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Predicting Cost Growth Using Programs Reviews and Milestones For DoD Aircraft

Scott J. Kozlak

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PREDICTING COST GROWTH USING PROGRAM REVIEWS AND MILESTONES FOR DOD AIRCRAFT

THESIS
March 2016

Scott J. Kozlak, Captain, USAF

AFIT-ENC-16-M-164

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

Department of Mathematics and Statistics

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Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Cost Analysis

Scott J. Kozlak, BS

Captain, USAF

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Scott J. Kozlak, BS

Captain, USAF

Committee Membership:

Dr. Edward D. White, Ph.D
Chair

Lt Col Brandon M. Lucas, Ph. D
Member

Michael J. Seibel, Civ.
Member

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Abstract

Past research shows predicting cost growth is an important topic with DoD systems. Researchers have attempted to predict total program cost growth as well as identify predictors of program cost growth. Our research addresses this through examining cost growth at reviews and milestones along an aircraft's schedule. We assess cost growth factors at four major reviews, Critical Design Review, First Flight, Development Test and Evaluation End, and Initial Operating Capability.

The first portion of the analysis focuses on identifying cost growth factors and percent of total cost growth at the four program reviews. The second portion identifies predictors of cost growth at the four reviews. In our results, we present a spike in procurement cost growth first occurring around First Flight and we identify the median percent of total cost growth at IOC, or 48 percent of program completion to be 91%. The second portion of the results identifies the three most common predictors of cost growth at program reviews: Bombers, Prototyping, and electronic aircraft system upgrades.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Edward White, for his guidance and support throughout the course of this thesis effort. His insight and experience was certainly appreciated. Additionally, I would like to thank my committee members, Lt Col Brandon Lucas and Mr. Mike Seibel who motivated this research and provided valuable knowledge and feedback. Most importantly, thank you to my wife and son for their endless love and encouragement.

Scott J. Kozlak

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PREDICTING COST GROWTH USING PROGRAM REVIEWS AND MILESTONES FOR DOD AIRCRAFT

I. Introduction

General Issue

Cost growth occurring in Department of Defense (DoD) weapon systems is a major problem for Congress. Cost growth forces Congress to adjust DoD funding and shift priorities in order to compensate for cost growth in major weapon systems. The RAND Corporation conducted a study in 1993 which states Major Defense Acquisition Programs (MDAPs) historically experience cost growth of 20 percent from the initial baseline estimate (Drezner et al., 1993).

Cost growth in weapon systems creates challenges for the DoD, Air Force, and civilian contractors involved in developing the United States' most advanced weapon systems. At any level, (DoD, Air Force, or contractor) cost growth challenges the parties involved and often forces difficult decisions in regards to funding. In a major DoD program, cost growth can remove funding from smaller programs, postpone program development, or eliminate programs. In order to better prepare the DoD for funding issues with MDAPs, Program Managers (PMs) must prepare for program cost growth.

Program Managers control the day-to-day operations with MDAPs. DoD programs face several types of risk: cost, schedule, and performance. Cost risk challenges all government weapon systems and could eliminate one or more programs from activation. Schedule risk causes program activation to delay, and the delays can jeopardize national defense. Performance risk limits the weapon system's ability to conduct the mission. If a weapon system experiences performance or schedule setbacks, cost risk is likely to follow.

No matter the type of risk, most programs will likely need additional funding to combat the problems. To better prepare for cost growth, PMs need to know when the cost growth will occur. Identifying when growth cost is likely to occur allows baseline estimates to reflect what could happen in a weapon system's future. Without more accurate cost estimates, PMs and cost estimators need to better prepare for the reality of requesting additional risk dollars to support MDAP cost growth.

Arena et al. (2006) found the average total program cost growth for programs similar to Air Force programs was 46%. The total program life cycle includes all program activity: Research and Development, Procurement, Operations and Sustainment, and Disposal. Cost growth negatively impacts DoD programs by tightening budget restrictions and minimizing funding flexibility for DoD leaders. For this research, cost growth is defined as the increase in cost from the Development Estimate (DE) to the Current or final Estimate CE) of the DoD program. The DE occurs at MS B when a program officially becomes a "program of record." There are many techniques to develop a cost estimate. The three most common methods used to develop cost estimates are: analogy, engineering build-up, and parametric. Each estimating method has its advantages depending on the degree of knowledge and the placement along the acquisition life cycle of the program under development. Chapter 2 further examines the three cost estimating techniques as well as several supplemental techniques.

Problem Statement

Instead of trying to generate more accurate estimates which allow programs to sustain less cost growth, PMs could better prepare for the event of weapon system cost growth. As the subsequent chapters will explain, this research identifies how much cost growth occurs at different reviews along an aircraft's schedule. In addition to identifying the amount of cost growth at different reviews, this research identifies significant predictors of cost growth at program reviews. With the knowledge of how much cost growth programs sustain at different reviews and what variables are significant predictors of cost growth, PMs can notify higher authorities before funding needs become a major problem, and their effects spread through DoD programs.

There are several techniques to measure where cost growth occurs. One way is to measure the percent complete of a program when cost growth occurs. Measuring cost growth at percent complete can cause discrepancies between programs because the percent complete can occur at different stages of weapon system's life cycle. A second technique is to examine specific dates that are consistent across MDAPs and test to see if cost growth occurs at the specific dates.

All MDAPs are required to pass certain reviews and milestones. Four common reviews for all major aircraft programs are Critical Design Review (CDR), First Flight (FF), Development Test & Evaluation End (DT&E), and Initial Operating Capability (IOC). The three Milestones for MDAP programs are Milestone A, B, C. In (2000) Milestones A, B, C replaced Milestones I, II, III. Further information on the transition from MS I, II, III, to A, B, C is available in Chapter 2. With the collection of program reviews, the model has four significant dates to test for statistical significance of cost growth across aircraft programs.

Research Objectives and Scope

The objective of this research is to better prepare PMs for cost growth in weapon systems. The way to better prepare for cost growth is to realize that cost growth is going to occur and plan for the cost growth well in advance so the weapon system and other DoD programs are not significantly impacted. The objective of this research is best summarized by the following objectives:

1- Identify a significant review along an Aircraft's schedule where cost growth occurs.
2- Identify predictors of cost growth at program reviews.

Graphically display trends of cost growth along an aircraft's schedule based

This research focuses on major aircraft weapon systems. Focusing specifically on aircraft allows for consistent analysis on one type of DoD platform. In theory, the development of all aircraft should follow a similar schedule. Based on the type of aircraft (Fighter, Bomber, Tanker), some portions of the program lifecycle may be more complex than others. The complexity has an effect on reviews and milestones in the program's schedule. If the research has statistically significant findings, the methods can expand to cover additional weapon system platforms.

Methodology

Since 1969, MDAPs are required to submit Selected Acquisition Reports (SARs) (Drezner et al., 1993). SARs outline a weapon systems status and report current funding estimates as well as actual expenses incurred. SARs are required to report annually, and provide a common ground to evaluate weapon systems. For our research, we use SARs to evaluate program estimates and actual costs. Additional information on SARs is available in Chapter 3.

This research uses several methods to conduct cost growth analysis. First, graphical analysis provides a method to examine the cost growth of each aircraft weapon system. Graphical analysis presents a visual depiction of cost growth which can aid in developing predictors. Next, logistic regression identifies if cost growth occurs at program reviews along an aircraft's schedule. Finally, Fisher's Exact Test and Odds Ratios identify possible predictors of cost growth and odds of an event occurring.

Preview

The following chapters discuss the Literature Review, Methodology, Analysis, Results, and Conclusion/Discussion. The Literature Review discusses approaches to cost estimating, relevant cost growth studies of the past, and potential predictor variables of cost growth. The Methodology chapter discusses Logistic Regression, Fisher's Exact Test, Odds Ratio, and how these three methods work together to identify predictors of cost growth. The Analysis and Results sections recaps the results of the research and provides significant predictors of cost growth at different stages of an aircraft's schedule that can help mitigate the DoD's inevitable cost growth problem. The Conclusion/Discussion addresses the goals of this research, discusses limitations of the study, and provides some thoughts on possible avenues for future research.

II. Literature Review

Chapter Overview

Chapter 2 provides an overview of topics related to cost estimating and cost growth in the DoD. First, we provide an outline on the important cost estimating techniques to provide background and an understanding of available tools to cost estimators. Second, we review historical studies of cost growth. Third, the literature review presents AFIT theses beginning in 2002 which used logistic and multiple regression to predict cost growth. Lastly, we offer a review of important predictor variables in estimating cost growth.

Cost Estimating Techniques

To develop a cost estimate, the cost estimator should perform certain processes. The estimator may develop the estimate using the weapon system work breakdown structure (WBS) and generate a best estimate for each piece of the WBS. The estimate must be in constant-year dollars, and include all assumptions in generating the cost model. In addition, the estimate should be time-phased by allocating the costs for parts of the weapons system to the years in which the costs will likely occur. After completing the cost, the estimator must validate their work. Methods for validating include double checking and cross checking for errors or double counting, comparing the estimate against other independent estimates for differences, and updating the estimates as data becomes available (GAO, 2009). The cost estimate is an iterative process which continues as a program moves through its lifecycle.

The Air Force Cost Analysis Handbook (AFCAH) and a GAO report of 2009 outline several ways to generate cost estimates. From the GAO report, there are three techniques commonly used by cost estimators to generate a point estimate: analogy, engineering build-up, and parametric. The 2009 GAO report compares the three most common methods used in cost estimating and is available in Table 1:

Table 1: Three Cost-Estimating Methods Compared (GAO, 2009)

Method	Strength	Weakness	Application
Analogy	▪ Requires few data ▪ Based on actual data ▪ Reasonably quick ▪ Good audit trail	▪ Subjective adjustments ▪ Accuracy depends on similarity of items ▪ Difficult to assess effect of design change ▪ Blind to cost drivers	▪ When few data are available ▪ Rough-order-of-magnitude estimate ▪ Cross-check
Engineering build-up	▪ Easily audited ▪ Sensitive to labor rates ▪ Tracks vendor quotes ▪ Time honored	▪ Requires detailed design ▪ Slow and laborious ▪ cumbersome	▪ Production estimating ▪ Software developments ▪ Negotiations
Parametric	▪ Reasonably quick ▪ Encourage discipline ▪ Good audit trail ▪ Objective ▪ Incorporates real-world effects	▪ Lacks detail ▪ Model investment ▪ Cultural barriers ▪ Need to understand model’s behavior	▪ Budgetary estimates ▪ Design-to-cost trade studies ▪ Cross-check ▪ Baseline estimate ▪ Cost goal allocations

Analogy

The Analogy method assumes that no matter how technologically advanced a new weapon system is, every weapon system is built upon the knowledge of a previous weapon system. Establishing links between the new system and a previous system is essential for the Analogy method. In order to create a traceable and repeatable estimate, analogy estimates should be as objective as possible. To create an objective estimate, the estimator must select a similar weapon system for comparison. Historical data from a previous weapon system allows the estimator to create the new weapon system estimate by adding complexity factors to account for the enhancements on the new weapon system.

Analogous estimates are at the beginning of a program when little actual costs is available to the estimator. Analogy estimating has several advantages: it is easy to use before details become available on the new weapon system, it is quick to develop and at little cost, and it is easy to comprehend as the estimate stems from another weapon system. The disadvantages of analogous estimates are the direct link of the estimate to another weapon system, the factors used are subjective, and no weapon system is a perfect match to generate an estimate (GAO, 2009).

Engineering build-up

When a detailed WBS is available, engineering build-up cost estimates are useful. Build-up estimates start at the lowest WBS level where labor hours and materials are available. From this point, an estimate for each WBS leaf is generated and the leaf estimates are added together to establish the total weapon system estimate. An example of a simple Aircraft WBS is available in Figure 1:

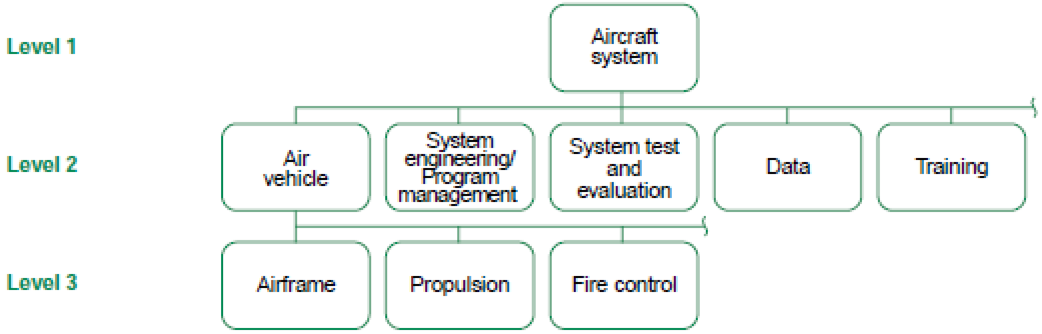


Figure 1: A Work Breakdown Structure with Common Elements (GAO, 2009)

Engineering build is a good technique because the method allows the estimator the ability to determine if he or she accounts for all pieces of the weapon system. Engineering build-up also allows the estimator to see which components are the major cost drivers and if the cost driver is transferable to other programs. The major disadvantages are build-up estimates are extremely expensive and time consuming, and all WBS elements must be available to generate a build-up estimate (GAO, 2009).

