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An Analysis of a Modular Open System Approach on Program Management Metrics for Cost and Schedule

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THESIS

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Abstract

A modular open system approach (MOSA) and its inclusion of open architecture are among the prevailing acquisition strategies for cost and schedule management. This approach involves the incorporation of reusable, modular packages that can be incrementally added and upgraded throughout programs' lifecycles. Many practitioners throughout the acquisitions community find that MOSA enables better opportunities for affordability, rapid acquisition, flexibility, enhanced competition, and innovation. A literature review reveals that few studies examine the interaction between MOSA and the extent to which it influences cost and schedule performance. However, no studies to date examine open architecture's impact via programmatic evaluation of Earned Value Management (EVM) and Nunn-McCurdy breach metrics. The program management process is critical to successful acquisition, and the use of open architecture affects performance metrics. EVM and Nunn-McCurdy breaches are important to consider because they offer tracking methodology for the overall health of a program in terms of cost and/or schedule. This research empirically investigates and compares EVM data for aircraft that do and do not employ open architecture. Additionally, this research examines the degree to which open architecture impacts the likelihood of Nunn-McCurdy breaches for all program types. Overall, findings support that the presence of open architecture is negatively associated with schedule performance around the halfway point for development contracts. It is theorized that programs adopting open architecture may be too overoptimistic estimating schedule.

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Kayla I. Vogler

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AN ANALYSIS OF A MODULAR OPEN SYSTEM APPROACH ON PROGRAM MANAGEMENT METRICS FOR COST AND SCHEDULE

I. Introduction

Background

The United States must push further ahead of its near-peer adversaries regarding weapon system development. However, it can only maintain its current position of technological superiority by placing heavy emphasis on acquisition speed. Agile development enables the ability to quickly adapt and dominate threats posed by any competitor. In an environment where agile development is critical for national defense, Open System Architecture (OSA) and a Modular Open System Approach (MOSA) play a crucial role in supporting rapid acquisition. In addition to rapid integration, advocates for OSA believe it provides significant cost savings and schedule savings (McCormick et al., 2018).

OSA is a system's physical components built with open, non-proprietary standards. OSA aims to enable future modifications and upgrades as cheaply and quickly as possible through modularity, reusability, integration efforts, design transparency, and strategic use of data rights. OSA usage as a defense acquisition strategy was first prioritized in 1994 by the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD AT&L) and grew to become a staple within the acquisition community. Per the Honorable Katharina (Katrina) McFarland, former Assistant Secretary of Defense Acquisition, approximately 75% of all DoD acquisition strategies use some form of OSA (Pellerin, 2014).

Starting in 2019, emphasis was placed on the modular aspect of OSA, and thus MOSA was established. MOSA is a design philosophy that utilizes modularity and standardization to design affordable and adaptable systems. MOSA incorporates the physical components of OSA and modularizes them as much as possible. Modularity is the development of standard features that interface seamlessly and can be easily ported to other systems. This ease of portability is a key reason why many proponents of open architecture believe that it enables system development to occur faster and cheaper (McCormick et al., 2018).

The Army, Air Force, and Navy stress the importance of MOSA through their tri-service initiative to push for more modularization. The Department of Defense (DoD) as a whole also recognizes the importance of MOSA by mandating its use by law. Title 10 U.S.C. 4401 mandates that all Major Defense Acquisition Programs must be developed with a MOSA to the fullest extent possible (2017). MOSA and its modular architecture have proven critical for innovation, accelerated progress, and maintaining technological dominance. Open standards, the backbone of MOSA, are well-defined, publicly available, non-proprietary, and widely accepted standards. The transparency of open standards allows for a collaborative environment to be fostered across government and industry. This collaboration is evident through several DoD programs such as Future Airborne Capability Environment (FACE) and Open Mission System (OMS). FACE supports avionics development and is a collaborative effort between the Air Force and Navy. It utilizes both open standards and business strategy to generate cost savings and provide warfighters with fully operational capability as quickly as possible. OMS is an Air Force initiative that supports avionics development through government-controlled open standards that promote the affordability of rapid integration. These programs share the common goal of collecting and implementing an agreed upon set of standards for reducing costs and enabling rapid development. MOSA has emerged as the leading strategy to push further innovation and support ongoing acquisition efforts to bring superior technology into the hands of the warfighter as quickly as possible.

Problem Statement

It is widely accepted that MOSA benefits acquisition strategy and many advocates strongly believe it offers substantial cost and schedule savings (McCormick et al., 2018). A few notable studies have considered how MOSA impacts cost and schedule (Cole, 2011; Cuff & Fersch, 2016; Minor, 2017; Brown et al., 2019). Cost and schedule are critical factors to consider because programs have to work within a set budget and deliver a product within a reasonable time period. Furthermore, cost and schedule were objective measures indicating the overall health and success of managing a program. Despite the interest in MOSA, no study to date investigates the impact of open architecture on program management metrics. Considering the widespread use of MOSA throughout the DoD, it is vital to fully understand the effects that MOSA has on program management performance. Previous research on cost and schedule is indeed important, but and a further look into MOSA's influence on program management is essential to understand the full scope of its relationship with the government acquisition process. This research demonstrates how MOSA impacts program management performance through the evaluation of Earned Value Management (EVM). EVM is a program management technique for informing decision-makers and assessing program performance. It is widespread within the acquisitions community and provides vital insight into a program's condition through various quantitative metrics that evaluate cost and schedule. If the widely accepted beliefs hold for reducing cost and schedule and improving program management, the analysis may show that EVM metrics are generally better for programs utilizing OSA.

In addition to EVM, this thesis analyzes MOSA and program management performance by evaluating Nunn-McCurdy breaches. Nunn-McCurdy breaches occur when programs reach certain spending thresholds beyond the original or current baseline. Breaches are indicative of poor program management concerning costs. Considering the widely accepted beliefs on

MOSA's benefits, the analysis may show that Nunn-McCurdy breaches occur less often for programs that employ MOSA. This research provides program managers, program offices, and senior leaders with an analysis of how MOSA impacts program management metrics. The results could support the current narrative of MOSA's superiority or lead the community to consider other, better alternatives.

Research Questions

A few questions must be examined to determine the influence of MOSA on programmatic metrics. These research questions revolve around verifying open architecture cost and schedule benefits from a program management perspective. EVM and Nunn-McCurdy breaches are tools for assessing program management, and these tools are the primary focus of the research questions.

1. How do EVM metrics (CPI and SPI) differ between systems that do and do not employ OSA?
2. How does the presence of OSA impact EVM metrics (CPI and SPI)?
3. How does the presence of OSA impact the likelihood of Nunn-McCurdy breaches?

Methodology

MOSA has the potential to reduce cost and schedule overruns (McCormick et al., 2018). Within the DoD, cost and schedule for major programs are typically tracked through Earned Value Management (EVM). EVM is a management tracking toolset mandated for all Major Defense Acquisition Programs (MDAP) and/or acquisition contracts greater than $20M (DoD Instruction 5000.02). Cost Performance Index (CPI) and Schedule Performance Index (SPI) are the EVM metrics utilized in this research. CPI and SPI data indicate whether a program's cost and schedule advanced as predicted. Cost Acquisition Requirement Description (CARD) documents for aircraft only are analyzed to determine whether or not a program employed MOSA. Contract information from the EVM Central Repository (EVM-CR) is analyzed to determine which specific contract efforts involved open architecture. Only development contracts are considered because MOSA as a design philosophy primarily impacts research, design, test, and evaluation (RDT&E) phase the most. The efforts involved in this analysis generally include system engineering, communication, and the avionics suite for OSA and non-OSA programs. This research utilizes a t-test and Wilcoxon Rank Sum test to determine whether significant differences exist between the OSA and non-OSA distributions. This research also uses regression modeling with CPI and SPI as the dependent variables. They are regressed on a binary variable for the presence of OSA and various control variables to determine the causal effect of OSA on the efficiency of program management. These control variables include dummy binary variables for service, contract type, and pre/post-Weapon System Acquisition Reform Act (WSARA) of 2009.

Finally, this research also analyzes the relationship between MOSA and Nunn-McCurdy breaches. Nunn-McCurdy breaches must be reported to congress for all MDAPs that experience cost overruns over a certain threshold. These cost overruns are measured through changes in Program Acquisition Unit Costs (PAUC) or Average Procurement Unit Costs (APUC) compared to the baseline. Breaches are significant if PAUC/APUC is 15% over the current baseline or 30% over the original baseline. Breaches are critical if PAUC/APUC is 25% over the current baseline or 50% over the original baseline. The Defense Acquisition Visibility Environment (DAVE) provides a list of programs that experienced significant and/or critical breaches. Again, CARDs are assessed to determine whether or not these programs contain OSA elements. Then, a logistics regression is used to determine if the presence of OSA impacted the likelihood of a Nunn-

McCurdy breach at the significant and critical thresholds. Finally, the occurrence of any breach, significant or critical, is regressed on a binary variable for the presence of OSA, along with various dummy variables for Air Force and pre/post-WSARA. The findings reveal whether or not OSA significantly influenced the rate of occurrence of Nunn-McCurdy breaches.

Scope and Limitations

The scope of the EVM analysis involves OSA and non-OSA work breakdown structure (WBS) elements for aviation programs. The conclusions for the EVM analysis are directly limited to aircraft only. A total of 117 WBS elements are analyzed for CPI and 99 for SPI. These elements are generally related to avionics, systems engineering, communications, and other systems linked with the flight computer. Data collection is limited to what could be verified as OSA versus non-OSA via CARD information collected from the Cost Assessment Data Enterprise (CADE). Data completeness and accuracy are limited to available inputs in CADE and EVM-CR.

The scope of the Nunn-McCurdy analysis utilizes data across all commodity types, including aircraft, missiles, ground-based vehicles, etc. Conclusions drawn from the Nunn-McCurdy analysis apply to the entire DoD, not just aircraft. A total of 43 programs with at least one significant or critical breach and 80 programs are analyzed in this research. Data collection is limited to active programs throughout the DoD between 1997 and 2019. The availability of CARDs for the OSA verification process also limited data. The data's completeness and accuracy are limited to CADE and DAVE inputs.

Thesis Overview

Chapter 2 discusses the background of OSA and summarizes past literature research. Chapter 3 summarizes the EVM and SAR data and proposes the research methodology for the

OLS and logistics regressions. Chapter 4 presents the results of the analysis and key findings. Finally, Chapter 5 summarizes the main takeaways of this research and provides input for future OSA studies.

II. Literature Review

Overview

The literature review begins with a brief discussion of the history of OSA and how the modular approach became prominent throughout the DoD. Next, this chapter discusses key concepts in detail, such as Open System Architecture (OSA), Modular Open System Approach (MOSA), open standards, etc. These related concepts illustrate what does and does not constitute open architecture. Next, this chapter briefly reviews Earned Value Management (EVM) and Nunn-McCurdy breaches. Chapter 2 then discusses the many purported benefits of MOSA regarding cost and schedule reduction. Many proponents accept these benefits as fact, but prior research is scarce. There is little empirical evidence showing that cost and schedule savings are significant and directly caused by integrating OSA. Furthermore, previous research has yet to investigate the effects of MOSA on program management metrics such as EVM and Nunn-McCurdy breaches. Chapter 2 reviews major sources of cost overruns that serve as control variables for the EVM and Nunn-McCurdy regressions. Finally, the end of this chapter summarizes the most relevant MOSA studies and discusses the future of open architecture.

MOSA History

The DoD prioritized OSA in 1994 when the Honorable Paul Kaminski, then Under Secretary of Defense Acquisition, Technology, and Logistics (USD AT&L), mandated its usage to the fullest extent possible. The formation of the Open Systems Joint Task Force (OS-JTF) was also initiated that same year. The OS-JTF was designed to oversee the adoption of OSA principles, provide guidance, and serve as a focal point for the community (Roark & Kiczuk, 1995). Another OSA policy was mandated in 2003 with the DoD Directive (DoDD) 5000.01, Defense Acquisition System Policy. This DoDD, recently updated in 2020, places heavy emphasis on including modularity and open standards for system upgrades and technical refreshes (DoDD 5000.01, 2020). Another critical open architecture policy came about with the Better Buying Power (BBP) initiative. BBP began in 2010 and was implemented in three rounds, with the most recent one, BBP 3.0, implemented in 2014 (Kendall, 2014). Generally, BBP focuses on improving DoD acquisitions and technology efforts through increased productivity and efficiency. Regarding modularity, BBP 3.0 discusses using modular designs to generate competition and innovation (Kendall, 2014). The necessity of modularity was codified into law in Title 10 U.S.C 4401, which explicitly states that "A major defense acquisition program that receives Milestone A or Milestone B approval after January 1, 2019, shall be designed and developed to the maximum extent practicable, with a modular open system approach to enable incremental development and enhance competition, innovation, and interoperability" (2017).

The modular design aspect of OSA is a force multiplier for the DoD. According to the previous Assistant Secretary of Defense Acquisition, Katrina McFarland, an estimated 75% of all DoD acquisition programs use it to some degree (Pellerin, 2014). BBP 3.0 and Title 10 U.S.C. 4401 were the driving forces behind the 2019 tri-service initiative for Modular Open System Architecture (MOSA) (MOSA for our Weapon Systems is a Warfighting Imperative, 2019). MOSA supports an integrated environment with collaboration between industry, government, systems engineering, and several other vital aspects, as depicted in Figure 1.

Figure 1: MOSA Integrated Environment

MOSA reportedly achieves rapid acquisition with reduced costs because the reuse of proven components theoretically cuts down on testing and verification time when those components are used in different systems (Patni, 2020). With less time spent on testing and verification, the shortened schedule and reduced efforts likely lead to cost savings.

Several effective MOSA programs are implementing modular design. These include, but are not limited to, Future Airborne Capability Environment (FACE), Open Mission System (OMS), Sensor Open Systems Architecture (SOSA), and Vehicular Integration for C4ISR/EW Interoperability (VICTORY). These programs are committed to modularity, open standards, and creating collaborative partnerships between government and industry. A complete list of OSA initiatives and their descriptions can be found in Appendix A.

Concepts

An open systems approach is the most critical concept for understanding the scope of this thesis. This approach can broadly be defined as the physical components of a system developed with open standards and non-proprietary technology (Kovach et al., 2021). The term 'open system' is not directly synonymous with this design philosophy. Although the approach involves readily available standards and open architecture, the systems that utilize it are not fully open for security purposes. Regular components directly impacting the system's safety and/or significant functions are shielded from the OSA-developed elements (Firesmith, 2015). The Navy defines open architecture levels based on the amount of documentation, usage of an open standard, ease of a modification, and ownership to support upgrades (Kovach et al., 2021). Figure 2 highlights the definitions for different levels of open architecture. An open approach includes architecture typically within the six to eight-level range.

OA Level	Definition
1	A **closed** system is a design-specific system that does not support affecting change to the system.
2	A **partially closed** system is a system with limited use of documented interfaces, which inhibits the ability to affect change.
3	A system at this level has a partial ability to enable change due to **supported interfaces**.
4	A system with **open interfaces** uses standards that are considered well-defined, governed, and supported to enable third party development.
5	A **partially open** system has a combination of both open and closed system characteristics and partially supports third party development.
6	An **open architecture** system employs open standards for key interfaces within a system to effect change with minimal development.
7	A system at this level enables **integration-focused development** in order to facilitate third party efforts.
8	System **reconfigurable** to support a change with minimal integration effort.
9	An **open system** fully supports change to enable rapid technology insertion through widespread third party development.

Figure 2: Open Architecture Levels and Definitions

The Open System Architecture Contract Guidebook for Program Managers (OSACGPM) is an important guidebook that details the inner workings of MOSA and how managers should incorporate it into their programs. This guidebook defines MOSA as an approach that capitalizes on the modular design of critical interfaces and technical architecture developed with open standards (OSACGPM, 2013). Modular design means that the interfaces are standardized such that they can more easily be used with other systems (Patni, 2020). In other words, the modular OSA components are interchangeable building blocks that can be developed independently from the overall system. Open standards are also critical for defining an open approach to system development. These standards are non-proprietary because they are widely available and unanimously supported throughout government and industry (OSACGPM, 2013).

MOSA can be broken down into the following five principles as listed by the OSACGPM (2013):

1. Modular designs based on standards, with loose coupling and high cohesion, that allow for independent acquisition of system components.
2. Enterprise investment strategies, based on collaboration and trust, that maximize reuse of proven hardware system designs and ensure we spend the least to get the best.
3. Transformation of the life cycle sustainment strategies for software intensive systems through proven technology insertion and software product upgrade techniques.
4. Dramatically lower development risk through transparency of system designs, continuous design disclosure, and Government, academia, and industry peer reviews.
5. Strategic use of data rights to ensure a level competitive playing field and access to alternative solutions and sources, across the life cycle.

Modularity and reusability are fundamental principles of MOSA because they are believed to decrease cost and schedule for program upgrades (Matthews et al., 2020). Modular and reusable components are not wholly plug-and-play, like a monitor that could be easily set and moved from one computer to another. Despite the lack of true plug-and-play parts, MOSA offers the reuse of modules that may reduce testing and verification time. The third principle of technology integration is fundamental because some legacy programs are utilizing MOSA for modifications and upgrades. The fast integration of updated components is necessary to outpace near-peers. The last two principles of design transparency and strategic use of data rights are essential because MOSA is only achievable through a collaborative environment. System designs are transparent due to open standards, which are strategically distributed across various platforms for government and industry consensus. The combination of these principles results in the most effective use of MOSA; a checklist for successful open architecture implementation (OSACGPM, 2013) can be found in Appendix B.

EVM is another important concept for this thesis and is defined as a performance measurement system that gives situational awareness of cost and schedule statistics for decision-makers to consider (Nizam & Elshannaway, 2019). In general terms, EVM is a toolset for evaluating program progress. EVM was first used within the DoD in 1967 and is now mandated for all DoD contracts greater than $20M per DoD Instruction (DoDI) 5000.02, Operation of the Adaptive Acquisition Framework (Nizam & Elshannaway, 2019). Because of the dollar threshold, many Major Defense Acquisition Programs (MDAP) have or should have EVM data. In addition, the American National Standards Institute/Electronic Industries Alliance 748 Standards (ANSI/EIA-748) outlines reporting requirements and best practices for EVM tracking. The ANSI/EIA-748 covers in-depth EVM terminology and methodology, including various cost and schedule metrics. There are many different EVM measures, but those necessary for this analysis are Cost Performance Index (CPI) and Schedule Performance Index (SPI). These are standardized measures that capture the ratio between the budgeted cost of work performed against the actual cost of work performed and the budgeted cost of work scheduled for CPI and SPI (Nizam & Elshannaway, 2019).

Nunn-McCurdy breaches, introduced in the 1982 National Defense Authorization Act (NDAA), are the final central concept for this thesis and can be defined as cost overruns in Program Acquisition Unit Costs (PAUC) or Average Procurement Unit Costs (APUC) (Blickstein et al., 2013). PAUC is development costs, procurement costs, and military construction costs all divided by the total number of procured units, and APUC is only procurement costs divided by the total number of procured units (Blickstein et al., 2013). Breaches can be significant or critical depending on how much PAUC or APUC has increased over the current or original baseline estimate. A breakdown of the significant and critical breaches and their thresholds can be found in Figure 3.

