g., ARP)	
Minimal Worst-Case ROI	121.00%
Most Likely ROI	304.00%
Range of ROI Depending on Program	240% - 600%

Case Study: The Value and ROI of NPS

Strategic and Intangible Value

In this section, we look at NPS as an analytical case study of ROI on military education. It is at the forefront of providing specialized graduate, postgraduate, and certificate-level programs supporting U.S. national security policies and priorities, including counterterrorism, homeland security, and security cooperation. While the Navy has the option to send its officers to private and public universities, an analysis of alternatives shows that in doing so, the Navy would sacrifice its agility and responsiveness and potentially even incur a higher cost. In fact, according to the *NPS Value Book*, "[cost] comparisons are being made erroneously between civilian universities market price (tuition) and NPS full costs. Tuition covers 15–25% of public and 25–30% of private universities' full cost ... Analysis has shown NPS to be average to below average in total costs" (Naval Postgraduate School, 2012a, p. 16). The higher cost of external civilian universities, the lack of direct application to the military, and the loss of control by the Navy or DoD over the curriculum show that civilian universities cannot meet the Navy's long-term needs for military education.

The cost-effectiveness of an NPS education was previously reported in the Memorandum for the Deputy Chief of Naval Operations (Gates et al., 1998). Specifically, it stated that if NPS and civilian programs differ in duration (e.g., 18 versus 28 months), any cost comparison must include the students' salaries and benefits. The Department of the Navy's Director, Assessment Division, estimated that the annual cost of salary, benefits, and housing per NPS-resident officer totaled $63,300, as compared to approximately $72,300 per officer student at other comparable civilian institutions. Higher civilian costs exist because most NPS officers live in base housing (Gates et al., 1998).

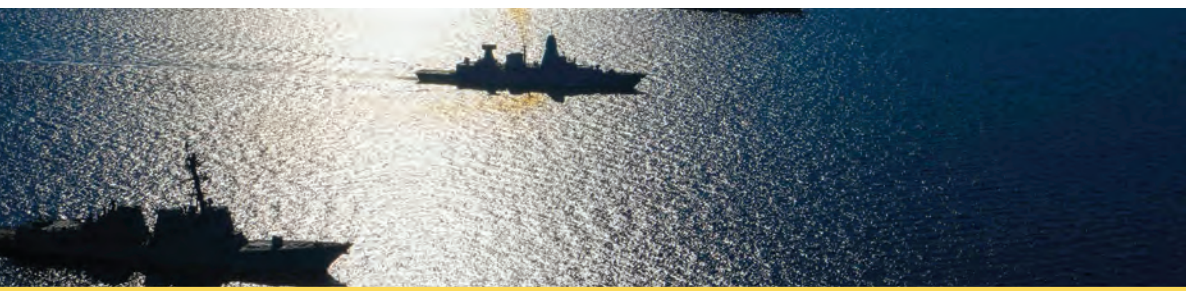
NPS was rated as high by the Base Realignment and Closure (BRAC) Technical Joint Cross Service Group (TJCSG) when over 146 technical facilities were examined to determine their value to defense Research, Development, Test and Evaluation (RDT&E; Department of Defense, 2005). The report identified the most important 13 technical areas in developing military strength, then evaluated each technical facility over three functional areas: research, development and acquisition, and test and evaluation.

> **While the Navy has the option to send its officers to private and public universities, an analysis of alternatives shows that in doing so, the Navy would sacrifice its agility and responsiveness and potentially even incur a higher cost.**

Naval maritime supremacy requires a Navy-oriented focus to meet the technical and professional challenges of the 21st century and beyond. The U.S. Navy requires focus on naval professional development by meeting the requirements of technological innovation and knowledge quality control. For the Navy, undergraduate, graduate, and professional military education is an investment, and, like any investment, its returns need to be evaluated.[4]

Tactical and Tangible Quantitative ROI for NPS

In order to quantitatively measure a robust ROI for NPS educational programs, the quantifiable benefits and costs are first obtained and analyzed, and later invoked in a life-cycle cost-benefit model with simulation. ROI is commonly a monetary or economic metric. This means we can determine ROI only based on the main tangible monetary benefits of an NPS education, such as the lower tuition costs and higher retention rate of NPS graduates. The retention rates modeling uses the Analytical Framework Approach, whereas the life-cycle cost-benefit modeling uses the Work Life-Cycle Approach previously examined. The life-cycle model used a modification of the Systems Approach with Utilization Metrics combined with the Frequency and Quantity-of-Use Approach. This was complemented with IRM methods in applying Monte Carlo simulation. The following subsections break down the methods into quantized analytical chunks.



NPS Graduates Show Higher Retention Rates in the Navy

Cohort data from the 1987 through 1995 graduating classes (Naval Postgraduate School, 2012b) show that 2 years after graduation, the retention rates are relatively high for NPS MS and PhD graduates, non-NPS civilian MS-level graduates, and non-NPS civilian BS-level graduates, ranging from 99.31% to 95.78% on average. *This high rate of retention in the first few years is to be expected as officers sent to graduate programs typically are required to "pay back" their education costs with guaranteed service for several years.* In comparison, at 17–22 years postgraduation, the NPS graduates showed a 55.42% DoD retention compared to 46.23% for non-NPS MS graduate programs and 13.07% for other non-NPS BS undergraduate programs. The total sample sizes for the data aggregation were 3,254 for NPS, 2,255 from other graduate programs, and 24,344 from other undergraduate programs.

An analysis of the cross-sectional retention bands for the three groups indicates a smooth laminar flow across all cohorts with respect to 2- and 4-year retention rates. More disturbance seems to be around the 10-year milestone, especially for the undergraduate degree holders, and less so for the NPS graduates. The highest volatility appears in the undergraduate degree holders' cross-section starting from the 10-year through the 15-year and 20-year milestones. A time-series analysis indicates sharp 10-year declines in retention. The drop is most precipitous for undergraduate degree holders. The analysis also shows a significant difference between the BS and

MS NPS graduates and a smaller but visually distinct difference between non-NPS MS and NPS graduates.

The average rates across these various cohorts in time reveal differences among all groups, and these differences are tested statistically using parametric ANOVA for single factor multiple treatments and confirmed with a nonparametric KW test. The null hypotheses tested were that, for each retention milestone, no statistically significant difference was evident among all three groups of graduates when comparing all groups at once. While both the ANOVA and KW tests can identify whether any differences surfaced among the three groups tested, they do not identify where the differences come from. Hence, further analyses using the one-tailed paired parametric *t*-test of two independent variables with unequal variances were run on every combination of the three groups, and the results were confirmed using the nonparametric two-variable Wilcoxon signed-rank test. The parametric tests were applied because we have large sample sizes, as noted previously, for example, up to 24,344 graduates in all the cohorts for the non-NPS undergraduate programs. This allows us to take advantage of the law of large numbers and the central limit theorem, justifying the use of parametric tests. The nonparametric tests were also applied because the averages were used, and the larger sample sizes were reduced to a smaller subset, where the underlying normality assumption may or may not be violated. In addition, the natural truncation of percentages (i.e., 0% to 100%) calls for the use of nonparametric methods.

The test results indicate that with an alpha significance level set at $\alpha = 0.05$, the one-tailed directional tests (the null hypothesis tested was that no difference exists in retention rates, versus the alternative hypothesis that the NPS graduates had higher retention rates than the non-NPS graduate degree holders, and greater than the non-NPS undergraduate degree holders) that in almost all cases, NPS graduates have statistically significantly higher retention rates than all non-NPS graduates. The only area showing nonsignificance is the 20-year average retention rates between NPS graduates and non-NPS graduate degree holders. This might be due to the authorized strength limitations imposed by Congress on the number of flag and general officers (Authorized Strength, 2012).

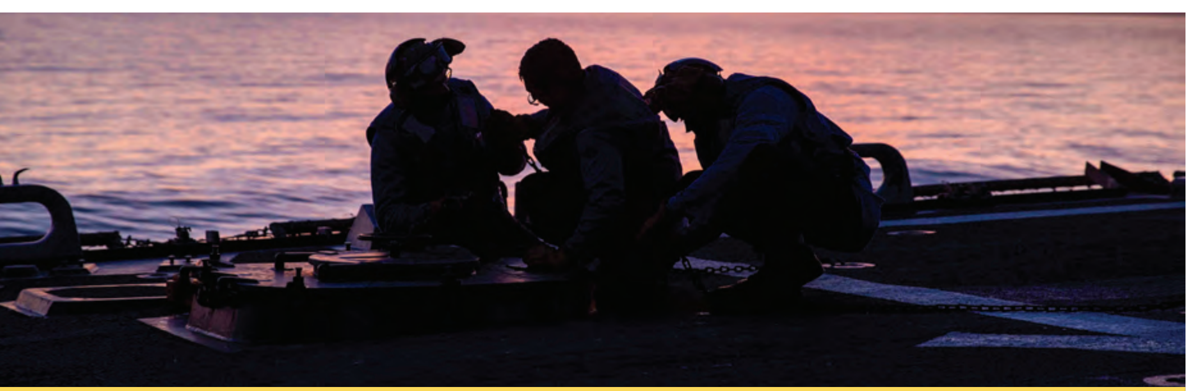
Retention Rates Are Fairly Predictable and Expected

Now that we have statistically established that NPS graduates tend to have a higher retention rate than non-NPS graduates, the question is whether this trend is predictable. Predictability is key for the DoD in terms of anticipating force readiness levels for the future, and having a more stable group of qualified Naval officers 10, 15, or 20 years out, which allows for the fleet to plan for future-readiness and future-capability levels.

A time-series indexed set of linear and nonlinear econometric models was tested, starting with simple linear and nonlinear functional forms. The coefficients of determination ranged from 77.4% to 99.6% predictive power, with adequate error measurements (Akaike, Bayes Schwarz, and Hannan–Quinn criteria). Using these models, the retention rates were forecasted and compared against the actual rates, and the forecast errors were generated. The mean absolute percentage error (MAPE) of predictions was computed, and the median of these errors fluctuates between 0.01% and 3.34%, which corresponds to a median forecast error of between ±0.11% and ±4.42%, as measured by the mean absolute deviation (MAD).

Further modeling is required as, although the initial error rates are well within reasonable bounds, we wish to see if more advanced functional forms can be used to predict these retention rates more accurately. The more exhaustive econometric functional forms tested included the standard linear and nonlinear models, followed by quadratic, log-linear, logistic, linear log, double log, reciprocal, and log-reciprocal models.

Using the best models for each group of graduates, the retention rates were again modeled and compared against the actuals to determine their viability and prediction errors. The results showed that using more complex functional forms provided higher efficacy levels and lower errors. Using these best prediction models, we can now run a more comprehensive life-cycle cost model.



ROI Analysis Using Cost and Benefit Life-Cycle Analysis of Alternatives

Based on the two preceding subsections, we know that NPS graduates have a higher retention rate (after the requisite "payback years," a student has to stay in the Service in return for the funded education) compared to non-NPS graduates (both graduate and undergraduate degree recipients), and we have shown that we can adequately predict these retention rates. Next, using these two main sources of information, we build a 20-year cost-benefit life-cycle model of a potential NPS student and future graduate and model this officer's tenure with the Navy, compared against the prospect of not having a graduate degree or obtaining said degree at a nonmilitary university. The cost of training a new replacement officer is the cost savings or benefits, compared to the educational cost investment required at NPS.

As mentioned, according to the *NPS Value Book*, "analysis has shown NPS to be average to below average in total costs" (Naval Postgraduate School, 2012a, p. 16). NPS continuously calculates various cost-per-student measures for naval and reimbursable students (NPS, personal communication, January 9, 2020). The NPS education cost model identifies and incorporates all costs at NPS associated with providing the academic/graduate education program. The model includes all direct costs of graduate, for-credit education as well as NPS overhead cost associated with the education. However, it excludes all direct costs of sponsored research activities; direct costs of executive or professional nondegree education at NPS; and the relevant allocated share of NPS general, administrative, and business overhead costs associated with NPS noneducation operations such as sponsored research.[5]

Predictability is key for the DoD in terms of anticipating force readiness levels for the future, and having a more stable group of qualified Naval officers 10, 15, or 20 years out, which allows for the fleet to plan for future-readiness and future-capability levels.

For this research, we obtained the tuition costs for some comparable private universities (tuition and required cost only, excluding housing and books) and the U.S. Treasury spot rates. We applied a nonlinear cubic spline interpolation to generate the annualized future rates. These rates were used as the cash flow's discount rate factor to obtain the net present value of benefits and compare them with the up-front, 2-year educational cost.

A 20-year life-cycle cash flow was created using the forecasted retention rates, costs of comparable private universities, the U.S. Treasury rates, and the cost of sending a graduate student to NPS. Other expenses such as books, room and board, the officer's salary, and miscellaneous reimbursable expenses were excluded because regardless of where the Navy sends its officers, these costs would still be borne. In this research, the key consideration is the apples-to-apples relative comparison of tuition and required costs of sending a junior officer either to NPS or a non-NPS private university to obtain a graduate degree. The absolute valuation of total costs is irrelevant.

We know that NPS graduates have a higher retention rate (after the requisite "payback years," a student has to stay in the Service in return for the funded education) compared to non-NPS graduates (both graduate and undergraduate degree recipients), and we have shown that we can adequately predict these retention rates.

Probability distributions were set up on the cost of a private graduate degree; the NPS equivalent cost; the educational and NPS cost inflation rates; the forecasted retention rates; and the cost of training, replacement, and retention of a new officer to take the place of one who is leaving. Whenever possible, distribution-fitting routines (e.g., Kolmogorov–Smirnov) were run on existing data, or theoretical metrics such as forecast standard errors were used in the simulation procedure. Simulation modeling was run using 1,000,000 trials for each input, and the relevant Monte Carlo-simulated NPV and ROI were computed.[6]

Simulation was required because every scenario and assumption is uncertain but fluctuates within reasonable bounds. For instance, the student may decide among various alternative civilian universities (tuition costs are bounded) and may have a higher or lower attrition rate (forecast errors are bounded). Costs of education at NPS and civilian institutions can also change, but, again, within reasonable values. Therefore, using simulation methods, we can incorporate all possible outcomes in a million scenarios of each assumption. For example, an officer might decide on NPS vs. MIT; stay for 12 years postgraduation; happen to enroll in the 2 years when interest rates are the highest, but the tuition rates were depressed due to low enrollment and budget cuts; or is a Navy SEAL, thereby requiring a higher replacement cost due to the specialized training requirements.

We performed an analysis of alternatives' ROI differential when the DoD sends a junior officer to NPS for a graduate master's degree compared to sending the same officer to a private university for a similar master's degree. Due to the higher retention rates and lower costs of students who attend and graduate from NPS, the results of our analysis show that the expected ROI is 673%, with a 90% confidence interval of the ROI between 541% and 821%, after accounting for all the uncertainties in the input parameters and assumptions. In other words, we can safely say that 95% of the time, given all the uncertainties and fluctuations in comparable costs and retention rates, sending an officer to NPS as compared to a private civilian graduate school will yield an additional 541% in ROI or a 6.41 return-to-cost ratio. Hence, for every $1 spent on an NPS education, the DoD obtains a benefit or return of $6.41 (the net benefit is $5.41 or 541%). This falls within the reasonable boundaries obtained for the ROI for naval acquisition research programs, as described previously.

Similarly, we performed an analysis of alternatives' ROI differential when the DoD sends a junior officer to NPS for a graduate master's degree compared to not sending the officer at all. This situation assumes that the officer has the requisite undergraduate bachelor's degree and stays at that education level. Due to the higher retention rates of NPS graduates at the DoD, we ascertained that the expected ROI is 469%, with a 90% confidence interval of the ROI between 361% and 590%, after accounting for all the uncertainties in the input parameters and assumptions. In other words, we can safely say that 95% of the time, given all the uncertainties and fluctuations in NPS costs and changes in retention rates over time, sending an officer to NPS as compared to the status quo will yield an additional 361% in ROI or a 4.61 return-to-cost ratio. Hence, for every $1 spent on an NPS education, the DoD obtains a benefit or return of $4.61 (the net benefit is $3.61 or 361%).

Finally, we performed an analysis of alternatives' ROI differential when the DoD sends a junior officer to a non-NPS civilian university for a graduate master's degree compared to not sending the officer at all. This scenario again assumes that the officer has the requisite undergraduate bachelor's degree and stays at that education level. Due to the higher retention rates of graduates, the results show that the expected ROI is 403%, with a 90% confidence interval of the ROI between 289% and 550%, after accounting for all the uncertainties in the input parameters and assumptions. In other words, we can safely say that 95% of the time, given all the uncertainties and fluctuations in civilian graduate education costs and changes in retention rates over time, sending an officer to any non-NPS graduate program will yield an additional 289% in ROI or a 3.89 return-to-cost ratio. Hence, for every $1 spent on non-NPS graduate education, the DoD obtains a benefit or return of $3.89 (the net benefit is $2.89 or 289%).

From the point of view of the DoD, for every dollar invested in NPS education, the benefits return anywhere between 5.69 and 7.73 times the investment (Table 6), but these ROI values are simply the tip of the iceberg, as the intangible value of a military graduate institution to the DoD is incalculable.

Results Summary

In summary, we can conclude that NPS graduates show a statistically significantly higher retention rate in the U.S. Navy. As expected, retention rates decline over time, but the decline is fairly predictable; and the rate of decline is statistically significantly less for NPS graduates than non-NPS graduate and undergraduate degree holders. More complex econometric models with different functional forms such as logistic, log-linear, and log quadratic models, were used to generate reasonable retention rates. These forecasts were then used to build life-cycle cost models and simulation models to determine the lifetime ROI for NPS students from the point of view of a DoD investment.

We see that not only does NPS provide significant intangible value to its students and the DoD as a whole, but it also provides quantifiable economic ROI. We see that from the point of view of the DoD, for every dollar invested in NPS education, the benefits return anywhere between 5.69 and 7.73 times the investment (Table 6), but these ROI values are simply the tip of the iceberg, as the intangible value of a military graduate institution to the DoD is incalculable.

TABLE 6. SUMMARY ROI FOR RESEARCH AND EDUCATION

ROI for Military Education (e.g., NPS)	
Delta ROI: NPS vs. Civilian Master's Program (Expected Value)	673.00%
Delta ROI: NPS vs. Civilian Master's Program (90% Confidence Interval)	541%–821%
For every $1 spent on NPS, the benefit gained is $7.73 on average	
ROI: NPS Master's Program vs. Status Quo Bachelor's Degree (Expected Value)	469.00%
ROI: NPS Master's Program vs. Status Quo Bachelor's Degree (90% Confidence Interval)	361%–590%
For every $1 spent on NPS, the benefit gained is $5.69 on average	
ROI: Civilian Master's Program vs. Status Quo Bachelor's Degree (Expected Value)	403.00%
ROI: Civilian Master's Program vs. Status Quo Bachelor's Degree (90% Confidence Interval)	289%–550%
For every $1 spent on any graduate degree, the benefit gained is $5.03 on average	

The simulated ROI's probability distributions for the three scenarios show that the NPS versus civilian MS program has the highest ROI (averaging and peaking at 673%) because the lower cost at NPS and resulting higher retention rates make it the most profitable. The NPS versus undergraduate status quo without attending any graduate programs (averaging and peaking at 469%) scenario reveals that, because the entire NPS cost is incurred, the ROI is lower than the differential cost for NPS versus civilian MS. Finally, the lowest comparable ROI, which is still significant (averaging and peaking at 403%), is achieved when an officer attends a civilian MS program as opposed to not attending any graduate studies at all. Hence, in summary, we see that graduate education for naval officers provides a significant return on the government's investment, and that NPS provides the best economic ROI, above and beyond all the qualitative and intangible values previously discussed.

These ROI values are comparable to the examples provided in the Work Life-Cycle Approach of a civilian MBA and MS graduate of 318% and the 304% average ROI from military research programs, both described earlier. The higher ROI for NPS also results from the lower cost of education and longer retention rates of its graduates.

Case Study: The Value and ROI of DAU

In this section, we present a brief case study of the value of DAU educational programs. DAU is a best-in-class corporate university for the Defense Acquisition Workforce, with online courses as well as live sessions. Its mission is to provide a global learning environment to develop qualified acquisition, requirements, and contingency professionals who deliver and sustain effective and affordable warfighting capabilities (see http://www.dau.edu). As such, it is a critical part of the DoD-sponsored acquisition education.

During FY2017–2018, DAU sent out surveys to tens of thousands of its course participants. These are standard end-of-course surveys taken immediately after the completion of a course as well as postcourse assessments that are sent as a follow-up several months later. In addition, surveys to the participants' supervisors were also submitted several months after the conclusion of the course. DAU uses a commercial web-based evaluation application, where some questions require a percentage response versus others requiring a 7-point Likert scale response (i.e., 1 for strongly disagree to 7 for strongly agree), to compare the survey results with other training organizations. Each year, tens to hundreds of thousands of DAU anonymous surveys are received and compared with millions of others in the database.

Of the 145 supervisors surveyed, over 95% of the respondents would value DAU education highly, with a Likert scale of 4 or higher.

The surveys contain standard educational questions, including the setup of the course, the facility, quality of graded materials, quality of the faculty, and length or pace of the course. Out of the two dozen or so questions, we were able to cull the necessary data for the most relevant questions that pertain to the value of DAU's programs. Of special interest is the supervisor's survey question on their view of the course's ROI. Of the 145 supervisors surveyed, over 95% of the respondents would value DAU education highly, with a Likert scale of 4 or higher.

Survey Modeling and Analysis Results

The survey results were subjected to multiple analytical models to see what critical information can be gained from these surveys. An Inter-Class Correlation for Inter-Rater Reliability Test as well as the Guttman's Lambda and Internal Consistency and Reliability Test were employed to determine whether the survey responses were statistically valid, trustworthy, reliable, and replicable. In addition, econometric modeling and multivariate tests were run. Some artificial intelligence algorithms, such as machine learning, were also applied to identify any patterns that might exist in the data (see Appendix).