Parametric

Parametric cost estimating uses statistics to develop relationships between historical weapon system actual costs and a new weapon system. Parametric estimating uses a top-down approach to estimating. Estimators create Cost Estimating Relationships (CERs) to predict future costs on historical data relationships. Examples of categories that use parametric estimating are weight, power, and lines of code. Regression is a common method to develop CERs. Regression analysis allows the estimator to make statistical inferences. The most important regression statistics to consider in parametric estimating are: R-squared (R^2), statistical significance (P-value), F Statistic, and t Statistic (GAO, 2009).

Additional Estimating Techniques

The DoD uses three additional cost estimating techniques: expert opinion, extrapolation from actuals, and learning curves. When no data are available, expert opinion is a useful estimating technique. Expert opinions are subjective estimates which provide a base for generating a cost estimate (GAO, 2009). To establish a credible expert opinion estimate, the cost estimator must solicit information only from the Subject Matter Expert’s (SME’s) field of study. Soliciting for point or range estimates from SMEs is often a difficult process. Frequently, experts are reluctant to give a point estimate and would prefer to submit subjective probability assessments. “Subjective probabilities are associated with one-time, non-repeatable, events whose probabilities cannot be objectively determined from a sample space of outcomes developed by repeated trials or experimentation" (Garvey, 2000). An example of a subjective probability is, "there is a 50% chance the airplane will exceed $1M to develop." This statement also states there is a 50% chance the airplane will not exceed $1M. There are always two sides to subjective probability assessments.

Extrapolation from actuals is a method used to estimate future costs based on actual costs or current costs. Averages, learning curves, and estimates at complete are examples of extrapolation techniques. In order to use extrapolation an estimator needs reliable data in the correct format (labor hours, material dollars, total cost) for the estimate. Extrapolation is best for follow on work or addition quantities of a weapon system where the estimator knows the exact costs to produce a weapon system (GAO, 2009).

Learning curves allow an estimator to generate a cost estimate based on the knowledge that organizations and the people involved work more efficiently the more they perform a task. The time to produce each aircraft should improve with each model built. GAO (2009) states the most common learning curve formula is:

$$Y = AX^{b} \tag{1}$$

The learning curve formula states, "as the number of units doubles, the cost decreases by a constant percent" (GAO, 2009). Figure 2 shows a visual explanation of the learning curve. Initially, the program experiences significant learning, but as the number of units developed increases the learning curve flattens.

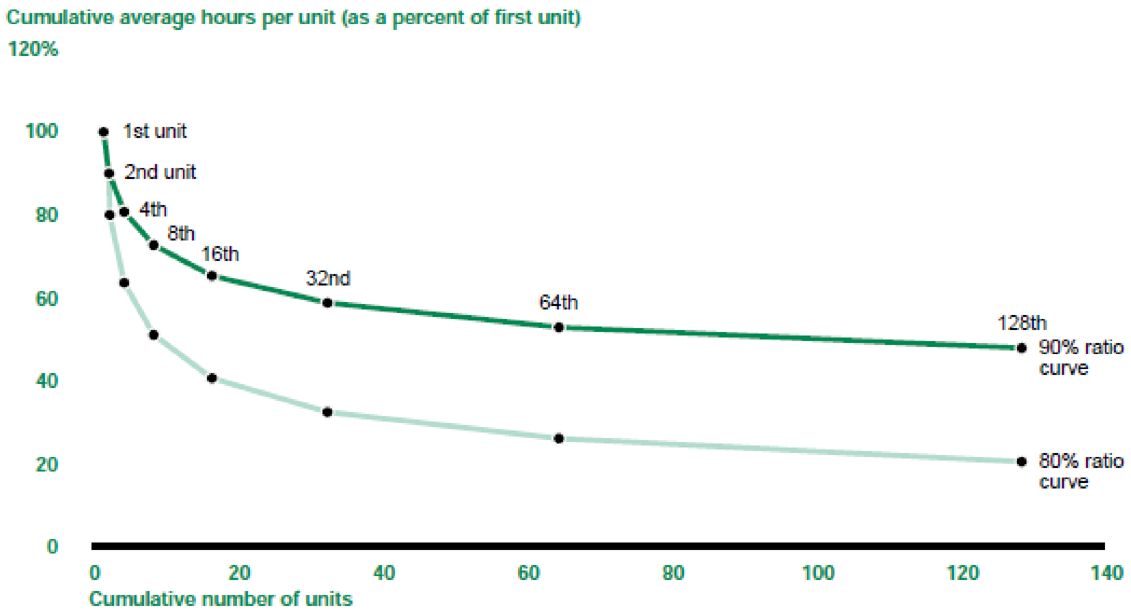


Figure 2: Learning Curve Slope (GAO, 2009)

Estimating Cost Growth

There are two common methods for calculating cost growth. The first method (2) is to calculate cost growth as a percentage of the original cost estimate. In the first method, the estimated cost is subtracted from the actual cost and then divided by the estimated cost (McNichols and McKinney, 1981).

$$\frac{(Actual - Estimated)}{Estimated} \tag{2}$$

The second method (3) is to calculate cost growth as a cost growth factor (CGF). The CGF method divides the estimate plus the cost variance (actual) by the estimate (Dresner et al., 1993).

$$\frac{Actual}{Estimated} \tag{3}$$

A CGF of 1.0 indicates the program did not go over or under the cost estimate, and the actual cost matched the estimated cost. If the CGF is greater than 1.0, the program sustained growth. Conversely, if the CGF is less than 1.0, the program did not sustain cost growth; rather, the program cost less than the estimate. To calculate the percent cost growth subtract 1 from the cost growth factor (Dresner et al., 1993).

Additionally, Arena et al. (2006) define cost growth as the increase in actual costs from the most resent cost estimate. With multiple cost estimates, CGFs can level out or change through time as the cost estimator implements new estimates for a weapon system. Arena et al. (2006) report that most previous studies discovered actual cost is greater than the estimated or baseline cost.

Three estimates exist within SARs: Planning Estimate (PE), Development Estimate (DE), and Current Estimate (CE) (Calcutt, 1993). PEs are the DoD estimate made during the Concept Exploration and Definition stage of the program lifecycle. DEs estimates occur at Milestone (MS) B or the start of EMD phase of the program lifecycle. CEs are the most up to date estimate. If a program is complete, the CE is the actual cost of the program (Calcutt, 1993).

Estimators calculate cost growth from a baseline estimate, the PE, DE, or CE. Typically, the DE at MS B is the baseline estimate for cost growth. MS B is the point in the schedule where a program enters full-scale development and officially becomes a "program of record." Once a program of record is established, the program is required to file official cost reports with Congress (Porter et al., 2009). As formal cost reports materialize, cost growth becomes easier to track, and it is for this reason the estimator measures cost growth from the DE when possible.

Standardization

Standardizing certain variables is necessary to compare programs evenly. The two variables with the biggest effect on cost growth are inflation and order quantity (Drezner et al., 1993). The standard approach to account for inflation is to convert all dollars to a single base-year value. According to Rusnock (2008) RAND prefers to adjust all program dollar values to values in the base-year, first year, of the estimate. A second approach is to adjust program dollar values to the last year, or current year, and make that year the base-year. Because this research includes some programs that are not complete, we use RAND's method and establish the base year as the first year of the estimate (Rusnock, 2008).

When establishing the DE, the weapon system has a planned number of units to procure. The estimator does not factor potential quantity changes into the weapon system estimate. To combat quantity changes, estimators generally use one of two methods. The first approach is to adjust the CE to reflect DE quantities. The second approach is to adjust the DE to reflect the CE. Rusnock (2008) describe three methods Hough (1992) outlines to adjust for quantity.

1. Standardize using variance listed in the SAR Quantity category only
2. Standardize using cost-quantity curves, thus adjusting all variances that occur at other than baseline quantities, or
3. Standardize using a hybrid approach by adjusting for quantity-related variances (both those listed in SAR Quantity category as well as those listed in other categories but described as quantity-related in the narrative portion of the SAR) and then adjusting the remaining variance using cost-quantity curves.

Arena, et al. (2006) state RAND adopted the second method described by Hough (1992). Additionally, RAND standardizes to the final quantity and not the quantity at the baseline estimate. Arena et al. (2006) identify the two major advantages of this method.

1. The actual cost is not changed. All estimates are adjusted to the actual cost and the actual cost is not changed.

2. If the other method were used, adjusting final procurement cost to baseline cost, the total CGF would be weighted more strongly by procurement cost growth (Arena et al., 2006)

In addition to standardizing inflation and quantity, Milestone (MS) notion is standardized. In 2000, MS notation shifted to MS A, B, C from MS, I, II, III. With the shift in notation, discussions arose about whether the notations are equivalent or not. Kassing et al. (2007) states MS II and MS B as well as MS III and MS C are equivalent. Below is the justification from Kassing et al. (2007) for establishing MS B and C equivalent to MS I, II:

> We use the current acquisition terminology set forth in DoD Directive 5000.1, May 12, 2003, throughout this document. In accordance with this terminology, Milestone B, as of 2000, represents the start of the system development and demonstration (SDD) phase of the DoD system acquisition process. It is defined somewhat differently than the Milestone II that was used before 2000, which was considered to be the start of the engineering and manufacturing development (EMD) phase. For our analyses, we treated these two milestones as comparable, so Milestone B is used throughout this monograph to mean Milestone B or an earlier equivalent. Similarly, Milestone C, the current designation for the start of the production phase, is used to mean Milestone C or its earlier equivalent, Milestone IIIA, which was the authorization to start low-rate initial production. (Kassing et al, 2007)

Lumb (2004) presented *DoD Business Transformation*, which outlines the differences between MS I, II, III and MS A, B, C notation. Figure 3 is a visual description of the differences between the 1996 notation and 2003 notation.

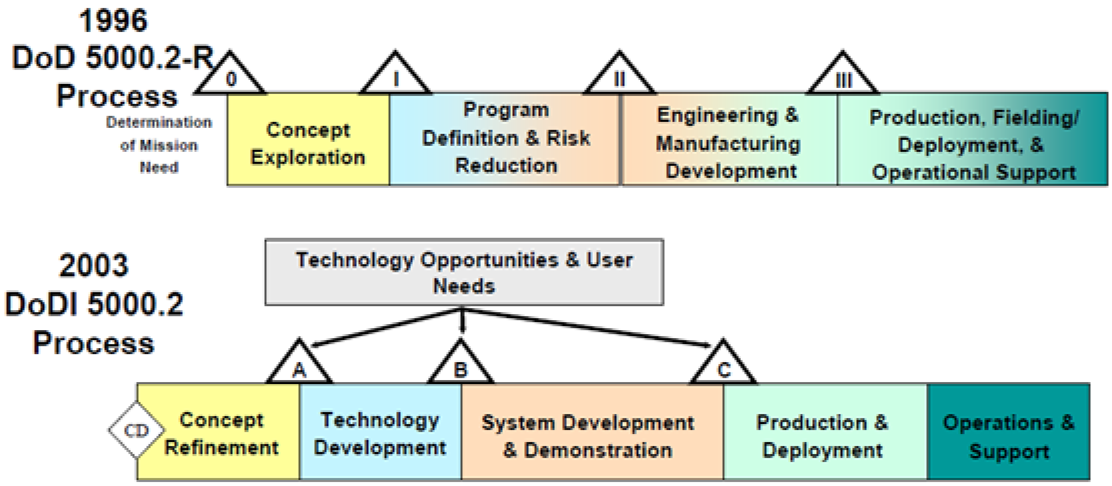


Figure 3: Defense Acquisition Milestones and Phases 1996 vs. 2003 (Lumb, 2004)

Cost Overrun

There are several ways to measure cost overrun. One method is to exam Earned Value Management (EVM) data and determines the difference between the original budgeted amount and the estimate at completion. A second method is to examine the cost growth factors which determine the amount of cost growth at a given point along a weapon system's schedule. Christensen (1994) used the first EVM Reports in his analysis of cost overrun in DoD weapon systems, and states as early as 10% of program completion cost over begins to exist. Along with identifying cost overruns early in the program, nearly all programs see cost overruns and never recover after the initial overrun. Examining aircraft specific programs, Christensen (1994) discovered about 75% of cost overrun occurs at 50% program completion. Christensen's (1994) research provides a starting ground for this research in determining how cost growth reacts based on aircraft program reviews.

Cost Growth Studies

This section of Chapter 2 identifies historical studies, which established methods for predicting cost growth in DoD weapon systems. The studies include a variety of different methods to predict cost growth and some of the significant predictors each study discovered. From the research to follow, this research utilizes some of the predictor variables to include in the methodology and analysis section. Several of the studies come from the RAND Corporation and others come from research interested in predicting cost growth.