	Significant Breach	**Critical Breach**
Current Baseline Estimate	≥15%	≥25%
Original Baseline Estimate	≥30%	≥50%

Source: 10 U.S.C. §2433.

Figure 3: Significant and Critical Breach Thresholds

Nunn-McCurdy breaches are important to consider because they are indicative of poor program management. For breached programs at significant and critical levels, these cost overruns translate into millions and millions of additional taxpayer spending. These breaches are also crucial because they must be reported to Congress and may result in canceled programs. Programs are automatically presumed terminated for critical breaches unless the Secretary of Defense (SecDef) certifies the program. Certified programs must revoke the previous milestone approval, restructure the program, and explain the root causes of cost growth to Congress (Blickstein et al., 2013).

MOSA Advantages and Disadvantages

As previously discussed, the U.S. must maintain an advantage over near-peer adversaries in developing and modernizing weapon systems. Many DoD platforms have long life spans and are continually serviced and upgraded throughout the lifecycle (Zimmerman et al., 2018). The nature of MOSA enables the rapid capability to keep up with new technological advancements by using non-proprietary open standards (McCormick et al., 2018). Components designed with MOSA leverage the advantage of previously proven and tested interfaces, mitigating the need to start from nothing. MOSA-developed components are also reusable within other systems, allowing for faster integration (McCormick et al., 2018). More specifically, MOSA incorporates reusable hardware and software interfaces that make integration simpler within other platforms. An example of successful rapid development due to MOSA occurred with the eT-7A Red Hawk advanced trainer. The eT-7A went from development to first test flight in only three years, much faster than other comparable programs (Boeing: eT-7A Red Hawk: eSeries Leader, 2020).

The acquisition community must pursue rapid acquisition while also being mindful of the associated costs. Proponents of MOSA contend that its widespread adoption is one of the best candidates to meet this challenge (McCormick et al., 2018; Zimmerman et al., 2018). Cost savings are purported to result from increased competition and eliminating unnecessary design and testing by reusable interfaces. The availability of open standards in the industry leads to increased competition among contractors because potential contractors can freely access these standards; contractors can review the standards and compete to offer the best product at a competitive price (OSACGPM, 2013). Therefore, the non-proprietary nature of MOSA broadens the options available to the U.S. government (Zimmerman et al., 2018). In addition to open standards, the reusability of modular designs is another critical factor in reducing costs. Modularity indicates the possibility of plug-and-play and reduced integration, testing, and verification costs (Patni, 2020). An example of reduced costs because of modularity is evidenced by the VICTORY program, which reported MOSA as a critical contributor for cost savings (Moore & Xiang, 2020). VICTORY incorporates open interface standards in the electronic systems of ground-based vehicles. Before VICTORY, these electronic components were integrated with a bolt-on approach, meaning each system had separate interfaces (Moore & Xiang, 2020). After VICTORY, modular elements for the hardware and software of electronic systems were implemented, resulting in shared interfaces and reduced costs. (Moore & Xiang, 2020).

Cost and schedule are the main two benefits of OSA, but mission flexibility and innovation are also significant advantages. OSA contributes towards mission flexibility because integrating new components or modifying existing technical architecture is reportedly easier with open architecture (Davendralingam et al., 2019). The modular open approach theoretically simplifies integration and modifications. Integration and changes are theoretically simplified because of MOSA; architecture is developed to integrate upgrades as efficiently as possible (Zimmerman et al., 2018). Therefore, upgrades and modifications can adjust quickly to keep up with technological advances. The capability of open architecture to seamlessly support modular upgrades potentially spurs innovation (Davendralingam et al., 2019). In the commercial world, modular computer components have exponentially impacted computer architecture innovation (Davendralingam et al., 2019). Such innovative developments may also be possible within the DoD for future programs adopting open architecture.

Despite the benefits of MOSA, there are also potential drawbacks. First, there are concerns about system security and increased vulnerability because of open standards (McCormick et al., 2018). Because these standards are agreed upon across government and industry and are potentially used across multiple platforms, hacking may be easier for U.S. adversaries. For example, if System A and B share some of the same open architecture, hacking into A may also aid in hacking B. Open standards pose a risk, but they do not indicate a completely open system; the open architecture interfaces are insulated or shielded from system aspects that impact safety and critical functions (Firesmith, 2015). Second, OSA may not be viable or practical for older legacy systems nearing the end of their life cycle. For example, consider the case of the B-52, which has been in service since 1955 and will retire sometime in 2050. Several ongoing efforts are to modernize the B-52, including the Radar Modernization Program (RMP). Based on the RMP's Selected Acquisition Report (SAR), the program office acknowledges that MOSA is neither cost-effective nor practical for the radar upgrade (2021). MOSA would require too much effort and time to re-design current off-the-shelf modular components to fit the B-52's legacy system (B-52 RMP SAR, 2021). This scenario could also be the case for several older systems not equipped with capabilities to integrate OSA.

Factors Impacting EVM Metrics

This thesis utilizes ordinary least squares regression (OLS) analysis to investigate the effects of MOSA on cost and schedule overruns. OSA is the main independent variable of interest for the regression, but other factors impact EVM metrics. For example, cost, branch of service, contract type, contract length, and the Weapons Systems Acquisition Reform Act (WSARA) 2009 may influence CPI and SPI.

1. Service

   EVM metrics are governed by the Earned Value Management Interpretation Guide (EVMIG) across the DoD. Little research has been done on whether or not there are systematic differences in EVM management between services. However, the services may interpret or implement the guidance in a manner that is different from one another.

2. Contract Type

   Cost-plus (CP) and fixed-price (FP) are two major contract vehicle types in the DoD. CP contracts require the government to pay all allowable costs and fees to contractors based on government evaluation of performance, incentivization of target costs, or negotiation (Olbum et al., 2019). In FP contracts, the government pays a set fee to contractors regardless of the actual costs incurred by the contractor. CP is riskier for the government than FP because contractors are incentivized to increase their allowable costs for profit maximization (Olbum et al., 2019). Furthermore, cost overruns for allowable costs are the government's responsibility for reimbursement. Given the risky nature of CP, OSA elements on CP contracts may perform worse on EVM metrics compared to OSA elements on FP contracts.

3. WSARA

   WSARA is a U.S. federal law enacted to improve the DoD's acquisition process for weapon systems (Weapons Acquisition Reform, 2012). The law was designed to address issues such as cost overruns, schedule delays, and performance shortfalls that had plagued many weapon system acquisition programs in the past. The law includes provisions to improve the management of weapon system programs, increase the use of competitive procedures, and enhance the role of the Office of the Secretary of Defense in the acquisition process. It also aims to increase the use of industry best practices and provide better oversight and accountability of weapon system acquisition programs. In the years following WSARA, the GAO analyzed 11 programs and found that WSARA reinforced early focus on requirement buildings, cost and schedule estimates, testing, and reliability (2012). In other words, post-

WSARA programs may experience better program management early in the development phase. It is expected that programs post-WSARA perform better on cost and schedule metrics than programs pre-WSARA.

In addition to these factors, contract completion is another variable of importance for CPI. Cumulative CPI becomes more stable over time as programs reach completion (Christensen & Payne, 1992; Christensen & Heise, 1993). When evaluating programs at the contract level, previous research finds that contracts are considered "complete" when they have a completion percentage of at least 92.5% (Tracy & White, 2011). At this point, costs are stable and predictive of the final cost for that contract. Completion percentage is not a factor in the model, but it is useful for a robustness check. Considering completed contracts only could change the CPI results because completion represents stability whereas non-completed contracts experience more variability in the data. Therefore, the regression may have more power to detect OSA's influence when analyzing contracts that are at least 92.5% completed.

Factors Impacting Nunn-McCurdy Breaches

This thesis also uses logistics regression to measure OSA's influence on the occurrence of Nunn-McCurdy breaches. In addition to OSA, other factors include cost, branch of service, commodity, and WSARA.

1. Service

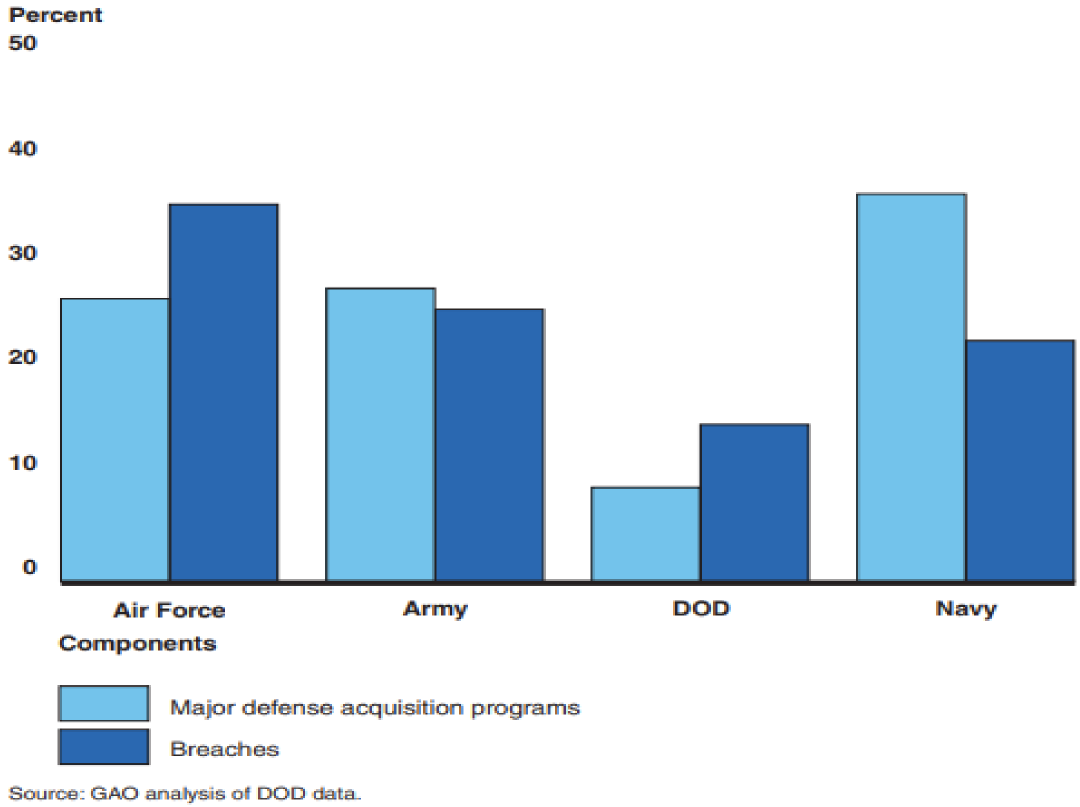


Figure 4: Rate of Nunn-McCurdy Breaches by Service

The different components throughout the DoD experience different rates of Nunn-McCurdy breaches. Per the GAO, the Air Force had the highest proportion of total breaches compared to the total number of its programs from 1997 – 2009 (2011). Figure 4 details the proportion of Nunn-McCurdy breaches and MDAPS by service. Service also serves as a proxy for commodity because certain services generally produce specific commodities. For example, a large portion of Air Force programs is aircraft, while a more significant portion of Army programs is ground-based vehicles. Considering that the Air Force produced the most breaches, it is no surprise that most breaches across the DoD occurred within aircraft, satellites, and helicopter programs. Whether or not a program was managed by the Air Force or not will serve as an essential control for the regression.

2. WSARA

WSARA aimed to make the Nunn-McCurdy process more rigorous and to provide better oversight and accountability for weapon system acquisition programs through several changes (Arena et al., 2014). First, programs must certify to Congress that the program is of higher priority over other programs whose funding is cut to make up for the cost growth of the current program. Second, the Performance Assessments and Root Cause Analyses (PARCA) office was established to support mandated root cause analysis; programs must address the findings from the analysis and restructure to mitigate the issues that led to the cost growth. Third, withdrawals of the most current milestone approval are mandated and no further progress can be made on new contracts without new approvals. WSARA introduced significant penalties and further oversight for Nunn-McCurdy breaches. It is highly possible that pre- and post-WSARA may significantly impact the regression analysis.

Table 1: Expected Impact of Critical Factors on EVM and Nunn-McCurdy Breaches[1]

	Expected Impact	
Factor	**EVM**	**Nunn-McCurdy Breaches**
OSA	+	-
Service	Unknown	Air Force: +
Contract Type (CP)	-	NA
WSARA	+	-

[1] For the Nunn-McCurdy breach column, (-) indicates a decrease in the probability of a breach while (+) indicates an increase in the probability of a breach occurring.

Previous MOSA Studies

Cole (2011) examines open architecture's role in risk uncertainty for cost and schedule parameters in Navy programs. This research surveys a diverse group of DoD employees with broad acquisition experience asking if OSA has produced the promised cost and schedule efficiencies. When this research was conducted, OSA was not as widespread as today, and many interviewees were not experienced or familiar with OSA principles. However, for the handful of interviewees that were knowledgeable about OSA, the study found that OSA resulted in cost savings and rapid development (Cole, 2011). One success story discussed in Cole's research is the United States Navy (USN) Acoustics-Rapid COTS Insertion (A-RCI) program. A-RCI was designed to take off-the-shelf computing technology and integrate them in rapid, periodic upgrades with an open architecture approach. As a result, it was found that a factor of nearly five to one was made for life-cycle program cost improvements (Boudreau, 2006). Overall, Cole (2011) concludes that OSA may be useful for certain programs; however, the specific attributes of which programs are best for OSA are not discussed, and the author suggests this as an area of further research.

Cuff and Fersch (2016) evaluate commercial efforts to investigate MOSA effects on cost and schedule. Commercial examples were utilized in this analysis because of the lack of precise, accessible data for DoD platforms developed with MOSA. Thus, the commercial operating systems for Android (open system) and iOS (closed system) were chosen because they are leaders in the cellphone industry. Cuff and Fersch contrast the two systems to emphasize the differences in cost and schedule for open and closed software. Although Apple is not a fully closed system, it is more closed than Android because Apple controls all updates for the baseline software (Cuff & Fersch, 2016). In the comparison analysis, the openness of Android offered more flexibility and lower procurement costs than iOS, but the development costs were not necessarily lower (Cuff & Fersch, 2016). Although development costs are not improved with open architecture, they claim that MOSA may be an optimal approach for the government because of the immense potential of reduced costs for the remaining lifecycle of programs. While this study shows promise for MOSA in the DoD, industry and government operate differently. Cell phones are not as complex as MDAPs and what works in the cellphone industry may not produce similar results within the DoD.

Another critical study is Minor's (2017) research on various Army programs and how MOSA influences positive returns on investment (ROI). He claims that the combination of modular architecture and open systems approach results in a high probability of a positive ROI for both new and legacy systems. The author also analyzes industry programs utilizing MOSA and finds that the industry is far more advanced in MOSA adoption and implementation. Finally, he urges the DoD to adopt some techniques heralded by the industry to include Open-Source Software (OSS) for bolstering cost savings. Minor considers OSS integral to MOSA and the main reason the industry has pulled ahead and is doing much better than the government. Although this study makes many optimistic claims about the benefits of MOSA, the methodology could be more transparent; the methodology does not go into depth about what kinds of tests were performed. Furthermore, the results are vaguely described and no specific data figures are provided for his tests. Despite these drawbacks, the research shows MOSA's potential to impact program management positively.

Brown et al. (2019) advocate for Open Mission Systems (OMS), open architectures explicitly designed for aircraft. This study analyzes OMS demonstrations and compares them against thirteen other non-OMS historical avionics programs with equivalent source lines of code (ESLOC) data. ESLOC data is representative of the amount of effort that was spent on developing code for a program. This study found that the OMS demonstrations reduced the cost per ESLOC and the total amount of ESLOC required for an upgrade versus the non-OMS programs (Brown et al. (2019). Additionally, the development time for the OMS programs was, on average less than the non-OMS programs (Brown et al. (2019). The research shows that OMS has the potential for improved cost and schedule compared to non-OMS. This study uses limited data to draw conclusions but provides a promising outlook for an open architecture approach. A summary of the OSA-focused literature on cost and schedule savings can be found in Table 2.

Table 2: Overview of Cost and Schedule MOSA Studies

Title	Author(s)	Background	So What
Risk Uncertainty and Open Architecture in the DoD Acquisitions System	Cole (2011)	Examined how OSA impacted risk uncertainty for cost and schedule parameters in Navy programs by surveying SMEs.	No general consensus amongst the experts on whether or not OSA consistently delivered on cost and schedule savings. Determined that OSA may be useful for only certain types of programs.
OSA: Cost and Schedule Saver or Driver?	Cuff and Fersch (2016)	Studied industry examples (Android and Apple operating systems) to compare cost and schedule performances.	OSA may be optimal appraoch for government because there is potential to reduce costs over entire lifecycle of a program.
Identifying the Return on Investment for Army Migration to a Modular Open System Approach for Future and Legacy Systems	Minor (2017)	Investigated Army and industry programs to determine whether or not MOSA generates positive returns on investment.	Combination of MOSA and opens systems approach result in a high probability of a positive return on investment for both new and legacy systems.
A Case for Open Mission Systems in DoD Aircraft Avionics	Brown et al. (2019)	Analyzed cost per equivalent source lines of code (ESLOC) for Open Mission System (OMS) and non-OMS programs.	OMS reduced cost per ESLOC and total amount of ESLOC required versus non-OMS programs. Provides a promising outlook for OSA reducing cost and schedule.

The Future of MOSA – Digital Transformation

MOSA plays a vital role in Digital Transformation, a coordinated effort to bring modern digital capabilities to acquisitions through a collaborative, integrated digital environment (DTO – USAF Digital Transformation Office). MOSA, a foundational aspect of Digital Transformation, is seamlessly integrated within the digital approach (Zimmerman et al., 2019). . Just as MOSA is an integration strategy for rapid development, Digital Transformation aims to apply rapid development to the whole system. Current programs that employ the Digital Transformation Approach with OSA elements include but are not limited to the Sentinel Ground Based Strategic Deterrent (GBSD) Program, Next Generation Air Dominance (NGAD) Program, B-52 Commercial Engine Replacement Program (CERP), and A-10 Wing Replacement Program (Zimmerman et al., 2019). Digital Transformation will likely take permanent hold within the DoD and continually be supported by developments in MOSA. The e-T7 is one of the first programs to be developed from the ground up with Digital Transformation, and it has proven successful. Per Boeing, first-time engineering quality increased by 75%, assembly hours reduced by 80%, and software development/verification time was cut in half (Boeing: eT-7A Red Hawk: eSeries Leader, 2020).

Summary

This chapter covers essential OSA history, definitions and concepts, advantages and disadvantages, prior studies on cost overruns and OSA, and OSA's future in digital transformation. OSA is used extensively throughout the DoD and has been established as a best practice for reducing cost and schedule (Kendall, 2014). However, there is a gap within the current literature in regards to OSA and analysis of program management metrics. The following chapter discusses the EVM and Nunn-McCurdy methodology for analyzing cost and schedule savings for OSA programs.

III. Methodology

Overview

Chapter three offers an in-depth look into the data and methodology used for analysis. First, this chapter discusses the data sources, data collection process, and inclusion and exclusion criteria for program data. Next, this chapter discusses the hypotheses, assumption testing, and analysis methods for answering the research questions on OSA vs. non-OSA for EVM metrics and Nunn-McCurdy breaches.