Conclusions from the Point of View of Supervisors

The main conclusions of the DAU postcourse and follow-up surveys from the point of view (POV) of supervisors are as follow:

- The survey responses reflect statistical consistency and reliability. This means that for the 145 supervisors who sent their employees for training, their responses exhibited statistical reliability. We conclude that the responses to the survey are valid and trustworthy, rather than being completed haphazardly and without any biases. Therefore, conclusions drawn based on the survey data are statistically valid.
- We find statistical significance indicating that, on average, supervisors view that the ROI is statistically significantly greater than zero (mid-point of a Likert scale).
- Organizations value the ROI to an employee's personal career growth as being the same as the ROI to the entire organization.
- Organizations view the ROI of a training initiative to the organization as going beyond its sole impact on an employee's job performance.
- Organizations view the ROI of a training initiative to an individual employee as greater than its sole impact on an employee's job performance. This might mean that the value of training is not entirely quantifiable or immediately actionable and that some value might be intrinsic, unmeasurable, and subjective.
- Organizations view the ROI to the organization as being more than a simple summation of actual enumerable skills or new knowledge learned. In addition, organizations perceive ROI as being more than applications of specific knowledge or skill sets on the job.
- Organizations see value if the training helped improve an employee's performance and enabled the employee to apply the knowledge and skills successfully, but only if it is also worthwhile to the employee's own career development based on specific goals and expectations set prior to the training

course. Each of these criteria by itself does not necessarily contribute to the perceived ROI, but only when they are combined holistically.

- Using distributional fitting, we see that the probability distribution of the estimated improvement percentage as a direct result of a training course (VAR12) shows, on average, a 50.7% increase in productivity, with three-quarters of the supervisors surveyed saying that productivity improvements were at least 32%.

Conclusions from the Point of View of Students

The main conclusions of the DAU postcourse and follow-up surveys from the POV of the students follow:

- For the 16,157 students who responded to the surveys, the responses as a whole exhibited statistical reliability as well as statistical consistency, indicating that no biases were evidenced in the data. We can conclude that the responses to the survey are valid and trustworthy, rather than being completed haphazardly. Therefore, conclusions drawn based on the survey data are statistically valid.
- The student's view at the end of the course in terms of the usefulness of the course material presented is materially and significantly different after spending time on the job.
- The student's view at the end of the course in terms of the amount of new knowledge learned that might apply to their job is materially and significantly different after spending time on the job.
- The student's view at the end of the course in terms of the amount of work time requiring the use of the new knowledge learned is materially and significantly different after spending time on the job.
- A statistically significant improvement in the student's work abilities is evident as a direct result of the training received.

- A statistically significant increase is evident in the ability to apply the knowledge and skills learned in class.
- A statistically significant amount of new knowledge is learned in class.
- At a future follow-up session, a former student's estimate of how much work improvement was a direct result of the training course depended on experience during the follow-up session and was not completely known immediately after the course ended.
- About three-quarters of the students surveyed believed that their productivity increased at least 20% after taking the course. We also see that the students' POV (Gumbel distribution) is more conservative than the supervisors' POV (normal distribution), but with a similar shape and scale.

Return on Investment Analysis

Finally, an analysis of the ROI is performed on the DAU courses. The conclusion is that the average ROI from the POV of the students and supervisors/organizations is between **411%** and **477%**, and the probability that, on average, any given course taken at DAU has at least **87%** and **93%** probabilities that the ROI is positive, from the POV of the student and the supervisor/organization, respectively.[7]

Conclusions

As the basis for reorienting education, the Department of the Navy (2018), through the Education for Seapower report, recommended the following strategic vision:

> The Naval Education Enterprise must produce leaders of character, integrity, and intelligence steeped not only in the art of war, the profession of arms, and the history and traditions of the Naval service, but also in a broader understanding of the technical and strategic complexities of the Cognitive Age, vital to assuring success in war, peace, and grey zone conflict; officer and enlisted leaders of every rank who think critically, communicate clearly, and are imbued with a bias for decisive and ethical action. (p. 14)

As such, the motivation for the main research question was whether military education and research have any value to the Department of the Navy and DoD in general, and, if so, how would one compute its ROI? We consider the fact that the drive for lifelong education in naval officers is a personal but also an institutional responsibility. Education is vital for the strategic viability and long-term lethality of our warfighting forces and country.

We can conclude that the intangible value of military education is significant in developing leadership and critical thinking skills for junior as well as senior officers. The military-oriented curriculum taught by faculty members with former military experience or knowledge allows the flow of institutional knowledge down to the students. Although these intangible and qualitative aspects of military education are significant, this current research focuses on the more quantitative measure of ROI.

We can conclude that the intangible value of military education is significant in developing leadership and critical thinking skills for junior as well as senior officers. The military-oriented curriculum taught by faculty members with former military experience or knowledge allows the flow of institutional knowledge down to the students.

Using NPS as a case study, we can further conclude that NPS graduates show statistically significantly higher retention rates in the U.S. Navy. Further, we can conclude that, as expected, retention rates decline over time, but the decline is fairly predictable, and the rate of decline is statistically significantly less for NPS graduates than non-NPS graduate degree holders and undergraduate degree holders. More complex econometric models with different functional forms such as logistic, log-linear, and log quadratic models were used to generate reasonable retention rates. These forecasts were then used to build life-cycle cost models and simulation models to determine the lifetime ROI for NPS students from the point of view of a DoD investment. Finally, machine learning algorithms in artificial intelligence were also applied for pattern recognition purposes.

The following are the main conclusions of the study:

- DoD-sponsored military education graduates tend to stay longer in the military, beyond their required payback years, which means their knowledge and capabilities are exploited for longer and the DoD needs to recruit and train fewer people in the long run.

- DoD-sponsored military education is less expensive than external universities, on average, while providing specific military education needed by the Services.
- DoD research performed at military universities is less expensive and more military-relevant than using private consultants.

Table 7 recaps the critical results from the research.

TABLE 7. SUMMARY ROI FOR RESEARCH AND EDUCATION

ROI for Military Research and Development (e.g., ARP)	
Minimal Worst-Case ROI	121.00%
Most Likely ROI	304.00%
Range of ROI Depending on Program	240%–600%
ROI for Military Education (e.g., NPS)	
Delta ROI: NPS vs. Civilian Master's Program (Expected Value)	673.00%
Delta ROI: NPS vs. Civilian Master's Program (90% Confidence Interval)	541%–821%
For every $1 spent on NPS, the benefit gained is $7.73 on average	
ROI: NPS Master's Program vs. Status Quo Bachelor's Degree (Expected Value)	469.00%
ROI: NPS Master's Program vs. Status Quo Bachelor's Degree (90% Confidence Interval)	361%–590%
For every $1 spent on NPS, the benefit gained is $5.69 on average	
ROI: Civilian Master's Program vs. Status Quo Bachelor's Degree (Expected Value)	403.00%
ROI: Civilian Master's Program vs. Status Quo Bachelor's Degree (90% Confidence Interval)	289%–550%
For every $1 spent on any graduate degree, the benefit gained is $5.03 on average	
ROI for Short or Specialized Military Courses (e.g., DAU)	
ROI on DAU Courses on Average	411%–477%
For every $1 spent on DAU, the benefit gained is $5.77 on average	
Global Average ROI (ARP, NPS, DAU): 485%	

In an earlier discussion, we saw that the ROI for military-based research has significant qualitative intangible worth as well as quantitative economic ROI. In summary, we can quantify that the ARP's ROI, based on an annual investment of $1.7 million, will range from the absolute worst case of 121% to an average of **240%–600%** for each specific program. The KVA method pegs the ROI at 253%. Therefore, using standard industry best practices, we conclude the average conservative ROI for the entire ARP program to be approximately **304%**.

Previously, the analysis was extended to look at the ROI of NPS. We see that from the point of view of the DoD, for every dollar invested in NPS education, the benefits return anywhere between 5.7 and 7.7 times the investment, which represents expected ROIs between **469%** and **673%** (Table 7). These ROI values are minuscule in comparison to the holistic, intangible, and qualitative value of a military graduate university to the DoD.

Using the DAU data, we determine that the ROI of military education in the defense acquisition world is between **411%** and **477%**, and the probability that on average any given course taken at DAU has at least **87%** and **93%** probabilities that the ROI is positive. The global average for DoD education on average provides the government with an ROI of approximately **485%**.

In conclusion, training only prepares the Warfighter to deal with the known factors of war (e.g., the importance of good marksmanship), but education prepares Warfighters to deal with the unknown factors (e.g., effective decision-making in risk-fraught, rapidly changing circumstances). Well-educated Warfighters create significant added value and make up lethal and effective combat-ready units for the future.

Limitations and Recommendations for Future Research

This research examined and created various theoretical constructs and empirical methods to generate ROI for military education and research. The current research both proposed these methodologies and used available data to simulate cash-flow life-cycle models. The recommended next steps of the research would be to obtain long-term data from current and previous students via survey instruments, interviews, and work performance data, and other requisite information that flows out of this data collection process. The data with higher fidelity can then be reprocessed through the methodologies described.

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Endnotes

[1] Knowledge Value-Added

KVA includes the following seven-step method (Housel & Kanevsky, 2007):

- Identify functional areas and core processes along with their subprocesses. It is quite useful to have at least two process- or functional-area SMEs to ensure reliable estimates.
- Establish common units and levels of aggregation of the process output to measure learning time. Other common-unit measures of output can also be used, such as tasks, computer code, or process instructions that may be contained in existing documentation as long as they are calibrated to a common level of complexity using learning times.
- Calculate the learning time (i.e., knowledge surrogate) required to execute each process or functional area.
- Designate a sampling time period long enough to capture a representative sample of the core processes or functional area's aggregated output.
- Multiply the learning time for each process by the number of times the process executes during the sample period.
- Calculate the cost to execute knowledge (e.g., learning time or process instructions) by the resource used to produce the outputs (i.e., people, technology) to determine process costs.
- Calculate ROK and ROKI.

[2] Integrated Risk Management and Real Options Analysis

Real-life conditions are fraught with uncertainty and risks. Understanding the knowledge inherent in, and accounting for, the effects of these uncertainties is crucial to successful management. When uncertainty becomes resolved through the passage of time, actions, and events, decision makers can make the appropriate midcourse corrections by applying the knowledge gained and making decisions along flexible strategies. Strategic Real Options is a discipline that incorporates this learning model and permits the decision maker to take advantage of the full range of options, whereas traditional analyses that neglect this strategic flexibility will grossly undervalue certain capabilities, projects, and strategies (Mun, 2016b).

The real options approach is part of the IRM process, an eight-step, quantitative, software-based modeling approach for the objective quantification of risk (such as cost, schedule, and technical). The approach can be applied to program management; resource portfolio allocation; return on investment to the military (maximizing expected military value and objective value quantification of nonrevenue government projects); analysis of alternatives or strategic flexibility options; capability analysis; prediction modeling; and general decision analytics (Mun, 2016a). The method supports project and capability selection among hundreds of alternatives constrained by fixed budgets and tight schedules to maximize capability and readiness at the lowest cost possible. This methodology is particularly amenable to resource reallocation and has been taught and applied by the author for the past 15 years at over 100 multinational corporations and encompassing over 50 projects at the DoD. The authors' books and methodology are now used and taught at more than 100 universities globally.

How much is a platform technology really worth when its initial costs are high and it is delivered with lower than desired initial capabilities, but with the potential for significant flexibility for future add-ons? Should the government build or buy a new untested technology? Is running a proof of concept a better strategy than executing large-scale acquisitions immediately? How is a Warfighter's capability extended with flexible weapon systems? Is a modular open architecture really worth the added costs?

The Strategic Real Options approach helps answer these questions and more, by estimating the value of military capability in a common and objective way across various alternatives and expressing the ROI of each option. These ROI estimates across the portfolio of alternatives provide the inputs necessary to predict the value of various options for accomplishing the recently stated Secretary of Defense reallocation goals. IRM incorporates risks, budget constraints, reallocation options, and total ownership costs in recommending a defensible path forward. This approach identifies risky projects and programs while projecting immediate and future cost savings, total life-cycle costs, flexibility alternatives, critical success factors, and portfolio optimization, while controlling for cost overruns and schedule delays. It provides an optimized portfolio of capability options while maintaining the value of strategic flexibility. The IRM approach incorporates multiple Nobel-prize winning and well-established theories and applications in corporate finance, investments, economics, statistics, mathematics, and decision sciences into a comprehensive and flexible process that is defensible, replicable, scalable, and extensible to all areas of the DoD (Mun, 2016b).

[3] Naval Postgraduate School Acquisition Research Program

Using valuation best practices in industry, we perform ROI analysis on the ARP program from various points of view to determine the final ROI:

- Some research provides significant ROI if the processes, recommendations, and actionable intelligence are executed. The ARP research will take minimal credit for the potential ROI (i.e., 1/1000 of the ROI savings) and attribute it to the ARP research.
- We look at the worst-case scenario, where even if the research results are not implemented, cost savings are still realized. This approach will generate the absolute minimal baseline of what the ARP ROI should be.
- In addition, graduate students (MS, MBA, PhD candidates) participate in the research, as well as attend symposiums. Students find value in the knowledge and experience gained, and we will capture these intangibles using Knowledge Value-Added methodologies to monetize and determine the knowledge-based ROI.
- Intangible and intrinsic value exists above and beyond any standard ROI calculations. These include the interactions of sponsors with researchers, graduate students, faculty, and program executive offices and commands with researchers; the live interactions of participants at the annual symposiums; and the knowledge dissemination.

[4] U.S. Naval Institute Study

Cost comparison analysis of a degree earned from NPS and a similar degree earned from a comparable civilian university was performed. While the degrees may be similar on the outside and just as challenging in their pursuit, civilian degrees certainly do not have the same tailored, defense-centric, militarily career-enhancing curriculum provided by NPS. This is a flaw inherent in any direct one-to-one cost comparison. Curricular requirements at NPS include Educational Skill Requirements (ESRs) dictated by the Secretary of the Navy that are intended to broaden the military student's educational experience. NPS provides Joint Professional Military Education (JPME) coursework from Navy War College faculty in order that officers satisfy their academic degree and joint military requirements within a single tour. Additional coursework is also required to ensure the student appreciates the military relevance of the academic subject material, thereby enabling immediate application upon rejoining the operational force. Similar courses are not available at civilian universities and represent a hidden, but necessary, cost in NPS' budget (Mauz & Gates, 2000).

[5] The *NPS Value Book*

In summary, the NPS cost model is broken into three points of view:

- Annual Cost-per-Student: This measure relates education costs to the effective number of full-time students on board. Higher or lower student credit loads are not reflected. In 2019, the NPS Cost-per-student full-time equivalence was approximately $40,000.
- Annual Normalized Cost-per-Student Full-Time Equivalent (SFTE): The NPS education model provides more education and more credit hours to students than comparable civilian universities, anywhere from 50% to 100% more. Assuming an average load increase of 75%, we can normalize NPS Cost/SFTE for comparison with standard student programs at other civilian universities. For 2019, the normalized Cost/SFTE was $34,000. NPS believes that this normalized Cost/SFTE is a more valid measure for cost comparisons.
- Annual Naval Normalized Cost/SFTE: This is a determination of cost per student, but only for Navy Direct-Funded students. In 2019, Naval Normalized Cost/SFTE was $42,000.

[6] Life-Cycle Cost Model Assumptions

A life-cycle cost model with Monte Carlo simulation was created with the following input assumptions:

- Graduate education tuition costs for nine comparable civilian public universities were obtained. The simulation assumes a triangular distribution.
- An annualized private education inflation rate ranging from 2.0% to 3.5% was simulated, based on the Common-fund Higher Education Price Index (HEPI).
- The relevant 1-year to 20-year U.S. Treasury rates from the U.S. Department of Treasury were used, and a nonlinear cubic spline interpolation was applied to determine the annualized forward rates. These are used as the government discount rates in the life-cycle model.
- NPS education cost used was triangulated among $34,000, $40,000, and $42,000 per year, based on the internal NPS cost model.
- NPS cost was accreted between 1.5% to 2.5% per year, based on normalized annual budgetary increases.

- The cost to train, retain, and replace a naval officer between the O-4 and O-6 levels was simulated to be between $250,000 and $500,000, depending on the billet, with a most likely cost of $350,000.
- A 20-year life-cycle model was used, and 1,000,000 simulation trials were run in the model for the uncertain assumptions in this list.

[7] Assumptions in the DAU ROI Analysis

Several assumptions are made to enable the ROI analysis, namely:

- We used DAU's own annual report to determine that there are over 152,557 students taking online courses and 44,326 graduates from resident courses in FY2019 (Defense Acquisition University, 2020).
- The FY2020 Congressional Budget request was for $163 million, which covers all operating costs of DAU, including any requisite travel expenses for its students, faculty salaries, operations and maintenance of its facilities, and other expenses.
- The average cost per student, averaged across online and resident programs, is between $900 and $4,500. The lower end applies to online courses versus resident courses at the upper end of the range, as well as varying depending on the course type and course level.
- Based on the survey of over 16,157 students, they attended 171 different courses, and the allocation of these course levels (100-, 200-, 300-, and 400-level courses) is unequally distributed among O-1 to O-6 officers (we excluded special seminars for flag officers), with the predominant number of students at the O-3 to O-5 levels, spread across multiple 100- and 200-level courses.
- Using the O-1 to O-6 pay scales (source: http://www.federalpay.org), and assuming that the faculty members are between GS-12 and GS-15 levels, a Monte Carlo risk simulation was run to determine the cost of education for an average course.
- Similarly, probability distributional and curve-fitting routines were run on the perceived enhanced efficiency and effectiveness at doing one's job, as determined from the 6-month follow-up surveys. Using these distributions, Monte Carlo risk simulations were run to determine the potential ROI.

Appendix

Survey Modeling and Statistical Results

The survey results were subjected to multiple analytical models to see what critical information can be concluded from these surveys. An Inter-Class Correlation for Inter-Rater Reliability Test as well as the Guttman's Lambda and Internal Consistency and Reliability Test were employed to determine whether the survey responses were statistically valid, trustworthy, reliable, and replicable. In addition, econometric modeling and multivariate tests were run. Some artificial intelligence algorithms, such as machine learning, were also applied to identify any patterns that might exist in the data.

Analytical Results from Survey of Supervisors

Inter-Class Correlation for Inter-Rater Reliability Test
VAR1; VAR3; VAR7; VAR8; VAR12
Inter-Class Correlation: 0.66
Spearman-Brown Correction: 0.96
Inter-Rater Reliability: 0.0000

VAR2; VAR4; VAR5; VAR6; VAR9; VAR10; VAR11; VAR13
Inter-Class Correlation: 0.63
Spearman-Brown Correction: 0.96
Inter-Rater Reliability *p* Value: 0.0000

One Variable T-Test for Means

VAR4, Two-Tailed *p* Value: 0.0000

Analysis of Variance (One Way ANOVA with Multiple Treatments)

VAR1; VAR3; VAR7; VAR8; VAR12
ANOVA *p* Value: 0.0000

VAR2; VAR4; VAR5; VAR6; VAR9; VAR10; VAR11; VAR13
ANOVA *p* Value: 0.0000

Nonparametric Kruskal–Wallis Test

VAR1; VAR3; VAR7; VAR8; VAR12
Kruskal Wallis *p* Value: 0.0001

VAR2; VAR4; VAR5; VAR6; VAR9; VAR10; VAR11; VAR13
Kruskal Wallis *p* Value: 0.0001

Two-Variable (T) Independent Equal Variance

VAR4; VAR9	*p* Value Two Tailed: 0.8021
VAR4; VAR2	*p* Value Two Tailed: 0.0058
VAR2; VAR9	*p* Value Two Tailed: 0.0022
VAR4; VAR11	*p* Value Two Tailed: 0.9592
VAR4; VAR13	*p* Value Two Tailed: 0.2287

Nonparametric Mann–Whitney Test

VAR4; VAR9	*p* Value Two Tailed: 0.9264
VAR4; VAR2	*p* Value Two Tailed: 0.0043
VAR2; VAR9	*p* Value Two Tailed: 0.0028

VAR4; VAR11	*p* Value Two Tailed: 0.7153
VAR4; VAR13	*p* Value Two Tailed: 0.1368

Basic Econometrics and Regression

Model Inputs: VAR4 vs. LN(VAR2); VAR6; VAR9; VAR13

Multiple R	0.94580	Maximum Log-Likelihood	-68.84037
R-Square	0.89454	Akaike Info Criterion (AIC)	1.01849
Adjusted R-Square	0.89152	Bayes Schwarz Criterion (BSC)	1.12113
Standard Error	0.39582	Hannan-Quinn Criterion (HQC)	1.06020
Observations	145		

	Coeff	Std. Error	T-stat	*p* value	Lower 5%	Upper 95%
Intercept	-0.22577	0.19891	-1.13507	0.25829	-0.61902	0.16748
LN(VAR2)	0.76059	0.19318	3.93730	0.00013	0.37867	1.14251
VAR6	0.22195	0.04354	5.09750	0.00000	0.13587	0.30803
VAR9	0.83622	0.04443	18.82177	0.00000	0.74838	0.92406
VAR13	-0.22733	0.06006	-3.78502	0.00023	-0.34608	-0.10859

ANOVA	DF	SS	MS	F-Stat	*p* Value
Regression	4	186.04	46.51	296.86391	0.00000
Residual	140	21.93	0.16		
Total	144	207.97			

Distributional Fitting: Continuous (Anderson–Darling)

Rank	MAPE %	AD	Distribution
1	13.47%	0.1976	Normal
2	15.37%	0.2108	Logistic
3	16.68%	0.3170	GumbelMax
4	27.51%	0.2899	GumbelMin

Best Fit Rank: 1
Fit Name: Normal
Anderson-Darling Statistic: 0.197647
MAPE: 0.134716
Mean: 0.506852
Sigma: 0.277159

Actual to Theoretical Four Moments:

0.512414	0.264282	0.028672	-0.771227
0.506852	0.277159	0.000000	0.000000

Analytical Results from Survey of Students

Inter-Class Correlation for Inter-Rater Reliability Test
VAR1; VAR2; VAR3; VAR4; VAR5; VAR6; VAR7
Inter-Class Correlation: 0.33
Spearman-Brown Correction: 0.93
Inter-Rater Reliability: 0.0000

VAR1; VAR3; VAR5; VAR7
Inter-Class Correlation: 0.74
Spearman-Brown Correction: 0.93
Inter-Rater Reliability *p* Value: 0.0000

VAR2; VAR4; VAR6
Inter-Class Correlation: 0.84
Spearman-Brown Correction: 0.96
Inter-Rater Reliability *p* Value: 0.0000

VAR8; VAR9
Inter-Class Correlation: 0.02
Spearman-Brown Correction: 0.04
Inter-Rater Reliability *p* Value: 0.0032

Analysis of Variance (One Way ANOVA with Multiple Treatments)

VAR1; VAR2; VAR3; VAR4; VAR5; VAR6; VAR7
ANOVA *p* Value: 0.0000

Nonparametric Kruskal–Wallis Test

VAR1; VAR2; VAR3; VAR4; VAR5; VAR6; VAR7
Kruskal Wallis *p* Value: 0.0000

Two-Variable (T) Independent Equal Variance

VAR1; VAR2	*p* Value Two-Tailed: 0.0000
VAR3; VAR4	*p* Value Two-Tailed: 0.0000
VAR5; VAR6	*p* Value Two-Tailed: 0.0000

Nonparametric Mann–Whitney Test

VAR1; VAR2	*p* Value Two-Tailed: 0.0000
VAR3; VAR4	*p* Value Two-Tailed: 0.0000
VAR5; VAR6	*p* Value Two-Tailed: 0.0000

Basic Econometrics and Stepwise Regression

ARRANGEMENT: Y<->X3;X7;X1;X5
Regression Results
OVERALL FIT

Multiple R	0.75271	Maximum Log-Likelihood	3753.34608
R-Square	0.56658	Akaike Info Criterion (AIC)	-0.46393
Adj R-Square	0.56647	Bayes Schwarz Criterion (BSC)	-0.45964
Standard Error	0.19180	Hannan-Quinn Criterion (HQC)	-0.46251
Observations	16142		

	Coeff	Std. Error	T-stat	*p* value	Lower 5%	Upper 95%
Intercept	-0.01274	0.00614	-2.07418	0.03808	-0.02479	-0.00070
VAR3	0.37981	0.01040	36.50831	0.00000	0.35942	0.40020
VAR8	0.02617	0.00132	19.87973	0.00000	0.02359	0.02875
VAR1	0.25276	0.01001	25.24347	0.00000	0.23314	0.27239
VAR5	0.05341	0.00968	5.51641	0.00000	0.03443	0.07239

ANOVA

	DF	SS	MS	F	*p* Value
Regression	4	776.01	194.00	5273.63619	0.00000
Residual	16137	593.63	0.04		
Total	16141	1369.64			

Hypothesis Test
Critical F-statistic (99% confidence with DFR1 and DFR2): 3.320336
Critical F-statistic (95% confidence with DFR1 and DFR2): 2.372483
Critical F-statistic (90% confidence with DFR1 and DFR2): 1.945208

Random Forest Supervised Data Mining

The Classification and Regression Trees (CART) model generates branches and subgroups of the categorical dependent variable (e.g., low-, medium-, high-retention, or low-, medium-, and high-satisfaction levels) using characteristic independent variables (officer rank, level of experience, number of years at an institution, education level pursued, etc.). CART is typically used for data mining and constitutes a supervised machine learning approach in artificial intelligence. This is a classification approach when the dependent variable is categorical, and the tree is used to determine the class or group within which a target testing variable is most likely to fall. The data are split into branches along a tree, and each branch split will be determined using Gini coefficients (information loss measures) based on the questions asked along the way. The final structure looks like a tree with its many branches. Additional splitting and stopping rules are applied along the way, and the terminal branches will provide predictions of the target testing variable. In the random forest approach, bootstraps of CART regression trees are run multiple times with different combinations of data points and variables to develop a consensus forecast of group assignments. Using a single set of training variables, the data and variables are bootstrapped and resampled. Each resampling will be run in the CART or regression tree model, and the consensus categorization results will be generated (Mun, 2021).