RAND and IDA Studies

Asher et al. (1980) developed a method to predict weapon system cost growth. SARs provided the data necessary to perform the analysis. Asher et al. (1980) divided the weapon system database into different categories according to the type of weapon system (aircraft, missile, ships, and other systems) and identified individual cost growth factors for each weapon system. They also developed a six-step approach to determine development and procurement cost growth. Their methodology allows for estimator interpretation and subjective evaluation of the data. With subjective estimates, there is little mathematical backing to support the estimates. In conclusion, Asher et al. (1980) state cost estimating will improve as the DoD program database grows with future historical programs.

Dresner et al. (1993) studied 128 weapon systems with development estimates. Their research studied CGFs of weapon systems during development, procurement, and total program duration. Dresner et al. (1993) found two main factors affect cost growth: inflation and quantity. Because inflation and quantity have such a dramatic effect on cost growth, they removed them from the study. With the two factors accounted for, cost growth increases individual weapon system cost on average 2.2% per year or about 20% through the life a program. Dresner et al. (1993) discovered development CGFs were 7% greater than procurement CGFs. Another finding of Drezner et al (1993) is modification programs sustain less cost growth than new start programs. Modifications, which cost less than new starts, may be an assumed finding as most developers expect an estimate for a weapon system modification to consist of prior knowledge that assists in establishing estimates which are more accurate compared to new developments. Drezner et al. (1993) discovered longer program duration correlates to significantly greater cost growth. Program duration was the only schedule variable that significantly correlated with cost growth.

The research of Arena et al. (2006) provides valuable information on CGFs for 68 completed programs with similar complexities to programs acquired by the U.S. Air Force. Arena et al. (2006) identified three major categories affecting cost growth: acquisition strategy, schedule factors, and other factors. Acquisition strategies include but are not limited to prototyping, modifications, competition in production, and contract incentives. Schedule factors that affect cost growth are program duration and schedule slip. Other factors to consider when assessing the cause of weapon system cost growth are poor cost estimates, and program management decisions (Arena et al., 2006).

The data used by Arena et al. (2006) came from SAR reports. The DoD’s largest weapon systems, MDAPs, are required to annually file SARs with Congress. SARs provide a consistent platform for programs to report financial data. Arena et al. (2006) only used completed weapon systems in their study. They defined completed weapon systems as systems that have greater than 90% production complete. By using completed weapon systems, Arena et al. (2006) assure their analysis included nothing but final costs.

The data analysis section includes a segmented approach to modeling CGFs. Arena et al. (2006) divided the data into funding categories, milestones, and commodity type, to account for possible changes in correlation with CGFs. The funding categories focused on development and procurement. The MS category primarily focuses on MS II, and III. Commodities are split into different categories which include but are not limited to: aircraft, missile, and ship (Arena, 2006).

The major findings from Arena et al. (2006) include significant cost growth at MS II and MS III. Completed programs reported 46% and 16% respectfully. The two CGFs reported show cost growth bias decreases as a program moves toward completion (Arena et al., 2006). This research is significant to our research because it presents evidence that cost growth occurs at MS II and III.

Bolton et al. (2008) examined 35 MDAPs from a SAR database and unlike most studies, did not standardize quantity produced. The justification for not standardizing was to produce a true representation of “realized” cost growth. Bolton et al. (2008) created four categories for cost variances: errors in estimating and planning, decisions by the government, financial matters, and miscellaneous sources. The results attribute total development and procurement cost growth to government decision making. The biggest drivers of cost growth are quantity changes (21%), requirements growth (13%), and schedule changes (9%). Cost estimating contributes to 10% of total program cost growth. Overall, Bolton et al. (2008) recommend program managers, service leaders, and Congress find ways to reduce the amount of changes to requirements and quantities produced to minimize cost growth. Additionally, improving cost estimates would yield a significant reduction in cost growth.

Leonard et al. (2013) focused on cost growth for the entire acquisition effort, and define the entire acquisition effort from a program point of commitment, typically MS B, to system development. The point of system development is met when a portion of production units planned at MS B are produced and delivered to the customer. Leonard et al. (2014) divide the examined programs into two groups: programs at least 5 years past MS B but less than 80% funded, and completed programs (at least 80% funded). In their results, three continuing space programs had cost growth greater than one standard deviation (extreme cost growth). When adding the F-35 to the three space programs, this group makes up 95% of cost growth for all continuing programs. Excluding the three programs, MDAPs started between 2003 and 2011 sustained minimal cost growth. With smaller programs experiencing minimal cost growth, enhanced scrutiny is placed on the DoD's largest systems. In conclusion, Leonard et al. (2014) anticipate four programs will consume the majority of MDAP funding for the next 20 years: F-35A, EELV, KC-46A, and the Long Range Strike Bomber.

AFIT Research

The topic of cost growth generates significant research attention at the Air Force Institute of Technology (AFIT). This section outlines several AFIT studies after 2002 where AFIT students developed methods to predict total cost growth in DoD weapon systems. The difference between past AFIT research and our current research is our researches focuses on cost growth at different reviews throughout the program lifecycle whereas past research focuses solely on total cost growth. Table 2 provides a list of the AFIT studies from 2002-2015.

Table 2: AFIT Research

White et al.	2004	Using Logistic and Multiple Regression to Estimate Engineering Cost Risk
Moore & White	2005	A Regression Approach for Estimating Procurement Cost
Bielecki & White	2005	Estimating Cost Growth From Schedule Changes: A Regression Approach
Lucas	2004	Creating Cost Growth Models for the Engineering and Manufacturing Development Phase of Acquisition Using Logistic and Multiple Regression
McDaniel & White	2007	Predicting Engineering and Schedule Procurement Cost Growth for Major DoD Programs
Genest & White	2005	Predicting RDT&E Cost Growth
Rossetti & White	2004	A Two-Pronged Approach to Estimate Procurement Cost Growth in Major DoD Weapon Systems
Monaco & White	2005	Extending Cost Growth Estimation to Predict Schedule Risk
Cross	2006	Data Analysis and its Impact on Predicting Schedule and Cost Risk
Foreman	2007	Predicting the Effect of Longitudinal Variables on Cost and Schedule Performance
Rusnock	2008	Predicting Cost and Schedule Growth For Military and Civil Space Systems
Deneve	2015	A Macro Stochastic Approach to Improved Cost Estimating for Defense Acquisition Programs
Brown et al.	2015	Time Phasing Aircraft R&D Using the Weibull and Beta Distributions

White et al. (2004) was the first of many studies to use logistic and multiple regressions to predict cost growth in DoD weapon systems. White et al. (2004) focused on predicting cost growth during the Engineering and Manufacturing (EMD) phase of the acquisition life cycle. Focusing on Research and Development (RDT&E) dollars and limiting the study to engineering cost growth, a logistic regression model predicted 70% of the validation data and identified schedule variables to have the most predictive ability (White et al., 2004). Limiting the study to the EMD phase allows the estimator to track all cost growth changes back to an actual change of the end item. Any cost growth in the EMD phase is due to a physical engineering change of the weapon system (White et al., 2004). Their research used SARs as the data source; and the focus was on the EMD portion of the SAR.

By using historical data and regression analysis, White et al. (2004) were able to use an objective approach to estimate cost growth. They used a two-step approach to measure cost growth as a percentage change from the development estimate to the final estimate. First, the research used logistic regression to determine if a program sustains cost growth. White et al. (2004) identified the programs sustaining cost growth, and then analyzed the programs which sustained cost growth through multiple regression to create a model which predicts cost growth in weapon systems. Through regression analysis, White et al. (2004) established a seven-variable cost growth model. The predictors include funding variables, Time variable, weapon classification, and length of program. Using an objective method to predict cost growth establishes a foundation for future programs to utilize in predicting cost growth (White et al., 2004).

Bielecki et al. (2005) and Moore et al. (2005) built upon the research of White et al. (2004) and generated models to predict cost growth in different funding appropriations using logistic and multiple regression. Bielecki et al. (2005) generated a model to predict cost growth in the RDT&E budget during the EMD phase of the program lifecycle, and

Moore et al. (2005) generated a model to predict cost growth in the procurement budget during the EMD phase. Their research validates the research of White et al. (2004) and provides further detail into the predictive characteristics of program cost growth in RDT&E and procurement budget categories.

In 2004, four AFIT students built on the research of White et al. (2004), Bielecki et al. (2005) and Moore et al. (2005). Lucas (2004), McDaniel et al., (2007), Genest et al., (2005), and Rosetti et al. (2004) used logistic and multiple regression to further enhance the ability to predict cost growth in DoD weapon systems. Lucas (2004) focused on developing a model to predict a range of cost growth for the combined RDT&E and procurement budgets in the EMD phase. McDaniel et al., (2007) generated a model to estimate cost risk early in program development which reduces the DoD cost growth rate. Genest et al., (2005) focused on the pre EMD phase of a weapon system to predict cost growth. Rossetti et al. (2004) generated a model to predict procurement and support cost during the EMD phase.

Cross (2006) used logistic and multiple regression to examine cost and schedule growth in DoD weapon systems. He focused on filling in gaps where data was missing from previous research, and validating the schedule growth research of Monaco et al. (2005) and the cost growth research of Genest et al. (2005). With a more complete data set, Cross et al. (2006) highly recommended using schedule growth model of Monaco et al. (2005), but saw no advantage in the cost growth model of Genest et al., (2005).

Foreman (2007) continue to build on the previous research of cost and schedule growth. His research focused on adding new data sources and longitudinal variables to account for changes in a program over time. With the new data and longitudinal variables, Foreman (2007) generated two regression models to predict schedule slip and three models to predict cost growth.

Rusnock (2008) focused on space systems. Using logistic and multiple regression, she generated a model to assist cost estimators in predicting the likelihood of cost and schedule growth in space systems. Her research focused on two data sets. The first data set included 21 DoD space programs required to submit SARs. The second data set included 71 NASA satellite and space development programs. The results of the research conclude that program cost and physical program size are predictors of cost growth. Additionally, Rusnock (2008) identified certain contractors as predictors of schedule growth.

Deneve et al. (2015) drove to identify a method to create more realistic cost estimates. Through analyzing historical procedures to predict cost growth, their research set out to estimate if specific groups of weapon systems react differently to cost growth. By grouping weapons systems together, Deveve et al. (2015) looked to increase the accuracy of estimating cost growth. To create a macro-stochastic estimation, Deneve et al. (2015) identify categorical variables have strong relationships to CGFs. The important groups fall into four categories: program type, iteration, funding years, and number of services.   In addition, the study only includes programs with MS B dates after 1987, and like many other cost growth factor studies, this studied examines SAR data. Deneve et al. (2015) conclude that the groupings help predict the total cost from the baseline estimate with the DoD's largest programs.

Brown et al. (2015) focused their research on the cumulative distribution function to model development expenditures. Their research identified the amount of program expenditures at 50% program completion. After calculating program expenditures, Brown et al. (2015) used regression analysis to determine which program characteristics best predict distribution patterns for Rayleigh, Weibull and beta distributions. The program characteristics identified and considered in the final regression models include: contract award before 1985, upgrade programs, length of development, and first flight percent schedule (Brown et al., 2015).

Predictor Variables

Researchers use many variables to predict cost growth. In general, there are four basic variable groups: categorical descriptors, schedule related, cost related, and performance related (Drezner et al., 1993). Categorical variables identify different groups where cost growth may exist and are useful because they allow the researcher to divide variables into different subsets for analysis. Common categorical subsets include prototype, service, new start or modification. Schedule variables are time related variables that can influence program performance and are calculated using calendar dates listed in SARs for Milestones and other important dates in a program such as, First Flight and Initial Operational Capability. From milestone dates, the percentage change from the planned date to actual date is calculated to identify schedule changes as a percentage (Drezner et al., 1993). Cost growth calculations use cost variables, which include cost growth factors, program size, and funding appropriation distribution (Drezner et al., 1993). Performance variables assist in predicting cost growth as well. Performance variables are similar to cost variables in way they are calculated. Performance variables indicate if a program achieves the performance goal or not (Drezner et al., 1993).

Arena et al. (2006) report where to expect differences between cost growth studies based on predictor variables. Three factors contribute to differences in cost growth:

service, weapon system type, and time trends. Service identifies which branch of the DoD a system belongs to: Army, Navy, Air Force, Marines, Coast Guard. Weapon system identifies which platform a system belongs to: aircraft, electrical system, munitions, satellite, and missiles. Time trend refers to the period, year or decade, in which the weapon system was developed and procured. One significant finding states cost growth was significantly higher before the Packard Initiatives in 1969 (Arena et al, 2006).

From studies using program information from SARs, Arena et al. (2006) identify the three most common factors affecting cost growth.