Data Collection

The Earned Value Management Central Repository (EVM-CR) is a DoD database containing a breadth of data on programs and contracts, including contract performance reports (CPR), integrated program management reports (IPMR), schedule analysis reports, and other contractor submissions. EVM-CR also provides contract summaries with various EVM metrics at the top level for contracts and WBS elements within contracts. EVM-CR hosts contract information for 57 aircraft programs with potential OSA efforts. To determine the integration strategy in each effort (i.e., OSA or non-OSA), each program's Cost Analysis Requirements Document (CARD) was obtained via the Cost Assessment Data Enterprise (CADE) system, a DoD database containing cost analysis data and documentation for DoD programs. CARDs provide in-depth descriptions of program requirements and are critical for the OSA validation process. If OSA is essential for developing program requirements, it would likely be mentioned somewhere in the CARD. Only the most recent narrative CARD for each program was utilized.

Keywords "open" and "modular" were searched within the CARDs to determine OSA's employment. Only 22 of 57 programs had CARD and EVM data available and were considered for further validation. Within those 22 programs, 17 were identified as employing OSA, while 5 were identified as not employing OSA. For these 22 programs, the most recent CPR or IPMR with complete data was used, leaving 14 OSA programs and 5 non-OSA programs.

EVM-CR provides a breakdown of EVM data by contract effort and work breakdown structure (WBS) on IPMRs and CPRs. Only contracts in the Research Development Test and Evaluation (RDT&E) or Engineering Manufacturing Development (EMD) phase were considered for further evaluation. OSA is likely to have the most significant impact on development because OSA is heavily involved in the beginning phases of programs. The WBS elements on these RDT&E and EMD contracts include avionics, systems engineering, systems integration, communications, and other systems that integrate with the flight computer. The budgeted cost of work scheduled (BCWS), budgeted cost of work performed (BCWP), and actual cost of work performed (ACWP) are pulled from only RDT&E and EMD contracts. CPI measures earned value against the actual cost of completed work packages. SPI is a measure of earned value against the planned value and data is collected at the halfway point of a contract. Table 3 details the calculations for CPI and SPI and their interpretations.

Table 3: CPI and SPI Calculation and Interpretation

	Calculation	Interpretation
CPI	= BCWP / ACWP	> 1 - Under Budget
		< 1 - Over Budget
SPI	= BCWP / BCWS	> 1 - Ahead of Schedule
		< 1 - Behind Schedule

For CPI, only the BCWP and ACWP from the most recent IPMR or CPR are used for calculations. This CPI is cumulative to date, but the contracts in the data set are at various completion points. Table 4 highlights the percentage of OSA and non-OSA efforts that are at least 92.5% complete. A full list of contract efforts and their percentage of completion can be found in Appendix C.

Table 4: Percentage of Completed Contracts

	Completed Contracts (> 92.5%)
OSA	46%
Non-OSA	29%

For SPI, the BCWP and BCWS from the IPMR or CPR within plus or minus one month of the contract's midway point were used for calculations. The halfway point rather than the most recent data points is used for SPI because this metric converges towards a value of "1" as the program reaches completion. Many of the contracts in this analysis are completed or nearing completion; thus, evaluating SPI at the midway point provides more value. A total of 93 OSA elements and 24 non-OSA elements were collected for CPI, while 75 OSA elements and 24 non-OSA elements were collected for SPI.

Generally, the EVM metrics within this study should center around a value of "1". Histograms of the data visualize the existence of a few potential outliers, formally identified by evaluating quantile ranges. Any data points three times the interquartile range past the lower and upper quantiles are outliers (McClave et al., 2023). Outliers exist within the CPI dataset for the CH-53K and F-22 programs. The CH-53K outlier occurs on an RDT&E flight control computer update effort in the systems engineering WBS element. The F-22 outlier occurs on an RDT&E modernization effort in the avionics WBS element. In reviewing the CH-53K and F-22 programs, there do not appear to be any coding errors in EVM-CR source data. All past EVM data points for these outliers are consistent across multiple periods. Furthermore, nothing in IPMR and CPR documents, which provide detailed contracts analysis, provides commentary on the high CPI values. After reviewing CPI, outlier analysis for SPI shows that are no outliers. A summary of the inclusion and exclusion criteria for the EVM data set can be found in Table 5. Finally, the programs and their selected WBS elements can be found in Appendix D.

Table 5: Inclusion, Exclusion Criteria for EVM Analysis

Category	Number Removed	Remaining Programs
Aircraft Programs in EVM-CR		57
Programs with CARDs	35	22
Programs with Complete Contract Data	3	19
Programs Identified with OSA		14
Programs Identified without OSA		5
Work Breakdown Structure (WBS) Elements		
CPI OSA WBS		93
CPI Non-OSA WBS		24
SPI OSA WBS		75
SPI Non-OSA WBS		24
Final Data Set for Analysis		**117 (CPI), 99 (SPI)**

On average, approximately 32% of contract efforts are categorized as OSA. Total OSA percentage ranges from as low as .05% all the way up to 95% depending on the program. These OSA efforts includes but is not limited to communications, systems engineering, avionics, and other elements related to the fight computer. A full breakdown of the percentage of OSA efforts can be found in Appendix E.

Next, data collection focused on the occurrence of Nunn-McCurdy breaches for programs that do and do not employ OSA. DAVE hosts a list of all Nunn-McCurdy breaches between 1997 and 2019. A total of 99 breaches, 52 critical and 47 significant, occurred across 69 unique programs. It is important to note that programs declaring a significant and critical breach in the same SAR year are listed only in DAVE as critical breaches. Unfortunately, the data set does not indicate if the breach occurred over the original or current baseline. Some programs breached multiple times at significant and/or critical levels. It is likely that multiple breaches within the same program are not independent, which would be problematic for regression analysis. Thus, only the first significant and/or critical breach was used within the analysis.

A list of all active programs between 1997 and 2019 was also pulled from DAVE. For non-aircraft not previously assessed in the EVM data collection process, CARDs were examined to determine their OSA status. Any programs without CARD data were removed from the data set. Approximately 74 unique programs employed OSA, while 52 programs did not employ OSA. Table 5 shows the inclusion and exclusion criteria for the Nunn-McCurdy data set. The complete list of programs and the types of breaches that occurred can be found in Appendix F.

Table 6: Inclusion, Exclusion Criteria for Nunn-McCurdy Breach Analysis

Category	Programs
Breached Programs in DAVE	99
Programs with CARDs	
Programs Identified with OSA	74
Programs Identified without OSA	52
Programs with Breach	43
Programs without Breach	80
Final Data Set for Analysis	**123**

EVM Analysis – Comparison Tests

1. How do EVM metrics (CPI and SPI) differ between systems that do and do not employ OSA?

CPI and SPI are used over other EVM metrics because they are normalized cost and schedule measurements. This research focuses on program management performance and CPI and SPI provide a comparative tool for rescaling the magnitude of BCWS, BCWP, and ACWP. First, the CPI mean for the OSA and non-OSA efforts are compared using a t-test. This parametric test determines whether or not there is any significant difference in means. Before employing a t-test, assumptions of independence and normality must be met. The independence of a program's contract and EVM data is assumed because it is not affected by or related to information for other programs. The normality assumption is tested with the Anderson-Darling test, which determines whether or not the distributions approximate a normal distribution. The next step evaluates whether the variances between the OSA and non-OSA elements are equal with the Levene test. Finally, variance is tested to determine the specific type of t-test. The CPI distributions are approximately normal and their variances are equal, resulting in the use of the pooled t-test.

The SPI distributions are not normal, thus Wilcoxon Rank Sum (WRS) tests are used instead of a t-test. This test compares the overall distributions or medians between samples to determine whether they differ significantly. A Levene test is also conducted for the SPI distributions to determine if the median hypothesis can be used for the WRS test. There is no equal variance for SPI, thus, a more general hypothesis about the shape of the distributions is used. A summary of the tests, hypotheses, and alphas for research question one can be found in Table 6.

Table 7: Summary of EVM Comparison Tests and Hypotheses

Test	Hypothesis	Alpha
Anderson-Darling	H_0: The distribution is approximately normal H_A: The distribution is not approximately normal	0.05
Levene	H_0: Variances for OSA and non-OSA efforts are comparable H_A: Variances for OSA and non-OSA efforts are not comparable	0.05
Student's t	H_0: The mean of CPI/SPI for OSA and non-OSA are comparable H_A: The mean of CPI/SPI for OSA and non-OSA are not comparable	0.05
Wilcoxon Rank Sum (Unequal Variance)	H_0: The distributions for OSA and non-OSA efforts are comparable H_A: The distributions for OSA and non-OSA efforts are not comparable	0.05

EVM and Nunn-McCurdy Regression Analysis

2. How does the presence of OSA impact EVM metrics (CPI and SPI)?

3. How does the presence of OSA impact the likelihood of Nunn-McCurdy breaches?

An ordinary least squares (OLS) regression is used to determine if OSA is a significant contributing factor for predicting CPI and SPI. In addition, logistic regression is used to determine if OSA is a significant contributing factor for predicting Nunn-McCurdy breaches. To develop OLS and logistic regressions, the following assumptions in Table 7 must be met (Hilmer & Hilmer, 2014). Meeting these assumptions ensures that the regression outputs results in unbiased beta estimates with minimum variance.

Table 8: OLS And Logistic Regression Assumptions

	OLS	Logistic
1	The model is linear in parameters	The dependent variable is a binary
2	The data are collected through independent, random sampling	The data are collected through independent, random sampling
3	The data are not perfectly mulitcollinear	The data are not perfectly mulitcollinear
4	The error term has zero mean	There are no strongly influential outliers
5	The error term is uncorrelated with each independent variable and all functions of each independent variable	There is a linear relationship between the independent variables and the logit of the dependent variable
6	The error term has constant variance	Sufficiently large sample size

First, there are no parameters with exponents in the model nor are there any parameters interacted with other parameters. Second, the data collection process features independent, random sampling because data was retrieved from separate aircraft programs. Third, multicollinearity is measured by assessing variance inflation factors (VIF). VIF identifies the presence of a correlation between independent variables and the strength of that correlation; any independent variables with a VIF score greater than five indicate too much correlation. Fourth, the inclusion of a y-intercept forces the mean of the residuals to equal zero, thus satisfying the assumption of the error term having zero mean. Fifth, the exogeneity assumption is a joint problem of omitted variable bias and correlation of independent variables with these omitted variables. Exogeneity is assumed to be satisfied because the variables included in the model are not expected to be significantly correlated with those in the error term. Furthermore, prior research shows that all relevant variables for cost and schedule growth are included in the model, mitigating omitted variable bias. Finally, assumption six is verified with a Breusch-Pagan test on the residuals, which tests whether heteroskedasticity is present within the model. The error term is not directly observable, so the test is performed on the residuals as a proxy for the error term.

By meeting all these assumptions, OLS provides the best linear unbiased estimators for predicting CPI and SPI.

In addition to testing the assumptions for the OLS regression, diagnostic tools such as Cook's distance and studentized residuals reveal the existence of influential outliers. Cook's distance measures a particular data point's influence on the regression results. Any Cook's distance greater than the 4/n rule of thumb is overly influential (Jayakumar et al., 2015). Studentized residuals normalize the residuals' variance so that the resulting distribution can be used for outlier detection. According to the rule of thumb, data points more than three standard deviations away from the mean of the studentized residuals are outliers (Paul & Fung, 1991). Any influential data points and outliers are removed from the data set and the model is rerun. Then, the models with and without the outliers are compared to determine the impact of removing influential outliers. For CPI regression only, a robustness check is performed by including only completed contracts in the analysis. Contracts that are at least 92.5% complete have a more stable cumulative CPI compared to contracts early on in the process.

Moving on to logistics regression, a binary dummy variable represents the dependent variable for the logistic regressions, satisfying the first assumption. Second, assumption two is met because the data collection process with DAVE and CARD data represents a random sampling of independent programs. Third, the multicollinearity is tested with VIF; any VIF scores greater than five indicate significant correlation among the independent variables. The fourth and fifth assumptions only apply to continuous independent variables of which there are none in the model; all independent variables are categorical and represented by binary dummy variables. Finally, the sufficiently large sample size assumption is verified according to the rule of thumb that there are at least ten observations for the least frequent outcome for each independent variable (Agresti, 2018). According to that rule, the sample should be at least 86, and the actual sample size is 123.

Table 9: Summary of OLS And Logistic Regression Assumption Testing

Assessment	Tool	Considerations/Hypothesis	Alpha
OLS Assumption Three	VIF	VIF Score > 5 indicates multicollinearity	NA
OLS Assumption Six	Breusch-Pagan	H_0: The residuals have constant variance H_A: The residuals do not have constant variance	0.05
OLS Influential Data Points	Cook's D	Influential Point = Any data point greater than 4/n	NA
OLS Outliers	Studentized Residuals	Outlier = Any data points more than three standard deviations away from the mean	NA
Logistic Assumption Three	VIF	VIF Score > 5 indicates multicollinearity	NA
Logistic Assumption Four	Dfbeta	Influential Point = Any data point greater than 2/sqrt(n)	NA

The Models

Two OLS regressions are run for the EVM analysis with CPI as one dependent variable and SPI as the other. A continuous variable represents SPI and CPI with distributions of only positive values. One regression is run for the Nunn-McCurdy analysis with an any breach dependent variable. This variable measures whether or not a program has ever significantly and/or critically breached at least one time where “1” represents a breach and “0” represents no breach. Table 9 highlights the models and Table 10 shows the expected impact of the independent variables.

Table 10: EVM and Nunn-McCurdy Breach Regression Models

Models
$CPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \varepsilon$
$SPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \varepsilon$
$Any\ Breach = \beta_0 + \beta_1 OSA + \beta_2 Air\ Force + \beta_3 WSARA + \varepsilon$

Table 11: Expected Impact of Independent Variables

	Expected Impact	
Independent Variables	**EVM - OLS Regression**	**Nunn-McCurdy - Logistics Regression**
OSA	+	-
Service	Unknown	Air Force: +
Contract Type	-	NA
WSARA	+	-

OSA is represented by a binary dummy variable where "1" represents OSA and "0" represents non-OSA efforts. Given that OSA purportedly reduces cost and schedule overruns, the expected impact of OSA is positive for the OLS regression. OSA has a negative expected impact on the logistics regression because it is expected to decrease the likelihood of breaches. For the EVM analysis, service is represented by a series of binary dummy variables where "1" describes either the Air Force or Navy and "0" represents the Army. The Air Force and Navy are both in the model because they have fixed-wing aircraft. The Army is the chosen dummy variable that is left out of the model because they only have rotary wing aircraft. In the Nunn-McCurdy regressions, service represents a continuous dummy variable where "1" reflects the Air Force and "0" reflects all other services that are not the Air Force; these other services include the DoD, Army, Navy, and Space Force. The contract type is represented by a binary dummy variable where "1" represents a cost plus contract "0" represents a fixed price contract. Finally, WSARA is represented by a binary dummy variable where "1" defines post-WSARA and "0" defines pre-WSARA. Post-WSARA includes all data points with contract start dates or program effective dates in 2010 and beyond and pre-WSARA includes data points up until 2009.

The impact of the independent variables is assessed with parameter effect tests. In other words, beta estimates and their associated variations are tested for whether or not they are statistically different from the null case. Beta estimates statistically different from the null case are assumed to significantly impact EVM and Nunn-McCurdy metrics. The hypotheses for these tests are as follows in Table 11.

Table 12: Hypotheses for Parameter Effect Tests

Test	Hypothesis	Alpha
Parameter Effect	H_0: A particular parameter was predictive for CPI/SPI or breaches H_A: A particular parameter was not predictive for CPI/SPI or breaches	0.05

Summary

A total of 117 EVM data points for aircraft are analyzed in this analysis with various empirical methods. First, EVM analysis comparing the means and distributions of programs with and without OSA are tested with a t-test and WRS. These tests show whether or not there is a significant difference between OSA and non-OSA efforts for CPI and SPI. The next portion of the EVM analysis uses OLS regression to examine the impact of OSA on CPI and SPI prediction. The modeling and parameter t-tests show the direction and strength of the OSA's relationship with CPI and SPI. Finally, the Nunn-McCurdy analysis on the impact of OSA on the likelihood of breaches is tested with a logistics regression. Approximately 123 programs throughout the DoD are analyzed in the model with parameter t-tests showing how OSA influences the likelihood of any breach occurring. This methodology determines the true value of OSA's influence on program management.

IV. Analysis and Results

Overview

Chapter 4 begins with descriptive statistics and assumption testing for determining parametric (t-test) or non-parametric tests (Wilcoxon Rank Sum). The results from these tests show whether or not there is any statistical difference in CPI and SPI metrics for OSA and non-OSA WBS elements. Chapter 4 then transitions to analyzing the CPI, SPI, and Nunn-McCurdy breach regressions. The results of these regressions show whether OSA has a significant influence on EVM metrics and the likelihood of Nunn-McCurdy breaches.

EVM – Comparison Testing

<u>CPI Descriptive Statistics</u>

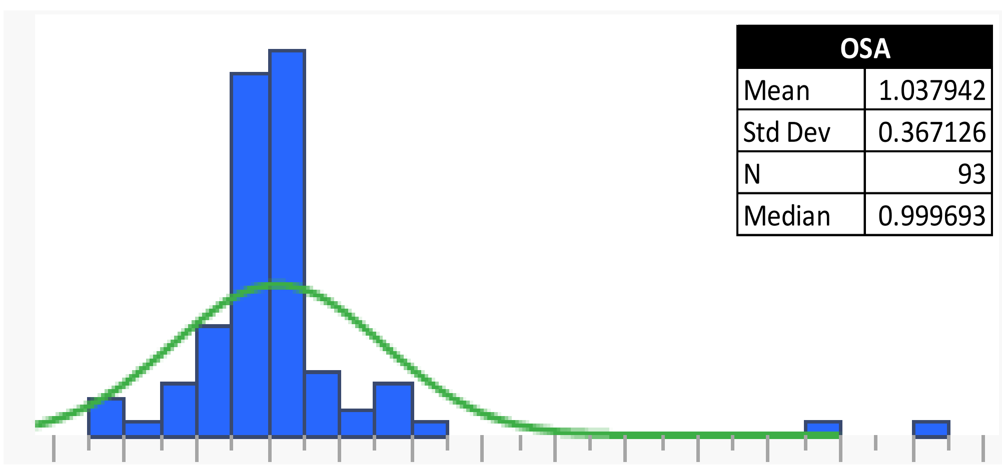


Figure 5: Histogram of OSA Distribution for CPI and Summary Statistics

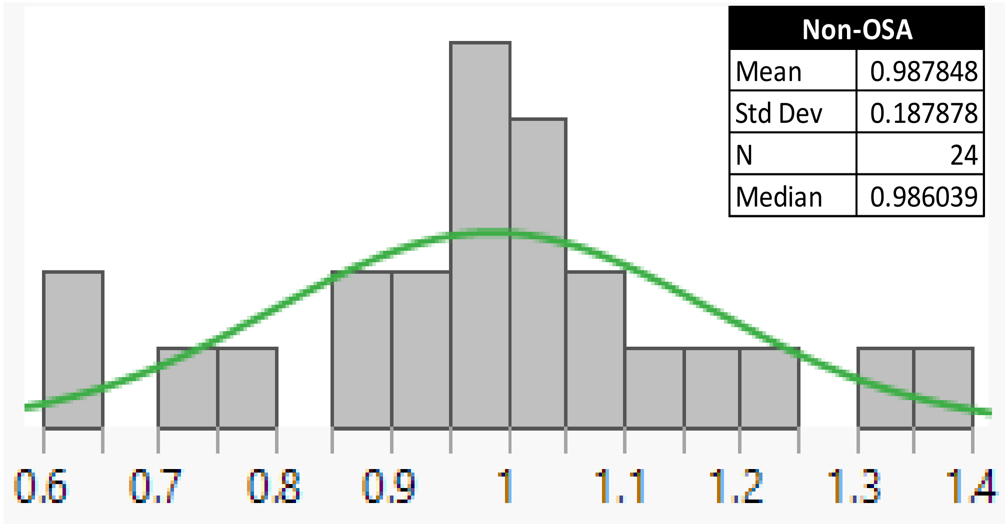


Figure 6: Histogram of non-OSA Distribution for CPI and Summary Statistics

The OSA distribution appears normally distributed and has a higher mean than the non-OSA distribution; the non-OSA distribution also appears approximately normal. The non-OSA efforts have approximately half the variation than the OSA efforts. Both distributions are centered closely around the value of "1", indicating that many efforts are on or near their target for budgeting. To do comparison testing, normality and variance assumptions are tested. The outcomes of these tests determine if the t-test or WRS test is used.