Bagging with 100 iterations and base learner with Cross-validation

Correlation coefficient	0.8659
Mean absolute error	0.0923
Root mean squared error	0.1470
Relative absolute error	37.356%
Root relative squared error	50.091%
Total Number of Instances	16,142

K-Means Clustering

A K-Means Clustering with Gaussian Mix model applies Naïve Bayes and likelihood estimations and are considered as unsupervised artificial intelligence machine learning algorithms. These approaches are applied to recognize patterns in data, learning from experience as more data is applied to the algorithm, drawing conclusions, and making predictions in terms of where certain groups of student characteristics (officer rank, level of experience, number of years at an institution, education level pursued, etc.) can be clustered or grouped together with the highest probability (Mun, 2021). This approach helps us to identify the types of students and their characteristics that are most likely to succeed at a certain metric (e.g., highest retention, best productivity levels, etc.).

Number of iterations: 19
Within cluster sum of squared errors: 8084.545176982922

Initial starting points (random):

Cluster 0: 1,0.8,1,0.7,0.5,0.6,0.5,7,7

Cluster 1: 0.1,0.1,0.1,0.1,0.1,0.1,0.1,5,6

Missing values globally replaced with mean/mode

Final cluster centroids:

		Cluster#	
Attribute	Full Data	0	1
	(16142.0)	(8044.0)	(8098.0)
VAR1	0.4754	0.7143	0.2382
VAR2	0.5071	0.5019	0.5123
VAR3	0.4385	0.6783	0.2003
VAR4	0.4941	0.4882	0.5000
VAR5	0.4060	0.6141	0.1994
VAR6	0.4555	0.4495	0.4616
VAR7	0.4398	0.6393	0.2416
VAR8	5.5050	6.2471	4.7678
VAR9	5.6808	5.6875	5.6742

Artificial Intelligence Multi-Layered Perceptron

Classifier model (full training set)

Linear Node 0

Inputs	Weights
Threshold	0.06925846705171
Node 1	-0.9353491867299
Node 2	1.00459405724956
Node 3	1.58048358855907
Node 4	-0.8778430933414

Distributional Fitting: Continuous (Anderson–Darling)

Rank	MAPE %	AD	Distribution
1	45.80%	0.2826	GumbelMax
2	46.98%	0.4680	Fréchet
3	53.94%	0.2703	Normal
4	57.65%	0.2782	Logistic
5	88.72%	0.3492	GumbelMin
6	289.64%	0.7048	TDist
7	447.11%	1.0000	Standard Normal
8	477.33%	1.0758	Weibull3
9	551.54%	0.4355	Exponential2
10	2710.10%	N/A	Uniform

Best Fit Rank: 1
Fit Name: GumbelMax
Alpha: 0.290457
Anderson-Darling Statistic: 0.282634
Beta: 0.276531
MAPE: 0.458042

Actual to Theoretical Four Moments:

0.439753	0.291298	0.234879	-0.931816
0.450074	0.354664	1.139547	2.400000

Author Biography

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Fleet Sustainment AND THE Fiscal Impact OF CONTRACTING RED AIR

Capt Thomas Tincher, USAF, and Lt Col Tim Breitbach, USAF

This article examines the potential impact to the government from the use of contractor aircraft to fly aggressor sorties. Results of research show that the burden on the government sustainment base will be eased by using contract aircraft instead of government aircraft to fly aggressor sorties. Specifically, the authors posit that using contract aircraft instead of certain fourth-generation and all fifth-generation aircraft is more cost effective. They also examine the maintenance and sustainment impact resulting from this finding. Finally, the article concludes with recommendations on when and why the use of contract versus organic capability is more cost effective.

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Keywords: *Aggressor Aircraft, Red Air, Sustainment, Fiscal, Contract, Contracted Air Support*

Image designed by Nicole Brate. Elements of the image furnished by NASA.

> It is the sense of Congress that ... it is critical that the Air Force has the capability to train against an advanced air adversary in order to be prepared for conflicts against a modern enemy force, and that in order to have this capability, the Air Force must have access to an advanced adversary force prior to United States adversaries' fielding a 5th-generation operational capability...
>
> —National Defense Authorization Act for Fiscal Year 2020

Background

One target of the United States' post-Cold War military downsizing was Air Force aggressor squadrons. The 65th Aggressor Squadron (AGRS) and the 64th AGRS (inactivated in 1989 and 1990, respectively) provided near-peer capabilities against which U.S. forces could train (U.S. Air Force [USAF], 2009, 2021a). The aggressor units from all Services have provided an essential training tool in replicating adversary tactics and threats, which have better prepared our armed forces for combat since their inception in response to the high losses in air combat during the Vietnam War (Tegler, 2021; USAF, 2021a). However, the need for aggressor aircraft throughout the military, and specifically weapons schools, had not gone away with the demise of the Soviet Union. The Department of Defense (DoD) had to find a way to provide aggressor training to its personnel despite reduced budgets and a shift in focus from "Great Power Competition" to fighting a Counter-Insurgency (COIN) war.

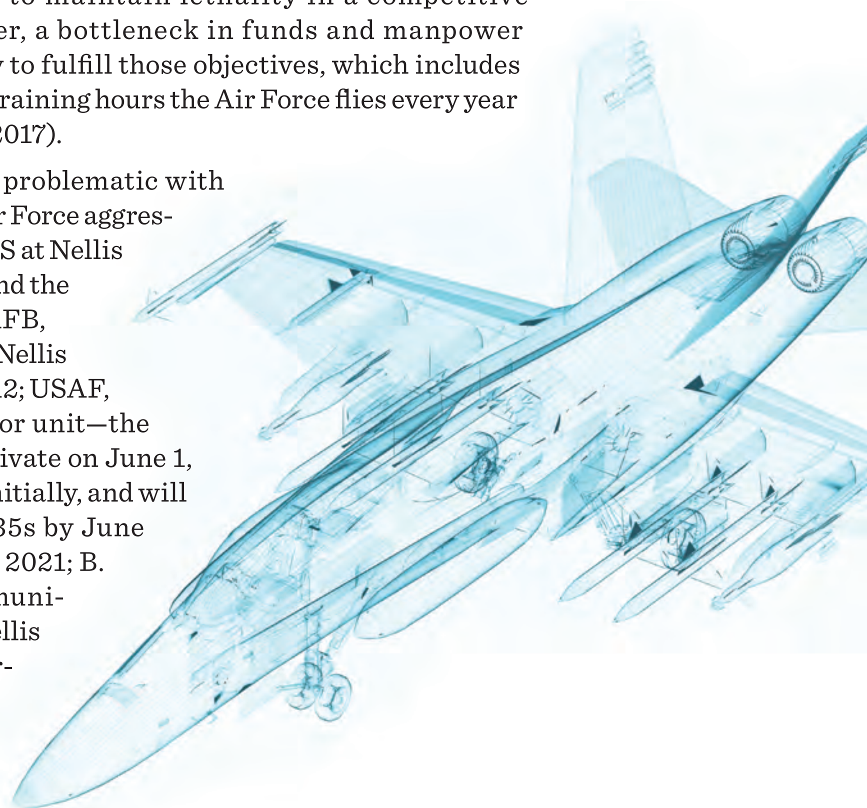
One solution in the Air Force was to maintain a smaller aggressor force in the form of the 414th Combat Training Squadron until the aggressor squadrons were reactivated over a decade later (Nellis AFB Public Affairs, 2012). Another option was to contract out aggressor services to private companies that could provide contractor-owned, contractor-operated (COCO) aircraft for a fee. This enabled military aircrews to obtain needed training while minimizing the hours flown off the life of a valuable, government-owned aircraft, thereby extending the operating life of those aircraft.

The contracted air support (CAS) industry has expanded rapidly since the 1990s. The industry includes airlift, combat training, and air refueling. Combat training and air refueling were areas of aviation primarily occupied by military or civil government crews and aircraft. Contracted training can include, but is not limited to, simulating missiles, Dissimilar Air Combat Training (DACT), Electronic Warfare, and working with Joint Terminal

Air Controllers (JTAC) (AIRUSA, n.d.; ATAC, n.d.; Blue Air Training, n.d.; Tactical Air Support, Inc., n.d. -a; Tegler, 2013; Top Aces, n.d.). The Red Air (or airborne aggressor mission) mission scope, which essentially replicates adversary tactics and threats, is extremely broad, and governments cannot always fill all of these roles from their own organic fleet.

Additionally, the 2018 National Defense Strategy Summary (NDS) called on the United States and its allies to refocus on deterring near-peer adversaries in a contested, multi-domain battlespace rather than fighting a sustained COIN war (DoD, 2018). Military aviation must adopt training objectives in line with the NDS to maintain lethality in a competitive environment. However, a bottleneck in funds and manpower limits the DoD's ability to fulfill those objectives, which includes approximately 60,000 training hours the Air Force flies every year (DoD, 2018; McLeary, 2017).

Fulfilling this need is problematic with only two operational Air Force aggressor units: the 64th AGRS at Nellis Air Force Base (AFB) and the 18th AGRS at Eielson AFB, both of which fly F-16s (Nellis AFB Public Affairs, 2012; USAF, 2008). A third aggressor unit—the 65th AGRS—will reactivate on June 1, 2022, with two F-35s initially, and will eventually have 11 F-35s by June 2024 (*Appropriations*, 2021; B. Smith, personal communication, April 8, 2022; Nellis AFB Public Affairs, personal communication, September 8, 2021; Secretary of the Air Force Public Affairs, 2019a).



The Air Force is also using operational squadrons as aggressors on a part-time basis, thus impacting training for those units' primary missions. This incurs temporary-duty costs to send a unit for aggressor duty at Large Force Exercises (LFE) like Red Flag, the opportunity cost of those aircrews flying missions outside of their primary duties, and a corresponding decrease in the service life of aircraft used for the aggressor mission. Aircraft become increasingly expensive to operate as they age, in part due to higher maintenance requirements and component scarcity (Congressional Budget Office, 2018; Sperry & Burns, 2001). As a result, the more that combat-coded units perform aggressor duty, the more stressed become the sustainment efforts for those aircraft, and the less the aircrew flying Red Air get to focus on honing primary combat skills. General Mike Holmes, former Commander, Air Combat Command, said:

> If we can bring on some contract Red Air, then not only do we get some dedicated people to train against, we also reduce the amount of time that our crews are spending at a zero-sum budget for flight hours pretending to be somebody else instead of training for their primary skills. (Pawlyk, 2017, para. 6)

Additionally, combat units are flying fourth- and fifth-generation fighters, which are increasingly complex and expensive to operate and maintain. Fourth-generation fighters (F-15s, F-16s, and F-18s) were designed in the 1970–80s and are highly maneuverable, multirole platforms with improved engines, radars, and avionics (Hebert, 2008; Lee, 2021). Fifth-generation fighters (F-22s and F-35s) were designed in the 1990s-2000s with stealth, improved avionics, active electronically scanned array (AESA) radars, and other modern technologies (Hebert, 2008; Lee, 2021).

Fifth-generation aircraft in particular are extremely valuable and have high operating costs. Lieutenant General Darryl Roberson, the former head of Air Education and Training Command, said, "We can't afford to have two F-35s fighting against two F-35s when the cost per flying hour is so expensive. And it's not optimizing what the airplanes are really built for" (Pawlyk, 2017, para. 45). An additional option the Air Force has used both at flag exercises and for search and rescue is the Civil Air Patrol (CAP). In May 2018, the Idaho Wing of CAP flew Red Air at GUNFIGHTER FLAG 18-2, supporting a multinational exercise and replicating threat aircraft not found in the United States' inventory (Capuno, 2018). The current Air Force consensus is that fourth- and fifth-generation aircraft should only be used as aggressors when the mission set demands it. Along these lines, the Air Force's Adversary Air (ADAIR) contract, awarded in 2019 to seven Red Air companies as part of an indefinite delivery/indefinite quantity contract, is capped at $6.4 billion and proposes to have contractors fly 37,000 of 60,000 annual training hours for the Air Force (DoD, 2019; McLeary, 2017). CAS aggressors will benefit the government from a sustainment standpoint by minimizing the sorties flown on DoD aircraft, and operationally by increasing training opportunities for aircrews.

Other Services have taken a different approach to aggressor training. The Department of the Navy (DoN) operates four aggressor squadrons—three Navy and one Marine—and has expanded its Red Air program since the fall of the Soviet Union. The Navy has utilized contracted aggressors since the 1990s, and in 2003 began purchasing used F-5s from the Swiss Air Force to utilize in the Marine Corps' VMFT-401 aggressor squadron. A total of 42 were purchased over several years (Axe, 2014; Burgess, 2021; DoN, 2019a). This provides a broader scope of aircraft for training operations with F/A-18 A to F models, F-16s, F-5s, and MH-60s available from dedicated DoN aggressor squadrons, and contractor aircraft can be temporarily acquired as needed (Hunter, 2020; Naval Installations Command, n.d).

The Coast Guard and Army have not made much use of aggressor aircraft compared to the other branches of the military, which tracks with their mission sets. The Coast Guard has used both its own federal aircraft and Coast Guard Auxiliary privately owned aircraft flown by civilian volunteers to fill aggressor roles in Radar Warning and Intercept training (North American Aerospace Defense Command, 2007). The Army currently has Unmanned Aerial Vehicles purchased from contractors for target use in training (Howard, 2018).

Problem Areas and Research Questions

The DoD's sustainment base is not sufficient to meet current requirements for the aircraft fleet. This is due to two decades of combat operations, aging infrastructure, and a shrinking and vulnerable commercial supply chain with many single-source suppliers (DoD Interagency Task Force [ITF], 2018). The sustainment benefit of CAS aircraft being utilized is that the government incurs the cost of a block of sorties from the contractor, who absorbs the capital costs of airframe hours burned off their aircraft and the resulting cost of downtime and maintenance. Furthermore, the contractor has an incentive to provide the contracted services at a minimum cost, while also absorbing the risk to aircraft and aircrews from training losses.

This research explores the gap in understanding on the impact to the government from a fleet sustainment and fiscal perspective of using COCO assets for aggressor training in lieu of traditional government-owned, government-operated aggressor aircraft. The purpose is to explore how the government has been impacted by the use of private contractors for aggressor training and to apply this knowledge to the constrained fiscal environment under which America's military aircraft fleet must operate. Additionally, the research gathers valuable information for the DoD regarding the impact of the use of contract aircraft on fleet sustainment and fiscal resources. It draws extensively from government and industry publications as well as media articles, and is, to our knowledge, the first academic study on this topic.

This rest of this article is organized as follows: The literature review considers various government, industry, academic, and media sources. The methods section will discuss the process used to gather operating cost data. The data analysis breaks down the calculations and formulas used to calculate a more accurate organic aircraft operating cost, then compares and contrasts that to the cost for contract aircraft. The final section includes the conclusions, recommendations based on the analysis and findings, and proposed future research topics.

Literature Review

Chapter Overview

The literature review focuses on reports, articles, and papers pertaining to aircraft sustainment, contracting aggressor aircraft, and the fiscal impact to the government. It provides data on the decreased health of the DoD's aircraft fleet and sustainment base, the increased demand for aggressor hours, and the CAS industry. This review seeks to outline the gap in research surrounding the impact of the use of CAS companies on fleet sustainment and government finances.

Why Contracted Air Support?

> In the world we're living in now, I don't want to have to trade an actual fighter squadron for an aggressor squadron because of limits on my budget. The next best thing is to see if we can contract some of that Red Air out.
>
> —Air Force General Mike Holmes (Giangreco, 2017, para. 8)

Aggressor sorties are undergoing significant change across the DoD. As fifth-generation aircraft come into the fleet, the demand for Red Air will increase due to the requirement for more opponents in training (Ausink et al., 2011). CAS fills part of the training gap caused by lack of organic resources, minimizes the impact to the government's fragile sustainment base, and is sometimes more cost-effective than using government aircraft and crews. It also allows unique training opportunities for military aircrews by providing them with adversary aircraft not found in the United States inventory. The aggressor units currently in service with the DoD all fly aircraft from the United States (Axe, 2014; Naval Installations Command, n.d.; Nellis AFB Public Affairs, 2012; USAF, 2008).

Impact of Limited Sustainment Capability

The DoD's sustainment capacity for all branches has been stretched near the point of failure. A report on the defense industrial base directed by Executive Order 13806 states:

> Since 2001, the DoD has operated at a very high tempo with unprecedented system usage in support of global deployments, changing previously accepted formulas that compute maintenance requirements … Overuse and underfunding in infrastructure and workforce has [*sic*] eroded materiel readiness levels and facility conditions, directly impacting DoD's ability to repair equipment and materiel quickly to ensure availability for training and future deployments. (DoD ITF, 2018, p. 23)

In a 2019 report to the Senate, the Government Accountability Office (GAO) found that 12 of 21 depots for air, ground, and sea assets surveyed had an average facility rating of "poor," and that 15 of 21 depots had equipment with an average age beyond its useful life (GAO, 2019). The DoD must identify ways to reduce the burden on the government's organic depots while maintaining combat readiness of its aircrews and maintenance personnel through training operations.

The U.S. Government operates 17 major organic depots to maintain almost 14,000 aircraft. This is a large enterprise, and much of it is aging along with the aircraft fleet (DoD ITF, 2018). Throughput at depot facilities is delayed, which can be in part attributed to a diminished public industrial base as well as degraded infrastructure and equipment (DoD ITF, 2018; GAO, 2018b, 2019). From Fiscal Years (FY) 2007 to 2017, the GAO identified a 45% decrease in on-time output from Naval Aviation depots, and a 17% decrease in on-time output from Air Force depots (GAO, 2019). The equipment at the Ogden, Oklahoma City, and Warner Robins Air Logistics Complexes (ALCs) has exceeded its useful life by an average of just over 11 years (GAO, 2019). In addition to normal Programmed Depot Maintenance (PDM), the depots need to work on major modifications and repairs to aircraft, such as an F-15 C and D model longeron replacement program and the radar modernization program, which installs AESA radars on F-15Es (J. MacPherson, personal communication, November 20, 2019). Additionally, unscheduled work is pushed out to the field through Time Compliance Technical Orders (TCTOs) such as TCTO 1694, which involves the inspection of certain longerons on F-15Es to prevent the aircraft from coming apart in flight (USAF, 2019a).

The requirement to send depot-level work out to the field illustrates how the depots' maintenance burden increases as the fleet ages. As the depot's capacity is exceeded, work that is normally performed at depot but does not require unique tooling and/or rare maintenance qualifications is sent to units in the field. This in turn has a direct impact on aircraft availability because the units' maintenance burden goes up without a corresponding increase in maintenance capacity. The increased maintenance work in turn means more and longer shifts for maintainers and embedded logistics personnel, which increases burnout and decreases retention. Aircrews also have an additional burden as they are required to conduct check flights that would have been previously flown at the depot, and they may have to limit training sorties due to reduced aircraft availability.

> **The DoD must identify ways to reduce the burden on the government's organic depots while maintaining combat readiness of its aircrews and maintenance personnel through training operations.**

A bottleneck of depot capacity means that operational squadrons can experience delays in having aircraft returned to them from a depot or may have aircraft delayed in going to a depot, which requires an engineering disposition to ensure that it will be safe. This decrease in aircraft availability can mean increased use of a smaller pool of airframes, which can induce the "death spiral," as maintenance needs increase and airframe life decreases more than the rest of the fleet. Admiral Troy Schoemaker, then-Commander of Naval Air Forces, testified to Congress that the Navy had to pull 94 F-18s from squadrons ashore to bring embarked squadrons up to the required number of aircraft for deployment. He stated:

> That strike fighter inventory management, or shell game, leaves nondeployed squadrons well below the number of jets required to keep aviators proficient and progressing toward their career qualifications and milestones, with detrimental impacts to both retention and future experience levels. (*Aviation Readiness*, 2017, p. 5)

The remaining aircraft in the nondeployed squadrons will be utilized more as a result of the moves.