1. Acquisition strategies: prototyping, modifications, contracts
2. Schedule factors: program duration, concurrency, and schedule slip
3. Other factors: increased system capabilities, unrealistic cost estimates, budget trends, and management behavior. (Arena et al., 2006)

As mentioned earlier, White et al. (2004) developed a method to predict cost growth and developed a long list of predictor variables divided into four main categories: program size, physical type of program, management characteristics, and schedule characteristics. Within the four categories listed, some of the variables are binary variables and some are continuous variables. An example of a binary variable is the function variable aircraft: 1 for yes the system is an aircraft and 0 for no the system is not an aircraft. An example of a continuous variable is program maturity (funding years complete). Program maturity is a "continuous variable which indicates the total number of years completed for which the program RDT&E or procurement funding budget" (White et al., 2004).

From 2003-2015 a wealth of AFIT research followed on the work of White et al. (2004). The follow on research used the predictor variable database from White et al. (2004) and added some of their own predictor variables to enhance the direction of their research. The AFIT research along with other previous studies provide a starting point for our research to predict cost growth in aircraft using program milestones and reviews. Table 3 list potential predictor variable categories for this research.

Table 3: Predictor Variables

Predictor	Previously Documented
Service	Arena et al. (2006), Deneve et al (2015),Dresner et al. (1993), McNicol (2004), White et al. (2004)
Weapon System Type	Dresner et al. (1993), Tyson et al. (1994), White et al. (2004)
Time Trends	Arena et al. (2006), Brown et al. (2015), Deneve et a. (2015), McNicol (1994), White et al. (2004)
Program characteristic	Brown et al. (2015), Dresner et al. (1993), Tyson et al. (1994), White et al (2004)
Contractor	Arena et al. (2006), White et al. (2004)
Program size	White et al. (2004)
schedule	White et al. (2004)
Aircraft type	Brown et al. (2015)
Program Cost	Brown et al. (2015), Deneve et al. (2015),Dibbly (1998)

Summary

The literature review presented information on methods for creating cost estimates, research on when cost growth occurs in weapon systems, significant research on cost growth, the development on logistic and multiple regression at AFIT, and potential variables to consider in our research. The next chapter, methodology, discusses how we approach addressing the goals of our research.

III. Methodology

Chapter Overview

The purpose of Chapter 3 is to describe the data this research uses in analysis and the methods used to evaluate the data. First, we discuss the data sources used for our analysis. Second, we discuss the data collection and evaluation process. Third, we present the method used to standardize the data. Forth, we briefly discuss the process to analyze cost growth at program reviews. Lastly, this section covers the procedures to identify predictors of cost growth in aircraft programs.

Data Source

The first step to predicting cost growth using program reviews and milestones is to establish a credible source of data. Significant cost growth studies in the past used SARs to gather data for their analysis. In Table 4, Arena et al. (2006) outlines six studies ranging from 1982 to 2006 that used SAR data to measure cost growth. Additionally the AFIT research stream from 2002-2008 used SARs to conduct logistic and multiple regression. More recently, Deneve et al. (2014) and Brown et al. (2015) used SARs in their research discussed in Chapter 2. With the studies above, we conclude that SAR data are a reputable source to begin model generation. An additional benefit of collecting data from SARs is that Congress requires MDAPs to update and report annually (Brown et al., 2015).

Table 4: CGF studies (Arena et al., 2006)

Citation	Source	Time Period	Sample
Tyson, Nelson, Om and Palmer (1989, Wolf (1990)	SARs (last SAR form Program or December 1987)	1960 -1987	89 weapon systems
Tyson, harmon, and Utech (1994)	SARs (Ist SAR for program of December 1992)	1962-1992	20 tactical missiles; 7 tactical aircraft
Dresner et al. (1993)	SARs (last SAR for program or December 1990)	1960-1990	128 programs with DE
Shaw (1982)	Last SAR for program or December 1982)	1973-1982	6 intercept missile programs
Asher and Maggelet (1984)	Last SAR for program or December 1983	As of 1983	52 systems with IOC
Arena et al. (2006)	Last SAR or December 2003	1968-2003	similar to those acquired by US Air Force

SARs include cost, schedule and programmatic information to evaluate program execution. The cost data includes estimates at different phases of a weapon system's life cycle. Typically, SARs provide a Planning Estimate (PE), Development Estimate (DE), and current or final estimate (CE). Along with program estimates, SARs report actual costs incurred by their respective program (Dresner et al.,1993).

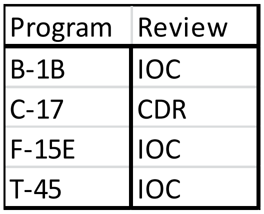
Over the years, several organizations developed databases based off of information in SARs (Arena et al. 2006). White et al. (2004) developed a database at AFIT to assist in the research stream that followed his work in logistic and multiple regression. RAND has complied a database with SAR information on DoD programs as well. This database provides annual SAR funding reports by appropriation as well as calculated cost growth measures (Arena, 2006). For our research, the RAND database proved to be a valuable source of SAR and cost data.

In addition to SARs, the Air Force Cost Analysis Agency (AFCAA) database of aircraft programs provides information on program review dates. The database includes

DoD aircraft programs along with significant program dates: MSII, CDR, First Flight, DT&E End, and IOC. The AFCAA database along with SAR data from RAND provides the framework for establishing the working database for this research.

The final source, *Deagel*, provided several program review dates to complete the database. *Deagel* is a civilian database that tracks civilian and military aircraft data. If SARs and the AFCAA database did not provide a review date, we referenced *Deagel* to complete the database. Additionally, for the programs with missing review dates, *Deagel's* review dates align with expected dates based off SAR and AFCAA database data. The dates selected from *Deagel* are available in Table 5.

Table 5: *Deagel* Program Dates



Program	Review
B-1B	IOC
C-17	CDR
F-15E	IOC
T-45	IOC

Data Collection

This research uses SAR data to analyze cost growth at program reviews. The research focuses on aircraft programs in the DoD. "Aircraft programs are defined as any fixed-wing, manned aircraft developed for one or more of the US DoD service branches" (Brown et al., 2015). Furthermore, the analysis includes only Acquisition Category 1 (ACAT 1) aircraft programs. ACAT 1 programs are the highest dollar value acquisition programs in the DoD. To achieve ACAT 1 designation a program must exceed $480M in Fiscal Year (FY) 14 dollars in Research and Development (R&D) or $2.8B in FY14 dollars in procurement funding (Acquisition Categories (ACAT) and Terms, 2014). Table 6 lists the 30 ACAT 1 Aircraft programs to evaluate in this research.

Table 6: Aircraft

A10	AV-8B
B1-B	B1-A
C17	E-8 JSTARS
EF-111A	E-3A AWACS
F14	B-1B CMUP Computer Upgrade
F15	B-2 RMP
F15E	C-5REP
F16	E-2D
F18A/B	E-6A
F18E/F	EA-18G
F22	F-35 (CV)
F35 (CTOL)	P-8A
T6	S-3A
T45	F22 Inc 3.2B
B-1B CMUP JDAM	E-3 AWACS RSIP

Limitations of SARs

SARs provide a standard repository to obtain required annual reports for MDAPs. However, there are some limitations to using SAR data in cost studies. Arena et al. (2006) and Hough (1992) discuss some of the limitations of SAR data.

1. SAR data are summary oriented
2. Estimates reported change over time
3. Future costs reflect budgeted values and do not necessarily correlate to cost estimates
4. Report requirements change over time
5. Cost variances are allocated inconsistently over time

6. Each program creates their SAR and all SARs do not necessarily report the same data.
7. Only largest DoD program submit SARs
8. Estimating techniques used are not reported with baseline and current cost estimates
9. SARs do not report risk and confidence levels.

Data Set

This research focuses on multiple funding categories and multiple program reviews. The funding categories are Development (Dev), Procurement (Proc), and total program cost. The program reviews are Critical Design Review (CDR), First Flight (FF), Development Test and Evaluation End (DTE), and Initial Operating Capability (IOC). Aircraft programs recorded the four program reviews for nearly all programs in this study. In the initial research, we considered other program review dates such as Preliminary Design Review (PDR), but the aircraft programs in the dataset returned PDR dates less than 50% of the time. Therefore, we decided to exclude PDR from our analysis.

In compiling IOC dates, some discrepancies emerged in identifying IOC dates. The reason is programs are not required to report IOC at a certain point in the program's schedule. Defense Acquisition University (DAU) (2015) defines IOC, "In general, attained when some units and/or organizations in the force structure scheduled to receive a system 1) have received it and 2) have the ability to employ and maintain it. The specifics for any particular system IOC are defined in that system's Capability Development Document (CDD) and Capability Production Document (CPD)." With IOC defined, IOC dates reported by aircraft programs in this research are consistent with the DAU definition, where some aircraft programs report IOC earlier in the schedule than other aircraft programs.

Lastly, in order to calculate the percent complete of a program we needed to identify program completion. Because we used SARs to analyze program cost growth, we use the final reported SAR as program completion. The final SAR (LS) identifies when all production is complete. The USD AT&L can consider terminating SARs when 90% of production units are complete or when a program is no longer considered an ACAT 1 program (AcqNotes, 2015). Because it is uncertain if termination of SAR reports occurs at 90% completion or at final production completion, we use the anticipated date of the last production unit completion as the LS and calculate the percent of completion based off that date.

Data Standardization

In order to conduct the analysis we need to standardize the aircraft program data. The first step is to account for inflation. OSD-Comptroller inflation rates convert all program SAR values to constant year (CY) 2015-dollar values. Standardizing the data allows us to evaluate CGFs at the CY15 dollar values instead of many fiscal year values where the significance of the CGF is unknown. See Table 7 for the complete list of programs and associated program costs.

Table 7: FY15 Program $ (Millions)

Program	Total $	Proc $	RDTE $	Program	Total $	Proc $	RDTE $
A10	$10,152.47	$8,682.68	$1,469.79	AV-8B	$17,811.30	$15,257.80	$2,553.50
B1-B	$53,005.07	$47,037.26	$5,967.81	B1-A	$56,031.66	$43,356.75	$12,674.91
C17	$50,462.38	$43,693.26	$6,769.11	E-8 JSTARS	$4,709.00	$2,270.64	$2,438.36
EF-111A	$1,881.74	$1,498.79	$382.96	E-3A AWACS	$12,086.19	$8,118.44	$3,967.75
F14A	$32,628.16	$27,680.35	$4,947.82	B-1B CMUP Comp	$553.56	$223.71	$329.86
F15	$35,059.04	$26,372.22	$8,686.82	B-2 RMP	$1,453.49	$647.37	$806.12
F15E	$72,474.22	$66,250.06	$6,224.16	C-5REP	$11,461.23	$9,592.62	$1,868.61
F16A/B	$18,384.15	$16,183.54	$2,200.62	E-2D	$16,066.89	$11,964.82	$4,102.08
F18A/B	$33,376.18	$27,908.10	$5,468.08	E-6A	$3,717.24	$3,087.41	$629.83
F18E/F	$89,745.97	$81,751.88	$7,994.10	EA-18G	$9,663.29	$7,621.59	$2,041.70
F22	$99,381.83	$72,505.63	$26,876.19	F-35 (CV)	$103,505.75	$84,190.95	$19,314.80
F35 (CTOL)	$124,116.40	$104,860.67	$19,255.72	P-8A	$33,664.17	$25,620.96	$8,043.21
T6	$4,086.23	$3,640.13	$446.09	S-3A	$15,313.25	$12,059.91	$3,253.35
T45	$6,746.34	$5,774.92	$971.42	F22 Inc 3.2B	$1,600.61	$355.66	$1,244.95
B-1B CMUP JDAM	$863.88	$289.64	$574.24	E-3 AWACS RSIP	$974.81	$384.78	$590.04

SARs list the quantities estimated and produced for each aircraft program. The quantities each aircraft program produces typically shift throughout the procurement stages of a program's lifecycle. In order to standardize the units produced for each aircraft program, the units are standardized to the final production amount. The method used in this study is the same method RAND adopted in 1998 (Arena, 2006). The standardization process uses learning curves (LC) and first unit cost (T1), which is derived from annual funding data provided in each program SAR (Arena, 2006). If the quantity reported in the baseline estimate is less than the final quantity, we calculate the cost of units not produced and add that value to the baseline estimate. Likewise, if the final quantity produced is less than the baseline estimate, we calculated the estimated cost of additional baseline units and subtract that value from the baseline estimate (Arena, 2006). Formulas 4-6 outline the calculations for Unit 1 cost, quantity adjustment, and calculating cost growth factors.