<u>CPI Assumption Testing</u>

Table 13: CPI Assumption Testing Results

	OSA	**Non-OSA**
Test	**P-Value**	
Anderson Darling	<.0001	0.344
Levene	0.5174	

Despite the appearance of a normal distribution, the OSA data does not pass the Anderson Darling test for normality and the null hypothesis of a normal distribution is rejected. Normality is not passed most likely due to the large peak in the middle in Figure 5. However, this is a “good fail” of normality in that it does not significantly impact or change parametric analysis with a t-test. The non-OSA data, on the other hand, passes the Anderson Darling test for normality indicating that the data follows the normal distribution. Next, the Levene test analyzes whether a statistical difference in variation between the OSA and non-OSA distributions exists. The results indicate a failure to reject the null hypothesis that the two distributions are of the same distribution. With the distributions established as approximately normal and with similar variance, the analysis proceeds with a student’s t-test.

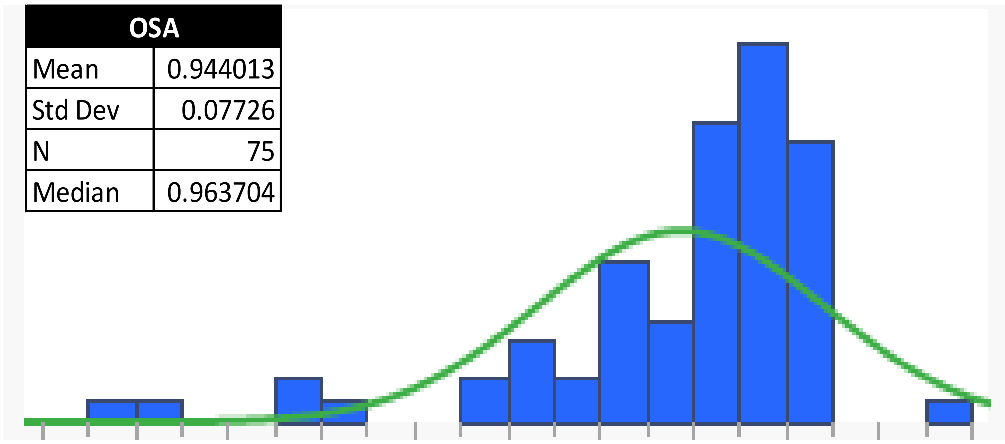
CPI Outlier Diagnostic

Table 14: CPI Outliers

Influential Data Points/Outliers			
Program	**CPI**	**Phase**	**WBS Element**
CH-53K	3.33	RDT&E	Systems Engineering
F-22	2.91	RDT&E	Avionics

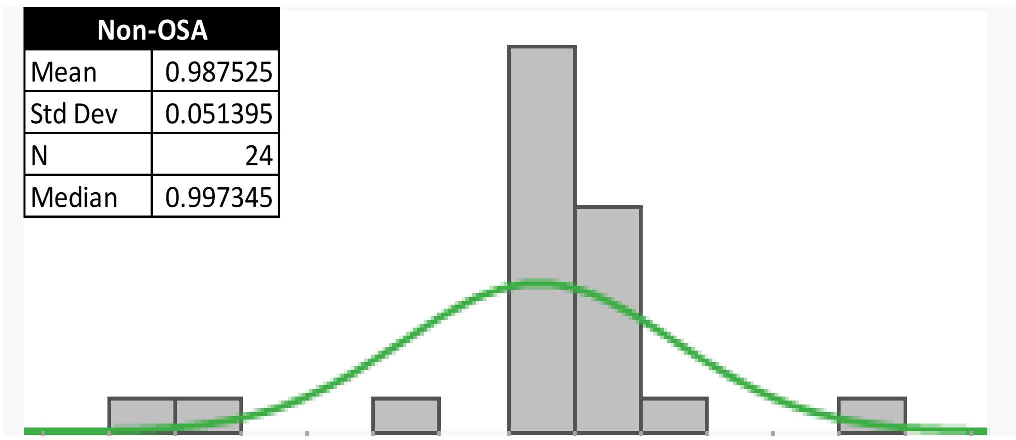
CPI outliers exist within the CH-53K and F-22 OSA programs. Removing these outliers does not significantly change any of the CPI results. The descriptive statistics, assumption testing and t-test results for the CPI analysis without outliers can be found in Appendix G.

SPI Descriptive Statistics



OSA	
Mean	0.944013
Std Dev	0.07726
N	75
Median	0.963704

Figure 7: Histogram of OSA Distribution for SPI and Summary Statistics



Non-OSA	
Mean	0.987525
Std Dev	0.051395
N	24
Median	0.997345

Figure 8: Histogram of non-OSA Distribution for SPI and Summary Statistics

These distributions include SPI values calculated around the halfway point of the contract. The OSA distribution has a slightly smaller mean compared to the non-OSA distribution. Moreover, the OSA distribution has a standard deviation comparable to the non-OSA distribution. Both the distributions are skewed left with maximum values no greater than "1.15". Both distributions appear slightly skewed to the left and normality is unlikely.

SPI Assumption Testing

Table 15: SPI Assumption Testing Results

	OSA	Non-OSA
Test	**P-Value**	
Anderson Darling	<.0001	<.0001
Levene	0.0269	

The distributions are not approximately normal nor do they have comparable variances and the null hypotheses for the Anderson-Darling and Levene tests are rejected. Without normality, non-parametric analysis with the Wilcoxon Rank Sum test is required.

CPI and SPI Comparison Results

Table 16: CPI and SPI Parametric/Non-Parametric Comparison Results

	Test	P-Value
CPI	Student's t	0.5199
SPI	Wilcoxon Rank Sum	0.0016

The CPI distribution means are not statistically different from each other and the null hypothesis for the student's t-test is not rejected. In other words, the presence of OSA has no real impact on program management of cost metrics. The SPI distributions are statistically different from each other and the null hypothesis for the Wilcoxon Rank Sum test is rejected. SPI for the non-OSA distribution appears to be slightly better than the OSA distribution because it is centered more closely to "1".

CPI Regression 1

How does the presence of OSA impact EVM metrics (CPI and SPI)?

Equation 1

$$CPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \mathcal{E}$$

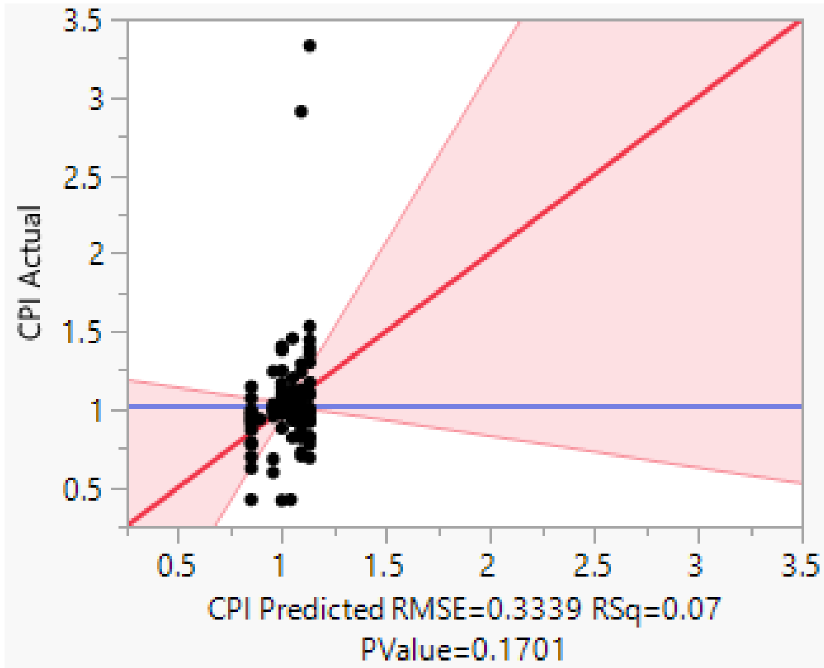


Figure 9: CPI Regression 1 Actual by Predicted Plot

Actual CPI values are not tightly clustered around the predictive model that uses OSA, service, contract type, and WSARA as explanatory variables. While this model's R^2 is relatively lowthere is little concern that omitted variable bias is influencing the beta coefficient. WSARA is likely the only variable of interest that could be correlated with OSA in a significant way due to WSARA and OSA being mandated around the same timeframe, but it is controlled for in the model. .

Model Results

Table 17: CPI Regression 1 Model Results

Parameter Estimates				
Variable	**Estimate**	**Lower 95%**	**Upper 95%**	**P-Value**
Intercept	0.799545	0.5169602	1.0821297	<.0001
OSA	-0.00035	-0.15839	0.1576907	0.9965
Air Force	-0.04178	-0.19783	0.114269	0.5968
Navy	-0.0836	-0.257714	0.0905115	0.3434
CP	0.240543	0.0375253	0.4435609	0.0207
WSARA	0.09274	-0.044289	0.2297688	0.1826

OSA was expected to have a positive relationship for improving CPI, but the parameter estimate is not positive. However, OSA's contribution to explaining the variation in CPI is very small and insignificant, indicating that OSA has essentially zero impact on CPI. This result makes sense given that the t-test showed how OSA and non-OSA distributions are not different. Surprisingly, cost-plus contracts are significant and have a positive rather than a negative beta estimate. It was expected that the risky nature of cost-plus contracts would decrease CPI because they introduce more variability of costs compared to fixed-price contracts. The beta estimate is relatively large and indicates a .24 upward adjustment on average for CPI in cost-plus contracts.

Model Assumptions and Diagnostics

Table 18: CPI Regression 1 VIF Scores

Variable	VIF
OSA	1.088358
Air Force	1.626848
Navy	1.474867
CP	1.300327
WSARA	1.115129

VIF scores for the CPI regression are less than five, meeting the standard for evaluation. Perfect multicollinearity is not a concern, which lends credibility to unbiased OLS beta estimates.

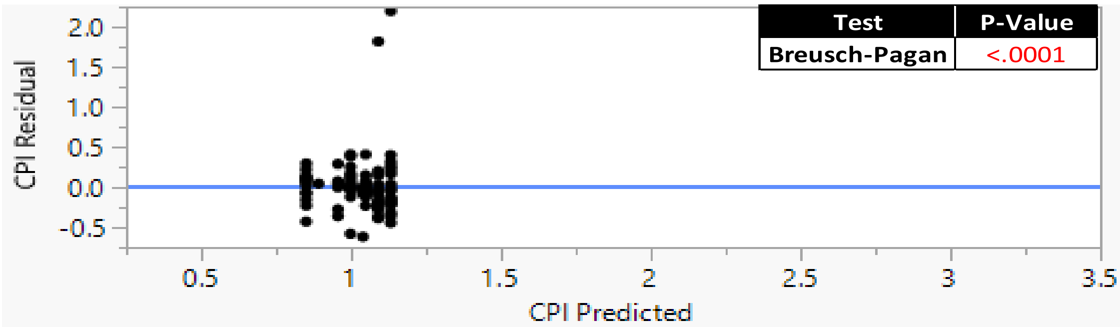


Figure 10: CPI Regression 1 Residual Plot

The residuals appear to have constant variance with the exception of two potential outliers. However, the Breusch-Pagan results indicate the residuals do not have constant variance and the null hypothesis is rejected. Constant variance of the residuals is an important assumption and failing this results in beta estimates without the best minimum variance. The potential outliers may be overly influential, leading to the lack of constant variance. Influential outliers are assessed next with Cook’s distance and studentized residuals.

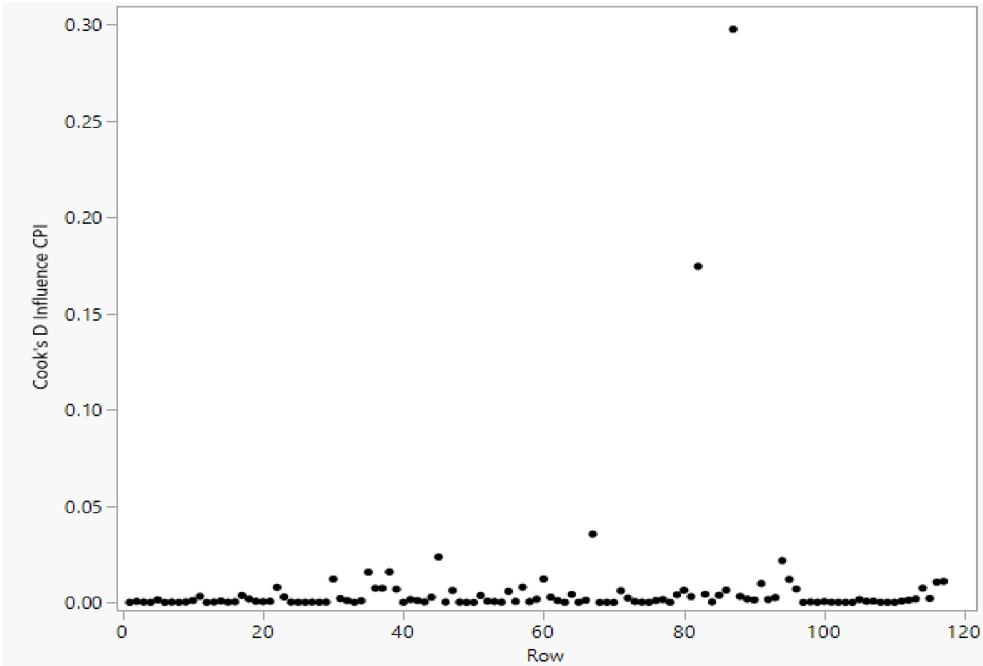


Figure 11: CPI Regression 1 Cook's D Plot. Rule of Thumb > .034

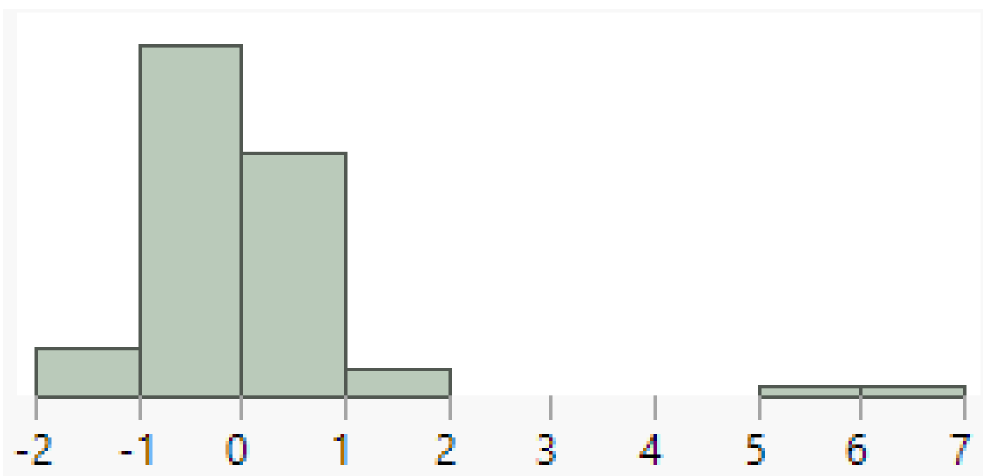


Figure 12: CPI Regression 1 Studentized Residuals

There are only two data points identified with Cook's distance as being overly influential according to the rule of thumb of four divided by the number of total observations. These observations are the same two data points that appear to be outliers in Figures 9 and 10. Table 18 formally identify these outliers with the studentized residuals diagnostic. CH-53K and F-22 programs exhibit unusual CPI metrics much higher than expected. These data points are both outliers and influential and are thus removed from the data set for the next iteration of the CPI regression model.

Table 19: CPI Regression 1 Influential Outliers

Influential Data Points/Outliers			
Program	**CPI**	**Phase**	**WBS Element**
CH-53K	3.33	RDT&E	Systems Engineering
F-22	2.91	RDT&E	Avionics

CPI Regression 2 (Without Outliers)

Equation 1

$$CPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \varepsilon$$

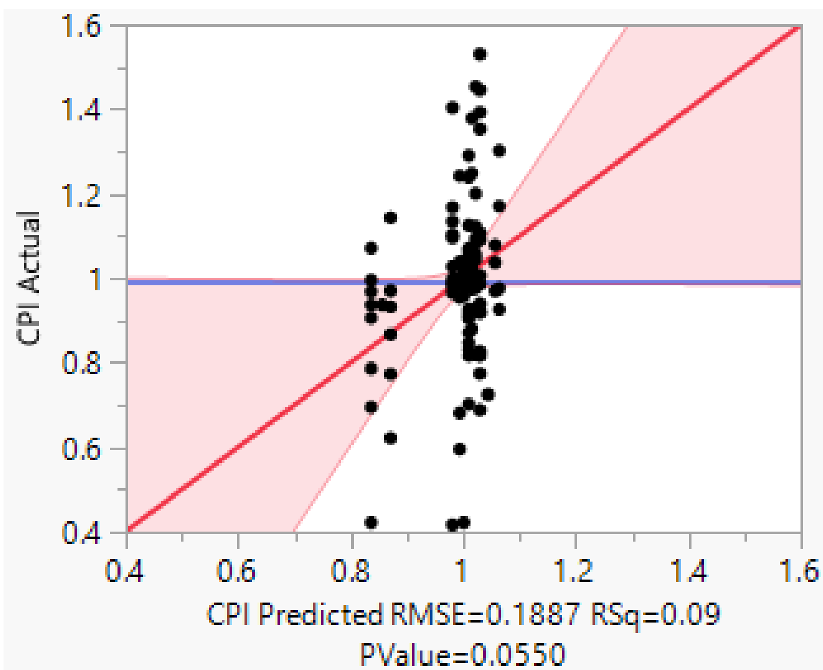


Figure 13: CPI Regression 2 Actual by Predicted Plot

Without the outliers, there is now a clear split between the OSA (right) and non-OSA (left) observations. In addition, the R^2 improved marginally from .07 to .09, suggesting that the model explains more of CPI's variation.