The depot bottleneck can be eased, in part, by decreasing the need for using organic depot assets. The government can focus manpower and funding to modernize and increase the capabilities of its organic depots to ensure a long-term solution for the depot bottleneck (DoD ITF, 2018). This will increase the availability of organic depot capacity for fleets that are core to the warfighting mission and will allow the use of contractors as necessary to maintain smaller aircraft fleets.

The defense industry maintains company-owned depot facilities, which service aircraft and components on a contract basis for the United States, partner nations, and the private aviation industry. For example, Northrop Grumman provides depot-level maintenance to the DoN for its F-5 aggressor fleet (Northrop Grumman, n.d.). The former Marine Corps Deputy Commandant for Aviation, General Steven Rudder, provided a written response to Representative Joe Wilson that the L-3 depot in Canada was being utilized by the Marine Corps to perform depot maintenance on their legacy Hornets (*Aviation Readiness,* 2017). Utilizing commercial assets has virtually eliminated the legacy F/A-18 depot backlog (*Aviation Readiness,* 2017). The Air Force awarded a $900 million contract to Lockheed Martin to provide depot-level maintenance of F-16s at their facility in Greenville, South Carolina, in December 2020. This was the first award of a contract for an industry-owned fighter depot within the continental U.S. by the Air Force (Partington, 2020). F-16s will go to Greenville for depot maintenance when no additional capacity remains at the Ogden ALC in Utah, the government F-16 depot (Partington, 2020). The first F-16 was inducted at Greenville in March 2021 (Adamczyk, 2021). Additionally, Northrop Grumman is refurbishing and upgrading ex-Royal Jordanian Air Force F-5s for the CAS company TacAir (Tactical Air Support, Inc.) (Rogoway, 2017). A benefit of TacAir and its competitors utilizing the defense industrial base to support their businesses is that it provides an additional revenue stream outside of military contracts and practical experience to the supply chain. Strengthening this supply chain only benefits the U.S. and its allies as a whole.

> **The increased maintenance work in turn means more and longer shifts for maintainers and embedded logistics personnel, which increases burnout and decreases retention.**

Impact on Aircraft Availability

Aircraft availability is defined as the "percentage of a fleet that is in a Mission Capable (MC) condition and not in a depot-possessed status or unit-possessed non-reportable possession" (Air Combat Command, 2018, p. 16). Table 1 shows an example of how aircraft availability is affected by depot possession, on-aircraft maintenance, and other factors that make an aircraft non-mission capable. This illustrates how each aircraft has a greater impact on unit readiness as the overall number of aircraft possessed by a unit decrease.

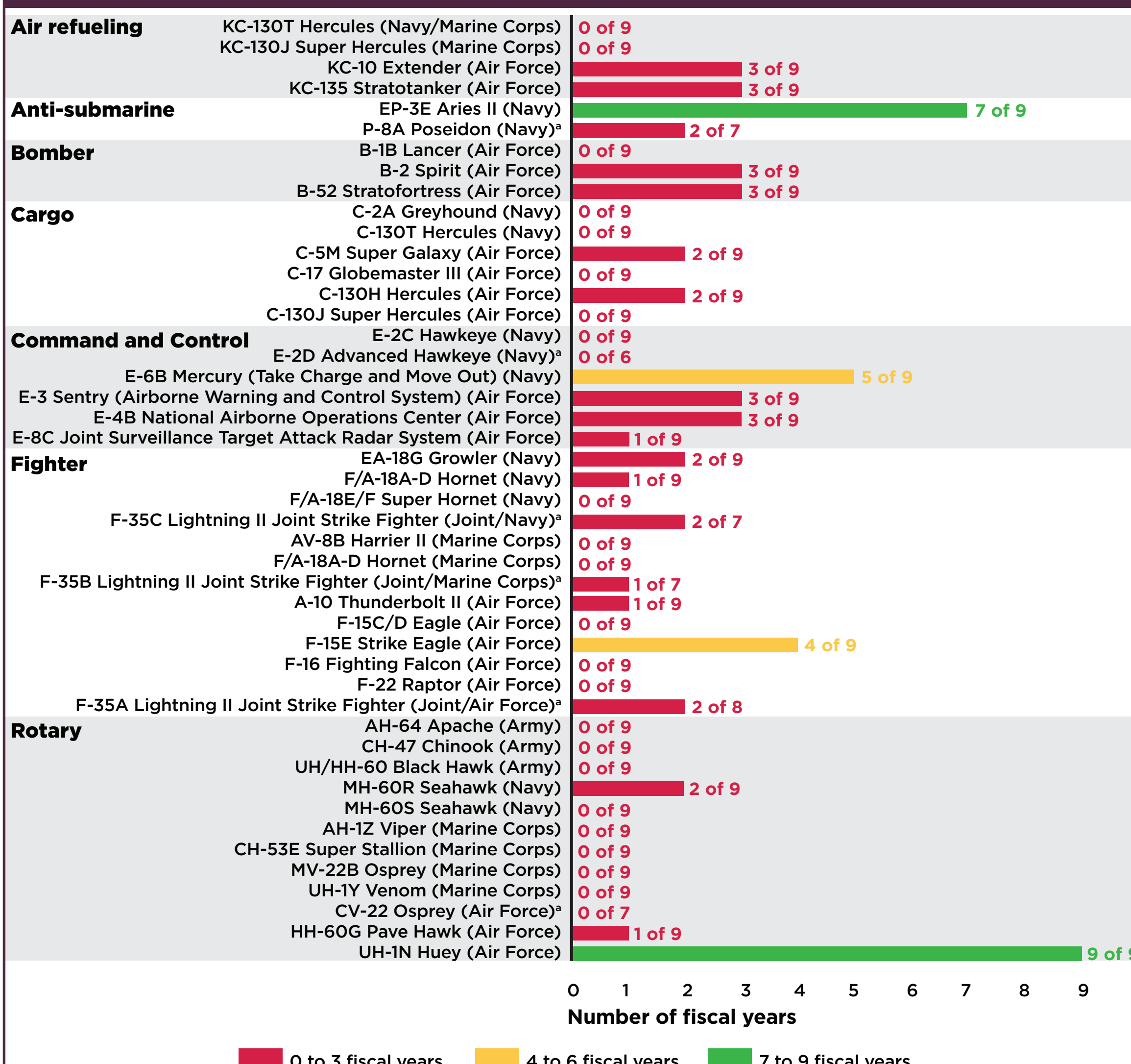
TABLE 1. AIRCRAFT AVAILABILITY CALCULATION EXAMPLE	MC	TAI	AA = ((MC/TAI)*100)
Ex.) A wing has 60 fighters. 10 are possessed by depot. 50 are possessed by the wing. 40 are mission capable.	40	50	AA = ((40/50)*100) = 80%
Ex.) The depot backlog gets worse. 20 aircraft are awaiting depot completion. 40 are possessed by the wing. 30 are mission capable.	30	40	AA = ((30/40)*100) = 75%

Note. Aircraft Availability = (Mission Capable [MC] hours/Total Aircraft Inventory [TAI] Hours)*100. Adapted from *Looking Forward with Aircraft Availability (AA)*, by J. Meserve, n.d. (https://www.sae.org/events/dod/presentations/2007LtColJeffMeserve.pdf). In the public domain.

The "death spiral" occurs as the need for aircraft remains static or increases while the available pool of aircraft shrinks due to the high usage. The way to break out of this is to decrease aircraft usage to a sustainable rate and increase maintenance capability. Utilizing contractor aircraft for aggressor missions will lessen the amount of sorties that government aircraft are flying. This will increase aircraft availability for government aircrew training sorties or for other core missions. When aircraft are flown less, their finite life in flying hours is preserved and the associated maintenance and logistics burden is minimized at the organizational, intermediate, and depot levels. If the aircraft are flown the same amount as before, but for training sorties for core missions or deployed missions, then the government is getting more utility from their aircraft than if they were burning hours flying sorties outside the scope of their primary mission.

A 2020 GAO study of 46 different types of aircraft from the USAF, DoN, and U.S. Army found that only three of the aircraft types met their Service's MC rate goal more than half the years between Fiscal Years (FY) 2011 and 2019. Six of the 13 fighters in the study did not meet the MC rate goal at all during the 9 years examined, as shown in Figure 1.

FIGURE 1. NUMBER OF TIMES SELECTED AIRCRAFT MET THEIR ANNUAL MISSION CAPABLE GOAL, FISCAL YEARS 2011 THROUGH 2019



Note. Adapted from *Weapon System Sustainment: Aircraft Mission Capable Rates Generally Did Not Meet Goals and Cost of Sustaining Selected Weapon Systems Varied Widely*, by Government Accountability Office, 2020 (https://www.gao.gov/assets/gao-21-101sp.pdf). In the public domain.

[a] These military departments did not provide mission capable goals for all 9 years for these aircraft.

FIGURE 2. SUSTAINMENT CHALLENGES AFFECTING SELECTED DEPARTMENT OF DEFENSE AIRCRAFT

	Aging Aircraft			Maintenance				Supply Support		
	Delays in acquiring replacement aircraft	Service life extension[a]	Unexpected replacement of parts and repairs	Access to technical data	Delays in depot maintenance	Shortage of trained maintenance personnel	Unscheduled maintenance	Diminishing manufacturing source[a,b]	Parts obsolescence[a,c]	Parts shortage and delay
Air refueling										
KC-130T Hercules (Navy/Marine Corps)		●	●		●				●	●
KC-130J Super Hercules (Marine Corps)		●	●	●	●					●
KC-10 Extender (Air Force)							●			●
KC-135 Stratotanker (Air Force)			●				●		●	
Anti submarine										
EP-3E Aries II (Navy)						●		●		●
P-8A Poseidon (Navy)				●						●
Bomber										
B-1B Lancer (Air Force)		●					●			●
B-2 Spirit (Air Force)									●	●
B-52 Stratofortress (Air Force)		●	●				●	●	●	●
Cargo										
C-2A Greyhound (Navy)		●	●		●	●	●	●	●	
C-130T Hercules (Navy)		●	●		●				●	
C-5M Super Galaxy (Air Force)			●				●			●
C-17 Globemaster III (Air Force)							●	●		
C-130H Hercules (Air Force)			●				●	●	●	●
C-130J Super Hercules (Air Force)			●				●	●	●	●
Command and control										
E-2C Hawkeye (Navy)			●		●	●	●	●	●	●
E-2D Advanced Hawkeye (Navy)					●	●	●	●	●	
E-6B Mercury (Take Charge and Move Out) (Navy)		●	●			●		●	●	
E-3 Sentry (Airborne Warning and Control System) (Air Force)			●					●		●
E-4B National Airborne Operations Center (Air Force)			●		●					●
E-8C Joint Surveillance Target Attack Radar System (Air Force)			●		●		●			

FIGURE 2. SUSTAINMENT CHALLENGES AFFECTING SELECTED DEPARTMENT OF DEFENSE AIRCRAFT (CONTINUED)

	Aging Aircraft			Maintenance				Supply Support		
	Delays in acquiring replacement aircraft	Service life extension[a]	Unexpected replacement of parts and repairs	Access to technical data	Delays in depot maintenance	Shortage of trained maintenance personnel	Unscheduled maintenance	Diminishing manufacturing source[a,b]	Parts obsolescence[a,c]	Parts shortage and delay
Fighter										
EA-18G Growler (Navy)					●	●		●	●	●
F/A-18A-D Hornet (Navy/Marine Corps)	●	●	●		●	●	●	●	●	
F/A-18E/F Super Hornet (Navy)		●	●		●	●		●	●	●
F-35ABC Lightning II Joint Strike Fighter (Air Force/Marine Corps/Navy)					●		●			●
AV-8B Harrier II (Marine Corps)	●		●		●	●		●	●	
A-10 Thunderbolt II (Air Force)			●					●		●
F-15C/D Eagle (Air Force)			●				●	●		●
F-15E Strike Eagle (Air Force)			●		●			●		●
F-16 Fighting Falcon (Air Force)		●	●		●		●	●		●
F-22 Raptor (Air Force)			●				●	●		●
Rotary										
AH-64 Apache (Army)					●					●
CH-47 Chinook (Army)			●		●		●	●	●	●
UH/HH-60 Black Hawk (Army)										●
MH-60R Seahawk (Navy)				●		●	●			●
MH-60S Seahawk (Navy)				●		●	●			●
AH-1Z Viper (Marine Corps)							●			●
CH-53E Super Stallion (Marine Corps)		●	●	●	●	●		●	●	●
MV-22B Osprey (Marine Corps)			●	●		●				●
UH-1Y Venom (Marine Corps)						●	●			●
CV-22 Osprey (Air Force)				●	●			●		●
HH-60G Pave Hawk (Air Force)			●		●		●	●	●	●
UH-1N Huey (Air Force)			●				●			●

Note. Adapted from *Aircraft Mission Capable Rates Generally Did Not Meet Goals and Cost of Sustaining Selected Weapon Systems Varied Widely*, Government Accountability Office, 2020 (https://www.gao.gov/assets/gao-21-101sp.pdf). In the public domain.

[a] A service life extension refers to a modification to extend the service life of an aircraft beyond what was planned.

[b] Diminishing manufacturing sources refers to a loss or impending loss of manufacturers or suppliers of items.

[c] Obsolescence refers to the unavailability of a part due to its lack of usefulness or because it is no longer current or available for production.

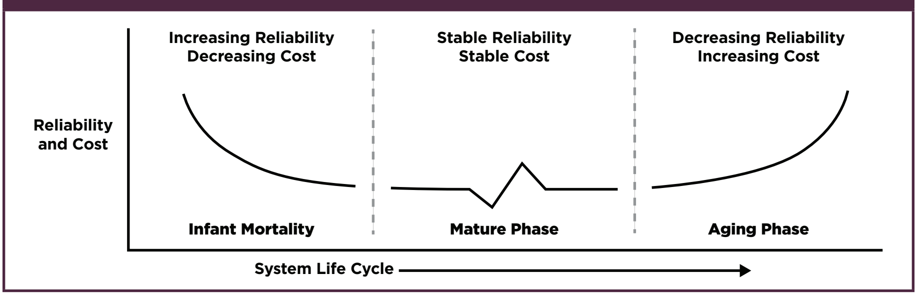
The GAO found that maintenance costs take up roughly 44% of Operations and Support (O&S) funds in FY2018 dollars for the aircraft types in the study, with maintenance costs increasing for 25 airframes, steady for four, and decreasing for 16. This fluctuation in cost can be partly attributed to planned divestitures for some aircraft types, acquiring new airframes, and increases in contractor support cost. Of the 10 fighters GAO examined for sustainment challenges, eight experienced parts shortages and delays, seven had delays in depot maintenance, nine had a diminishing manufacturing source, and eight had unexpected replacement of parts and repairs, as shown in Figure 2 (GAO, 2020). Utilizing contract aircraft can assist with aircraft availability for the fighter airframes by filling some training roles in their mission sets, thereby preserving airframe life to be used in sorties best suited to government aircraft.

Increase in Maintenance Costs of Aging Aircraft

The United States military aircraft fleet is becoming increasingly expensive to operate. This is due to both higher maintenance costs and higher capital costs; as aircraft age, modifications are performed and new airframes are acquired (DoD ITF, 2018). The government must look at the operating cost of government-owned aircraft and contractor-owned aircraft and decide which is more cost effective for eligible mission sets. The goal is to decrease costs without compromising the mission.

Maintenance costs rose for 25 of the 46 aircraft surveyed between FYs 2011 and 2019 in the Weapon Systems Sustainment study (GAO, 2020). Multiple aircraft types in the military fleet are well beyond their original service lives and are experiencing part shortages and obsolescence. This drives increased maintenance as older parts require replacement or repair and the mean time between failures shrinks. A result is a phase transition in the classic "bathtub curve" of reliability, as shown in Figure 3.

FIGURE 3. AIRCRAFT LIFE CYCLE COSTS



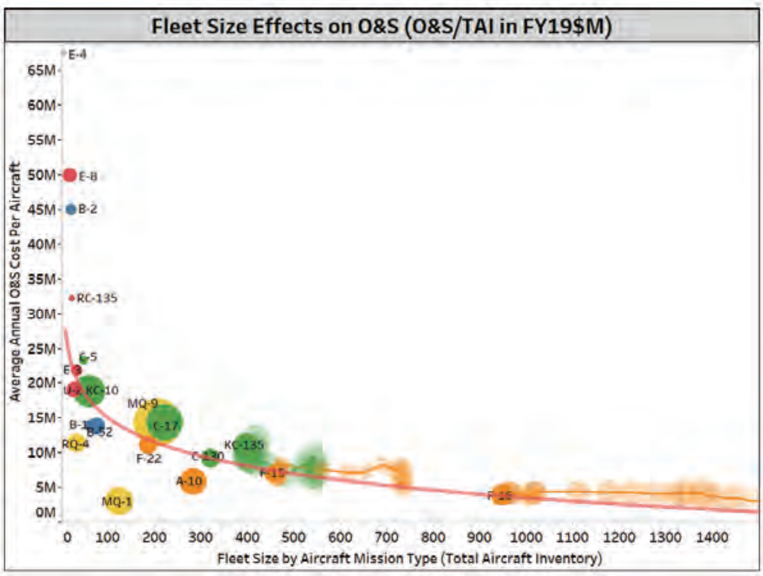
Note. Adapted from *Life Cycle Cost Modeling and Simulation to Determine the Economic Service Life of Aging Aircraft*, by K. R. Sperry & K. E. Burns, 2001. (https://apps.dtic.mil/dtic/tr/fulltext/u2/p014090.pdf). In the public domain.

Aircraft have three stages in their operational life. In the immature phase, the first variant of an aircraft is coming online. The supply chain and maintenance infrastructure are maturing, and the aircraft are becoming more reliable and cheaper to operate. Economies of scale are experienced across the enterprise. This is currently occurring with the F-35. In the mature phase, the aircraft has a stable operating cost and a stable reliability due to established performance and support infrastructure. In the aging phase, the aircraft becomes more expensive to operate and less reliable as the supply chain begins to wither and aircraft components wear out (Sperry & Burns, 2001). Our fighter fleet as a whole is transitioning into the aging phase, with an average aircraft age of 28 years. Mindful of the implications to great-power competition, General Charles Brown, the U.S. Air Force Chief of Staff, said "that's not going to compete well with adversaries" (Newdick, 2021a, para. 21).

The inconsistency of U.S. Government purchasing has been a major reason why vendors leave the defense industry (DoD ITF, 2018).

The longer the fleet can be kept in the mature phase of its life cycle, the longer it will be consistently reliable and lethal without the higher cost and sustainment effort of the aging phase. By utilizing contract aircraft for aggressor duty, the government pays a fee and has no further burden. Organic aircraft are utilized in their primary mission set, and operating life is preserved. An additional advantage of keeping fleets in the mature phase of their life cycle is that there will be larger fleets due to aircraft not being divested in the aging phase. Figure 4 illustrates the economy of scale of larger fleets. Fixed costs can be amortized over more aircraft, and inventory theory states that fewer spares must be kept on hand for the same fill rates (Center for Strategic and International Studies [CSIS], 2021). This benefits the sustainment base by being able to purchase consistent and/or large lots of components. The inconsistency of U.S. Government purchasing has been a major reason why vendors leave the defense industry (DoD ITF, 2018). Additionally, an increased number of human and capital resources can be concentrated on maintaining a given fleet without having to lose throughput while adjusting focus to sustain another airframe.

FIGURE 4. FLEET SIZE EFFECTS ON OPERATIONS AND SUSTAINMENT



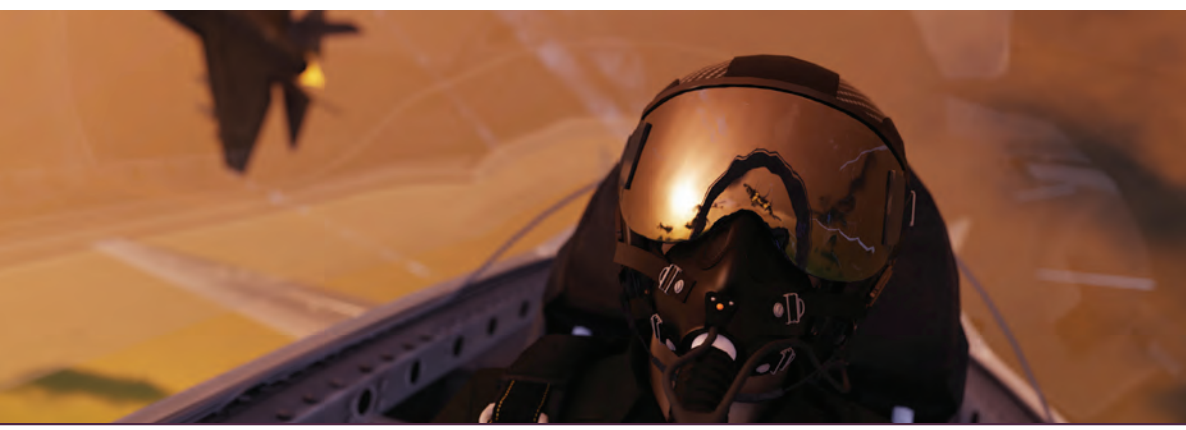
Note. Adapted from *MITRE U.S. Air Force Aircraft Inventory Study Executive Summary*, by Center for Strategic and International Studies, 2018 (https://aerospace.csis.org/wp-content/uploads/2019/09/MITRE-AF-Summary.pdf). In the public domain. O&S = Operations and Support; TAI = Total Aircraft Inventory.

Gaps in Organic Adversary Capability

The demand for private companies able to support military training requirements is growing as the operating cost of legacy fighters continues to rise and aircraft are retired as the F-35 is fully integrated. Demand for adversary aircraft should increase, and newly retired fourth-generation fighters will be available for purchase by Red Air companies such as Top Aces and AIRUSA (Hudson, 2021; Hunter, 2021; Rogoway, 2022). Fifth-generation fighters require a larger number of adversaries in training to effectively replicate higher end combat scenarios. Due to the higher operating cost of each airframe, it is not fiscally feasible to have squadrons with fifth-generation aircraft fly their own Red Air (Ausink et al., 2011).