Calculate Unit 1 cost:

$$\frac{\left(\dfrac{\text{Cost}}{Quantity}\right)}{Quantity^{\left(\frac{LN\,(\text{Current }LCSlope)}{LN\,(2)}\right)}} \tag{4}$$

Preform Quantity Adjustment:

$$((\text{CurrentQty})(\$CurrentT1)(\text{CurrentQty})^{\frac{Ln(\text{Current }LCSlope)}{Ln(2)}}) - ((BaselineQty)(\$CurrentT1)(\text{BaselineQty})^{\frac{Ln(\text{Current }LCSlope)}{Ln(2)}}) \tag{5}$$

Calculate Cost Growth Factor:

$$1 + \left(\frac{CostVariance - QtyAdjustment}{BaselineCost}\right) \tag{6}$$

In equations 4 and 5, the current learning curve slope is used to calculate Unit 1 cost and perform quantity adjustments. The learning curve slope explains that people and organizations work more efficiently as more units are produced. The theory states that as the number of units doubles, the cost to produce decreases at a certain rate. This is the reason why learning curve slopes are important to calculating cost growth factors in aircraft programs. LN represents the Natural Logarithm in the equations 4 and 5.

Data Tables

Table 8 displays the complete CGFs for the 30 aircraft weapon systems in the analysis. The table outlines the appropriation and program review for each CGF. The blank fields in Table 8 are due to (1) a program not meeting the completion of a program review at the time of this analysis, or the program fell below a SAR reporting threshold and no longer required annual reports or (2), we were unable to find a recorded date for that review. For example, the F-35 has yet to complete Development Test & Evaluation and the B1-A fell below a reporting threshold in 1978 and was no longer required to make annual SAR reports; therefore, the fields are blank in Table 8.

Descriptive Statistics

After calculating the cost growth factors, we calculate some descriptive statistics from the cost growth factors. The research examines how many programs and the percent of programs which sustain cost growth at each review, the mean, median, standard deviation and interquartile range of the cost growth factors at each review, and the maximum and minimum responses of cost growth at each review. These statistics help better understand how cost growth factors behave over time. In addition, we calculate the percent of program completion at each review. With the percent cost growth and percent program completion at each review, we plot the points which provides a visual tool to analyze cost growth over time. Formula 7 displays the formula necessary to calculate percent of total cost growth.

Percent of total Cost Growth:

$$\frac{\left(\mathrm{Re}\,view-1\right)}{(LS-1)} \tag{7}$$

Table 8: Cost Growth Factors

	Development					Procurement					Total				
Aircraft	CDR	FF	DTE	IOC	LS	CDR	FF	DTE	IOC	LS	CDR	FF	DTE	IOC	LS
A10	1.09	1.19	1.18	1.19	1.27	1.03	1.22	1.28	1.22	1.34	1.03	1.22	1.28	1.22	1.33
B1-B	1.05	1.05	1.17	1.16	1.31	0.99	0.98	0.96	0.96	0.98	1.00	0.99	0.99	0.98	1.02
C17	1.22	1.36	1.41	1.54	1.81	1.08	1.31	1.29	1.45	1.72	1.05	1.33	1.47	1.47	1.75
EF-111A	0.97	1.38	1.48	2.10	2.10	0.92	1.53	1.62	1.62	1.62	0.93	1.48	1.60	1.79	1.79
F14	1.32	1.32	1.47	1.48	1.83	1.03	1.03	1.19	0.92	1.18	1.08	1.08	1.24	1.02	1.29
F15	0.98	0.98	1.09	1.09	1.37	1.05	1.04	1.32	1.23	1.28	1.03	1.03	1.19	1.19	1.30
F15	1.07	1.07	1.09	1.09	1.48	1.00	1.00	1.01	1.01	1.01	1.02	1.03	1.04	1.04	1.34
F16	1.00	1.25	1.28	1.31	2.51	1.00	1.12	1.10	1.13	1.08	1.00	1.13	1.12	1.15	1.27
F18	1.08	1.11	1.15	1.15	1.36	1.02	1.11	1.33	1.35	1.45	1.03	1.11	1.29	1.31	1.43
F18	0.99	0.95	0.98	0.98	0.98	1.00	1.02	0.96	0.95	1.01	1.00	1.01	0.96	0.96	1.01
F22	1.12	1.19	1.50	1.47	1.64	1.03	1.10	1.61	1.46	1.62	1.05	1.13	1.58	1.47	1.63
F35 (CTOL)	1.25	1.24		1.53		1.36	1.36		1.82		1.26	1.30		1.69	
T6	1.02	1.02	0.84	0.86	0.90	1.00	1.00	1.42	1.44	1.47	0.99	0.99	1.13	1.36	1.41
T45	1.07	1.09	1.31	1.31	1.53	1.10	1.21	1.50	1.48	1.70	1.10	1.20	1.48	1.48	1.68
B-1B CMUP JDAM	0.85	0.80	0.77	0.77	0.77	1.05	1.09	1.05	1.05	1.02	0.94	0.90	0.88	0.88	0.87
AV-8B	1.00	1.01	1.21	1.20	1.30	1.00	1.03	0.98	0.86	0.92	1.00	1.03	1.02	0.91	0.98
B1-A	0.96	1.15			1.10	1.00	1.11			1.21	0.99	1.12			1.20
E-8 JSTARS	0.98	1.22	2.13	2.12	2.41	1.92	1.92	1.87	1.90	1.86	1.06	1.55	2.01	2.02	2.15
E-3A AWACS		1.52	1.55	1.49	1.71		1.31	1.33	1.32	1.28		1.38	1.41	1.28	1.43
B-1B CMUP Comp	0.98	0.97	1.02	1.00	0.95	1.00	0.84	1.16	1.02	0.95	0.99	1.07	1.16	1.08	1.07
B-2 RMP	0.88	0.81	1.02	0.93	0.93	1.00	0.99	1.14	1.06	1.04	0.93	0.89	1.07	0.99	0.98
C-5REP	0.87	0.97	1.00	1.02		1.04	1.03	1.00	1.22		1.01	0.99	1.00	1.21	
E-2D	1.00	1.06	1.26	1.50		1.00	1.09	1.31	1.27		1.00	1.08	1.30	1.33	
E-6A	1.11	1.12	1.11	1.12	1.12	0.97	0.78	0.81	0.82	0.90	1.02	0.87	0.90	0.91	0.98
EA-18G	1.05	1.08	1.04	1.04		1.05	1.04	1.04	1.02		1.05	1.05	1.05	1.05	
F-35 (CV)	1.24	1.50		1.53		1.36	1.66		1.70		1.34	1.63		1.62	
P-8A	0.96	0.99	1.11	1.12		1.00	1.01	0.95	0.95		0.99	1.01	1.00	1.00	
S-3A		1.08	1.10	1.08	1.09		1.00	1.02	1.00	1.06		1.02	1.04	1.02	1.07
F22 Inc 3.2B	0.99					0.99					0.99				
E-3 AWACS RSIP	1.02	1.07	1.07	1.07	1.07	1.00	1.41	1.57	2.05	2.06	1.01	1.21	1.27	1.45	1.46

Methodology

Lastly, we discuss the process to identify predictors of cost growth at program reviews. Step 1: we use logistic regression to identify which programs are likely to sustain cost growth at specific program reviews. Step 2: we use the results of the logistic regression to identify which continuous variables are predictive of cost growth. Step 3: we convert any significant continuous variables to categorical variables. Step 4: we analyze these categorical variables and identify which are significant using Fisher’s Exact Test. If appropriate, Step 5: we use the Odds Ratio to calculate the odds of the significant categorical variables occurring.

Logistic Regression

The AFIT research stream from 2002-2008 used logistic regression as the first step to identifying cost growth in weapon systems. With this research, we follow the past of using logistic regression to identifying the likelihood of a program sustaining cost growth. Logistic Regression uses binary (0 or 1) to identify if a program sustains cost growth or not. If a program has a CGF greater than 1, positive cost growth, the program receives a value of ‘1’. If a program has a CGF less than or equal to 1, negative to no cost growth, the program receives a value of ‘0’. In our research, we do not model the likelihood of no or negative cost growth. The purpose of identifying programs with positive cost growth is to focus the attention of the estimator on the “troubled programs”. If an estimator can identify predictors of positive cost growth in the troubled programs, they may determine a method to cut down total cost growth and eliminate cost growth across DoD weapon systems.

With a small sample size of aircraft programs, we split the predictor into two categories, categorical variables and continuous variables. Logistic regression examines the continuous variables in an attempt to identify predictors of cost growth. For logistic regression, the program’s cost growth (0/1) is the (y) dependent variable, and the (x) independent variable is one of the continuous variables (or predictor variables) listed in Table 9. The research analyzes each independent variable at the 12 combinations of dates (CDR, FF DTE, IOC) and appropriations (Development, Procurement, Total). To determine if an independent variable is significant, we examine the p-value associated with each test. In order to consider an independent variable predictive, the p-value must be less than 0.10 which is our chosen significance level. Ideally, the p-value returned is less than

0.05, but for this analysis, we include any variable less than 0.10 since our study is more exploratory in nature than confirmatory.

After identifying significant continuous variables, we convert the continuous variables into a binary categorical variable. To convert a continuous variable to a categorical variable it is necessary to identify a "break or split" in the data. At this break or split, we code categorical variables as: one side of the split equals '0' and the other side equals '1'. Converting the continuous variables to categorical variables is important for this study because of the small sample size of aircraft.

Table 9: Continuous Variables used in Logistic Regression Analysis

Continuous Variables
% RDTE Funding @ MSB
Estimate MSB-IOC
Proc Qty/Months
MSB Cost/ Aircraft
Proc QTY @ MSB
Total $ @ MSB
Proc $ @ MSB
RDTE $ @ MSB
Months from MSA-MSB
Months from MSB-CDR
Months from MSB-FF
Months from MSB-DTE
Months from MSB-IOC
Months from FF-DTE

Fisher's Exact Test

Medical studies often use Fisher's Exact Test to determine if (x) variables are predictive in determining medical results or (y) variables. Kennedy et al. (2015) and Pavelites et al. (2014) use Fisher's Exact Test to determine if (x) variables are predictive of medical outcomes. Their research methods relate closely to the goals of this research. For this reason, we use Fisher's Exact Test to determine if predictors of cost growth, (x) variables, are significant predictors of cost growth (y variable) in aircraft.

Due to a small sample size, only thirty aircraft programs, Fisher's Exact Test is an appropriate test for independence between a program having cost growth and the explanatory variables considered in this thesis. Fisher's Exact Test uses contingency tables, most commonly $2 * 2$ tables, to test for independence. Fisher's Exact Test makes two assumptions. First, the test assumes all observations are independent. Second, the test operates under fixed, or conditioned, row and column totals. The second assumption distinguishes Fisher's Exact Test from other statistical independence tests with unconditioned rows and columns (McDonald, 2009). A benefit of using Fisher's Exact Test is the test does not estimate the probability of a value; rather the test calculates the exact probability of receiving the observed data.

Fisher's Exact Test accommodates both 1-tailed or 2-tailed hypothesis tests, but this research uses just 1-tailed hypothesis tests to identify if a categorical factors increases the chances a program will have a CGF > 1.0. The null hypothesis states the categorical variable does not effect the CGFs. For a right tailed Fisher's Exact Test the alternate hypothesis is that the CGF will be more likely greater than 1 for the categorical factor '1' than '0'.

- H_o: the factors are the same
- H_a: the probability (CGF>1) is greater for the factor = '1' than '0'

As will be shown in the next chapter, some predictor variables actually are predictive of a CGF<1. In that case, we conduct a left tailed Fisher's Exact Test to confirm the findings.

In this scenario, the null hypothesis remain the same as the right tailed test, but the alternate hypothesis changes to:

- H_a: the probability (CGF>1) is greater for the factor = ‘0’ than ‘1’

From the complete pool of predictor variables, Fisher’s Exact Test examines the categorical variables, which are given in Table 10, vs positive cost growth at the 12 review and appropriation combinations. In addition to the categorical variables in Table 10, we convert significant continuous variables to categorical variables and include them in the Fisher’s Exact Test analysis.

Table 10: Categorical Variables used in Logistic Regression Analysis

Categorical Variables	
Fighter/ Attack	Cohort 3
Bomber	Cohort 4
ISR	Fairchild
Trainer	Rockwell
Cargo/Tanker	McDonnel Douglas
Air Force	Northrop Grumman
Aircraft	General Dynamics
Prototype	Lockheed Martin
Modification	Boeing
MSB>1985	Beech Aircraft
% RDTE Funding >50%	

Odds Ratio

The Odds Ratio (OR) is useful when interpreting the results of contingency tables. Because Fisher’s Exact Test uses $2 * 2$ contingency tables, we are able to calculate the Odds Ratio with the same data tables. The Odds Ratio is the ratio of the odds of an event occurring in one group to the odds of the same event occurring in another group. This research predicts cost growth given different (x) predictor variables. To calculate the OR, first identify that an aircraft has (x) variable and then compute the odds the same (x) variable has cost growth. Second identify the aircraft that do not have the (x) variable and then calculate the odds the same (x) variable has cost growth. Finally, divide the odds for step one by the odds of step two to determine the odds ratio. This ratio is stable for relatively moderate to large sample sizes. Due to our small sample size there is a possibility the OR will be unstable. We later show this is the case. Therefore, we are ultimately unable to use the OR to make statistical inferences.