Model Results

Table 20: CPI Regression 2 Model Results

Parameter Estimates				
Variable	**Estimate**	**Lower 95%**	**Upper 95%**	**P-Value**
Intercept	0.862206	0.70137	1.0230419	<.0001
OSA	-0.03433	-0.123789	0.0551217	0.4485
Air Force	-0.01991	-0.109376	0.0695598	0.6601
Navy	-0.00749	-0.106708	0.0917215	0.8813
CP	0.173292	0.0580584	0.2885259	0.0035
WSARA	0.02869	-0.049229	0.1066085	0.4671

Removing the CH-53K and F-22 observations do not significantly change the model results. OSA still lacks significance and has a relatively small, negative impact on CPI while cost plus is still significant with a relatively large, positive impact on CPI. It is important to note that all of the confidence intervals became smaller, indicating that this model has less uncertainty around the beta estimates.

Model Assumptions and Diagnostics

Table 21: CPI Regression 2 VIF Scores

Variable	VIF
OSA	1.086541
Air Force	1.64519
Navy	1.490767
CP	1.307661
WSARA	1.118776

VIF scores for the second CPI regression changed marginally and remained less than five. Again, perfect multicollinearity is not a concern because it does not exist in the model.

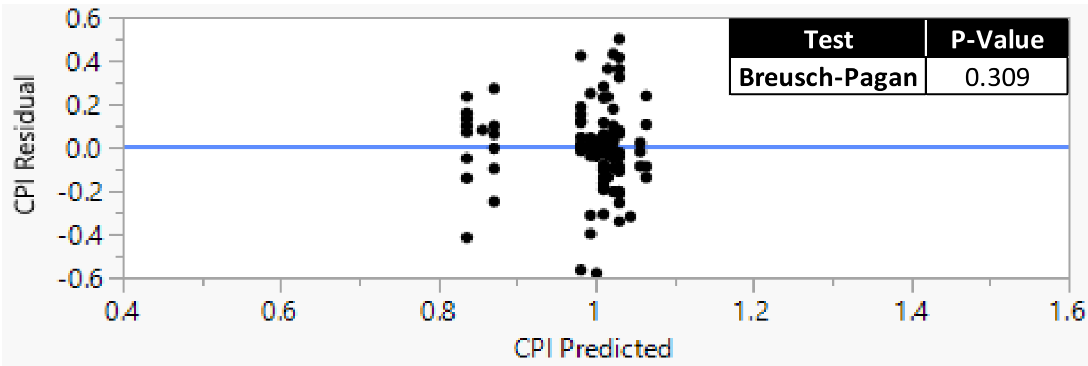


Figure 14: CPI Regression 2 Residual Plot

The residual variance is clearly different for the OSA (right) and non-OSA (left) distributions in Figure 14, but the overall patterns appear consistent. Removing the outliers changed the significance of the Breusch-Pagan results. In this case, the null hypothesis that the residuals have constant variance cannot be rejected. Now that the second iteration of the CPI model meets the assumption of constant variance, the estimates are efficient and have minimum variance.

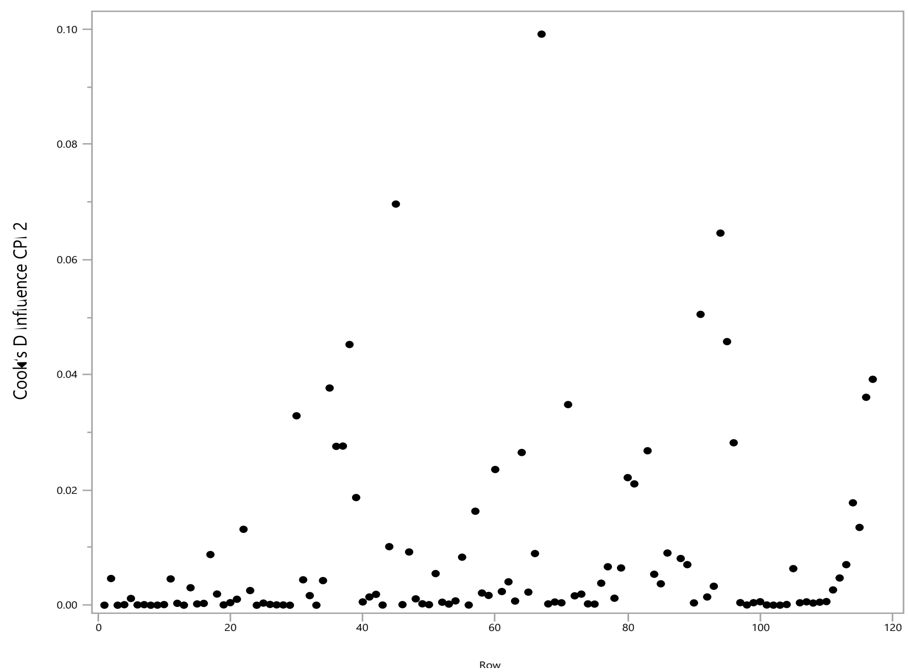


Figure 15: CPI Regression 2 Cook's D Plot. Rule of Thumb > .035

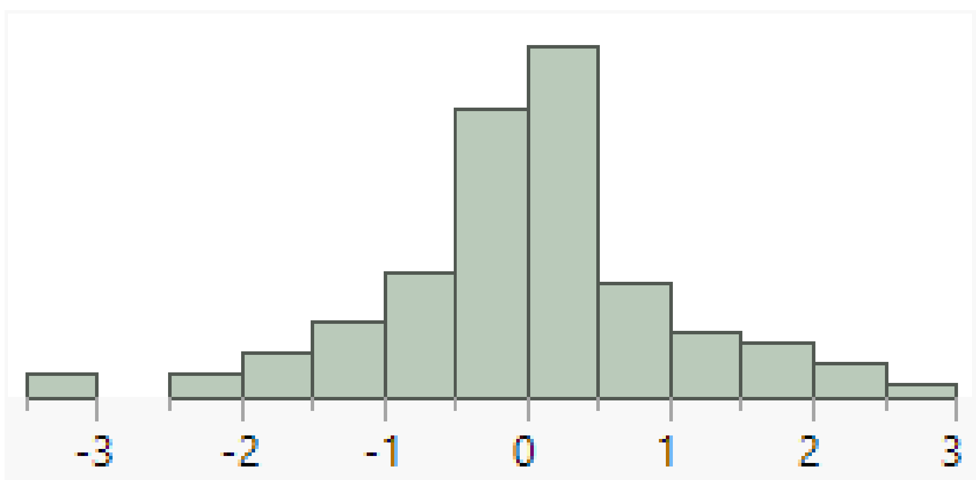


Figure 16: CPI Regression 2 Studentized Residuals

Removal of the outliers significantly changed Cook's distance plot. With the rule of thumb suggesting anything over .035 as influential, several data points become influential that were not before. In assessing the studentized residuals for outliers in Table X, two outliers are readily apparent because they are beyond three standard deviations from the mean. Only two observations identified as influential and outliers are listed in Table 22; these data points include another observation from the F-22 program and the addition of the UH-60M. Rather than being very high like the outliers identified in the previous regression, these influential outliers are low. There are no further iterations of the CPI regression models because removing more and more influential outliers would consistently result in the appearance of new outliers.

Table 22: CPI Regression 2 Influential Outliers

Influential Data Points/Outliers			
Program	**CPI**	**Phase**	**WBS Element**
F-22	0.416	RDT&E	Systems Engineering
UH-60M	0.421	RDT&E	Air Vehicle System Software

It is important to note that the CPI regression included contracts ranging from 16% - 100% complete. Contract completeness is an important factor to consider because CPI stabilizes over time as contracts reach completion. Overall, approximately 43% of the contracts are complete; a regression is run with just this data as a robustness check on the previous results. OSA is still insignificant, however the p-value dropped from .4485 (CPI Regression 2 without outliers) to .1435. Although the OSA results did not change meaningfully, CP does in that it is no longer significant with the p-value increasing from .0035 (CPI Regression 2 without outliers) to .6742. The full regression results of this robustness check can be found in Appendix H.

SPI Regression 1

Equation 2

$$SPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \varepsilon$$

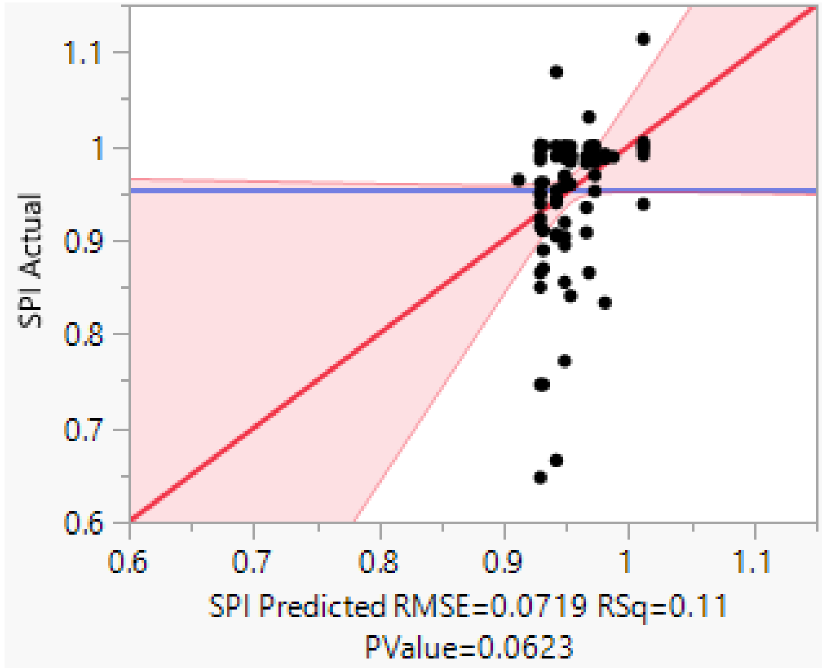


Figure 17: SPI Regression 1 Actual by Predicted Plot

Actual SPI values are spread around the predictive model that uses OSA, service, contract type, and WSARA as predictive variables. The R^2 is small and indicates approximately 11% of SPI's variation is explained by the model. WSARA is likely one of the only variables that are possibly correlated with OSA and anything left in the error term is not significantly correlated with OSA. The inclusion of WSARA in the model as a control variable is critical for unbiased estimates for OSA.

Model Results

Table 23: SPI Regression 1 Model Results

Parameter Estimates				
Variable	**Estimate**	**Lower 95%**	**Upper 95%**	**P-Value**
Intercept	0.974952	0.9105022	1.0394009	<.0001
OSA	-0.03893	-0.074263	-0.003598	0.0312
Air Force	0.019508	-0.016428	0.0554438	0.2838
Navy	0.01275	-0.02812	0.0536192	0.5371
CP	0.017221	-0.028158	0.0626003	0.453
WSARA	-0.02406	-0.058664	0.0105453	0.1707

OSA is the only significant variable outside the intercept and the null hypothesis is rejected. OSA's negative relationship with SPI indicates that it does not improve schedule management at the program level. The magnitude of this effect is relatively large considering that most programs aim to stay between an SPI of .9 to 1; a downward adjustment of .04 could signify significant schedule slippage for programs that use OSA.

Model Assumptions and Diagnostics

Table 24: SPI Regression 1 VIF Scores

Variable	VIF
OSA	1.114203
Air Force	1.56753
Navy	1.356609
CP	1.355979
WSARA	1.154294

All VIF scores are less than five, indicating no perfect multicollinearity or limited correlation between independent variables in the SPI model.

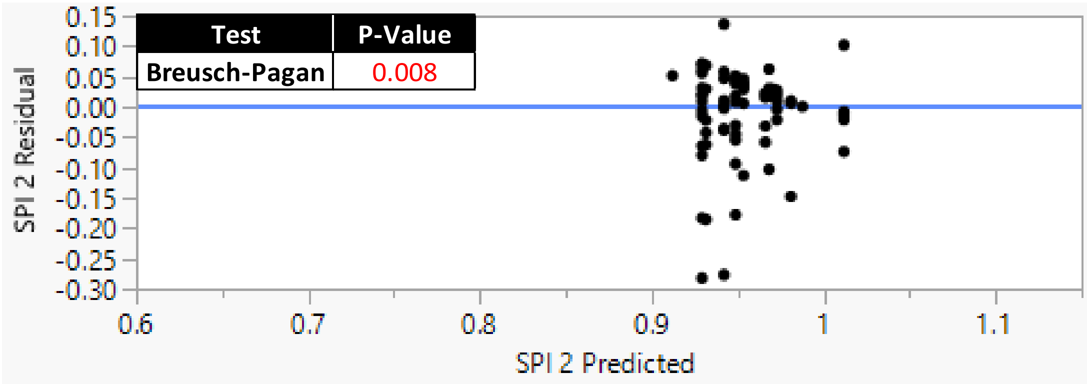


Figure 18: SPI Regression 1 Residual Plot

The residuals appear to skew more negatively and are not constant throughout Figure 18. Indeed, the residuals do not have constant variance and the null hypothesis for the Breusch-Pagan test is rejected. Without constant variance of the residuals, the OLS regression model does not produce results with the most efficient minimum variance. These results may be skewed because of the presence of influential outliers.

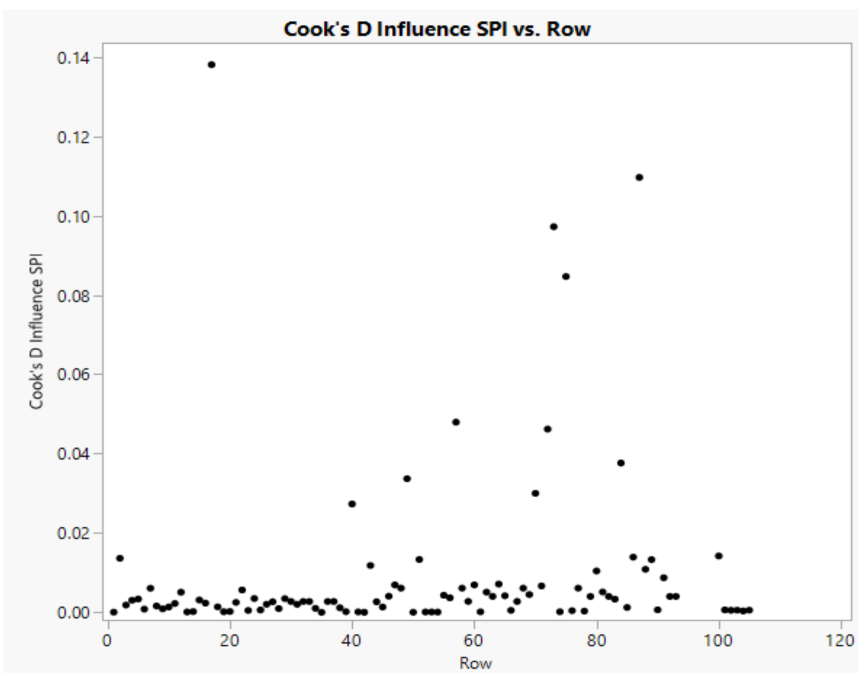


Figure 19: SPI Regression 1 Cook's D Plot. Rule of Thumb > .04

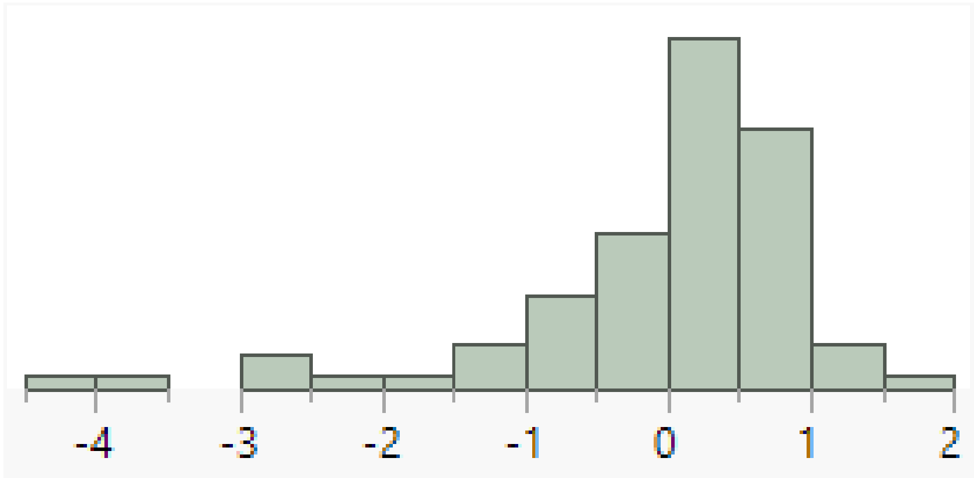


Figure 20: SPI Regression 1 Studentized Residuals

Cook's distance rule of thumb of four divided by the number of observations identifies several data points as overly influential. In reviewing the studentized residuals in Figure 20, only two of these observations are influential outliers. Table 25 reveals that these data points come from the CH-53K and P-8A programs and have low SPI values. These data points are removed from the dataset and the regression is rerun to check the robustness of the model.

Table 25: SPI Regression 1 Influential Outliers

Influential Data Points/Outliers			
Program	**SPI**	**Phase**	**WBS Element**
CH-53K	0.647	RDT&E	Systems Engineering
P-8A	0.665	RDT&E	Mission Computer

SPI Regression 2

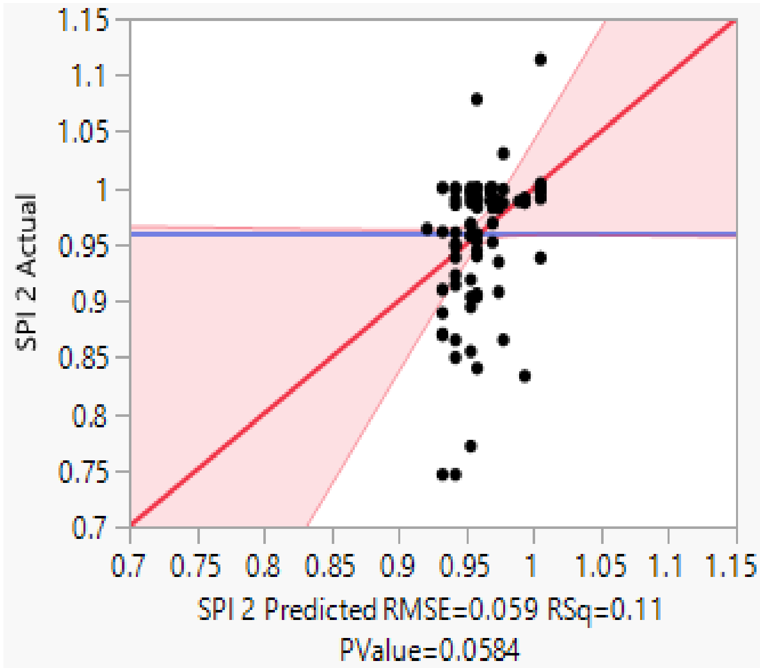


Figure 21: SPI Regression 2 Actual by Predicted Plot

Without the CH-53K and P-8A outliers, the actual by predicted plot for the second SPI regression is very similar to the first one in Figure 17. Furthermore, the R^2 value did not change at all with the removal of the influential outliers.