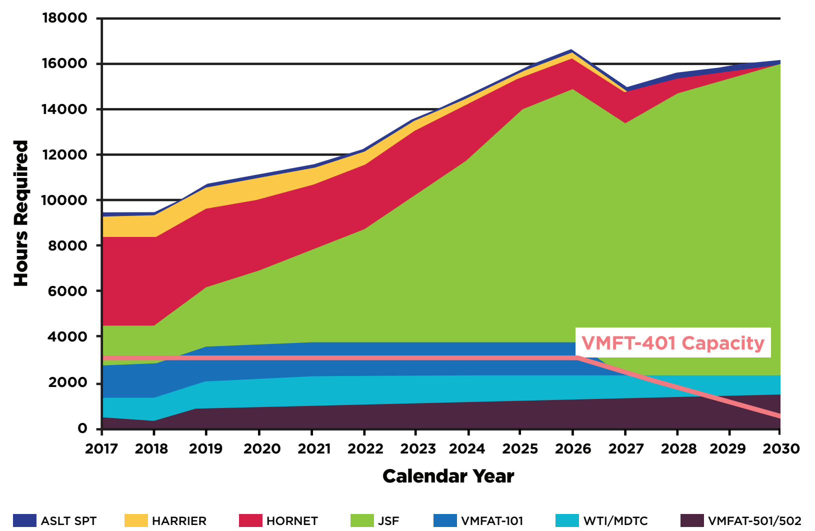
The USAF is utilizing CAS at Nellis AFB, Kingsley Field, and other bases, and more have been added under the Combat Air Force/Contracted Air Support (CAF/CAS) contract (DoD, 2019; USAF, 2017). The DoN has contract air support at several of their installations to provide training to embarked units as well as shore-based forces. This will decrease the number of hours put on government airframes flying as Red Air.

The USAF began its large push towards utilizing contract adversaries in 2016 (USAF, 2017). After the closing of the 65th AGRS at Nellis AFB, Draken International was awarded a 1-year contract worth $4.5 million to fly aggressor lines at Nellis (Giangreco, 2017). Draken was founded in 2012 and is a CAS company that provides adversary air, electronic attack, target towing, and other services in the United States and Europe (Draken, 2021). Draken will be providing adversary services at Nellis until June 4, 2022, under the current contract (Gustafson, 2018; Rogoway, 2022). The CAF/CAS indefinite delivery/indefinite quantity contract the Air Force awarded in 2019 secured a significant training capacity (DoD, 2019). The two aggressor squadrons currently fielded by the Air Force, plus units flying their own Red Air, will not be enough to meet the demand for training hours. The number of hours in the CAF/CAS contract exceeds current industry capacity, which is reflected in the expansion of the private fighter fleets of several CAS companies mentioned earlier in this article.



The U.S. Marine Corps (USMC)'s 2018 Aviation Plan projects a need for adversary hours well in excess of what their single adversary squadron can support. As shown in Figure 5, the shortage for 2019 is roughly 8,000 hours. This must be flown by aircraft other than those in VMFT-401. In 2026, the projected shortage for adversary hours is about 13,500 hours, with squadron capacity projected to decline to about 500 hours in 2030. This leaves significant gaps in what the organic aggressor assets can support (USMC, 2018). The aggressor squadrons organic to the other branches of the Service will already be in heavy demand by their own branches, so they will not be available to backfill the unfulfilled training hours. The demand for adversary hours in excess of what the organic resources can support is why the CAS companies are a very valuable training asset for the military.

FIGURE 5. U.S. MARINE CORPS ADVERSARY (AIR TO AIR) REQUIREMENTS



Note. Adapted from *2018 Marine Aviation Plan*, by U.S. Marine Corps, 2018 (https://www.aviation.marines.mil/Portals/11/2018%20AvPlan%20FINAL.pdf). In the public domain. ASLT SPT = Assault Support; JSF = Joint Strike Fighter; VMFAT = U.S. Marine Fighter Attack Training Squadron; VMFT = U.S. Marine Fighter Training Squadron; WTI/MDTC = Weapons & Tactics Instructor/Marine Division Tactics Course.

Admiral John Mustin, Chief of the Navy Reserve, said:

> Within the next decade, 62% of the Navy Reserve's current Adversary aircraft will be retired due to the high cost of each service hour, or because they have reached the end of their service life. Recapitalization and expansion of Adversary capacity in the Navy Reserve presents a cost-effective, sustainable solution to develop warfighting readiness. In FY20, active component Strike Fighter squadrons flew 13,129 hours of Adversary support, generating more than half of the total Navy Adversary hours while adding costly flight hours on inventory-limited fleet aircraft. (*Appropriations,* 2021, p. 16)

This represents a very significant projected gap in capability within an essential mission area of the Naval Aviation Reserve component (dedicated adversary units are only in the Navy Reserve) (Hunter, 2020). The reported plans to acquire F/A-18 Super Hornets and surplus Air Force F-16s bring newer aggressors into the high-end fight, increasing training value, and also partly mitigating sustainment concerns (*Appropriations,* 2021; Hunter, 2020).

Capabilities of Contract Aggressors

Adversary air companies are purchasing third-generation fighters, such as the Mirage F1 and the F-5, and upgrading them to be able to "simulate advanced threat aircraft capabilities and tactics in an (air-to-air) environment" among other requirements (Air Combat Command, 2017a, p. 5). Additionally, fourth-generation fighters have been acquired by several companies. Top Aces bought 29 early-block F-16s from Israel, and AIRUSA purchased 46 F/A-18 A and B models from the Royal Australian Air Force (RAAF)—the entire remaining fleet after the Australians sold 25 F/A-18s to Canada (Hudson, 2021; Hunter, 2021; Rogoway, 2022). Aircraft features essential for replicating a threat aircraft are maneuverability, radar cross-section, helmet-mounted display, fire-control radar, infrared search and track system, and electronic attack capability (Felker, 2020).

The wide variety of aggressor aircraft available for contract or purchase offers multiple opportunities for DACT, as well as significant expansion of fourth-generation adversary capacity by 75 aircraft, depending on contract options (Hudson, 2021; Hunter, 2021; Rogoway, 2022). The various contract aircraft types allow for many different flight profiles and missions, such as air intercept, low-and-slow aircraft, supersonic aircraft, cruise missile simulation, electronic attack, Basic Fighter Maneuvers, close air support, Beyond Visual Range training, Offensive Counter-Air, and Defensive Counter-Air (ATAC, n.d.; Draken, 2021; Top Aces, n.d.).

Performance Concerns and Limitations of Contract Aggressors

Aircraft modifications and certain organic capabilities are essential for ensuring that adversary aircraft can present a realistic threat in multiple aspects of combat training. Detailed examples of contract aircraft capabilities are provided in Appendix A. The third-generation fighters' overall effectiveness as a threat is increased considerably over the original model due to the upgrades, but they are still limited in pure aircraft performance by the older engine and airframe designs. Mustin stated in testimony to the House that the Navy maintains F-5s (third-generation fighters) "to provide low-to-mid level threat replication" (*Appropriations,* 2021, p. 15). The fourth-generation fighters bring an aircraft performance advantage to the fight right away with their newer airframe designs and more powerful engines when compared with third-generation aggressors. A potential higher contract cost of fourth-generation aggressors compared to third-generation offerings is not known at the time of this writing.

Top Aces is mitigating the older avionics of its early-block F-16s with upgrades, and the AIRUSA F/A-18s are being acquired in the same operational configuration they had in the RAAF (Hudson, 2021; Rogoway, 2022; Top Aces, 2021). However, as noted out of Navy Aggressor units, contractual limitations, regardless of aircraft and crew capabilities, may limit the operational performance of the contract aircraft, even for basic fighter maneuvers (Hunter, 2020). Similar capability concerns have been brought up with regard to the Air Force's ADAIR contract. The issue is whether advanced adversary fighter capabilities are being adequately represented and even whether the contract aircraft are equivalent to the current F-16C aggressors (Felker, 2020). While acknowledging the limitations of current contract aggressors, the DoD still needs aggressor capacity and cannot fill the gap organically. Contract aggressors are able to fill many needed training lines with no sustainment impact to the DoD and at a lower cost per flying hour.

Use of Simulators

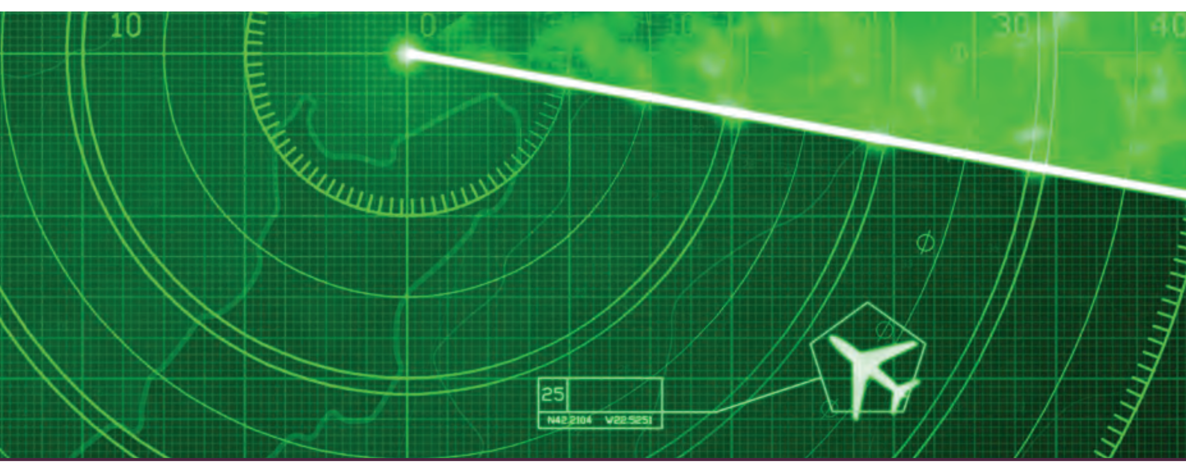
Simulators are used in military and industry for emergency procedures, practicing specific actions, or full missions. As the technology develops, the utility of simulators for air combat training will increase. In Laird (2014), Rear Admiral Scott Conn, former Commander of the Naval Strike and Air Warfare Center said:

> ...in a simulated environment, I can have aircrew jump in a device, and I can train them at the integrated level across the entire kill chain for various missions. I can conduct this high-end training very quickly, a lot of reps and sets if you will, at reduced cost. (p. 37)

Use of simulators will additionally reduce the sustainment burden as well as the cost of operating aircraft, but it is not a substitute for live flight (Laird, 2014).

Future Organic Aggressors

A future low-cost adversary aircraft could be a modified version of Boeing's T-7A Redhawk or the Lockheed Martin-Korea Aerospace Industries (KAI) T-50 (Lockheed Martin, 2022; SecAF Public Affairs, 2019b). Being able to field a fleet of cost-efficient dedicated aggressors would provide organic resources to meet training requirements without negatively impacting the fleet health of our dedicated combat aircraft. The DoD as a whole could follow the DoN's example and look overseas to purchase more low-time F-5s in order to bolster the aggressor fleet (Axe, 2014). By leveraging resources already in place for T-7s, the CAF can take advantage of the efficiencies gained through a large fleet of the same basic aircraft type to minimize cost and burden on the sustainment base (CSIS, 2021).



The Air Force is planning to utilize low-rate initial production F-35As in the 65th AGRS to provide its initial aircraft (Felker, 2020; National Defense Authorization Act, 2019; SecAF Public Affairs, 2019a). This provides an organic fifth-generation dedicated aggressor force, which is essential for accurately replicating fifth-generation threats in near-peer fights (Felker, 2020). As the F-35 fleet grows, the CAF can leverage efficiencies in fleet size, just as the T-7 referenced earlier, to minimize the cost and sustainment burden (CSIS, 2021).

Mustin is proposing that Naval Aviation acquire used Air Force F-16s to employ in the Navy Reserve's aggressor fleet (*Appropriations,* 2021). It was also reported that the VFC-12 "Fighting Omars," which had been operating legacy F/A-18s, will receive Block 1 F/A-18 E and F's (Hunter, 2020). The Navy will not have enough older Super Hornets to replace the legacy aggressor F-18 A to D models that it is divesting (*Appropriations,* 2021). Replacing some of the legacy Hornets with F-16s rather than Super Hornets will allow for DACT opportunities between dedicated aggressors flying F-16s and regular Naval Aviation units flying Super Hornets (Newdick, 2021b). Additionally, the Navy will be able to utilize the existing Air Force supply chain and large sustainment base to its benefit for the F-16s (CSIS, 2021). The Navy will still be using older aggressor aircraft, which will require more maintenance, but keeping flying hours down across combat-coded Naval Aviation units will keep those aircraft in fighting condition for longer.

Literature Conclusion

A literature gap is pervasive throughout DoD on the growing depot, sustainment, and maintenance burden from aging aircraft and on the underutilization of CAS companies. Maintenance metrics were shown to demonstrate the potential death spiral effect that limited aircraft availability can have on an already heavily tasked fleet. As aircraft age, the maintenance effort and operating cost drastically increase. There is a gap in organic aggressor capabilities, and analysis is needed to understand the potential impact on training and the sustainment enterprise. To meet demand, the military is repurposing older, but still capable, fourth-generation aircraft as aggressors as well as contracting Red Air companies. The capabilities and limitations of contract aggressors are discussed so their use can be considered with a clear understanding of how training may be impacted. Appendix B is a full overview of CAS companies, which demonstrates the breadth and capabilities of the industry and what it can offer to the U.S. Government. This research contributes to the DoD's body of knowledge by demonstrating the impact that additional use of contract aggressors may have: It is a potential trade-off of increased aircraft availability and decreased sustainment burden on the organic fleet versus potential shortcomings in the performance of contract aircraft as compared to fourth- or fifth-generation aggressor aircraft.

Methodology

Data Collection

Government publications, industry publications, and media articles were used for source data on the aggressor mission, CAS industry, and aircraft sustainment and operating costs. Table 2 summarizes the type, source, and range of data used in the analysis.

Data were gathered in three ways. First, relevant metrics were taken from the publications and sources referenced in Table 2. Second, raw data were gathered from the Navy's VAMOSC and the AFTOC databases for the relevant airframes. Third, personnel involved in Service Life Extension Programs (SLEPs), or modification programs, were contacted for data. Obtaining operating costs and other competitive information from the individual contracting companies was difficult, as this is sometimes proprietary information and can affect bids. The authors have taken precautions to ensure any information that could impact a bid is properly controlled. Classified data are not utilized. For Official Use Only (FOUO) information was used in the initial, limited distribution study, but all bid-specific data have been removed from this article. It can be made available upon request to authorized requestors.

TABLE 2. DATA SOURCE TABLE

Data Type	Source	Use
Aircraft Data	VAMOSC AFTOC Selected Acquisition Reports Media Articles Subject Matter Experts	Identify inventory, cost data, SLEP/SLM, modifications, airframe life
Contract Air Support	Industry Websites GAO Media Articles	Company Red Air fleet size, fleet makeup, hours flown, what entities have used contracted Red Air
Fiscal	GAO CSIS FedBizOpps Media Articles	Cost of purchase, SLEP/SLM, modifications; contract award data
Sustainment	GAO CSIS DTIC ETARs RAND Subject Matter Experts	Fleet size, state of depot infrastructure, SLEP/SLM, modifications, examples of fleet-wide repairs
Congressional Briefings	Air Combat Command Homeland Security Digital Library	Adversary air plans and data, impact of sustainment limitations

Note. AFTOC = Air Force Total Ownership Cost; CSIS = Center for Strategic and International Studies; DTIC = Defense Technical Information Center; ETARs = Engineering Technical Assistance Requests; GAO = Government Accountability Office; SLEP = Service Life Extension Program; SLM = Service Life Modification; VAMOSC = Visibility and Management of Operating and Support Costs.

TABLE 3. AGGRESSOR CONTRACT COST PER FLYING HOUR				
Organization	Award Cost (millions)	Annual Flt Hours	Contract Length	CPFH
USN NAS Fallon	$118.90	1,700	5	**$13,988**
USAF Nellis ADAIR II (low est)	$280	4,500	5	**$12,444**
USAF Nellis ADAIR II (high est)	$280	5,600	5	**$10,000**
USAF CAF/CAS	6,400	36,162 (sorties)	10	**$17,698**

Note. ADAIR = Adversary Air; CAF/CAS = Combat Air Force/Contracted Air Support; CPFH = Cost Per Flying Hour; Flt = Flight; NAS = Naval Air Station; USN = U.S. Navy.

Analysis Methods

The operating costs published by the Office of the Under Secretary of Defense (Comptroller), or OUSD(C), do not reflect the capital costs of original airframe purchase or follow-on modifications. Additionally, depreciation of the airframe's value to the government was not accounted for in the data. To enable increased accuracy of analysis of the cost per flying hour (CPFH), the capital costs of each Mission Design Series were factored into the CPFH. Microsoft Excel spreadsheets were used to aggregate data by airframe for the government aircraft and to aggregate data by contract for the Red Air companies.

Table 3 shows the initial purchase cost, original airframe life, cost of a service life extension, the total amount of airframe hours the life was extended by, and the cost of any major modifications. All costs were then normalized to Fiscal Year 2017. The data were used to calculate hourly operating costs for government aircraft based on capital and operating costs. The capital cost was then divided by the airframe life (hours) to determine how much the airframe would depreciate per flight hour. The depreciation per hour was added to the Operations and Maintenance (O&M) cost published by the OUSD(C) (2017). Equation 1 shows the breakdown in the CPFH for government aircraft (Boito et al., 2015).

$$Government\ CPFH = DoD\ O\&M\ Hourly\ Cost + \left(\frac{Capital\ Cost\ of\ Airframe}{Airframe\ Life\ in\ Hours}\right) \quad (1)$$

The hourly operating cost of a contractor aircraft was determined based on the award value and contracted flight hours. The award value and contracted number of flying hours were obtained for Red Air contracts at several Air Force bases and naval air stations (NAS). The contract cost, substituted for O&S costs and divided by the contracted flying hours, is shown in Equation 2 (Boito et al., 2015).

$$Contract\ CPFH = \left(\frac{Contract\ Award\ Value}{Contracted\ Flying\ Hours}\right) \quad (2)$$

Government CPFH

Ownership cost data were obtained from the AFTOC database and the VAMOSC database. These data include multiple cost metric categories and were used to calculate operating cost with full-spectrum expenditures. These data include the capital costs of the aircraft, including the initial purchase price, modifications, SLEPs, and fiscal year constant dollars for all government expenditures. The ownership cost data were amortized by the authors across an aircraft's life in flying hours to identify the CPFH for government-owned aircraft.

Calculations were made to estimate the CPFH of government aircraft using open-source information as well as AFTOC, VAMOSC, and other government sources. This was accomplished for aircraft listed as filling adversary roles for their respective military branches by obtaining the purchase price, cost of a SLEP, the cost of any major modifications, and then normalizing the financial data to FY2017 by using the Annual Average Consumer Price Index Research Series (U.S. Bureau of Labor Statistics, 2022). After normalization, Equation 1 was used and the costs were divided by the total airframe life in hours after any SLEPs had been performed (Boito et al., 2015). The OUSD(C)'s reported O&M cost per flying hour (which includes direct operational costs such as fuel, maintenance, aircrew pay, etc.) was then added, and a working estimate for the CPFH was obtained.

Results and Analysis

This section analyzes the operating costs of government aircraft, including depreciation of the airframe value, and compares and contrasts that data with the CPFH of a contracted aircraft within several contract air support awards. We show the CPFH of both contract and government aircraft (Table 4, Table 5) and discuss the impact to the government.

TABLE 4. DEPARTMENT OF DEFENSE AIRCRAFT COST PER FLYING HOUR

Equation 3: Government CPFH = DoD O&M Hourly Cost + (Capital Cost of Airframe/Airframe Life in Hours)

MDS	DoD O&M Hourly Cost (OUSD(C) 2017)	Capital Cost of Airframe (Including SLEP/ modifications) Normalized to FY2017 Dollars	Airframe Life in Hours (including SLEP)	Capital Cost Amortized per Hour (Boito et al., 2015)	O&M + Amortized Capital Cost = Total Cost per Flying Hour	Fleet Size (Total Force)	Sources of Data for Calculating Cost per Flying Hour
USAF				*E/F*	*B+G*		
A	*B*	*E*	*F*	*G*	*H*		
F-15C	$20,792.00	$45,068,475.99	9,000.00	$5,633.56	$25,799.61	249 (split C/D)	(Trimble, 2011; USAF, 2019b)
F-15D	$21,117.00	$45,068,475.99	9,000.00	$5,633.56	$26,124.61	249 (split C/D)	(Trimble, 2011; USAF, 2019b)
F-15E	$16,659.00	$54,577,244.26	8,000.00	$6,822.16	$23,481.16	219	(Trimble, 2011; USAF, 2019c)
F-16C	$7,692.00	$30,680,147.70	12,000.00	$2,556.68	$10,248.68	1017 (split C/D)	(Garbarino, 2018; USAF, 2015)
F-16D	$7,663.00	$30,614,287.39	12,000.00	$2,551.19	$10,214.19	1017 (split C/D)	(Garbarino, 2018; USAF, 2015)
F-22A	$35,294.00	$176,068,248.50	8,000.00	$22,008.53	$57,302.53	183	(Majumdar, 2017; USAF, 2021b)
F-35A	$17,243.00	$87,073,255.62	8,000.00	$10,884.16	$28,127.16	435+ (split A/B/C)	(Insinna, 2018; Lockheed Martin, 2018, 2021)
T-38	$3,326.00	$7,615,583.68	12,000.00	$634.63	$3,960.63	546	(Archer, 2015; Essary, 2017; Lloyd, 2018; USAF, 2014)
USN/ USMC							
F-16A	$8,067.00	$22,006,680.58	8000.00	$2,750.84	$10,817.84	10	(DoN, 2019b; USAF, 2015)
F-16B	$8,627.00	$22,006,680.58	8000.00	$2,750.84	$11,377.84	4	(DoN, 2019b; USAF, 2015)
FA-18E	$10,832.00	$70,629,956.75	9000.00	$7,847.77	$18,679.77	274	(Boeing Media, 2018; Larter, 2018; Secretary of the Navy, 2015, 2018)
FA-18F	$10,948.00	$70,629,956.75	9000.00	$7,847.77	$18,795.77	234	(Boeing Media, 2018; Larter, 2018; Secretary of the Navy, 2015, 2018)
F-5E/F	$3,326.00	$924,470.44	1500.00	$616.31	$3,942.31	43	(NAVAIR News, 2021; Secretary of the Navy, 2005, 2008)

Note. CPFH = Cost Per Flying Hour; DoD O&M = Department of Defense Operations and Maintenance; MDS = Mission Distribution System; OUSD(C) = Office of the Under Secretary of Defense (Comptroller); SLEP = Service Life Extension Program; USAF = U.S. Air Force; USMC = U.S. Marine Corps; USN = U.S. Navy.