Summary

The Methodology chapter discussed the data sources used to gather program funding information for this research as well as the methods used to standardize the data. Next, we described how to calculate the cost growth factors. Finally, Chapter 3 presented the methods used to analyze the data: descriptive statistics, logistic regression, Fisher's Exact Test, and Odds Ratio.

IV. Analysis and Results

Introduction

Chapter 4 starts with a presentation of the descriptive statistics associated with each aircraft program and presents graphs on how the cost growth behaves over time. Next, we present the results of logistic regression followed by Fisher's Exact Test and, if appropriate, the Odds Ratios. Finally, we present a total analysis of the results.

Descriptive Statistics

Descriptive statistics provides insight into the CGFs associated with each review and appropriation. The categories included in descriptive statistics are sample size, number of programs with cost growth, percent of programs with cost growth, mean, median, standard deviation, interquartile range, minimum, and maximum. We used Microsoft Excel to calculate the descriptive statistics in the tables to follow.

Table 11 provides complete descriptive statistics for the aircraft dataset.

Table 11: Descriptive Statistics

	Category	N (Sample Size)	Programs w/ Cost Growth	% Programs w/ Cost Growth	Mean	Median	Standard Deviation	IQR	Minimum	Maximum
Development	CDR	28	14	50%	1.04	1.01	0.11	0.10	0.85	1.32
	FF	29	22	76%	1.12	1.08	0.17	0.21	0.80	1.52
	DTE	26	22	85%	1.21	1.13	0.27	0.26	0.77	2.13
	IOC	28	23	82%	1.26	1.16	0.32	0.42	0.77	2.12
	LS	23	18	78%	1.41	1.31	0.46	0.60	0.77	2.51
	Category	N (Sample Size)	Programs w/ Cost Growth	% Programs w/ Cost Growth	Mean	Median	Standard Deviation	IQR	Minimum	Maximum
Procurement	CDR	28	13	46%	1.07	1.00	0.19	0.05	0.92	1.92
	FF	29	22	76%	1.15	1.09	0.24	0.21	0.78	1.92
	DTE	26	20	77%	1.22	1.18	0.25	0.32	0.81	1.87
	IOC	28	21	75%	1.26	1.22	0.32	0.45	0.82	2.05
	LS	23	19	83%	1.29	1.21	0.33	0.53	0.90	2.06
	Category	N (Sample Size)	Programs w/ Cost Growth	% Programs w/ Cost Growth	Mean	Median	Standard Deviation	IQR	Minimum	Maximum
Total	CDR	28	15	54%	1.03	1.01	0.08	0.06	0.93	1.34
	FF	29	23	79%	1.13	1.08	0.19	0.20	0.87	1.63
	DTE	26	19	73%	1.21	1.15	0.26	0.27	0.88	2.01
	IOC	28	21	75%	1.25	1.20	0.29	0.44	0.88	2.02
	LS	23	19	83%	1.32	1.30	0.31	0.40	0.87	2.15

For the histograms of CGFs at the 12 reviews and appropriation combinations, see Appendix A.

In our analysis, we look to identify cost growth factors of programs at different reviews. Figure 4 through Figure 6 provide a visual representation of the aircraft programs with positive cost growth factors vs percent of program completion. Each of the program reviews is identified by a different shape as presented in the legend of the figures. Our analysis only includes programs that sustain cost growth because our goal is to identify how much cost growth and the percent of total cost growth an aircraft program is likely to sustain given the program sustains cost growth. We are not concerned with programs that do not experience cost growth because those programs are performing as expected.

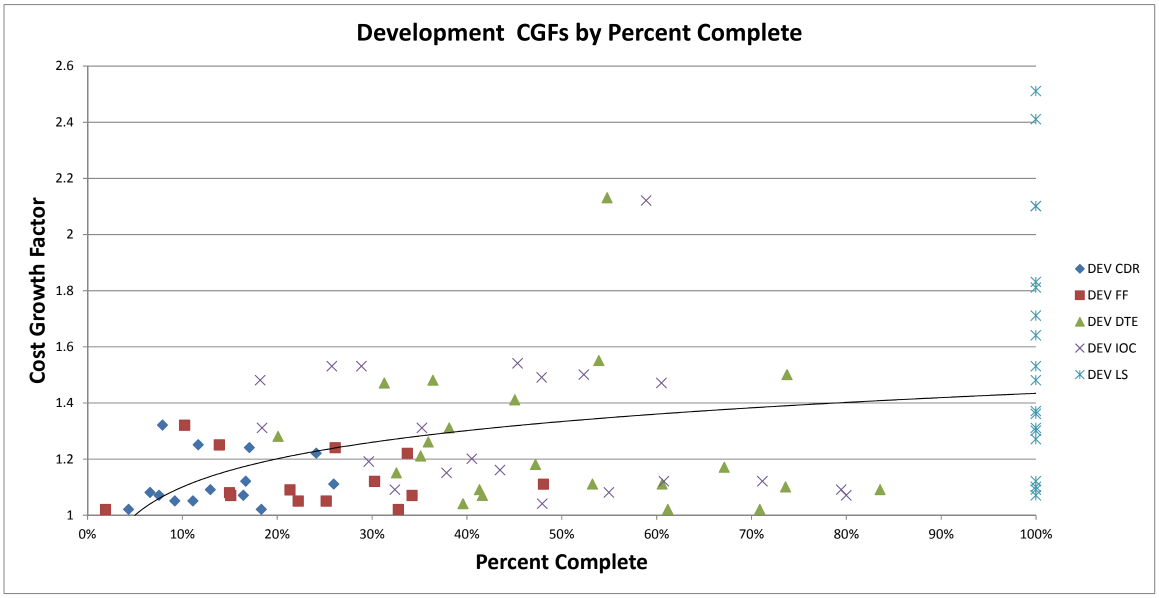


Figure 4: Development Cost Growth

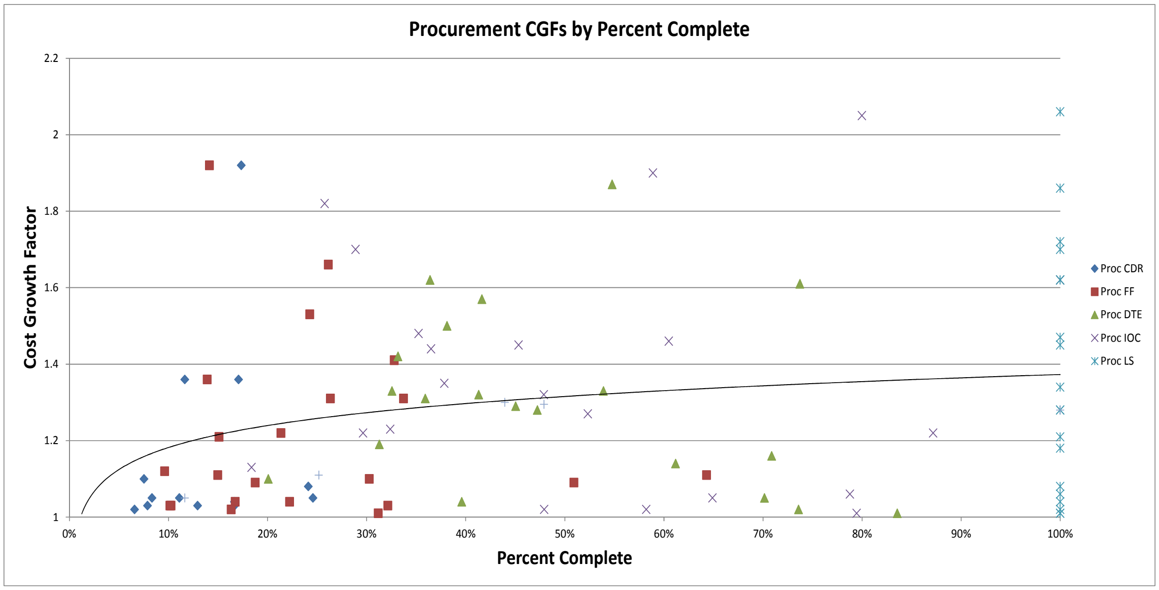


Figure 5: Procurement Cost Growth

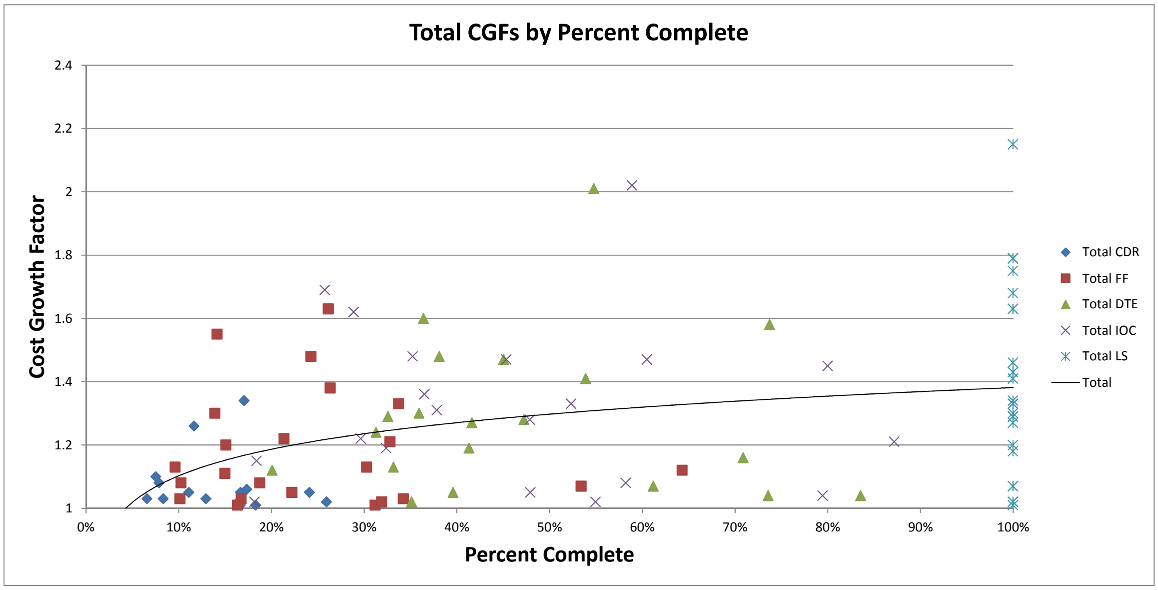


Figure 6: Total Cost Growth

In addition to Figure 4 throughFigure 6, Table 12 lists the descriptive statistics from MSB to each program review in months. Table 13 identifies the mean and median CGF at each aircraft review. Table 14 lists the percent complete at each review and the associated percent of total cost growth at that review. Table 15 lists the average months complete at each review and the associated percent of total cost growth at that review. Lastly, Figure 7 through Figure 10 graphically display the information presented in Table 14 and Table 15.

Table 12: Descriptive Statistics MSB-Review (Months)

	MSB - CDR	MSB-FF	MSB-DTE	MSB-IOC	MSB-LS
mean	25.0	43.6	81.3	88.9	185.8
median	17.2	34.5	74.1	78.1	176.0
stdev	19.0	24.0	32.3	36.9	95.6
max	84.2	117.7	170.6	158.3	452.5
min	1.0	4.0	39.5	32.5	57.9

Table 13: CGF at Program Reviews

Cost Growth Factor		
Review	mean	median
DEV CDR	1.12	1.09
DEV FF	1.19	1.14
DEV DTE	1.26	1.18
DEV IOC	1.34	1.20
DEV LS	1.56	1.43
PROC CDR	1.16	1.05
PROC FF	1.22	1.11
PROC DTE	1.31	1.30
PROC IOC	1.37	1.32
PROC LS	1.37	1.28
TOT CDR	1.08	1.05
TOT FF	1.18	1.12
TOT DTE	1.29	1.26
TOT IOC	1.35	1.31
TOT LS	1.40	1.34

Table 14: % Program Completion vs % program CG

Mean % complete vs % mean tot CG				Median % complete vs % med total CG		
Review	% complete	mean % CG		Review	% complete	med % CG
DEV CDR	13%	22%		DEV CDR	12%	20%
DEV FF	27%	33%		DEV FF	25%	32%
DEV DTE	49%	47%		DEV DTE	44%	41%
DEV IOC	51%	60%		DEV IOC	48%	47%
DEV LS	100%	100%		DEV LS	100%	100%
PROC CDR	13%	44%		PROC CDR	12%	18%
PROC FF	27%	59%		PROC FF	25%	39%
PROC DTE	49%	83%		PROC DTE	44%	107%
PROC IOC	51%	101%		PROC IOC	48%	114%
PROC LS	100%	100%		PROC LS	100%	100%
TOT CDR	13%	19%		TOT CDR	12%	15%
TOT FF	27%	45%		TOT FF	25%	35%
TOT DTE	49%	72%		TOT DTE	44%	75%
TOT IOC	51%	86%		TOT IOC	48%	91%
TOT LS	100%	100%		TOT LS	100%	100%