<u>Model Results</u>

Table 26: SPI Regression 2 Model Results

Parameter Estimates				
Variable	**Estimate**	**Lower 95%**	**Upper 95%**	**P-Value**
Intercept	0.972765	0.9198399	1.0256908	<.0001
OSA	-0.03556	-0.064564	-0.006547	0.0169
Air Force	0.011385	-0.018317	0.0410876	0.4484
Navy	0.015893	-0.018365	0.0501512	0.3592
CP	0.020903	-0.016351	0.0581569	0.268
WSARA	-0.01616	-0.04465	0.0123352	0.2629

There are no significant changes to the parameter estimates in terms of strength and the direction of their relationship with SPI. OSA is still significant at the 95% confidence level and its beta estimate only changed from -.039 to -.036, indicating the robustness of OSA's estimate. The confidence intervals for all variables became smaller because the removal of the outliers decreased uncertainty of the beta estimates.

Model Assumptions and Diagnostics

Table 27: SPI Regression 2 VIF Scores

Variable	VIF
OSA	1.108153
Air Force	1.559666
Navy	1.358496
CP	1.35196
WSARA	1.1533

The VIF scores remain less than five, suggesting limited multicollinearity or correlation between independent variables within the model.

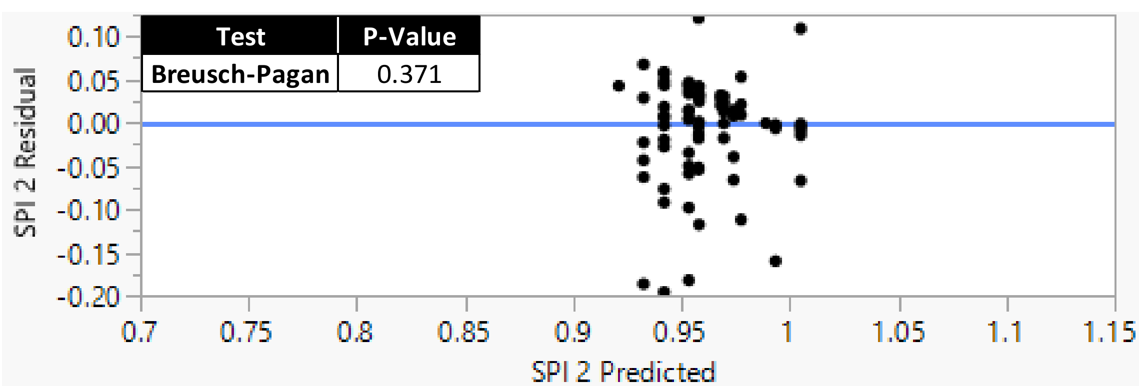


Figure 22: SPI Regression 2 Residual Plot

Removing the influential outliers significantly impacts the residual's variance. The residuals now show constant variance and the null hypothesis for the Breusch-Pagan test is not rejected. Meeting the assumption of constant variance is essential for this analysis because it is required for OLS to produce estimates with minimum variance. The shrinking of the confidence intervals between the first and second SPI regressions highlights the important of constant variance.

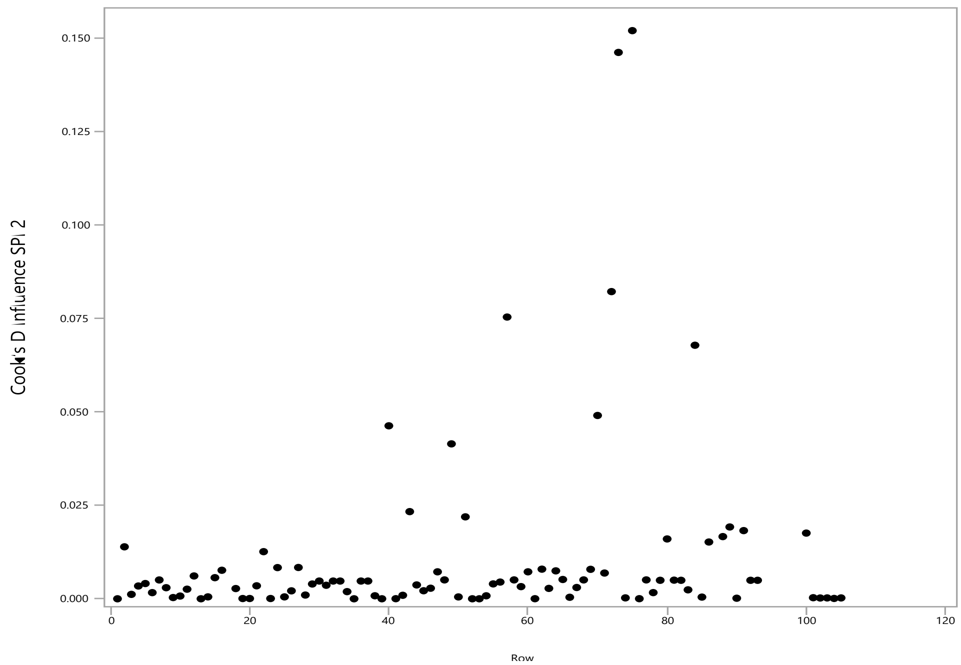


Figure 23: SPI Regression 2 Cook's D Plot. Rule of Thumb > .041

Similar to Figure 19, Figure 23 shows that several data points are influential. Only three are also outliers of these influential data points, as identified in Figure 24. The influential outliers in Table 28 reveal that these contracts are behind schedule compared to other contracts. It is interesting to note that throughout all the regression, CH-53K and F-22 programs have had multiple contracts identified as influential outliers for both CPI and SPI.

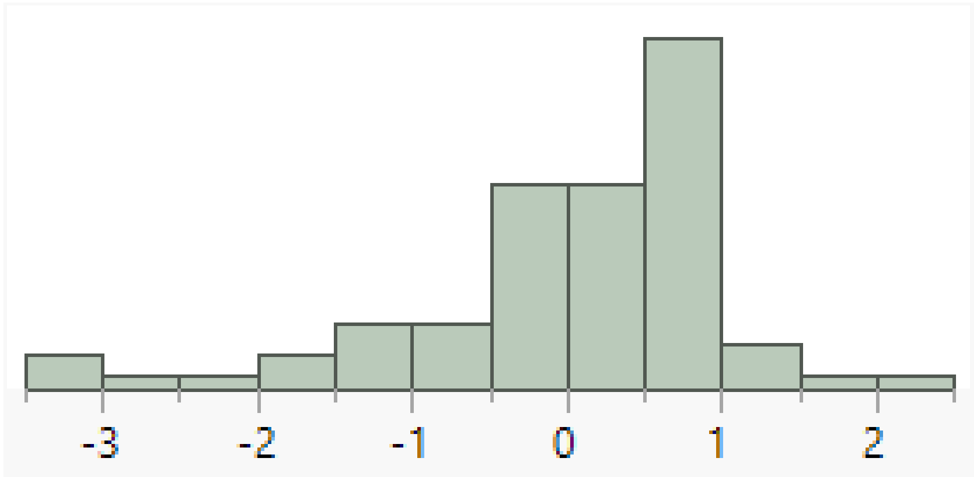


Figure 24: SPI Regression 2 Studentized Residuals

Table 28: SPI Regression 2 Influential Outliers

Influential Data Points/Outliers			
Program	**SPI**	**Phase**	**WBS Element**
APT	0.746	EMD	Communication/Identification
CH-53K	0.746	RDT&E	Communication/Identification
F-22	0.771	RDT&E	Avionics

Nunn-McCurdy Any Breach Regression

How does the presence of OSA reduce the likelihood of Nunn-McCurdy breaches?

<u>Descriptive Statistics</u>

Table 29: Nunn-McCurdy Breach Data Summary

Breach Type	Number of Unique Breached Programs	Number of Unique Non-Breached Programs	Total Number of Programs	Percent of Breaches
Any Breach	43	80	123	34.96%

Any breach is representative of programs that have breached at least one time significantly or critically. Out of 123 programs, 43 have experienced at least one breach while 80 have never breached between 1997 – 2019. 63% of the breached programs are identified as employing MOSA while 37% do not employ MOSA. The analysis is conducted with any breach and does not progress with individual tests for significant or critical breaches[2].

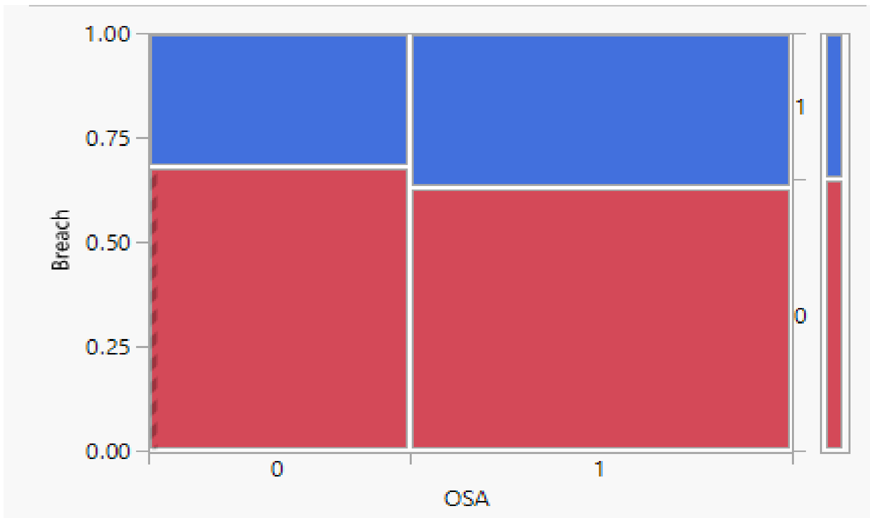


Figure 25: Nunn-McCurdy Breach Mosaic Plot

The mosaic plot in Figure 25 shows no significant difference in any breach occurrences across programs that do and do not employ OSA. The chi-squared p-value of .568 supports the conclusion that OSA does not significantly impact the likelihood of breaches.

<u>Model Results</u>

Equation 3

$$\text{Any Breach} = \beta_0 + \beta_1\text{OSA} + \beta_2\text{Air Force} + \beta_3\text{WSARA} + \varepsilon$$

---

[2] Separate tests for significant and critical breaches are unnecessary due to the lack of significance found in the combined test.

Table 30: Nunn-McCurdy Regression Model Results

Variable	Estimate	Odds Ratio	Lower 95%	Upper 95%	Effect Likelihood Ratio P-Value
OSA	0.22026202	1.246403	0.568103	2.734577	0.5817
Air Force	-0.1116832	0.894327	0.391493	2.043002	0.7907
WSARA	-1.1692601	0.310597	0.131416	0.734083	0.0052

The impact of OSA on Nunn-McCurdy breaches is not statistically different from zero with a p-value of .58. Adopting OSA does not play a significant role in increasing or decreasing the likelihood of breach occurrence. The impact of the Air Force variable is also not significant at the 95% confidence level. The only significant variable in the regression is WSARA, which is associated with a decrease in the likelihood of a breach. Programs initiated post-WSARA decrease the Nunn-McCurdy odds by approximately one-third.

Model Assumptions and Diagnostics

Table 31: Nunn-McCurdy Regression VIF Scores

Variable	VIF
OSA	1.000222
Air Force	1.009234
WSARA	1.009203

VIF needs to be less than five to pass the model's assumption of no perfect multicollinearity. All the VIF scores meet that criterion, thus there is not a high level of correlation amongst the OSA, Air Force, and WSARA variables.

Results Summary

Table 32: Summarized Results of all Analysis

EVM Analysis			
	Methdology	**P-Values**	**Interpretation**
CPI Comparison of Means	Student's t	0.5199	OSA and non-OSA means are comparable.
SPI Comparison of Distributions	WRS	0.0016	OSA and non-OSA distributions are not comparable. OSA distribution is skewed more towards the left and has more variability.
CPI Regression 1	$CPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \mathcal{E}$	OSA: .9965 CP: .0207	OSA is not predictive for estimating CPI. CP is predictive for estimating CPI and is associated with increases in CPI.
CPI Regression 2 (Without Outliers)	$CPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \mathcal{E}$	OSA: .4485 CP: .0035	OSA is not predictive for estimating CPI. CP is predictive for estimating CPI and is associated with increases in CPI.
SPI Regression 1	$SPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \mathcal{E}$	OSA: .0312	OSA is predictive for estimating SPI and is associated with decreases in SPI.
SPI Regression 2 (Without Outliers)	$SPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \mathcal{E}$	OSA: .0169	OSA is predictive for estimating SPI and is associated with decreases in SPI
Nunn-McCurdy Analysis			
	Methdology	**P-Values**	**Interpretation**
Breach Regression	$Breach = \beta 0 + \beta 1 OSA + \beta 2 Air\ Force + \beta 3 WSARA + \mathcal{E}$	OSA: .5817 WSARA: .0052	OSA does not significantly impact the likelihood of breach occurrence. WSARA decreases the likelihood of breach occurrence by one-third.

Overall, the means of OSA and non-OSA contract efforts are comparable for CPI, indicating that OSA does not significantly impact the program management of cost. The regression results also show that OSA is not a significant factor for predicting or explaining the variation in CPI. The removal of the outliers does not change the overall outcomes, indicating that the model is robust to overly influential data points.

Although CPI results do not show that OSA adoption impacts cost management practices, the SPI results paint a cautionary picture. When measured at the halfway point of a contract effort, SPI produces significantly different distributions for OSA and non-OSA elements. These OSA distribution has greater variability and a smaller mean and median compared to the non-OSA distribution. Furthermore, the SPI regression analysis shows that OSA is a significant contributing variable for decreasing SPI. OSA is thought to increase speed of acquisition and this may create overconfidence when predicting the schedule. One speculative explanation for the drastic decrease in SPI seen in OSA programs could be linked to this overconfidence phenomenon. Influential outlier removal does not substantially change the second iteration of the SPI regression, suggesting model robustness. Finally, the breach regression shows that only WSARA is significant for predicting the likelihood of a breach occurring; WSARA decreases that likelihood by a factor of approximately one-third.

V. Conclusion and Recommendations

Introduction

This research has three main objectives related to MOSA's impact on program management performance in terms of cost and schedule. Effective program management performance is tracked through EVM and Nunn-McCurdy breach analyses. The first objective is to determine whether there is any significant difference in EVM metrics between aircraft programs that do and do not employ OSA. Parametric and non-parametric comparative tests investigate these differences for CPI and SPI distributions. CPI and SPI offer normalized metrics for comparing avionics, systems engineering, and other contract efforts related to open architecture within various DoD aircraft. The second objective is to determine if the presence of OSA significantly impacts cost and schedule EVM metrics. MOSA proponents strongly believe it has positive benefits for mitigating cost and schedule overruns. OLS regression models investigate if these beliefs hold true in regards to program management metrics. The last objective is to model the effect of OSA on the likelihood of Nunn-McCurdy breaches across all commodities. Breaches, which may signify poor cost management, are not dealt with lightly; repercussions can include termination of the program. OSA may have the potential to impact the rate at which breaches occur. A logistic regression model investigates the extent to which OSA influences breach occurrences. EVM and Nunn-McCurdy regressions use the following models and the results from the analyses meet the objectives stated above.

Table 33: EVM and Nunn-McCurdy Regression Models

Models
$CPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \varepsilon$
$SPI = \beta_0 + \beta_1 OSA + \beta_2 Service + \beta_3 Contract\ Type + \beta_4 WSARA + \varepsilon$
$Any\ Breach = \beta_0 + \beta_1 OSA + \beta_2 Air\ Force + \beta_3 WSARA + \varepsilon$

Results Discussion

1. How do EVM metrics (CPI and SPI) differ between systems that do and do not employ OSA?

Table 34: EVM Comparison Test Results

	Test	P-Value
CPI	Student's t	0.5199
SPI	Wilcoxon Rank Sum	0.0016

The mean of OSA's distribution is 1.04, which is higher than the non-OSA mean of .988. However, the difference in means is not significant enough per the results of the student's t-test to conclude OSA programs perform better. While OSA does not contribute towards higher CPI metrics on average for aircraft programs, it does not decrease program cost management performance either. The SPI results are interesting because the distributions for OSA and non-OSA are significantly different. However, it must be cautioned that the OSA distribution for schedule management is slightly worse than the non-OSA distribution.

2. How does the presence of OSA impact EVM metrics (CPI and SPI)?

Table 35: Expected vs Actual Impact of EVM Independent Variables

	Expected Impact	Actual Impact	
Independent Variables	EVM - OLS Regression	EVM - OLS Regression	Significant
OSA	+	CPI, SPI: -	CPI: No SPI: Yes
Service	Unknown	CPI: - SPI: +	CPI:No SPI: No
Contract Type	-	CPI, SPI: +	CPI: Yes SPI: No
WSARA	+	CPI: + SPI: -	CPI: No SPI: No

Unfortunately, the presence of OSA is not a significant predictive factor for explaining CPI. Cost management is roughly the same regardless of MOSA and incorporating open architecture. Cost plus is significant at the 95% confidence level and is associated with increased CPI. Removing CH-53K and F-22 outliers within the CPI distributions does not significantly change these results. In analyzing only completed contracts, CPI remains insignificant, while CP is no longer significant.

The SPI results are interesting in that OSA significantly contributes to schedule management. SPI is measured at the halfway point of a contract because efforts show stability around that timeframe. At that halfway point in the schedule, the presence of OSA decreases SPI by a factor of .04. It is important to note that effective program management typically falls on a scale of .90 – 1. Anything above this range is unusual and anything below this range indicates issues of schedule slippage. An increase of .04 is substantial because the effective range of an acceptable SPI is only .10; a difference of .04 may produce considerable difficulties for staying on schedule. These schedule improvements may translate to additional costs throughout the entire lifecycle of a program because schedule slippage may lead to the accumulation of extra costs. The widely held belief that MOSA is beneficial for schedule most likely causes overconfidence in schedule estimation.

3. How does the presence of OSA impact the likelihood of Nunn-McCurdy breaches?

Table 36: Expected vs Actual Impacts of Nunn-McCurdy Independent Variables[3]

	Expected Impact	Actual Impact	
Independent Variables	Nunn-McCurdy - Logistics Regression	Nunn-McCurdy - Logistics Regression	Significant
OSA	-	+	No
Service	Air Force: +	Air Force: -	No
WSARA	-	-	Yes

Evidence suggests that OSA has no real impact on the likelihood of Nunn-McCurdy breaches. Unfortunately, breaches are tracked at the program level and cannot be broken down into specific contract efforts that directly relate to open architecture. Moreover, MOSA is just one component of program management; several factors at play may overshadow the contributions of MOSA for managing costs at the program level.

Conclusions

This research aims to investigate the impact of MOSA and open architecture on program management metrics. EVM and tracking of Nunn-McCurdy breaches offer good tools for evaluating program management. Evidence suggests that MOSA has no significant impact on CPI for aircraft, regardless of whether contracts are completed or not. Findings do not support MOSA significantly improving cost measurements, but that does not mean that open architecture

[3] For the Nunn-McCurdy breach column, (-) indicates a decrease in the probability of a breach while (+) indicates an increase in the probability of a breach occurring.

does not improve actualized costs. Programs that employ MOSA may very well experience reduced costs compared to programs without MOSA, but they may not manage those costs effectively. While MOSA does not affect CPI, there is evidence that the inclusion of open architecture in the development stage negatively affects SPI. At the halfway point of a contract, the utilization of open architecture indicates a .04 decrease in SPI. Considering that most SPIs fall within the range of .90 – 1, a .04 decrease can make an impactful difference. One possible explanation for this unexpected result is that programs may overestimate MOSA's ability to promote rapid acquisition. Generally, experts tend towards overconfidence in what they believe to know and are prone to various biases (Kahneman, 2011). Overestimating the schedule benefits means that unrealistic goals are set and schedule slippage is more likely to happen. Although MOSA does not improve schedule performance, MOSA is still critical for getting major weapon systems to warfighters as quickly as possible; programs that utilize this approach can experience faster development than programs that do not use it. MOSA should continue to be utilized to the fullest extent possible with the caveat that overoptimism of MOSA's capabilities can detrimentally impact schedule management.