TABLE 5. AGGRESSOR CONTRACT COST PER FLYING HOUR

Equation 2: Contract CPFH = Contract Award Value/Contracted Flying Hours

Award Cost	Annual Flight Hours	Years of Contract	Cost Per Flight Hour	References
U.S. Navy NAS Fallon				
$118.9 million	1,700	5	—	(Boito et al., 2015; GAO, 2018b; Hudson, 2018a; Rogoway & Trevithick, 2018)
CPFH = $118.9 million/(1,700 hours*5 years)			=$13,988.24	
U.S. Air Force Nellis ADAIR II				
$280 million	4,500 (low estimate)	5	—	(Air Combat Command, 2017a; Boito et al., 2015; Howarth, 2018; Hudson, 2018b)
CPFH = $280 million/(4,500 hours*5 years)			=$12,444.44	
$280 million	5,600 (high estimate)	5	—	
CPFH = $280 million/(5,600 hours*5 years)			=$10,000	
Award Cost	**Estimated Annual Sorties**	**Years of Contract**	**Cost Per Flight Hour**	**References**
U.S. Air Force CAF/CAS				
$6,400,000,000	36,162	10	—	(Air Combat Command, 2017b, 2017c, 2017d, 2017e, 2019; Boito et al., 2015; DoD, 2019; Giangreco, 2017; Hudson, 2020).
CPFH = $6.4 billion/(36,162*10)			=$17,698.14	

Note. ADAIR = Adversary Air; CAF/CAS = Combat Air Force/Contracted Air Support; CPFH = Cost Per Flying Hour; NAS = Naval Air Station.

Combat Air Force Contract Air Support CPFH

The CAF ADAIR contract was awarded on October 18, 2019, to seven companies as part of an indefinite delivery/indefinite quantity contract not to exceed $6.4 billion. The contract is estimated to be complete in 2024 but could run up to 10 years. The performance work statements in the 2017 solicitation are: Eglin AFB (Air Combat Command, 2017b); Hickam AFB Support, Kelly Field Annex Support (Air Combat Command, 2017c); Tyndall AFB (Air Combat Command, 2017d); Langley AFB (Air Combat Command, 2017e); and Kingsley Field Air National Guard Base (Air Combat Command, 2017f), totaling 14,936 hours of flying by contract adversaries. A minimum guarantee of $15,800,000 was obligated for FY2020 upon the contract award (DoD, 2019). The CPFH was calculated using Equation 2 and utilizing data from the Air Force's 2017 Adversary Air Plan, Hudson's (2018a) Red Air article, and the CAF/CAS award information. The award cost was substituted for total O&S costs and divided by the estimated flying hours of the 10-year contract (Air Combat Command, 2017a, 2019; *Air Force Magazine,* 2017; Boito et al., 2015; Crews, 2018; DoD, 2019; Giangreco, 2017; USAF, 2017). The average contract air CPFH is estimated to be $17,698.

Nellis ADAIR II Contract CPFH

Draken International was awarded a contract capped at $280 million to provide adversary air services at Nellis AFB in the spring of 2018 (Gustafson, 2018). According to the solicitation notice, the contract is for a period of 5 years and is for a range of flying hours between 4,500 and 5,600. The government will disburse $56,000,000 per year during the contract. The CPFH at the low and high ends of the hour range was calculated using Equation 2 (Boito et al., 2015). If Draken flies only 4,500 hours per year, the cost will be $12,444 per flight hour, and if 5,600 hours are flown per year, the cost will be $10,000 per flight hour.

U.S. Navy NAS Fallon Contract

TacAir was awarded a contract to fly adversary air at NAS Fallon in support of the Naval Aviation Warfighting Development Center (NAWDC) and the Navy Strike Fighter Tactics Instructor Program (GAO, 2018a). The solicitation stated the contract duration is for 5 years and is capped at $235 million (GAO, 2018a). TacAir bid $118.9 million to fly their F-5 aircraft, which is well under the cap and won the contract despite a protest by their competitor, ATAC (GAO, 2018a; Rogoway & Trevithick, 2018). TacAir stated that they expect to fly about 1,700 hours per year (Hudson, 2018a). Equation 2 was used to calculate the U.S. Navy's CPFH under this contract (Boito et al., 2015; GAO, 2018a; Hudson, 2018c; Rogoway & Trevithick, 2018). If TacAir flies the estimated 1,700 hours per year used in the calculation, each flight hour will cost about $13,988.24.

Cost to Government

As shown in Table 4 and as is made clear from the CPFH equation, aircraft that have longer lives are much cheaper to fly per hour than those aircraft with shorter lives. F-16s, T-38s, and F-5s are highlighted as the most economical fixed-wing aircraft with a Red Air mission set. The single most expensive aircraft to fly per hour is the F-22A. Additionally, aircraft with larger combined fleet sizes have a lower operating cost. The F-16 is currently the cheapest USAF front-line fighter and also has the largest fleet size within U.S. inventory at about 45% of the total fighter fleet (CSIS, 2021; Partington, 2020; Pawlyk, 2021). The Air Force already operates T-38 aggressors, partly due to the expense of operating the F-22 (Tirpack, 2014).

The Air Force will pay an estimated average fixed cost of $17,698 per hour to the various contract air companies under the CAF/CAS contract, or a maximum of $12,444.44 per hour under the Nellis ADAIR II contract, with no follow-on costs of depot maintenance or opportunity cost of aircrews not being combat mission ready for their primary missions. The CAF ADAIR contract CPFH is cheaper than flying F-15s, F-22s, or F-35s, and more expensive than F-16s or T-38s. The CAF ADAIR contract aircraft flying hour costs only 38% of the F-22 CPFH. The results of the data in Tables 3 and 4 show that the DoD will benefit financially from the USAF's fighter fleet (with the exception of F-16s and T-38s) being augmented in aggressor roles by contract aircraft. The F-16, F-35, and F-15E are experiencing delays in depot maintenance (GAO, 2020). The F-22 has experienced degradation of its low-observable coating as well as an unforecasted demand for components (i.e., failures; GAO, 2020). The Air Force's sustainment efforts will be aided by minimizing the burden placed on the organic depot system by the F-16, F-35A, and F-15E fleets. However, the F-16 fleet can now expand to Lockheed Martin's depot if Ogden ALC's capacity is exceeded, so the delays in depot maintenance may be mitigated due to larger capacity (Partington, 2020). The F-16 should still be considered for use as an organic aggressor due to its lower CPFH and the training value of having fourth-generation fighters as aggressor aircraft.

The DoN will not incur any of the depreciation costs or resulting maintenance of the sorties flown by contract aircraft, nor will any burden be put on the fleet readiness centers.

The DoN has more organic aggressor assets than the Air Force but needs still more aggressor aircraft. The DoN will pay $13,988.24 per contract flight hour at NAS Fallon, which is more expensive than the operating costs of NAWDC's F-16s or the F-5 fleet but is significantly cheaper than the operating costs of F/A-18 E and F models. The F/A-18 E and F models have both experienced delays in depot maintenance and have also seen unforecasted component demand (GAO, 2018a, 2020). The DoN will not incur any of the depreciation costs or resulting maintenance of the sorties flown by contract aircraft, nor will any burden be put on the fleet readiness centers. Given that the Navy has personnel shortages and maintenance delays at its depots, shrinking the amount of sustainment work for the F/A-18 fleet will benefit the Service (GAO, 2018a, 2020). The contract aircraft will also increase aircraft availability for adversary lines, which will have a positive impact on the Navy's ability to conduct combat training in line with the NDS focus on near-peer adversaries and Great Power Competition (DoD, 2018).

Conclusions and Recommendations

Conclusions

It is more cost-effective to use aggressors procured under the Air Force's CAF/CAS contract than organic F-15s, F-22s, or F-35s. However, CAS sorties, on a CPFH basis, will be more expensive than F-16 or T-38 aggressor sorties. The cost difference is especially apparent when considering fifth-generation aircraft, with the CAF/CAS flying hour costing only 38% of the F-22 CPFH. The Navy pays $13,988.24 per contract flight hour at NAS Fallon, which is a higher operating cost than NAWDC's F-16s or the F-5 fleet, but less than the operating costs of F/A-18 E and F models. Overall, the government benefits financially from contract aircraft being used in lieu of its F-15s, F/A-18s, F-22s, and F-35s. It would be cheaper for the DoD to fly its own F-16, F-5, and T-38 sorties.

The F-16, F-35, and F-15E are experiencing delays in depot maintenance, and the F-16 fleet also is receiving a SLEP (GAO, 2020; USAF, 2019a). The F-22 has experienced higher than expected demand for spares and a higher than expected degradation rate of the low observable coating (GAO, 2020). Additionally, the F-15 C and D fleet is having longerons replaced at depot, which consumes capacity (GAO, 2020; Mather, 2020). Per the data in Figure 2 and the Time Change Technical Order (TCTO), the Air Force's sustainment efforts will be aided by minimizing the burden placed on the depot system by the F-15, F-16, and F-35 fleets. Similarly, Naval Aviation will not incur any of the depreciation costs or resulting maintenance of the sorties flown by contract aircraft, nor will any burden be put on the fleet readiness centers. The F/A-18 fleet is also delayed at depot, so shrinking the amount of sustainment work for that fleet will benefit the DoN (GAO, 2018a, 2020). The F-5 fleet's depot work is accomplished by Northrop Grumman and does not impact the Navy, apart from the contractor's fee and aircraft downtime (Northrop Grumman, n.d.). The DoD's sustainment efforts will be assisted by minimizing the number of sorties flown by the F-15, F-16, F/A-18, and F-22.

Overall, the government benefits financially from contract aircraft being used in lieu of its F-15s, F/A-18s, F-22s, and F-35s. It would be cheaper for the DoD to fly its own F-16, F-5, and T-38 sorties.

Utilizing contractor air assets where it is practical and legal minimizes the hours flown on organic aircraft. This decreases the burden on an overtasked aircraft maintenance supply chain and limits wear and tear on expensive components. The depot maintenance and other costs of ownership incurred by the contractor are already included in the quote for services provided by the contractor.

Recommendations and a Way Forward

A combination of contract aircraft, lower cost DoD aircraft, and higher end DoD aircraft will provide an optimal fleet mix to meet the need for aggressor sorties while minimizing the DoD's sustainment and fiscal burden and maximizing training value. Procurement of the T-7A Red Hawk or refurbishing the F-5 and T-38 aircraft currently in the inventory will provide organic capacity to support aggressor training hours at a lower CPFH and without burning the airframe life off frontline fighters. The Air Force pursuing a similar upgrade program to the Navy's F-5 Avionics Reconfiguration and Tactical Enhancement/Modernization for Inventory Standardization (ARTEMIS) program for any F-5 and T-38 aggressors will increase utility of those aircraft for air combat training (NAVAIR News, 2021). Continued procurement of the F-35 means there will be greater efficiencies gained as the fleet size increases, which will lower the fiscal impact of using fifth-generation aircraft as aggressors. Also, more fourth-generation aircraft will become available for use in aggressor squadrons as F-35s replace them in front-line units. Additionally, the expansion of the CAS industry means that the government will continue to have the option of contracting private fleets with diverse aggressor aircraft options.

The DoN is partly taking this approach through existing CAS awards and allocated $39,676,000 in the FY2020 budget to purchase 22 F-5E/F fighters from Switzerland (Rogoway, 2019a). This will allow the DoN to increase their F-5 aggressor fleet by half at 30% the cost of a new F-35C in the FY2019 budget (DoN, 2019b; Rogoway, 2019b; Secretary of the Navy, 2018). The former Swiss F-5s will receive modernized cockpits, avionics, and associated aircraft architecture under the ARTEMIS program (NAVAIR News, 2021). The long-term benefits will include increased capacity to train aircrews with an aircraft that is historically reliable, low-maintenance, and already has established maintenance contracts with private depots, thus having little impact on organic depot capacity (Northrop Grumman, n.d.). By continuing to use CAS and sustainment services, the DoN is minimizing its sustainment workload.

The Air Force has awarded the CAF/CAS contract, securing aggressor support for the next 10 years (Giangreco, 2017). Additionally, as the T-7A trainer from Boeing and Saab begins to be procured, the Air Force can utilize those airframes as aggressors. Specifically,

> Increased adversary air sortie generation is possible because the T-X's lower operating cost—presently expected to be less than half the cost per hour of a fourth-generation fighter, and perhaps a fifth the cost of a fifth-generation fighter—allows the pilots to train more for the same, or less, cost. (Holmes, 2019, para. 25)

If many of the Air Force's aggressor sorties could be taken on by dedicated aggressors, potentially 40% of sorties within USAF operational fighter squadrons can be repurposed for training for the primary mission or cancelled (Holmes, 2019).

Increasing the organic aggressor fleet carries potential downsides. Most notably, it means funding is diverted from acquisition of combat aircraft and put into purchasing or refurbishing trainer airframes, and some combat aircraft are diverted to aggressor units. It could mean increased sustainment burden on the government depots unless sustainment contracts with private entities are procured. The personnel requirements for the aircrew, maintenance, and other workers needed to run a flying unit and staff the sustainment base are major considerations as well.

Ultimately, the DoD should increase the use of dedicated aggressors and identify a balance of contract aircraft, dedicated low-cost government aircraft, and dedicated higher end government aircraft that allow for the best training value to increase lethality and survivability while minimizing impact to the sustainment base. This research helps decision makers understand the costs and benefits of contract versus organic, and that there are trade-offs across the different solutions. Contracting out aggressor sorties and procuring low-cost organic aggressor aircraft with sustainment contracts through private entities will increase aggressor capacity and aircrew training in their primary roles while minimizing part-time Red Air sorties from front-line units and, in turn, the fiscal and sustainment burden to the government. This will have a significant impact on the readiness of the fighter fleet in terms of combat preparedness, sustainment, and fleet life. The overall operating and sustainment cost of the aircraft fleet will decrease by transferring flying hours and associated airframe life consumption from fighters to trainers or privately owned aircraft, while the operators of the DoD fighter fleet will be more effective due to increased flight time in their primary role.

The DoD should conduct a self-assessment in 3 to 5 years to see how use of contractor aggressors has impacted its sustainment efforts and financial state.

Future Research

Additional research should examine the training value provided by contract aggressor units versus DoD-owned assets. This is a major concern from within the flying communities, and is a key question that must be asked in addition to the CPFH: Is the quality of the training maintained when contract air is used? Additional research could also examine contracted aircraft options for other training missions, as well as how developing simulator technology can be used to integrate virtual assets and make live execution more effective (Laird, 2014). If a system bottleneck for aircrew training is aircraft availability, could contract aircraft help alleviate the problem? Finally, the DoD should conduct a self-assessment in 3 to 5 years to see how use of contractor aggressors has impacted its sustainment efforts and financial state. After the CAF/CAS contract has been in effect for several years, the Air Force will have sufficient data to assess the actual cost of these programs and how the use of contract aircraft has affected the sustainment base. The DoN has been using CAS aggressors long enough that it likely has sufficient current historical data to perform an analysis of how the department's sustainment efforts and fiscal resources have been affected.

Final Statement

The United States is refocusing on near-peer competition and the high-end fight rather than primarily engaging in counterinsurgency operations (DoD, 2018). The sustainment base is stretched thin across the naval, ground, and air components of the DoD (GAO, 2018b, 2019). Additionally, there is a large shortage of aggressor sorties across the force, which is detrimental for aircrew combat training (Ausink et al., 2011; USMC, 2018). Contract aggressors can increase training capacity and allow aircrews from regular units to focus on their primary roles. Utilizing contract rather than organic Red Air may also lead to a decrease in sorties and a reduced demand on the sustainment base, which will be of particular benefit to the F-15, F-16, F/A-18, and F-22. Contract aggressors under the CAF ADAIR contract are also cheaper per flying hour than F-15s, F/A-18s, F-22s, and F-35s. Overall, an increase in dedicated aggressor aircraft will enable regular units to increase training capacity, decrease the fiscal impact and strain on the fighter aircraft sustainment base, while preserving front-line fighter aircraft as the United States returns its focus to Great Power Competition.

Appendix A
Examples of Contract Red Air Capabilities

The following examples showcase some of the avionics modifications or inherent abilities of contract fighters associated with the ADAIR contract. A full profile of each contract aggressor can be found at the various Red Air company websites, which are included in the reference list.

ATAC's Mirage F1s have been modified with advanced Global Positioning System (GPS) and upgraded glass cockpits. The Vice President of Business Development for ATAC, Richard Zins, stated that the company is planning to upgrade their F1s with AESA radars (Hudson, 2020).

Tactical Air Support has added a modern glass cockpit system, a Mechanically Scanned Array radar system with integrated threat replication software, their aircrew fly with helmet mounted cueing systems (HMCS), and the aircraft can accept infrared search and track systems or other payloads (Hudson, 2020; Duotech Services, 2021; Tactical Air Support, n.d. -b).

Top Aces intends to upgrade its F-16s with AESA radar, HMCS, tactical datalink, a high off-boresight capability, and the open-architecture Advanced Aggressor Mission System (Hudson, 2021; Top Aces, 2021).

The AIRUSA F/A-18s come with the Elta EL-L/8222 EW pod, an AN/APG-73 radar, the Northrop Grumman AN/AAQ-28 LITENING targeting pods, Link 16 data link system, and 68 Joint HMCS to provide a high off-boresight capability. Don Kirlin, the owner of AIRUSA, said that the Electronic Warfare pod and radar are integrated so the F/A-18s can simultaneously jam and engage threat aircraft (Rogoway, 2022).

Appendix B

Overview of Contract Air Support Companies

Airborne Tactical Advantage (ATAC) was founded in 2003 and has received multiple contracts for aggressor services since the company got its start (ATAC, n.d.). They have supported training to the Air Force, Navy, Marines, and Army in air-to-air, air-to-ground, and air-to-ship tactics. They were acquired by Textron Airborne Solutions in 2016. They operate the F-21 Kfir, Mk-58 Hawker Hunter, and the L-39 Albatross at five different locations in the United States and the Pacific (ATAC, n.d.). ATAC has purchased almost the entire French Air Force inventory of Mirage F1s, including spare engines and parts (Reed, 2018). ATAC's first flight of a refurbished Mirage F1B took place on August 22, 2019 (Rogoway & Trevithick, 2018). ATAC's Mirage F1s have been modified with advanced GPS and upgraded glass cockpits and may receive AESA radars in the future (Hudson, 2020).

Draken International was founded in 2012, growing from the Black Diamond Jet Team. They will buy aircraft speculatively and have parts of their fleet sit dormant until they are required for a contract (Tegler, 2013). This allows them to minimize their own O&S costs and be able to bid on a wider range of contracts. They operate the L-159E Honey Badger, A-4 Skyhawk, MB-339CB, MiG 21BIS, L-39 Albatross, Mirage F-1M, Atlas Cheetah, and various transport and support aircraft. They currently operate at multiple locations in the United States and in Europe. They support training for air-to-air, air-to-ground, and missile defense, and they can provide various other services, including buddy tanking for probe and drogue-equipped aircraft (Draken, 2021). Draken is currently under contract to fly Red Air at Nellis AFB (Gustafson, 2018).

Tactical Air Support, Inc. (TacAir), founded in 2005, was intended to replicate a weapons school in the services they offer. They currently provide adversary support for the Naval Aviation Warfighting Development Center at NAS Fallon. In 2018, they won a $118.9 million, 5-year contract to provide Red Air for the Navy at NAS Fallon, beating out ATAC, who previously held the contract (GAO, 2018a; Hudson, 2018a). They proposed to use five F-5s, with more in reserve at Reno. ATAC proposed to purchase F-16s from Jordan and operate them as aggressors. TacAir's bid was significantly less than ATAC's, in part due to the much lower operating cost of an F-5 as compared to an F-16 (Rogoway & Trevithick, 2018). They have acquired F-5s from the Royal Jordanian Air Force and will be operating them at NAS Fallon. They operate F-5s, A-29 Super Tucanos, and SF-260s at NAS Fallon, Nevada; Reno, Nevada; and St Augustine, Florida. TacAir also provides personnel to assist customers with their training requirements (TacAir, n.d. -b).

Top Aces offers adversary air services and was founded in 2000. They provide training to the United States, Canadian, Australian, and German militaries (Top Aces, n.d.). They fly the Dornier Alpha Jet, the A-4 Skyhawk, the Learjet 35A; and have acquired F-16s but are not flying them in contracts yet (Top Aces, 2021). Top Aces provides services for air-to-air, air-to-ground, naval and air defense training, and test and evaluation missions (Top Aces, n.d.). The company achieved the industry record of 75,000 hours of air combat training while flying at Marine Corps Air Station Miramar (Verdict Media Ltd., 2019).

Omega Air Refueling provides refueling services to aircraft from the United States and other countries' militaries. They were founded in the late 1990s by converting a former Pan American 707 into a drogue-equipped tanker, effectively creating a KC-135 analog, or a KC-707. They converted a former Japan Airlines DC-10 into a drogue-equipped tanker in 2008, creating a KC-10 analog, or a KDC-10. Omega Air acquired two boom-equipped KDC-10s from the Netherlands in 2019 (Omega Air Refueling Services, Inc., n.d.). While not a Red Air company, they show how the military contractor air industry has expanded into multiple domains of aviation previously only occupied by military forces. Omega Air fills a gap in Naval Aviation's capability since the U.S. Navy has no strategic tankers currently in service. Naval Aviation as a whole has an organic buddy-tanking capability and the Marines operate KC-130s.

AIRUSA was founded to fill the gap in organic training capability caused by limited budgets and military drawdowns. They provide air-to-air training, JTAC training, and flight test support services. They fly the BAE Hawk, Dornier Alpha Jet, the L-59 Albatross, and the MiG-29. AIRUSA has provided aircraft support for the U.S. military, Canadian military, and civilian contractors (AIRUSA, n.d.). AIRUSA purchased 46 F/A-18s from the Royal Australian Air Force in 2020 (Rogoway, 2022).

Blue Air Training focuses on providing air-to-ground training to the U.S. military, including close air support, forward air controlling, reconnaissance, artillery calls for fire, and intelligence/surveillance/reconnaissance mission sets. They fly the A-90 Raider, BAC-167 Strikemaster, AH-6 Little Bird, and IAR-823. The company operates from Las Vegas, Yuma, Oklahoma City, and Pensacola (Blue Air Training, n.d.).

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Maintenance Cost Growth in AGING AIRCRAFT: ANALYSIS OF A NEW DHS Dataset

Image designed by Nicole Brate

Nicholas J. Ross

This article finds that maintenance cost per flight hour increases by 8.0% as the average age of a fleet of aircraft increases by 1 year. Cost growth appears to decrease slightly as aircraft age, with an older group of aircraft showing maintenance cost per flight hour increasing by 7.6%. This is based on analysis of a new database from U.S. Customs and Border Protection Air and Marine Operations (CBP AMO). The article employs a Fixed Effect (FE) Least-Squares Dummy Variable (LSDV) regression model based on panel data from Fiscal Year 2015 (FY2015) to FY2020. The conclusion describes possible areas of additional research.