Table 15: Months Complete vs % Program CG

Mean months vs % mean total CG				Median months vs % median total CG		
Review	months	mean		Review	months	median
DEV CDR	24.1	22%		DEV CDR	17.2	20%
DEV FF	43.6	33%		DEV FF	34.5	32%
DEV DTE	81.3	47%		DEV DTE	74.1	41%
DEV IOC	88.9	60%		DEV IOC	78.1	47%
DEV LS	185.8	100%		DEV LS	176.0	100%
PROC CDR	24.1	44%		PROC CDR	17.2	18%
PROC FF	43.6	59%		PROC FF	34.5	39%
PROC DTE	81.3	83%		PROC DTE	74.1	107%
PROC IOC	88.9	101%		PROC IOC	78.1	114%
PROC LS	185.8	100%		PROC LS	176.0	100%
TOT CDR	24.1	19%		TOT CDR	17.2	15%
TOT FF	43.6	45%		TOT FF	34.5	35%
TOT DTE	81.3	72%		TOT DTE	74.1	75%
TOT IOC	88.9	86%		TOT IOC	78.1	91%
TOT LS	185.8	100%		TOT LS	176.0	100%

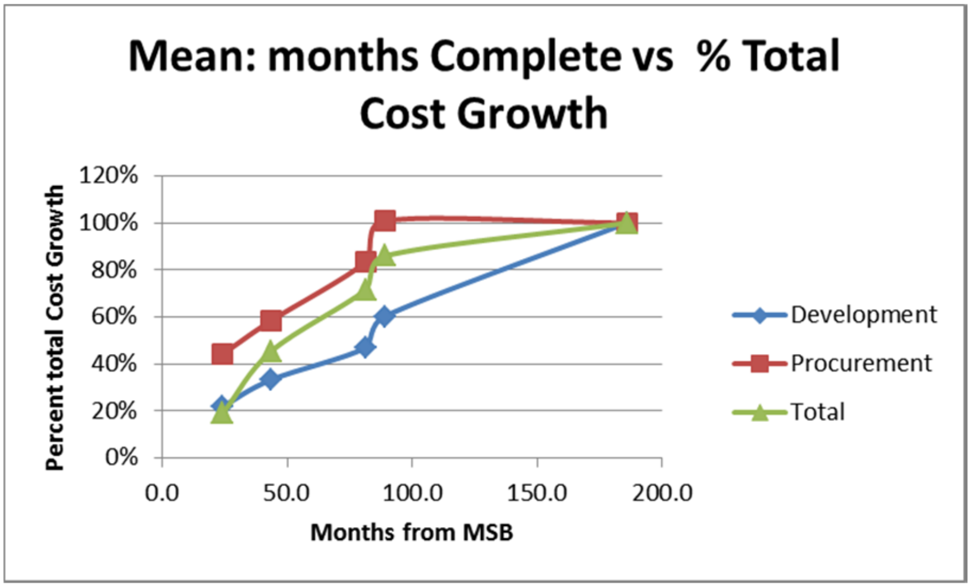


Figure 7: Mean months Complete vs % Total Cost Growth

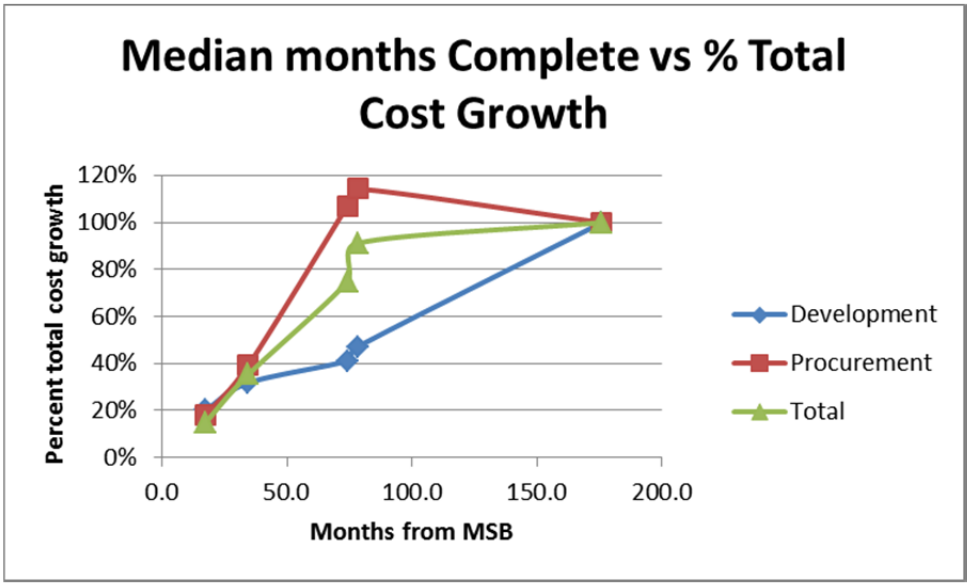


Figure 8: Median months Complete vs % Total Cost Growth

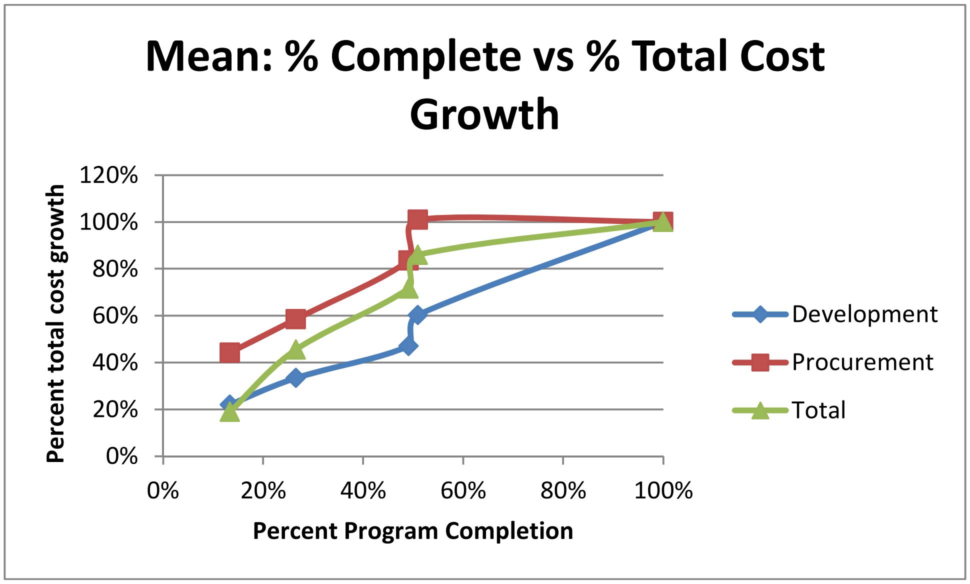


Figure 9: Mean % Complete vs % Total Cost Growth

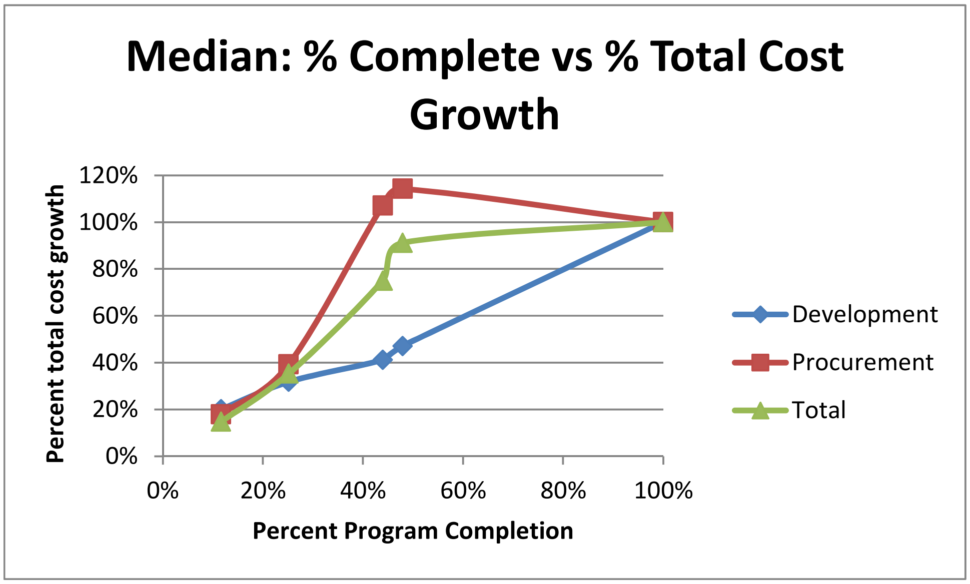


Figure 10: Median % Complete vs % Total Cost Growth

In the analysis to follow, we primarily address the median values from Table 12 through Table 15. The reason for analyzing the median is the variability in the data as presented in Figure 4 through Figure 6. The figures show some of the data points could be more influential than other data points. These extreme values have a tendency to shift the mean to those points. Influential data points, however, do not have as profound affect on the median, and it is for this reason we focus our analysis on the median. Table 12 and Table 13 provide summary tables of months from MSB and CGFs at the reviews. The median CGFs at the last SAR (LS) are: DEV = 1.43, Proc = 1.28, Total = 1.34. These values are the median CGFs expected when SARs are no longer required, or a program production concludes. This information also shows that the median CGFs for development are greater than procurement and total CGFs. Examining procurement CGFs, the largest median CGFs occur at DTE and IOC, not at the LS. This information leads to further analysis that Table 14 and Table 15 assist in explaining.

As stated previously, our analysis includes four reviews where we examine CGFs. The four reviews all occur before 50% schedule completion. IOC is typically the last review (sometimes DTE has a later date), with median percent complete of 48%. Because IOC has the latest, in terms of schedule, median percent complete, we further analyze this review. Table 14 presents valuable information on CGFs in terms of percent of schedule completion. At IOC, the procurement median CGF is 114% of total cost growth. This states that the median CGF at IOC is greater than the median LS CGF, or the program has reached greater than its peak CGF at IOC. For total, 91% of total cost growth occurs at IOC. For development, a much smaller percent of total cost growth occurs at IOC, 47%. Table 15 identifies the median months from MSB and the percent of total cost growth experienced. The median time from MSB to IOC is 78.1 months or 6.5 years. Therefore, our analysis states that the median percent of total cost growth is 91% at a median time of 6.5 years after MSB.

The information from Table 12 through Table 15 lends itself to the same analysis for CDR, FF, and DTE as it did for IOC. At CDR, the percent of total cost growth and percent of program completion are closer to the same percent than those values at IOC. At FF, the same percentages, percent of total cost growth and percent of program completion, begin to separate as presented in Table 14. AT FF, total percent of total cost growth is 35% and total percent of program completion is 25%. For total, we begin to see percent of total cost growth rise faster than percent of program completion. At DTE, total percent of total cost growth is 75% and total percent of program completion is 44%. Again the percent of total cost growth is rising faster at this point compared to percent of program completion. Lastly, we turn back to the information presented on IOC and see 91% of total cost growth occurs at 48% schedule completion. With this information, we see a steep rise in percent of total cost growth between FF and IOC.

Procurement percent of total cost growth at CDR is 18% and percent of program completion is 12%. At FF the percent of total cost growth is 39% and percent of program completion is 25%. At FF, the percent of total cost growth begins to increase more rapidly than percent of program completion. At DTE, percent of total cost growth is 107% and percent of program completion is 44%. At IOC, percent of total cost growth is 114% at 48% program completion. As seen in Figure 7 through Figure 10, procurement experiences a large increase in percent of total cost growth around DTE and IOC. DTE and IOC occur at 44% and 48% complete and it is at this point that a program sees a CGF greater than the CGF at program completion.

Development percent of total cost growth does not behave the same way as procurement cost growth. At CDR, percent of total cost growth is 20% at 12% program completion. FF percent total cost growth is 32% and percent of program completion is 25%. With CDR and FF, the percent of total cost growth compared to percent of program completion is not too different, ~7-8%. At DTE the percent of total cost growth is 41% and at IOC the percent of total cost growth is 47%. Both of these percentages of total cost growth are less than percent of program completion and far less than the percent of total cost growth experienced with procurement at the same reviews.

The information presented on percent of program total program cost growth can tie back to a median CGF at each review. Table 13 lists the mean and median CGFs by appropriation and review. For example, the median total CGF is 1.31 at IOC and 1.34 at the LS. Additional discussion on this material is offered in Chapter 5.

Logistic Regression

Logistic regression identified individual (x) variables that are predictive of (y) variables, or cost growth, at different reviews in a weapon system. Table 16 indicates the variables that are significant predictors of cost growth at the associated appropriation and review. Columns that are highlight grey with an ‘X’ indicate the variable is predictive at the 0.1 significance level (P-value<0.10). Columns that not highlighted with an ‘X’ indicate the variable is predictive at the 0.05 significance level (P-value< 0.05).