Nunn-McCurdy breach analysis shows that the presence of OSA does not significantly impact the likelihood of breach occurrence. Instead, it is WSARA that plays a significant role in that it decreases the possibility of a significant or critical breach by a factor of 1.25. Since WSARA implemented sweeping acquisition changes in 2009, the acquisitions community has improved in cost estimating and program management early in development. MOSA also plays a crucial role in development, but may not be as impactful for cost management as assumed by many practitioners in the field.

Recommendations for Future Research

This research is limited by only using the Cost Analysis Requirements Description (CARD) document to verify programs employing OSA. Further research could verify programs' OSA or non-OSA status by contacting program offices. Also, the program offices may be able to provide a clear picture of which specific program elements utilize OSA. More precise data could better show OSA's direct impact on EVM metrics and Nunn-McCurdy breaches. For example, an improved data set could reveal that OSA and CPI are significantly related. Further research could expand the EVM data set by including more than just aircraft. Aircraft operate differently from other commodities, and results may differ for ships, ground-based vehicles, etc. Given the surprising results for SPI, future research may want to explore why exactly OSA is negatively associated with schedule performance. Finally, future research could shift focus to Digital Transformation, an initiative to modernize acquisition capabilities through a collaborative, digital environment. OSA plays a role in the Digital Transformation environment, and it would be interesting to analyze how this initiative as a whole impacts cost and schedule once more data is available.

Appendix A: MOSA Initiatives and Descriptions (Kovach et al., 2021)

Open Architecture	Organization	Description
Software Communications Architecture (SCA) [1]	Department of Defense, Joint Tactical Networking Center	Created to standardize software based radio infrastructure and architecture[2]
Government Reference Architecture (GRA) [12]	Army CERDEC	Goal to shorten development and delivery schedule and lower the life cycle costs of A2G communication terminals[2]
Future Airborne Capability Environment (FACE™)	The Open Group Sponsored by NAVAIR	Reduce Long lead times, cumbersome improvement processes, lack of re-use, platform-unique design, and extensive testing requirements in aviation software development[2]
Hardware Open Systems Technologies (HOST)	U.S. Air Force, Army, and Navy	Hardware component level Open Architecture describing how embedded electronic cards plug in via standard electro-mechanical interfaces[13]
Open Mission Systems (OMS) & Universal Command and Control Interface (UCI)	Collaborative effort between U.S. Air Force and Industry	Enables agile integration of subsystems and services in platforms through a consensus-based open architecture[4, 14]
Functional Architecture for Strategic Reuse (FASTR)	U.S. Air Force, Army, and Navy	Focuses on decomposition of platform mission level capabilities into lower-level, common functional modules, to be leveraged across multiple platforms/product lines[15, 16]
Sensor Open Systems Architecture (SOSA)	Collaborative effort between the Air Force, Navy, Army, Department of Defense (DoD), and Industry	A technical Open Systems Architecture standard in order to maximize C4ISR sub-system, system, and platform affordability, re-configurability, and hardware/software/firmware re-use[17]
C4ISR/EW Modular Open Suite of Standards (CMOSS)	U.S. Army	A collection of standards developed for commonality across multiple C4ISR platforms reducing system size, weight, and power (SWaP) through sharing hardware and software components[18]
Common Open Architecture Radar Program Specification (COARPs)	U.S. Air Force	Standard for portable radar processing modes between radar sensor subsystems[19]
Modular Active Protection System (MAPS)	U.S. Army	Open Architecture for sensors and countermeasures in vehicle protection systems[20]
Modular Open RF Architecture (MORA)	U.S. Army CERDEC	Simplify radio systems, offer rapid insertion, and broader interoperability through Open Architecture while reducing SWaP on future ground vehicles[21]
STANdardization AGreement (STANAG)	NATO member nations	An agreement for implementing standardization to facilitate interoperability between NATO member nations[22]
Universal Armament Interface (UAI)	US DOD and NATO initiative	Aims to decouple store integration from the software upgrade cycle of platforms[23]
Vehicular Integration for C4ISR/EW Interoperability (VICTORY)	Collaborative effort between U.S. Army and Industry: VICTORY Standards Support Office (VSSO)	Created to correct the "bolt-on" methodology for deploying new equipment on U.S. Army vehicles[24]
WOSA	Joint effort by AFRL, DARPA, and the Open Systems Joint Task Force	Provides an open systems "bridge" between legacy embedded mission systems and off-board C3I sources and systems[25, 26]

Appendix B: OSA Checklist for Effective Implementation (OSACGPM, 2013)

- ✓ For components which are expected to evolve to meet new or unforeseen performance requirements, does the Government have at least Government Purpose Rights (GPR) in any software or documentation being developed or used to build the system?
- ✓ Are proprietary components well-defined, limited in scope, and designed so that others are not precluded from interfacing with the component or other parts of the system or from developing and providing components with comparable or improved performance and form, fit and function?
- ✓ Are your program's design artifacts disclosed "early and often" and freely available for reuse by another program or third parties?
- ✓ Is design disclosure enabled by keeping data, code and design artifacts in a repository either maintained by or overseen by the Government, or those made available through the Forge.mil Program (http://www.forge.mil/); providing the artifacts electronically upon requests made via the Government; allowing requesting parties to obtain them directly from the source firm through a process involving review and approval from the Government; or requiring that contractors allow the program to have continuous, real-time visibility, access to and the ability to download artifacts from the development environment?
- ✓ Does the program use widely-accepted and supported standards to define interface definitions or key interfaces that are published and maintained by recognized organizations?
- ✓ Does your program encourage continuous competition for components, modules, and tasks? Is it easy for your follow on contract to go to anyone other than the incumbent?
- ✓ Does your program utilize commodity products (i.e., COTS products with a large user base)? Can the decision leading to the selection of specific COTS products be supported with test results, architectural suitability, "best value" assessments, etc.?
- ✓ Does your program reuse modules or components that are also being used by other programs with different product vendors?
- ✓ Does the program plan and directive documentation specify that anything the Government paid to develop be made available for delivery to the Government with all of the developmental artifacts and unlimited usage rights?
- ✓ Does your program use an integrated team/peer review approach to identify how changes affect the system?
- ✓ Is the infrastructure of your system open? (Operating System, Databases, Communications, Interfaces, Tools)
- ✓ Does porting to a new hardware platform require minimal time and resources?
- ✓ Has the program completed an open architecture return on investment analysis to determine which components might yield the greatest benefits from OSA?

Appendix C: Contract Completion
OSA < 92.5%

Program	OSA	WBS	% Complete
CH 53K	1	Avionics	16%
CH 53K	1	Systems Engineering	16%
F-22	1	Avionics	32%
F-22	1	Avionics	37%
F-22	1	Avionics	37%
F-22	1	Systems Engineering	37%
F-22	1	Systems Engineering	37%
ARH	1	Data Displays	48%
ARH	1	Communications	48%
CH 53K	1	Avionics	50%
CH 53K	1	Systems Engineering	50%
APT	1	Communication/Identification	62%
APT	1	Navigation/Guidance	62%
APT	1	Mission Computer/Embedded Training	62%
APT	1	Automatic Flight Control	62%
F-22	1	Systems Engineering	66%
F-22	1	Avionics	66%
CH 53K	1	Systems Engineering	67%
CH 53K	1	Avionics	67%
CH 53K	1	Systems Engineering	67%
P-8A	1	Mission Computer	72%
P-8A	1	Communications	72%
P-8A	1	Systems Engineering	72%
F-22	1	Avionics	78%
F-22	1	Avionics Infrastructure	82%
F-22	1	Avionics	82%
MQ-1C	1	Systems Engineering	82%
MQ-1C	1	Avionics	82%
F-22	1	Avionics	82%
F-22	1	Systems Engineering	82%
UH-60M	1	Systems Engineering	85%
UH-60M	1	Air Vehicle System Software	85%
F-22	1	Avionics	85%
C-130	1	Avionics Hardware	86%
C-130	1	System Integration	86%
CH 53K	1	Systems Engineering	87%
CH 53K	1	Communications/Identification	87%
CH 53K	1	Air Vehicle Application	87%
PAR VC-22B	1	Avionics	87%
PAR VC-22B	1	Systems Engineering	87%

OSA > 92.5%

Program	OSA	WBS	% Complete
P-8A	1	Systems Engineering	93%
P-8A	1	Communication/Identification	93%
P-8A	1	AV Application	93%
P-8A	1	Navigation/Guidance	93%
F-22	1	Avionics	93%
CRH	1	Avionics	93%
C-5	1	Avionics	94%
F-22	1	Avionics	94%
MQ-4C	1	Communications/Identification	95%
MQ-4C	1	Systems Engineering	95%
MQ-4C	1	AV Application	95%
E-2D	1	Avionics	95%
E-2D	1	Systems Engineering	95%
F-22	1	Avionics	95%
AH-64E	1	OSA	96%
F-22	1	Avionics	97%
F-22	1	Systems Engineering	97%
F-22	1	Avionics	97%
F-22	1	Systems Engineering	97%
F-22	1	Avionics	97%
F-22	1	Systems Engineering	97%
P-8A	1	Multipurpose Control Display Unit (MCDU)	98%
P-8A	1	Avionics Flight Management Computer (AF	98%
F-22	1	Avionics	98%
E-2D	1	Avionics	98%
F-22	1	Avionics	98%
F-22	1	Systems Engineering	98%
F-22	1	Avionics	98%
E-2D	1	Avionics	98%
E-2D	1	Systems Engineering	98%
F-22	1	Systems Engineering	99%
F-22	1	Avionics	99%
CH 53K	1	Systems Engineering	99%
CH 53K	1	Communications/Identification	99%
AH-64E	1	Communications	100%
AH-64E	1	Mission Computer	100%
AH-64E	1	Aviation Mission Planning	100%
MQ-1C	1	Systems Engineering	100%
MQ-1C	1	Systems Engineering	100%
MQ-1C	1	Air Vehicle Software	100%
F-22	1	Systems Engineering	100%
F-22	1	Avionics	100%
F-22	1	Avionics	100%

Non-OSA < 92.5%

Program	OSA	WBS	% Complete
F/A-18EF	0	Systems Engineering	56%
C-17A	0	Systems Engineering and Integration	62%
C-17A	0	Avionics/Flight	62%
KC-46A	0	Systems Engineering	66%
KC-46A	0	Aircraft Systems 3	66%
KC-46A	0	Aircraft Systems 2	66%
KC-46A	0	Aircraft Systems 1	66%
F/A-18EF	0	Systems Engineering	68%
F/A-18EF	0	Systems Engineering	69%
KC-46A	0	Communications/Identification	79%
KC-46A	0	Central Computer	79%
KC-46A	0	Systems Engineering	79%
C-17A	0	Avionics/Flight	81%
C-17A	0	Systems Engineering and Integration	81%
KC-46A	0	Systems Engineering	87%
CH-47F	0	Avionics Subsystem	87%
CH-47F	0	Systems Integration	87%

Non-OSA > 92.5%

Program	OSA	WBS	% Complete
C-17A	0	Systems Engineering and Integration	95%
C-17A	0	Avionics/Flight	95%
CH-47F	0	Systems Integration	95%
CH-47F	0	Avionics Subsystem	95%
HC/MC-130	0	Communications/Identification	100%
HC/MC-130	0	Systems Engineering	100%
HC/MC-130	0	AV Applications Software	100%

Appendix D: EVM Programs and WBS Elements

Programs	WBS
OSA	
AH-64E Remanufacture	OSA, Communications, Aviation Mission Planning, Mission Computer
APT - Advanced Pilot Training T-7A	Communications/Identification, Navigation/Guidance, Mission Computer/Embedded Training, Automatic Flight Control
ARH - Armed Reconnaissance Helicopter	Communications, Data Displays
BLACK HAWK UPGRADE (UH-60M)	MFD Software, System Integration
C-130 AMP Avionics Modernization Program	Avionics Hardware, System Integration
C-5 RERP - C-5 Aircraft Reliability Enhancement and Re-engining Program	Avionics
CH-53K - Heavy Lift Replacement	Avionics, Systems Engineering, Communications/Identification, Air Vehicle Applications
CRH - Combat Rescue Helicopter	Avionics
E-2D AHE - E-2D Advanced Hawkeye	Avionics, Systems Engineering
F-22 - RAPTOR Advanced Tactical Fighter Aircraft/F-22A Increment 3.2B Modernization	Avionics, Systems Engineering
MQ-1C GRAY EAGLE - Unmanned Aircraft System	Avionics, Air Vehicle Software, Systems Engineering
MQ-4C Triton - Unmanned Aircraft System	AV Application, Systems Engineering, Communications/Identification, Mission Control
P-8A Poseidon Multi-Mission Maritime Aircraft	AV Application, Communications/Identification, Systems Engineering, Mission Computer
PAR - Presidential Aircraft Recapitalization (VC-25B)	Avionics, Systems Engineering
UH-60M Upgrades	Air Vehicle System Software, Systems Engineering
Non-OSA	
C-17A - GLOBEMASTER III Flexible Cargo Aircraft	Avionics/Flight, Systems Engineering and Integration
CH-47F Modernized Cargo Helicopter	Avionics Subsystem, Systems Integration
F/A-18E/F Super Hornet Aircraft	Systems Engineering
HC/MC-130 Recapitalization Aircraft	AV Applications Software, Communications/Identification, Systems Engineering
KC-46A Tanker Modernization	Aircraft Systems, Systems, Engineering, Communications/Identification, Central Computer

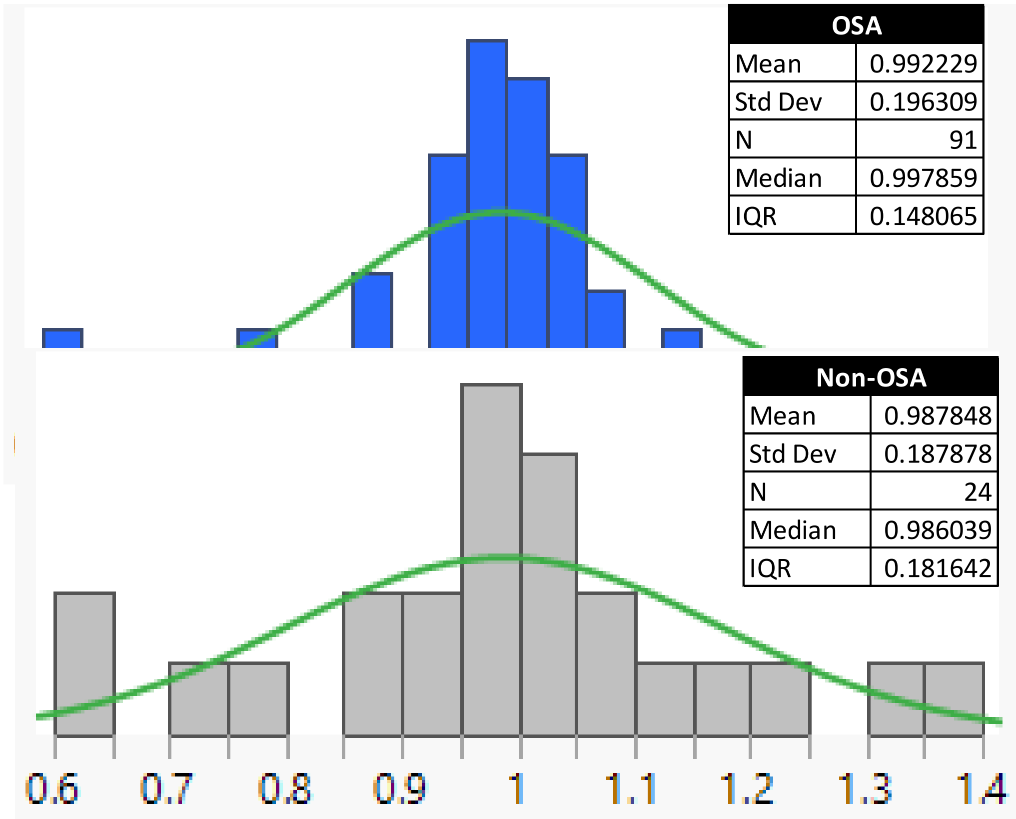
Appendix E: Percentage of OSA by Contract Effort

Program	Contract	Effort	% OSA by Effort
F-22	FA8611-13-D-2850	DO 0001	95.31%
F-22	F33657-02-D-0009	DO 55 Ph1/Ph2	83.65%
P-8A	N00019-16-G-0001	Increment 3 - CI CDR	78.16%
F-22	F33657-02-D-0009	DO 71 - Increment 3.2 Lab and Test Aircraft Upgrad	76.57%
P-8A	N00019-04-C-3146	RDT&E	75.06%
CH 53K	N00019-19-G-0029	DDSR Phase II	67.67%
CH 53K	N00019-19-G-0029	CH-53K Flight Control Computer (FCC) Update	64.92%
F-22	F33657-02-D-0009	DO 77 - Crypto Modernization	60.02%
E-2D	N00019-17-F-1604	FMS/AFMC RI	59.35%
F-22	F33657-02-D-0009	DO 82 – Increment 3.2A, Phase C-D	55.36%
F-22	F33657-02-D-0009	DO 73 - CLIN 202 - Inc 3.2 Full Phase B	54.34%
F-22	F33657-02-D-0009	DO 73 - CLIN 201 - Inc 3.2 Accelerated Phase B	53.41%
F-22	FA8611-13-D-2850	D.O. 004	50.93%
F-22	FA8611-13-D-2850	DO 0003	46.84%
P-8A	N00019-16-G-0001	DO 2005 - Increment 3 Platform Integration	46.75%
F-22	F33657-02-D-0009	DO 69 - Software Support	45.51%
F-22	FA8611-13-D-2850	D.O. 009	40.86%
MQ-1C	W58RGZ-18-D-013	GETS - Tech Svcs	39.90%
MQ-1C	W58RGZ-13-C-013	P3I (4.3.2 SW)	36.42%
F-22	FA8611-13-D-2850	DO 0005	34.33%
C-130	F33657-01-C-0047	C-130 AMP	32.52%
PAR VC-22B	FA8625-16-C-6599	Preliminary Design	28.82%
CRH	FA8629-14-C-2403	EMD	25.52%
MQ-4C	N68786-17-G-1010	IFC-4 Part B	22.79%
E-2D	N00019-15-C-0091	POST-IOC	22.31%
MQ-4C	N00019-08-C-0023	SDD	21.74%
F-22	FA8611-13-D-2850	TO 0013	21.37%
CH 53K	N00019-19-G-0029	ILS Multi Products and Support	19.18%
F-22	FA8611-13-D-2850	DO 0006	14.35%
ARH	W58RGZ-05-C-023	RDT&E	11.95%
UH-60M	W58RGZ-06-D-004	DO. 0001: UH-60M P3I Upgrade	11.75%
F-22	FA8611-13-D-2850	DO 0014	11.39%
CH 53K	N00019-19-G-0029	CH-53K Data Concentrator Unit (DCU) and Blade Fold	11.35%
C-5	F33657-02-C-2000	C-5 RERP SDD	10.40%
AH-64E	W58RGZ-05-C-000	Block III SDD Phase 1	10.09%
APT	FA8617-18-F-8001	APTS EMD	9.82%
F-22	FA8611-13-D-2850	DO 0008	8.58%
MQ-4C	N00019-08-C-0023	STDA	8.43%
AH-64E	W58RGZ-15-C-004	SDD Version 6	7.59%
E-2D	N00019-13-C-0135	Aerial Refueling EMD	6.88%
CH 53K	N00019-06-C-0081	Sys Dev and Dem (SDD)	6.00%
P-8A	N00019-04-C-3146	RDT&E	3.71%
F-22	FA8611-13-D-2850	TO 0012	1.20%
CH 53K	N00019-06-C-0081	CLIN 0101-0102	1.09%
F-22	FA8611-13-D-2850	DO 0007	1.04%
F-22	F33657-02-D-0009	DO 88	0.83%
F-22	FA8611-13-D-2850	DO 0016	0.05%