This project's findings may be interesting to the U.S. Coast Guard (USCG) and the Department of Defense (DoD). USCG aircraft conduct many similar missions to AMO's aircraft (both organizations are part of the Department of Homeland Security [DHS]). DoD may find the analysis interesting for three reasons. First, while many of AMO's approximately 200 aircraft are based on commercial designs, it includes military aircraft such as the UH-60, P-3, and MQ-9. Second, many of DHS's acquisition and maintenance processes mirror DoD's. Third, AMO's data are a new dataset for examining aircraft maintenance costs already analyzed using DoD databases such as the Air Force Total Ownership Cost (AFTOC) and Naval Visibility and Management of Operating and Support Costs (VAMOSC) databases.

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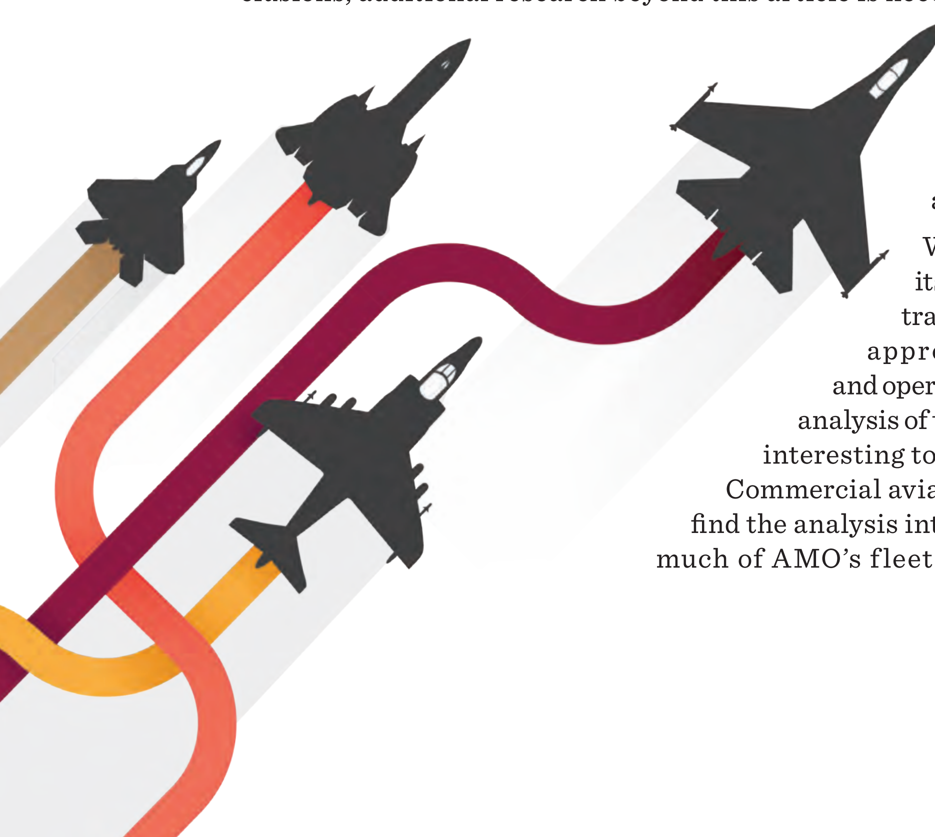
To what extent do maintenance costs increase as aircraft age? This article seeks to answer this question by analyzing historical data from U.S. Customs and Border Protection Air and Marine Operations (CBP AMO). It employs a Fixed Effect (FE) Least-Squares Dummy Variable (LSDV) regression model based on panel data from Fiscal Year 2015 (FY2015) to FY2020. The key finding is that when controlling for the type of aircraft, maintenance cost per flight hour increases by 8.0% as the average age of a fleet of aircraft increases by 1 year. Since this magnitude was higher than anticipated, the conclusion describes possible areas of additional research.

AMO currently operates a fleet of approximately 200 aircraft. These aircraft support four key mission areas: law enforcement, domain awareness, extended border and foreign operations, and contingency and national security operations (U.S. CBP, 2019, pp. 4–5). Federal Law Enforcement Officers (LEOs) operate the aircraft while AMO relies primarily on contractors to perform maintenance.

The impact of aircraft age on maintenance costs is interesting to AMO because a key implication is that reducing the average age of its fleet would reduce AMO's maintenance cost per flight hour. This is especially important now because AMO is currently procuring new aircraft for the Multi-Role Enforcement Aircraft (MEA) program, it may be purchasing new aircraft for the Medium Lift Helicopter (MLH) program, and it is considering two completely new aircraft programs to replace legacy aircraft—Light Enforcement Platform (LEP) and P-3 Replacement. However, as described in the conclusions, additional research beyond this article is necessary to identify exactly when it becomes more cost effective to replace aging aircraft with new aircraft.



While AMO has its own unique contractor maintenance approach, missions, and operational tempo, the analysis of this report may be interesting to other audiences. Commercial aviation entities may find the analysis interesting because much of AMO's fleet are commercial aircraft integrated with law enforcement equipment. The U.S. Coast Guard (USCG) may find the analysis interesting because its aircraft fleet conducts many missions that are similar to AMO's fleet (both organizations are part of the Department of Homeland Security [DHS]). The Department of Defense (DoD) may find the analysis interesting for three reasons. First, while much of AMO's fleet consists of commercial aircraft, it includes military aircraft such as the UH-60, P-3, and MQ-9. Second, many of DHS's acquisition and maintenance processes mirror DoD's. Third, AMO's data are a new dataset for examining aircraft maintenance costs already analyzed using DoD databases such as the Air Force Total Ownership Cost (AFTOC) and Naval Visibility and Management of Operating and Support Costs (VAMOSC) databases.

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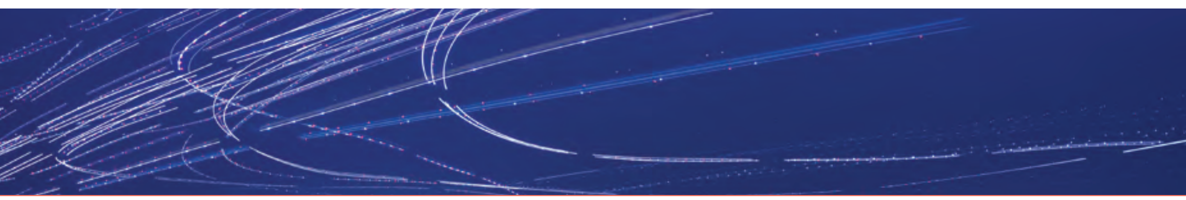
Literature Review

Importance of O&S Costs

Examining operating and support (O&S) costs is important for understanding the total life-cycle cost of a system. Maintenance in turn is an important part of O&S costs. Jones et al. (2014) stressed the importance of the O&S phase, estimating "an approximate range of 44–56% (mean) or 48–63% (median) for the proportion of life-cycle costs attributable to O&S" (p. 456). Building on Jones et al., O'Hanlon et al. (2018) looked at "the relative magnitude of the elements within the O&S CES [Cost Element Structure] for aircraft platforms" (p. 268). Analyzing U.S. Air Force (USAF) data from 1996 to 2016, they found that unit-level maintenance is approximately 50% of unit-level manpower costs, and maintenance is approximately 31% of total O&S costs (p. 273).

O&S Costs for Aircraft

Other authors have looked specifically at aircraft O&S costs. Considering maintenance labor productivity and economies of scale with location, Robbert (2013) made two interesting observations. First, he noted that having more experienced maintainers helped reduce maintenance costs for the USAF reserve components relative to their active counterpart (p. xi). Second, he observed that the dispersion of the bases of the USAF's reserve components limited the ability to achieve economies of scale (p. xii). This problem could also apply to AMO, which has many dispersed, small operating sites.



Bunecke et al. (2018) researched O&S cost growth for 21 different fixed-wing airframes. They found annual maintenance cost growth of 1.8% "after accounting for inflation, total available inventory, flying hours, and the total planned (organic and CLS [Contractor Logistics Support]) depot maintenance" (p. 245).

Boito et al. (2015) looked at various metrics for comparing aircraft operating and support costs within DoD. They made an interesting observation that "59 percent of total direct USAF aircraft O&S costs and 57 percent of total direct Navy aircraft O&S costs" contain some variable components "while the remaining costs are fixed" (p. 9).

Fioriti et al. (2018) analyzed multiple characteristics in addition to an aircraft's age. They developed cost estimating relationships at the component level for estimating maintenance costs for commercial aircraft.

Myers et al. (2021) examined the impact of engine upgrades on O&S costs for USAF C-5, C-130, and C-135 aircraft. They found that increased fuel efficiency from upgraded engines helped reduce O&S costs. However, the impact on maintenance costs was less clear: Engine upgrades appeared to reduce maintenance costs for C-5 and C-130 aircraft but increase maintenance costs for C-135 aircraft.

Aging and Maintenance Costs

When looking at aircraft maintenance costs, many previous studies have examined the relationship between an aircraft's age and maintenance costs. Pyles (2003) examined the long-term impact of age on USAF aircraft maintenance and modification. Keating and Dixon (2003) analyzed when to replace aging aircraft with increasing maintenance costs by examining examples of a USAF C-21A executive transport and a KC-135 tanker.

Dixon (2006) researched the impact of age on maintenance costs per flight hour by creating a dataset of commercial aircraft cost from Federal Aviation Administration (FAA) data. Dividing aircraft into three categories—new, middle age, and old—he found 17.6%, 3.5%, and a statistically insignificant 0.7% annual increase in maintenance cost per flying hour for planes 0–6 years old, 6–12 years old, and more than 12 years old, respectively (p. xii). While Dixon's results should not be applied to aircraft older than 25 years, the result is still surprising because this "suggests that total aircraft maintenance costs may plateau, at least for certain aircraft ages" (p. xiv).

The Congressional Budget Office (CBO, 2018) and Trunkey (2018) examined the impact of age on USAF's aircraft and the size of the USAF budget on the impact of O&S cost per flight hour. CBO (2018) discusses the commonly cited "bathtub" three-phased model for operating costs: Operating costs decline during an "immature phase," remain stable in the "mature phase," and increase during the "aging phase" (p. 3). Most of the aircraft in the CBO's study were in the "aging" phase. The CBO estimated "that the real cost growth associated with aircraft aging generally ranged from 1.5% to 4.1% over the 1999–2016 period" (CBO, 2018, p. 1).

Model Specification

Based on the literature review, an important factor for maintenance costs is an aircraft's age: the older the aircraft, the more expensive the maintenance costs. However, two potential caveats deserve consideration. First, the three-phased bathtub life-cycle model discussed in the CBO's study (2018, pp. 2–3) suggests that cost growth starts in the aging phase. Second, Dixon (2006)—in contrast to the bathtub model—suggests that maintenance costs may stop growing at a certain age. Aging could lead to higher maintenance costs because of material degradation and technological obsolescence (Pyles, 2003, p. 30). The amount an aircraft is operated would also influence maintenance costs: as flight hours increase, one would expect maintenance costs to increase; however, cost per flight hour could decrease if an aircraft has large fixed costs. The type of the aircraft will influence maintenance costs with larger and/or more complex aircraft costing more to maintain than smaller and/or less complex aircraft.

The regression model uses proxies for these elements. For age, the model uses the average of the ages of all aircraft for a specific type. The age in turn is calculated in years from the manufacturing date for each aircraft. To control for operation, the model calculates cost per flight hour based on annual maintenance costs and flight hours. To control for the type of the aircraft, the model uses dummy variables, which also serve as the y-intercept for the model.

The model presented here is a Log-Lin model, which is consistent with other studies (e.g., CBO, 2018; Dixon, 2006; Keating & Dixon, 2003). In a Log-Lin model, a one-unit change in an independent variable causes a percentage change in the dependent variable (Gujarati & Porter, 2009, pp. 162–163; Pyles, 2003, pp. 22–23; Studenmund, 2006, p. 215).

An important factor for maintenance costs is an aircraft's age: the older the aircraft, the more expensive the maintenance costs.

Deterministic Specification

$$\ln\left(\frac{M_{it}}{F_{it}}\right) = \beta_1 D_{1i} + \ldots + \beta_{10} D_{10i} + \beta_{11} A_{it}$$

Where:

M_{it}	The annual maintenance costs for an aircraft variant
F_{it}	The annual flight hours for an aircraft variant
β_1	The y-intercept (this applies for β_1 through β_{10})
D_{1i}	A dummy variable equaling one or zero depending on the aircraft variant (this applies for D_{1i} through D_{10i})
β_{11}	The percent change in maintenance cost per flight hour for a 1-year increase in average age of an aircraft variant
A_{it}	The average age of an aircraft variant

In the specification, the model has 10 dummy variables to account for each aircraft type. The dummy variable equals either one or zero depending on the aircraft variant. This determines which β (i.e., β_1 through β_{10}) to use as the model's y-intercept. The specification does not include an additional y-intercept term to avoid a dummy-variable trap (Gujarati & Porter, 2009, p. 597).

Stochastic Specification

The actual estimated model includes a stochastic error term because several explanatory variables cannot explain all the variation in the dependent variable. This error term captures variation in the dependent variable not explained by the independent variables. It is assumed to be random and to have constant variance. The stochastic specification is identical to the deterministic specification except for the fact that it incorporates a stochastic error term μ_{it}.

$$\ln\left(\frac{M_{it}}{F_{it}}\right) = \beta_1 D_{1i} + \ldots + \beta_{10} D_{10i} + \beta_{11} A_{it} + \mu_{it}$$

Data

The analysis presented here is based on panel data of AMO's aircraft fleet from FY2015 to FY2020. These are the years for which data are currently available. It includes all the aircraft that are in AMO's fleet organized by these categories:

1. AS350/H-125
2. B200
3. B350

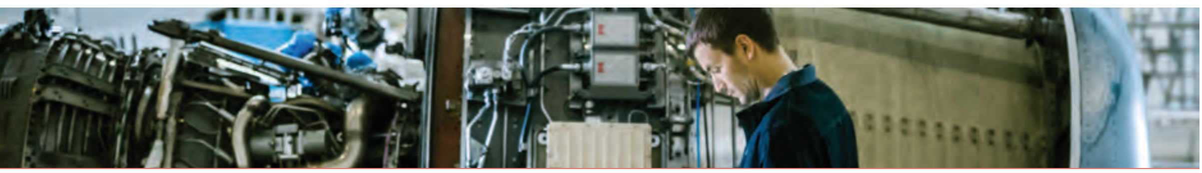
4. C206 (standard and "Night Owl" variants)
5. DHC8
6. PC12
7. P-3 (Airborne Early Warning [AEW] and Long-Range Tracker [LRT] variants)
8. S76
9. UAS (MQ-9)
10. UH-60 (A, L, and M variants)

The dataset excludes B350 data for FY2015 and FY2016 because the maintenance costs incorrectly included procurement costs of new aircraft. It also corrects for duplicate data entries for the P-3 in FY2020. AMO maintains fact sheets with more information on these aircraft. (U.S. CBP, 2022).

As covered under the specification section, the dependent variable is the natural log of total maintenance cost for an aircraft variant in a given fiscal year divided by the total number of flight hours for an aircraft variant in a given fiscal year. The data source for maintenance costs and flight hours is AMO's Common Costing Analysis Tool (CCAT). The CCAT consolidates data from multiple sources within AMO such as Customs Automated Maintenance Inventory Tracking System (CAMITS); Computerized Aircraft Reporting and Materiel Control (CARMAC); Systems, Applications, and Products (SAP); and the National Aviation Maintenance Contract (NAMC) (Guidehouse, 2020).

Unlike some DoD databases such as Naval VAMOSC, the CCAT does not differentiate between maintenance and continuing system improvements. That means repairing equipment on an aircraft and replacing equipment on an aircraft with improved equipment are both counted under maintenance. For instance, the DHC8 aircraft is currently undergoing a major continuing systems improvement project, and these costs are counted under maintenance.

The maintenance costs were adjusted for inflation to U.S. Government FY2020 dollars using the DHS inflation table as of April 30, 2020. This inflation table is based on Gross Domestic Product (GDP) data from the Bureau of Economic Analysis (BEA) as of April 29, 2020.



As covered under the specification section, the main independent variable is the average age for each variant of aircraft. The data source for the aircraft's manufactured year—used for calculating its age—is based on two data pulls, as of September 11, 2017 and February 23, 2021, of aircraft inventory reports. AMO's Material Readiness Group provided both reports. Age for an aircraft equals the year of the observation minus the aircraft's manufactured year.

TABLE 1. DESCRIPTIVE BASELINE STATISTICS, FY20$

	CPFH	Age (Years)
Minimum	$579	3
Median	$2,474	19
Average	$3,896	22
Maximum	$12,349	53
Standard Deviation	$3,090	14

FIGURE 1. AVERAGE AIRCRAFT AGE AND COST PER FLIGHT HOUR

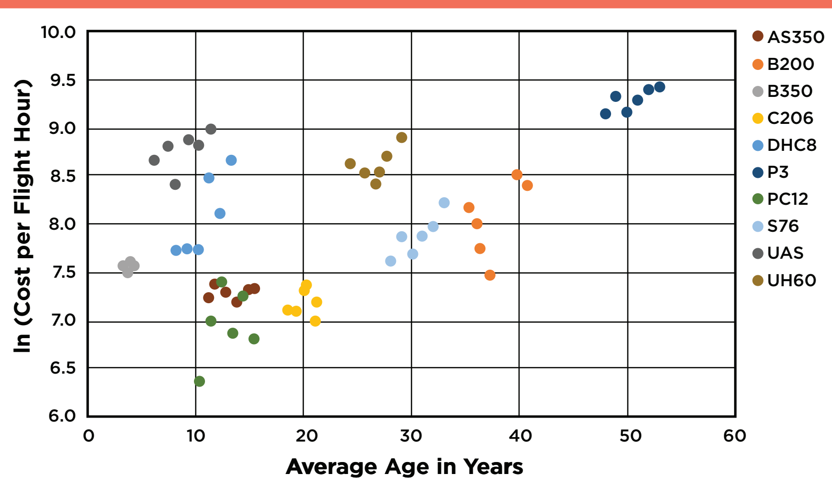


Table 1 reports the descriptive statistics for cost per flight hour and age. Figure 1 displays the dataset graphically.

A potential problem with regression analysis is high correlation among independent variables, potentially causing multicollinearity. Not only can multicollinearity impact the signs and magnitude of the estimated coefficients, it can also depress the *t*-statistics of the coefficients. Table 2 reports the correlation matrix of the natural logs of the independent variables. Since the values in the correlation matrix are between 0.800 and -0.800 (Gujarati & Porter, 2009, p. 338; Studenmund, 2006, pp. 257–258), this would suggest that multicollinearity is not a major problem in the dataset. However, one should note that the correlation matrix does not prove that multicollinearity does not exist in the dataset.

TABLE 2. CORRELATION MATRIX

	AGE	AS350	B200	B350	C206	DHC8	P3	PC12	S76	UAS	UH60
AGE	1.000										
AS350	-0.216	1.000									
B200	0.379	-0.115	1.000								
B350	-0.359	-0.092	-0.092	1.000							
C206	-0.049	-0.115	-0.115	-0.092	1.000						
DHC8	-0.279	-0.115	-0.115	-0.092	-0.115	1.000					
P3	0.695	-0.115	-0.115	-0.092	-0.115	-0.115	1.000				
PC12	-0.226	-0.115	-0.115	-0.092	-0.115	-0.115	-0.115	1.000			
S76	0.207	-0.115	-0.115	-0.092	-0.115	-0.115	-0.115	-0.115	1.000		
UAS	-0.326	-0.115	-0.115	-0.092	-0.115	-0.115	-0.115	-0.115	-0.115	1.000	
UH60	0.114	-0.115	-0.115	-0.092	-0.115	-0.115	-0.115	-0.115	-0.115	-0.115	1.000

TABLE 3. BASELINE REGRESSION RESULTS

Dependent Variable: LN(MAINT/FH)
Method: Panel Least Squares
Sample: 2015 2020
Periods included: 6
Cross-sections included: 10
Total panel (unbalanced) observations: 58

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
AGE	0.080	0.018	4.498	0.000
AS350	6.238	0.250	24.951	0.000
B200	5.066	0.670	7.563	0.000
B350	7.264	0.126	57.660	0.000
C206	5.583	0.365	15.278	0.000
DHC8	7.223	0.208	34.787	0.000
P3	5.276	0.897	5.883	0.000
PC12	5.921	0.243	24.336	0.000
S76	5.447	0.547	9.961	0.000
UAS	8.065	0.177	45.457	0.000
UH60	6.498	0.481	13.522	0.000
R-squared		0.936		
Adjusted *R*-squared		0.922		

Results

Baseline Model

Table 3 shows the regression results. One can interpret the coefficient for age as follows: a 1-year increase in the average age for a type of aircraft causes maintenance cost per flight hour to increase by 8.0% when holding all other variables constant.

As expected, the sign of age is positive. However, the magnitude of age appears to be larger than one would expect when compared to other studies. It could imply that if AMO does not add or remove any aircraft from its fleet, maintenance cost per flight hour doubles approximately every 9 years. For comparison purposes, based on USAF data, CBO found that cost per flight hour increased by 1.5% to 6.7%, depending on the aircraft type (CBO, 2018, p. 12). It is important to note that this CBO report includes all operating costs, not just maintenance. As noted previously, Dixon (2006) found that commercial aircraft's maintenance cost per flight hour increased by 17.6% for aircraft 0–6 years old, 3.5% for aircraft 6–12 years old, and 0.7% for aircraft more than 12 years old (although this was statistically insignificant) (p. xii).

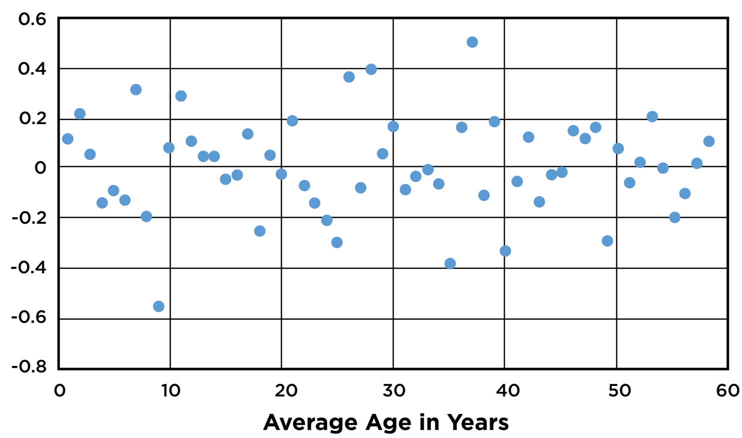
Based on the *p* values, all the coefficients are statistically significant at the 1% level. Looking at the equation as a whole, the adjusted R-squared value of 92.2% means that 92.2% of the variation of maintenance cost per flight hour around its mean is explained by the estimated regression equation, adjusted for degrees of freedom.

Heteroskedasticity and Serial Correlation

A key assumption for regression analysis is that the error terms have constant variance (no heteroskedasticity) and are uncorrelated (no serial correlation). Heteroskedasticity and serial correlation can impact the standard errors of the coefficients of the estimated regression equation, thereby making hypothesis testing unreliable.

A graph of the residuals can suggest if an estimated regression equation suffers from serial correlation and/or heteroskedasticity. Figure 2 shows a plot of the residuals of the estimated regression equation. The lack of an obvious trend could suggest that the estimated regression equation suffers neither from serial correlation nor heteroskedasticity.

FIGURE 2. RESIDUALS



One way to test for first-order serial correlation is to use the Durban-Watson statistic (for a good description of this test, see Studenmund [2006], pp. 327–328, 616–617). The null hypothesis is that no positive serial correlation exists. If the Durban-Watson statistic is less than d_L, one rejects the null hypothesis. If the Durban-Watson statistic is between d_L and d_U, the test is inconclusive. For the estimated regression equation, $d_L \approx 1.072$ and $d_U \approx 1.817$. Since the Durban-Watson statistic for the estimate regression equation is 2.213, one fails to reject the null hypothesis. This suggests that the estimated regression equation does not suffer from positive first-order serial correlation.

While testing for heteroskedasticity with panel data can be complex, one of the approaches for hypothesis testing that accounts for heteroskedasticity is to use White's robust standard errors. Table 4 reports White's robust standard errors for the coefficient of age using several different methodologies available in the program Eviews (the computer program used to run the regressions). One should note that in all cases, the coefficient of age remains statistically significant at the 1% level.

TABLE 4. HETEROSKEDASTICITY AND STANDARD ERRORS FOR THE COEFFICIENT OF AGE

	Std. Error	*t*-Statistic	Prob.
Ordinary	0.018	4.498	0.000
White Cross-Section (Period Cluster)	0.010	8.075	0.001
White Period (Cross-Section Cluster)	0.020	3.994	0.003
White (Diagonal)	0.018	4.529	0.000
White Two-Way Cluster	0.013	6.218	0.002

TABLE 5. "NEW" AIRCRAFT DESCRIPTIVE STATISTICS, FY20$		
	CPFH	**Age (Years)**
Minimum	$579	3
Median	$1,934	11
Average	$2,952	10
Maximum	$7,984	15
Standard Deviation	$2,225	4

TABLE 6. "OLD" AIRCRAFT DESCRIPTIVE STATISTICS, FY20$		
	CPFH	**Age (Years)**
Minimum	$1,101	19
Median	$3,633	31
Average	$4,778	33
Maximum	$12,349	53
Standard Deviation	$3,534	11

Robustness Check: The Impact of Age

Dixon (2006) showed that growth in maintenance cost per flight hour in commercial aircraft changed, depending on the age of the aircraft. While the dataset used here is too small to permit use of Dixon's categories, it was possible to split the dataset in half, with a "new" and an "old" group. Table 5 and Table 6 show the descriptive statistics while Table 7 and Table 8 show the regression results for both groups.

TABLE 7. "NEW" AIRCRAFT REGRESSION RESULTS

Dependent Variable: LN(MAINT/FH)
Method: Panel Least Squares
Sample: 2015 2020
Periods included: 6
Cross-sections included: 5
Total panel (unbalanced) observations: 28

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
AGE	0.084	0.029	2.881	0.009
AS350	6.184	0.397	15.584	0.000
B350	7.249	0.163	44.525	0.000
DHC8	7.180	0.324	22.129	0.000
PC12	5.869	0.385	15.225	0.000
UAS	8.030	0.272	29.530	0.000
R-squared		0.908		
Adjusted *R*-squared		0.887		

TABLE 8. "OLD" AIRCRAFT REGRESSION RESULTS

Dependent Variable: LN(MAINT/FH)
Method: Panel Least Squares
Sample: 2015 2020
Periods included: 6
Cross-sections included: 5
Total panel (balanced) observations: 30

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
AGE	0.076	0.022	3.506	0.002
B200	5.203	0.817	6.369	0.000
C206	5.656	0.441	12.815	0.000
P3	5.460	1.096	4.983	0.000
S76	5.558	0.665	8.352	0.000
UH60	6.596	0.584	11.297	0.000
R-squared		0.948		
Adjusted *R*-squared		0.937		

The coefficient of age remained statistically significant at the 1% level for both groups. Compared to the baseline, the coefficient increased by 0.4% from the baseline for "new" aircraft and decreased by 0.4% from the baseline for "old" aircraft. This is similar to Dixon's (2006) finding that cost-per-flight-hour growth decreases as aircraft age. However, the magnitude of the age coefficient remains higher than what one would expect based on Dixon's (2006) and the CBO's (2018) research.

Conclusions

The analysis presented here suggests that maintenance cost per flight hour increases by 8.0% as the average age of a fleet of aircraft increases by 1 year. This cost growth likely decreases slightly as aircraft age, with an older group of aircraft showing maintenance cost per flight hour increasing by 7.6%. An implication of this finding is that since maintenance cost per flight hour increases as aircraft age, purchasing new aircraft to replace older aircraft could reduce aircraft maintenance costs. However, additional research is necessary to identify the exact point at which it is cost effective to replace aging aircraft. It is unclear why the growth is higher than what Dixon found. However, the AMO dataset differs in several ways from Dixon's (2006) dataset: AMO's dataset covers only 6 years, AMO's aircraft tend to be older than many of the aircraft used by commercial airlines, AMO uses a mix of civilian and repurposed military aircraft, AMO's aircraft are equipped with law enforcement mission equipment, and AMO's missions and maintenance strategy differ from commercial airlines.

As noted earlier, the results presented here are also greater than CBO's (2018) findings. A possible explanation is that CBO looked at all operating costs as opposed to focusing on maintenance. Since AMO's maintenance percentage growth is greater than the USAF's operating cost percentage, this could suggest that maintenance costs grow faster than other operating costs.

One should only view this article as a starting point: At least three possible avenues for additional research on aircraft aging and cost growth exist. First, one could update the analysis annually as AMO's CCAT is updated. Second, as noted previously, a limitation in the dataset is that, unlike some DoD databases, the CCAT does not differentiate between maintenance and continuing system improvements. If the CCAT is revised to differentiate between these two elements, one could re-run the analysis to identify to what extent the costs are being driven by maintenance and continuing system improvements, respectively. Third, instead of analyzing AMO's fleet as a whole, one could focus on a specific aircraft type and conduct analysis at the aircraft tail-number level.

Another avenue of further research would be to examine when it is cost-effective to replace aging aircraft. This article has focused on the question: "To what extent do maintenance costs increase as aircraft age?" However, this question leads to the follow-on question, "At what point does it become more cost effective to replace aging aircraft with new aircraft?" Answering this question using analysis of data from the CCAT could help inform AMO's decisions as it replaces its oldest UH-60s and considers whether to pursue the P-3 replacement and LEP programs to replace legacy aircraft.

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Appendix
Acronyms and Abbreviations

AEW	Airborne Early Warning
AFTOC	Air Force Total Ownership Cost
AMO	Air and Marine Operations
BEA	Bureau of Economic Analysis
CAMITS	Customs Automated Maintenance Inventory Tracking System
CARMAC	Computerized Aircraft Reporting and Materiel Control
CBO	Congressional Budget Office
CBP	U.S. Customs and Border Protection
CCAT	Common Cost Analysis Tool
CES	Cost Element Structure
CLS	Contractor Logistics Support
DHS	Department of Homeland Security
DoD	Department of Defense
FAA	Federal Aviation Administration
FE	Fixed Effect
FY	Fiscal Year
LEO	Law Enforcement Officer
LEP	Light Enforcement Platform
LRT	Long-Range Tracker
LSDV	Least-Squares Dummy Variable
MEA	Multirole Enforcement Aircraft
MLH	Medium Lift Helicopter
NAMC	National Aviation Maintenance Contract
O&S	Operating and Support
SAP	Systems, Applications, and Products
TY	Then Year
USAF	U.S. Air Force
USCG	U.S. Coast Guard
VAMOSC	Naval Visibility and Management of Operating and Support Costs

Author Biography

Mr. Nicholas J. Ross

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Featured Book

The Hundred Year Marathon: China's Secret Strategy to Replace America as the Global Superpower

Author: Michael Pillsbury

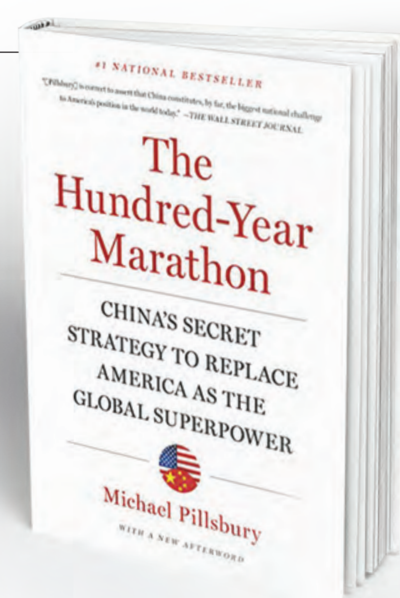
Publisher: St. Martin's Griffin

Copyright Date: 2016

Hard/Softcover/Digital: Softcover, 352 pages

ISBN-13: 9781250081346

Reviewed by: David Riel, Professor of Acquisition Management, DAU



Review:

The last page of Pillsbury's *The Hundred Year Marathon* asks the question, "why would thirty-five Chinese military officers publish a little-noticed book entitled *Science of Strategy* that advocates a global network of Chinese military bases?" The answer to that question provides the very rationale why every member of the Defense Acquisition Workforce should read this book. The China threat is real. As Sun Tzu said, "If you know the enemy [competitor] and know yourself, you need not fear the result of a hundred battles. If you know yourself but not the enemy [competitor], for every victory gained you will also suffer a defeat." This book invites you to better understand China and their hundred year marathon strategy to become the singular global superpower.

Author Michael Pillsbury, a former CIA agent and acknowledged expert on China, introduces us to China's strategy beginning with the 1949 founding of the People's Republic of China by Mao Zedong and forwards us to the present, all the while illuminating their historic advances towards the China Dream, described by current President Xi Jinping as a resurgent China reclaiming "its rightful place atop the global hierarchy" (p. 17). Yet, while the threats exposed by Pillsbury are worthwhile knowing, the reason every acquisition professional should read this book is because it explains why both Congress and the Department of Defense are driving significant changes to the way we acquire weapon systems via the Adaptive Acquisition Framework (AAF).

In Secretary of Defense Lloyd Austin's Message to the Force memorandum (March 4, 2021), he states that "The Department will prioritize China as our number one pacing challenge and *develop the right operational concepts, capabilities, and plans* to bolster deterrence and maintain our competitive advantage." The ability to "*develop the right operational concepts, capabilities, and plans*" requires understanding China's approach to their military buildup. Pillsbury provides insight by exploring China's approach of developing Assassin's Mace weapons, which are weapons that "are far less expensive than the weapons they destroy" (p. 147). These asymmetric weapons, designed to destroy or overcome the effects of more complex, expensive weapons, can be successful if our acquisition community does not achieve speed in exploiting new, innovative technologies, as well as constantly upgrading our systems to stay ahead of these Assassin's Mace weapons by what former Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics Dr. Will Roper described as "smart modernization." Our newer acquisition pathways—the Middle Tier of Acquisition and the agile approach to software development, the Software Acquisition pathway—are two avenues for accomplishing that.

The Hundred Year Marathon serves as a wake-up call for every Defense Acquisition Workforce member to do everything within their power and abilities to deliver war-winning/war-deterring capabilities at the speed of relevance, while ensuring that the technology is secure. China is our primary pacing challenge. Our necessity to deliver cutting-edge technological advantages to our Warfighters securely and quickly has never been more urgent. Pillsbury's book provides the evidence to solidify that necessity. Sun Tzu knew that you better understand your competition. This book will enable you to do just that.

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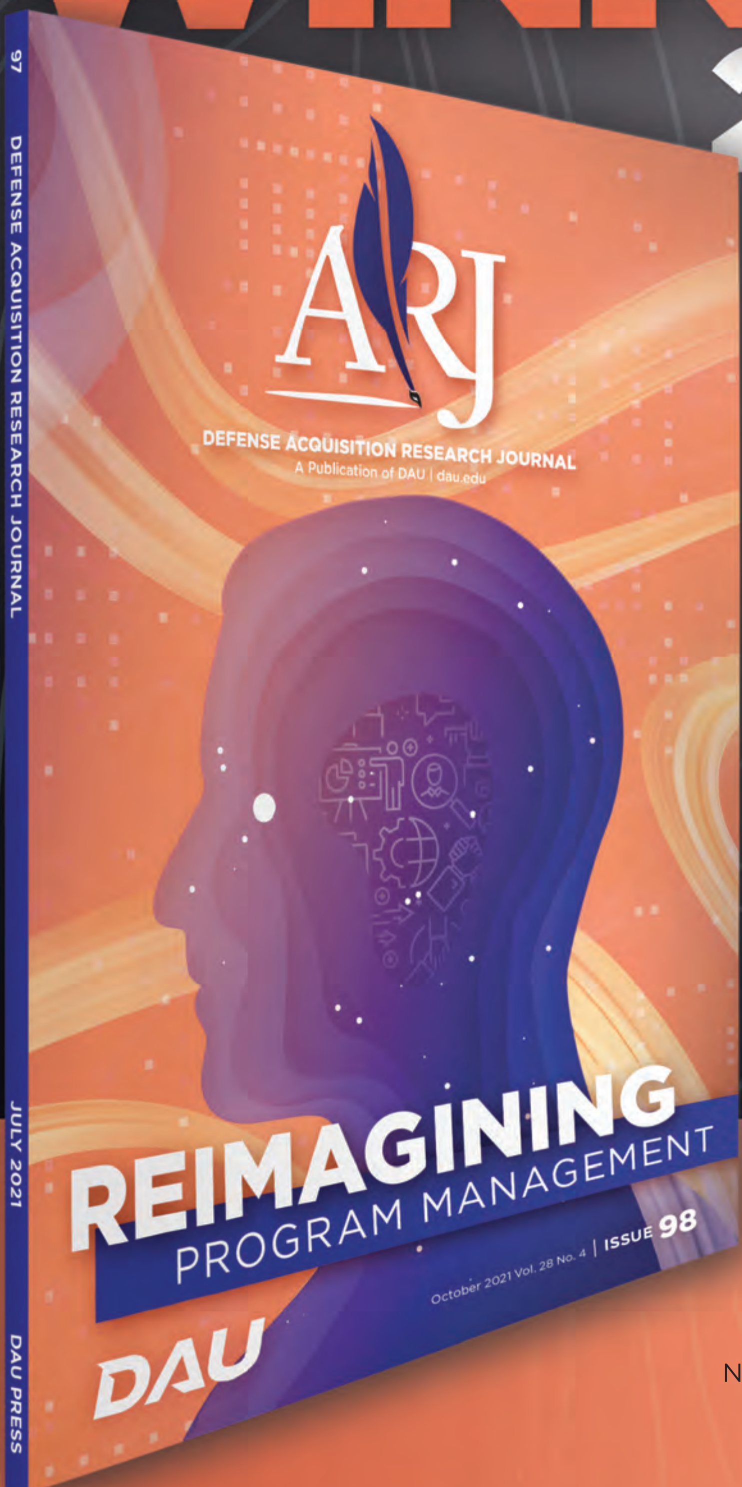

Norene Johnson, Emily Beliles, and Nicole Brate

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Evaluation of U.S. Special Operations Command's Supply Chain Risk Management for the Security, Acquisition, and Delivery of Specialized Equipment

Office of the Department of Defense Inspector General

Summary:

In 2011, the DoD established policies that require DoD organizations authorized to procure materiel, services, and equipment to assess and mitigate threats, vulnerabilities, and disruptions to the DoD supply chain primarily through Program Protection Plans (PPPs). The U.S. Special Operations Command (USSOCOM) Commander is authorized to develop and acquire specialized equipment and is required by policy to ensure supply chain security, such as antitampering and cyber, industrial, and information security. We found that USSOCOM supply chain risk management procedures did not comply with DoD policies until November 2020. Specifically, USSOCOM policy did not require USSOCOM program managers to complete PPPs for acquisition programs, nor did USSOCOM policy require USSOCOM program managers to ensure that contractor-developed, Program Protection Implementation Plans (PPIPs) that address weaknesses

identified by PPPs were in place. While USSOCOM addressed these policy deficiencies in November 2020, USSOCOM personnel did not develop plans to prioritize and implement these policy requirements for active contracts. USSOCOM agreed with our two recommendations. One recommendation is closed, and the other recommendation is resolved but will remain open.

APA Citation:

Office of the Department of Defense Inspector General. (2021). *Evaluation of U.S. Special Operations Command's supply chain risk management for the security, acquisition, and delivery of specialized equipment* (Report No. DODIG-2021-125). https://media.defense.gov/2021/Sep/16/2002855097/-1/-1/1/DODIG-2021-125_REDACTED.PDF

Cybersecurity: Federal Agencies Need to Implement Recommendations to Manage Supply Chain Risks

U.S. Government Accountability Office

Summary:

Federal agencies continue to face software supply chain threats. In December 2020, the Department of Homeland Security's Cybersecurity and Infrastructure Security Agency issued an emergency directive requiring agencies to take action regarding a threat actor that had been observed leveraging a software supply chain compromise of a widely used enterprise network management software suite—SolarWinds Orion. Subsequently, the National Security Council staff formed a Cyber Unified Coordination Group to coordinate the government response to the cyberattack. The group took a number of steps, including gathering intelligence and developing tools and guidance, to help organizations identify and remove the threat. During the same month that the SolarWinds compromise was discovered, the Government Accountability Office (GAO) reported that none of 23 civilian agencies had fully implemented selected foundational practices for managing information and communication technology (ICT) supply chain risks—known as supply chain risk management (SCRM).

APA Citation:

Cybersecurity: Federal agencies need to implement recommendations to manage supply chain risks, Subcommittees on Investigations and Oversight and Research and Technology, Committee on Science, Space and Technology, House of Representatives, 117th Cong. (2021) (testimony of Vijay A. D'Souza). https://www.gao.gov/assets/gao-21-594t.pdf

Securing the Microelectronics Supply Chain: Four Policy Issues for the U.S. Department of Defense to Consider

Jared Mondschein, Jonathan W. Welburn, and Daniel Gonzales

Summary:

The ever-tightening financial constraints of semiconductor manufacturing have led to the business reality faced by U.S. consumers and leaders in 2021: The U.S. market share of global semiconductor manufacturing capacity has fallen from about 38% in 1990 to 12% in 2020 and is expected to decline to less than 10% by 2030. The growing realization of these economic trends and their implications for U.S. national and economic security has resulted in a national conversation and a growing chorus of academic, industry, and government stakeholders arguing for varying policy solutions. Out of this dialogue have emerged critical knowledge gaps that will hamper decision-makers' ability to make informed policy. The authors have identified high-priority questions that should drive U.S. policy but that require additional data and insights, and they explore these questions in this Perspective.

APA Citation:

Mondschein, J., Welburn, J. W., and Gonzales, D. (2022, February). *Securing the microelectronics supply chain: Four policy issues for the U.S. Department of Defense to consider*. RAND. https://www.rand.org/pubs/perspectives/PEA1394-1.html

The Risk to Reconstitution: Supply Chain Risk Management for the Future of the U.S. Air Force's Organic Supply Chain

David Loska and James Higa

Summary:

The future retirement of U.S. Air Force (USAF) legacy weapon systems removes their associated funding from within the Air Force Working Capital Fund and their parts from its organic supply chain inventory. The trending outsourcing of product support to contracted logistics support and its potential long-term consequences to the USAF government-owned, government-operated, organic supply chain and the reconstitution

capabilities it enables in the USAF's organic industrial base, suggests the need to assess its risks. Although there is an existing body of research into the risks of outsourcing the USAF's industrial repair, and federal legislation such as Core 50/50 laws enacted to institutionalize its risk management, there is comparatively little research into the outsourcing risks to the long-term viability of the supply chain on which that repair capability is dependent. The aim of this research is to fill that research gap by assessing and modeling those risks. This research concludes by providing several future research directions that may be evaluated to provide more detail on outsourcing of product support and its effects on the USAF's organic industrial base.

APA Citation:

Loska, D., & Higa, J. (2020, May). The risk to reconstitution: Supply chain risk management for the future of the US Air Force's organic supply chain. *Journal of Defense Analytics and Logistics, 4*(1), 19–40. https://doi.org/10.1108/JDAL-03-2019-0005

Information Technology: Federal Agencies Need to Take Urgent Action to Manage Supply Chain Risks

U.S. Government Accountability Office

Summary:

Few of the 23 civilian Chief Financial Officers Act agencies had implemented seven selected foundational practices for managing information and communications technology (ICT) supply chain risks. Supply chain risk management (SCRM) is the process of identifying, assessing, and mitigating the risks associated with the global and distributed nature of ICT product and service supply chains. Many of the manufacturing inputs for these ICT products and services originate from a variety of sources throughout the world. None of the 23 agencies fully implemented all of the SCRM practices and 14 of the 23 agencies had not implemented any of the practices. The practice with the highest rate of implementation was implemented by only six agencies. Conversely, none of the other practices were implemented by more than three agencies. Moreover, one practice had not been implemented by any of the agencies.

APA Citation:

U.S. Government Accountability Office. (2020). *Information technology: Federal agencies need to take urgent action to manage supply chain risks* (GAO Report No. 21-171). https://www.gao.gov/assets/gao-21-171.pdf

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DAU Press

Fort Belvoir, VA

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.*

Contributors are encouraged to seek the advice of a reference librarian in completing citation of government documents because standard formulas of citations may provide incomplete information in reference to government works. Helpful guidance is also available in *The Complete Guide to Citing Government Information Resources: A Manual for Writers and Librarians* (Garner & Smith, 1993), Bethesda, MD: Congressional Information Service.

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.

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- Completed submission checklist

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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
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Author Deadline	Issue
July	January
October	April
January	July
April	October

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