Appendix F: Nunn-McCurdy Critical Breaches by Program

Significant	Critical	None	
AEHF	AEHF	AARGM-ER	HC/MC-130 Recap
AGM-88E AARGM	AIM-9X Block 1	ACS	IAMD
ARH	Apache Block III (AB3)	AFIPPS	ISPAN Inc 4
B-1B CMUP	ARH	AH-64E New Build	JDAM
C-130 AMP	ATACMS-BAT: P3I	AH-64E Remanufacture	JLTV
Chem Demil-ACWA	B-1B CMUP	AMDR	JSIPS
Chem Demil-CMA	C-130 AMP	AMF JTRS	KC-46A
Chem Demil-CMA Newport	C-5 RERP	AMPV	LHA 6
COMANCHE (RAH-66)	CH-47F	AOC-WS	M2 M3 Bradley
EFV	Chem Demil-ACWA	APT	MGUE Inc 1
F/A-18 E/F	Chem Demil-CMA	ASAS	MIDS
F-35	Chem Demil-CMA Newport	AV-8B REMANUFACTURE	Minuteman III
FBCB2	DDG 1000	B61 Mod	MP-RTIP
H-1 Upgrades (4BW/4BN)	E-2D AHE	BLACK HAWK (UH-60A/L)	MPS
JASSM	EFV	C-130J	MQ-1C Gray Eagle
Javelin	F-22	C-17A	MQ-25
JLENS	F-35	C-5 AMP	MQ-4C Triton
JPATS	GPS OCX	CANES	MUOS
JTRS HMS	H-1 Upgrades	CEC	Navy ERP
LCS MM	JASSM	CH-47F Block II	NGEN
Longbow Apache: A/C Mods	JLENS	CH-53K	NGJ Midband
NAVSTAR GPS	JPALS Inc 1A	CIRCM	P-8A
NPOESS	JPATS	CRH	PAC-3 MSE
RQ-4A/B UAS Global Hawk	LPD 17	CSSCS	PAR
SBIRS High	NPOESS	CVN 68	PIM
SDB II	RMS	CVN 78	SADARM
SSN 774	RQ-4A/B UAS Global Hawk	DCAPES 2a	SDB I
V-22	SBIRS High	DCAPES 2b	SM-6
WIN-T Inc 2	WGS	DDG 51	Space Fence Inc 1
	WIN-T	DEAMS	SSBN 826
		DHMSM	Stryker
		ECSS	T-45TS
		EPS	T-AKE
		F-22 Inc 3.2B Mod	T-AO
		FAAD C2	THAAD
		FAB-T	Titan
		G/ATOR	TSAT
		GFEBS	UH-60M Black Hawk
		GPS III	VH-92A
		GPS IIIF	WIN-T Inc 3

Appendix G: CPI Descriptive Statistics and Assumption Testing (Without Outliers)

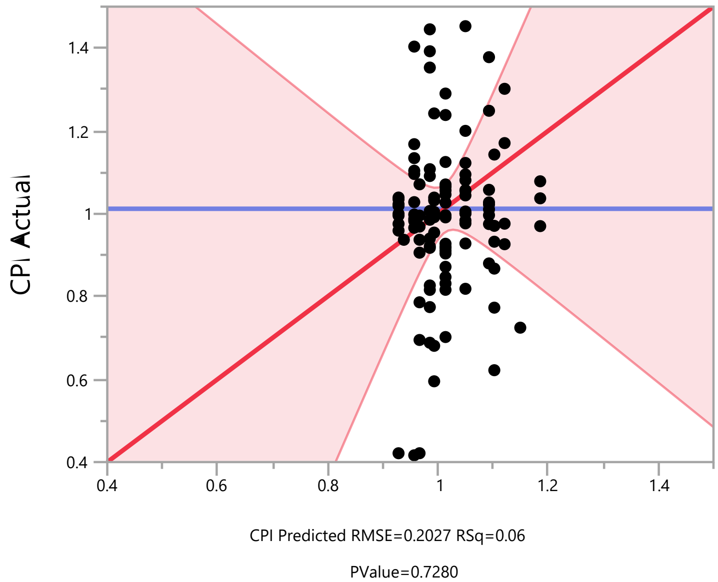


	OSA	Non-OSA
Test	**P-Value**	
Anderson Darling	<.0001	0.335
Levene	0.8733	

	Test	P-Value
CPI (Without Outliers)	Student's t	0.922

Appendix H: CPI Regression Robustness Check (Completed Contracts Only)

Actual by Predicted Plot



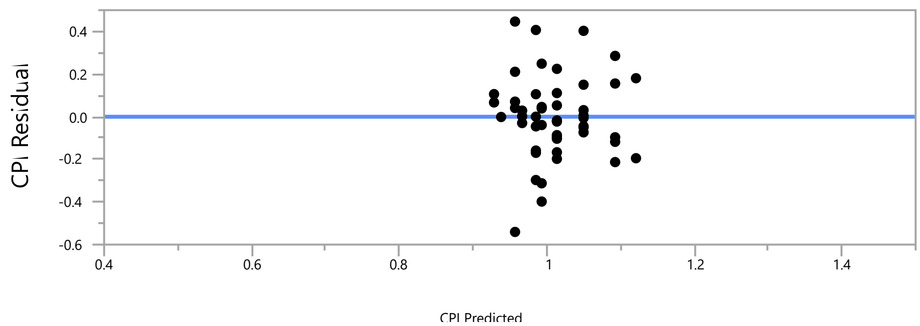
Model Results

Parameter Estimates				
Variable	**Estimate**	**Lower 95%**	**Upper 95%**	**P-Value**
Intercept	1.0170835	0.7056267	1.3285403	<.0001
OSA	-0.135681	-0.319285	0.0479232	0.1435
Air Force	0.0284705	-0.12018	0.1771213	0.7014
Navy	0.0646223	-0.105294	0.2345388	0.4475
CP	0.0471183	-0.177243	0.2714796	0.6742
WSARA	0.0567433	-0.076389	0.1898756	0.395

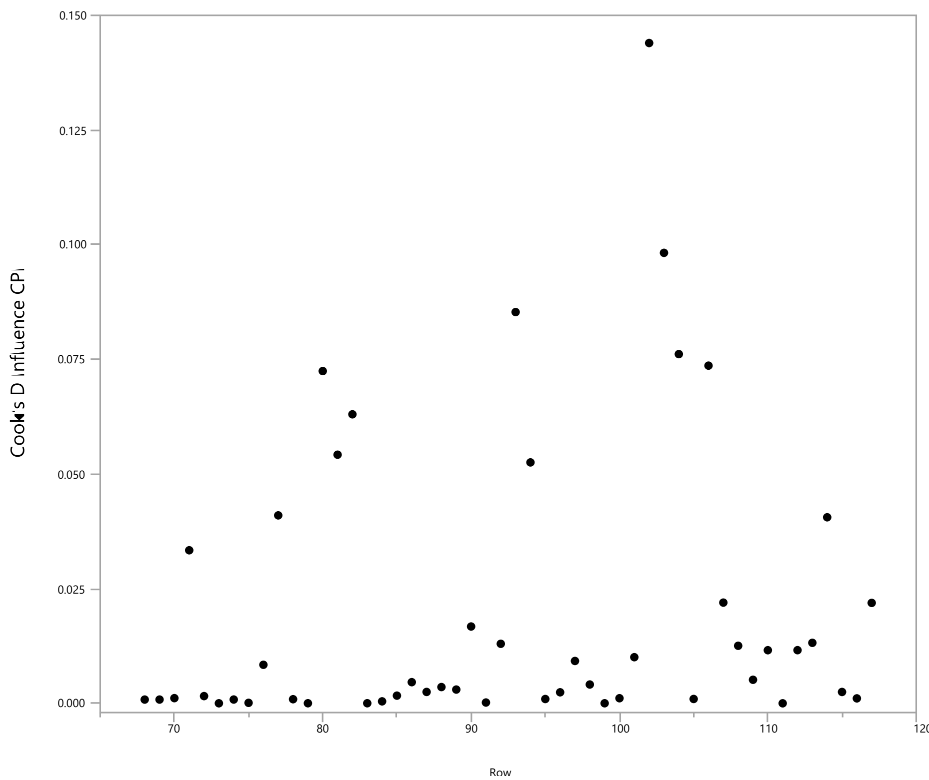
VIF Scores

Variable	VIF
OSA	1.2156199
Air Force	1.651901
Navy	1.7432779
CP	1.1096327
WSARA	1.2230787

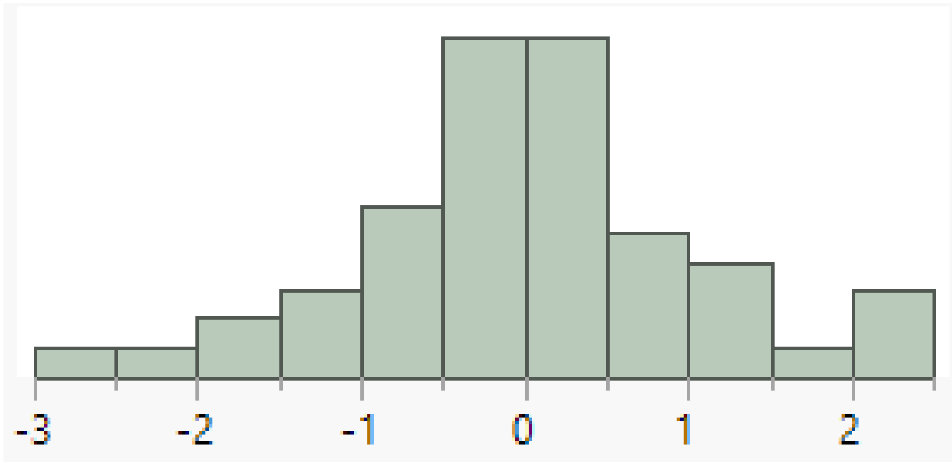
Residual by Predicted Plot



Cook's D



Studentized Residuals



Bibliography

Agresti, A. (2018). *An introduction to categorical data analysis*. John Wiley & Sons.

Arena, M. V., Blickstein, I., Gonzales, D., Harting, S., Lewis, J. L., McGee, M., McKernan, M., Nemfakos, C., Osburg, J., Rudavsky, R., & Sollinger, J. M. (2014). *DoD and Commercial Advanced Waveform Developments and Programs with Multiple Nunn-McCurdy Breaches, Volume 5*. RAND Corporation. http://www.jstor.org/stable/10.7249/j.ctt14bs3w4

B-52 Radar Modernization Program Selected Acquisition Report (2021). U.S. Air Force.

Blickstein, I., Nefakos, C., & Sollinger, J. (2013). Digging Out the Root Cause: Nunn-McCurdy Breaches in Major Defense Acquisition Programs. *Defense ARJ*, *20*(2), 128-153.

Boeing: T-7A Red Hawk: eSeries leader. (2020). Retrieved September 20, 2022, from https://www.boeing.com/features/innovation-quarterly/2020/12/t-7a-red-hawk-eseries-leader.page

Boudreau, M. (2006). *Acoustic rapid COTS insertion: a case study in spiral development.* Acquisition Research Program, Graduate School of Business and Public Policy, Naval Postgraduate School.

Brown, M., Fass, R., & Ritschel, J. (2019). A Case for Open Mission Systems in DoD Aircraft Avionics. *Air & Space Power Journal*, *33*(4), 83-93.

Cole, S. F. (2011). *Risk, uncertainty and open architecture in the DoD acquisition system*. NAVAL POSTGRADUATE SCHOOL MONTEREY CA.

Christensen, D., & Payne, K. (1992). Cost performance index stability: fact or fiction?. *Journal of Parametrics*, *12*(1), 27-40.

Christensen, D. S., & Heise, S. R. (1993). Cost performance index stability. *National Contract Management Journal*, *25*(1), 7-15.

Cuff, V., & Fersch, B. (2016). OSA: Cost and Schedule Saver or Driver?. International Cost Estimating and Analysis Association Symposium.

Davendralingam, N., Guariniello, C., Tamaskar, S., DeLaurentis, D., & Kerman, M. (2019). Modularity research to guide MOSA implementation. *The Journal of Defense Modeling and Simulation*, *16*(4), 389-401.

Department of Defense Directive 5000.01, The Defense Acquisition System. (2020). DoDD 5000.01, "The Defense Acquisition System," September 9, 2020 (acqnotes.com)

DoD MOSA Tri-Service Mem. MOSA for our Weapon Systems is a Warfighting Imperative. (2019). Modular Open Systems Approach-Tri-Service Memo.pdf (dau.edu)

DTO – USAF Digital Transformation Office. (n.d.). Retrieved September 2, 2022, from https://dafdto.com/

Firesmith, D., Open System Architectures: When and Where to be Closed. SEI Blog. (2015). Open System Architectures: When and Where to be Closed (cmu.edu)

Government Accountability Office. (2011). Trends in Nunn-McCurdy Cost Breaches for Major Defense Acquisition Programs. (GAO Publication No. 11-295R). Washington, D.C.: U.S. Government Printing Office.

Government Accountability Office. (2012). Weapons Acquisition Reform: Reform Act is Helping DoD Acquisition Programs Reduce Risk, but Implementation Challenges Remain. (GAO Publication No. 13-103). Washington, D.C.: U.S. Government Printing Office.

Jayakumar, GS David Sam, and A. Sulthan. "Exact distribution of Cook's distance and identification of influential observations." *Hacettepe Journal of Mathematics and Statistics* 44.1 (2015): 165-178.

Kahneman, D. (2011). *Thinking, fast and slow*. macmillan.

Kendall, F. (2014). Better buying power 3.0. *Office of the Under Secretary of Defense for Acquisition, Technology and Logistics*, p. *19*.

Kovach, N. S., Natarian, B., & Littlejohn, K. (2021). The rise of open architectures in the US Department of Defense. Open Architecture/Open Business Model Net-Centric Systems and Defense Transformation 2021 (Vol. 11753, pp. 12-23). SPIE.

Matthews, B., DuBois T., & Collier P., (2020). A Key Requirement to National Security, A Case for Enforcing Modular Open Systems Approach Requirements. *Defense Standardization Program Journal*, 15–20.

McClave, J., Benson, G., & Sincich, T. (2023). *Statistics for Business & Economics, 13TH EDITION*. Cengage Learning India Pvt. Ltd.

McCormick, R., Cohen, S., Hunter, A. P., Sanders, G., Mooney, S., & Herschlag, D. (2018). Open-Systems Architectures. National Technology and Industrial Base Integration: How to Overcome Barriers and Capitalize on Cooperation (pp. 33–47). *Center for Strategic and International Studies* (CSIS). http://www.jstor.org/stable/resrep22430.7

Minor, P. (2017). *Identifying the Return on Investment for Army Migration to a Modular Open Systems Approach for Future and Legacy Systems*. Defense Acquisition University Aberdeen Proving Ground United States.

Moore, S. & Xiang, P. (2020). Modular Open Systems Approach Overview and Efforts. *Defense Standardization Program Journal*, pp. 21–36.

Nizam, A., & Elshannaway, A. (2019). Review of earned value management (EVM) methodology, its limitations, and applicable extensions. *Journal of Management & Engineering Integration*, *12*(1), 59–70.

Open System Architecture Contract Guidebook for Program Managers (1.1). (2013). Department of Defense. Open System Architecture (OSA) Contract Guidebook for Program Managers June 13.pdf (acqnotes.com)

Orly Olbum, O., Lee, S. L., & Braxton, P. (2019). *Contractually Speaking: The Story of DoD Contract Vehicles*. ICEAA. https://www.iceaaonline.com/wp-content/uploads/2019/06/BP05-Paper-Contractually-Speaking-The-Story-of-DOD-Olbum.pdf

Patni, H. (2020). Modular Open Systems Approach Overview and Efforts. *Defense Standardization Program Journal*, pp. 5–8.

Paul, S. R., & Fung, K. Y. (1991). A generalized extreme studentized residual multiple-outlier-detection procedure in linear regression. *Technometrics*, *33*(3), 339-348.

Pellerin, C. (2014). Open Architecture Cuts Cost, Promotes Competition, Official Says. U.S. Department of Defense. https://www.defense.gov/News/News-Stories/Article/Article/603587/

Roark, C., & Kiczuk, B. (1995). Open system avionics architectures where we are today and where we need to be tomorrow. In *Proceedings of the IEEE 1995 National Aerospace and Electronics Conference. NAECON 1995* (Vol. 1, pp. 263-270). IEEE.

Requirement for modular open system approach in major defense acquisition programs, 10 U.S.C. § Section 4401. (2017). 10 USC 4401: Requirement for modular open system approach in major defense acquisition programs; definitions (house.gov)

Tracy, S. P., & White, E. D. (2011). Estimating the final cost of a DoD acquisition contract. *Journal of Public Procurement*.

Zimmerman, P., Gilbert, T., & Salvatore, F. (2019). Digital engineering transformation across the Department of Defense. *The Journal of Defense Modeling and Simulation*, *16*(4), 325–338.

Zimmerman, P., Ofori, M., Barrett, D., Soler, J., & Harriman, A. (2019). Considerations and examples of a modular open systems approach in defense systems. *The Journal of Defense Modeling and Simulation*, *16*(4), 373-388.

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A modular open system approach (MOSA) and its inclusion of open architecture are among the prevailing acquisition strategies for cost and schedule management. This approach involves the incorporation of reusable, modular packages that can be incrementally added and upgraded throughout programs' lifecycles. Many practitioners throughout the acquisitions community find that MOSA enables better opportunities for affordability, rapid acquisition, flexibility, enhanced competition, and innovation. A literature review reveals that few studies examine the interaction between MOSA and the extent to which it influences cost and schedule performance. However, no studies to date examine open architecture's impact via programmatic evaluation of Earned Value Management (EVM) and Nunn-McCurdy breach metrics. The program management process is critical to successful acquisition, and the use of open architecture affects performance metrics. EVM and Nunn-McCurdy breaches are important to consider because they offer tracking methodology for the overall health of a program in terms of cost and/ or schedule. This research empirically investigates and compares EVM data for aircraft that do and do not employ open architecture. Additionally, this research examines the degree to which open architecture impacts the likelihood of Nunn-McCurdy breaches for all program types. Overall, findings support that the presence of open architecture is negatively associated with schedule performance around the halfway point for development contracts. It is theorized that programs adopting open architecture may be too overoptimistic estimating schedule.

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