Table 16: (x) Variables Tested as Predictors of Cost Growth

Logistic Regression	DEV CDR	DEV FF	DEV DTE	DVE IOC	Proc CDR	Proc FF	Proc DTE	Proc IOC	Total CDR	Total FF	Total DTE	Total IOC	Total
%RDTE Funding @ MSB	X	X		X									3
ProcQty/Months	X				X								2
Proc QTY @ MSB	X				X								2
Months from MSA-MSB	X												1
Estimated MSB-IOC (Mos)													0
MSII Cost Per Aircraft													0
Total $ @ MSB													0
PROC $ @ MSB													0
RDT&E $ @ MSB													0
Mos. From MSB-CDR													0
Mos. from MSB-FF													0
Mos. from FF-DT													0
Mos. from MSB-DT													0
Mos. from MSB-IOC													0
Total	4	1	0	1	2	0	0	0	0	0	0	0	8

After determining which continuous variables are significant in predicting cost growth, we convert the continuous variable into a categorical variable to investigate its effect as analyzed in Fisher's Exact Test. *% RDTE Funding @ MSB* already exists as categorical variable, *% RDTE funding >50%*. If a program has RDTE funding greater than 50% of total program funding at MSB, this variable equals '1' and all else equals '0'. The next two significant continuous variables: *ProcQty/ Months* and *ProcQTY @ MSB* are highly correlated. *ProcQty/Months* and *Proc QTY @ MSB* are 0.8684 correlated as seen in Figure: 11.

This correlation is significant enough to prevent both variables from being included in a regression model together. Therefore, we include one categorical variable to account for both continuous variables. The new categorical variable is *Proc Qty > 450* where programs with procurement quantities greater than 450 receive a '1' and all other programs receive a '0'. The last continuous variable to convert to categorical is *Months MSA-MSB.* The new categorical variable is *Months MSA-MSB >=50* where any program with months from MSA to MSB greater than or equal to 50 receives a '1' and all other programs receives a '0'.

When examining *Proc Qty* vs CGF we discovered a "break in the plotted points around 450. At this point we divided *Proc Qty* into the two groups stated earlier and tested to see to see if the same "x" variables were predictive as the continuous variable Proc Qty. The results were the same and we conclude that *Proc Qty > 450* is a valid categorical variable. The same methodology was followed for determining the categorical variable *Months MSA-MSB >= 50.* With all predictive continuous variables, transitioned to categorical, we now turn to Fisher's Exact Test results.

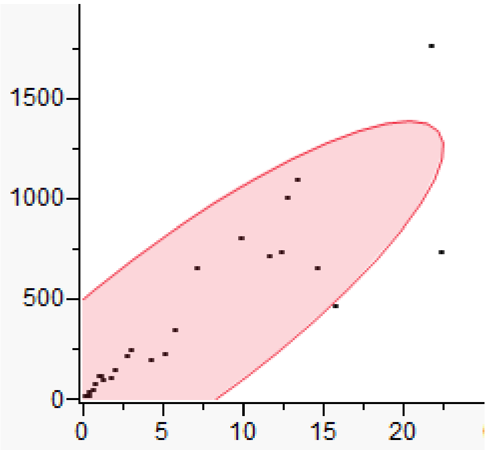


Figure: 11: Correlation between ProcQTY @ MSB and ProcQTY/ Months

Fisher's Exact Test

Fisher's Exact Test tests for statistical associations between categorical (x) variables and a dependent (y) variable. Table 17 indicates significant predictors of cost growth at different program reviews and appropriations. Columns that are highlight grey with an 'X' indicated the variable is predictive at the 0.1 significance level (P-value<0.10). Columns that not highlighted with an 'X' indicate the variable is predictive at the 0.05 significance level (P-value< 0.05).

Table 17: Fisher's Exact Test Results Identifying Significant (x) Variables

Combined	DEV CDR	DEV FF	DEV DTE	DVE IOC	Proc CDR	Proc FF	Proc DTE	Proc IOC	Total CDR	Total FF	Total DTE	Total IOC	
Proc Qty > 450	X				X								2
Months MSA-MSB >= 50	X												1
Bomber		X		X					X	X		X	5
Weapon Type Aircraft	X	X		X					X				4
Prototype		X		X		X		X				X	5
MSB estimate >1985		X	X	X									2
Modification					X	X				X			3
% RDTE Funding >50%	X	X											2
Air Force								X					1
Fighter/ Attack										X			1
	5	5	1	5	2	2	0	2	2	3	0	2	

The p-values only indicate if the variable is significant or not. In order to determine the significance of each variable it is necessary to identify if the results are ‘left’ or ‘right’ tailed test. For each (x) variable identified as significant in Table 17, Table 18 - Table 27 identify the appropriation, review, tail, and probability, as well as a short explanation of what the results indicate.

Looking across the appropriation type and review dates, we can see what type and how many explanatory variables are statistically predictive. For example (x) Variables in development are significant 16 time, (x) variables in procurement are significant 6 times and (x) variables in total funding are significant 7 times. This result indicates development (x) variables are more predictive compared to procurement and Total.

Table 18: the probability of a CGF greater than 1 is greater for programs with Proc Qty > 450

X Variable	Appn	Review	Tail	Prob
Proc Qty > 450	DEV	CDR	Right	0.0601
Proc Qty > 450	Proc	CDR	Right	0.0601

Table 19: the probability of a CGF greater than 1 is greater for programs with Months MSA-MSB >=50

X Variable	Appn	Review	Tail	Prob
Months MSA-MSB >= 50	Dev	CDR	Right	0.043

Table 20: the probability of a CGF less than 1 is greater for Bomber Aircraft

X Variable	Appn	Review	Tail	Prob
Bomber	Dev	FF	Left	0.0747
Bomber	Dev	IOC	Left	0.0115
Bomber	Total	CDR	Left	0.0131
Bomber	Total	FF	Left	0.0456
Bomber	Total	IOC	Left	0.0376

Table 21: the probability of a CGF greater than 1 is greater for Aircraft Programs than Electronic Upgrade Programs

X Variable	Appn	Review	Tail	Prob
Weapon Type Aircraft	Dev	CDR	Right	0.0489
Weapon Type Aircraft	Dev	FF	Right	0.0339
Weapon Type Aircraft	Dev	IOC	Right	0.0115
Weapon Type Aircraft	Dev	FF	Right	0.0349

Table 22: the probability of a CGF greater than 1 is greater for programs with Prototypes

X Variable	Appn	Review	Tail	Prob
Prototype	Dev	FF	Right	0.0187
Prototype	Dev	IOC	Right	0.0886
Prototype	Proc	FF	Right	0.0547
Prototype	Proc	IOC	Right	0.0386
Prototype	Total	IOC	Right	0.0934

Table 23: the probability of a CGF less than 1 is greater for programs with MSB estimate > 1985

X Variable	Appn	Review	Tail	Prob
MSB estimate > 1985	Dev	FF	Left	0.049
MSB estimate > 1985	Dev	DTE	Left	0.0478
MSB estimate > 1985	Dev	IOC	Left	0.0306

Table 24: the probability of a CGF less than 1 is greater for Modification Programs

X Variable	Appn	Review	Tail	Prob
Modification	Proc	CDR	Left	0.0642
Modification	Proc	CDR	Left	0.0642
Modification	Total	FF	Left	0.0019

Table 25: the probability of a CGF less than 1 is greater for programs with % RDTE Funding > 50%

X Variable	Appn	Review	Tail	Prob
% RDTE Funding > 50%	Dev	CDR	Left	0.0824
% RDTE Funding > 50%	Dev	FF	Left	0.0747

Table 26: the probability of a CGF greater than 1 is greater for Air Force Programs

X Variable	Appn	Review	Tail	Prob
Air Force	Proc	IOC	Right	0.0189

Table 27: the probability of a CGF greater than 1 is greater for Fighter/ Attack Aircraft

X Variable	Appn	Review	Tail	Prob
Fighter/ Attack	Total	FF	Right	0.0169

We intended to present ORs for each Fisher’s Exact Test but the small sample size produced unstable results. As an example the OR for months MSA-MSB >= 50 produced an OR with an approximate 95% Confidence Interval for (1.06, 166.37). This large width suggests instability of the OR.

For references on the contingency tables used to calculate Fisher’s Exact Test and Odds Ratios, please see the Appendix. From the results in Table 18 through Table 27, we can determine which direction is beneficial for programs to sustain less cost growth throughout the program schedule. Table 28 indicates the cells coded “Grey” are positive and the cells coded “White” are negative in terms of their impact on a program sustaining cost growth.

Table 28: Categorical Variable Stoplight

Nominal Variable	NO = '0'	Yes = '1'
Proc Qty > 450	▨	
Months MSA-MSB >= 50	▨	
Bomber		▨
Weapon Type Aircraft	▨	
Prototype	▨	
MSB estimate >1985		▨
Modification		▨
% RDTE Funding >50%		▨
Air Force	▨	
Fighter/ Attack	▨	

Additionally, Table 17 identifies the how many of the 12 possible reviews and appropriation combinations a (x) variable is predictive for. Table 29 is a compressed version of Table 17 and lists the (x) variables from greatest to least number of reviews and appropriations significant. The results show Bomber and Prototype have the greatest results with (5/12) significant followed by Weapon Type Aircraft with (4/12) significant.

Table 29: Significant #

X variable	# significant
Bomber	5
Prototype	5
Weapon Type Aircraft	4
Modification	3
Proc Qty > 450	2
MSB estimate >1985	2
% RDTE Funding >50%	2
Months MSA-MSB >= 50	1
Air Force	1
Fighter/ Attack	1

Overall, our analysis generated significant results. Table 12 through Table 15 and Figure 4 through Figure 6 display valuable information on how aircraft cost growth behaves over the life of a program. At IOC, total percent of total cost growth is 91% at 48% program completion. For procurement, 114% of total program cost growth occurs at 48% program completion and for development, only 47% of total program cost growth occurs at 48% program completion. Additionally, for procurement and total, a spike in percent of total program cost growth occurs around FF whereas development cost growth follows a steadier path.

The second part of the analysis involving logistic regression and Fisher's Exact Test returned significant results in predicting program cost growth. Bomber, Prototype, and Weapon type are the most predictive variables of cost growth. Additionally, explanatory variables are predictive in development 16 times, procurement 6 times, and total 7 times.

V. Conclusions and Recommendations

Chapter Overview

Chapter 5 revisits the initial investigative research questions to support our analysis and conclusions. Second, we offer limitations of the research and a brief discussion on one of the intended goals we were not able to accomplish. Lastly, we provide several ideas for future research and a summary of how this research provides value to the Air Force and DoD.

Research Goals Answered

In our research, we look to identify a significant review along an aircraft's schedule where cost growth occurs. After identifying cost growth factors at four program reviews, we look to identify predictors of cost growth at that point in time. Lastly, the research graphically depicts the trends of cost growth along an aircraft's schedule.

1. *Identify a significant review along an Aircraft's schedule where cost growth occurs.*

Up to this point, research examined at what percent of program completion cost overrun or cost growth begins (Christensen, 1994). Christensen (1994) identified cost overruns starting around 10% program completion. In our research, we do identify CGFs at all four reviews in the analysis, but our analysis provides more valuable information than simply identifying where cost growth occurs. From Table 14 and Table 15 we gain important information on how cost growth behaves depending on the appropriation and the review along an aircraft program's schedule.

As presented in Chapter 4, the median percent of program completion for IOC is 48% and the median percent of total cost growth for total appropriation is 91%. Therefore, we identify the cost growth factor of a program at IOC to be very close to the cost growth factor at program completion. When we examine total FF, we see the first major spike in percent of total cost growth compared to percent of program completion. At FF, the median percent of total cost growth is 35% at 25% program completion. Here we see a spike in the rate of cost growth, which could be attributed to a program actually needing to display some capability for the aircraft. FF is not the first time we see cost growth.

The percent of total cost growth at CDR is 15% where the percent of program completion is 12%. At CDR, an aircraft's cost growth is growing at roughly the same percentage of schedule completion. When looking at DTE, total percentage total cost growth is 75% at 44% program completion. So, at DTE, there is a major spike in percent of total cost growth. From Figure 6, we see DTE does not necessarily occur before IOC. The reason for this is stated is Chapter 3, where IOC does not necessarily occur at the same point along a program's schedule. Because of this, DTE can occur after IOC depending on where IOC is identified in a program's CDD. Due to shifts in IOC, the point of greatest CGF could occur at DTE or IOC.

Looking deeper into the appropriations, development and procurement, we see much different results for percent of total cost growth vs percent of program completion. For development, median percent of total cost growth at IOC is 47% whereas median percent total cost growth for procurement is 114%. With this information, we are likely to see development cost growth after IOC but do not expect to see any procurement cost growth after IOC. With this information, we should focus our attention on development after IOC to minimize total program cost growth.

Our analysis also identifies the amount of time from MSB to each program review. The median months from MSB to each review is available in Table 12. The median time from MSB to IOC is 78 months or 6.5 years. Therefore, at a median of 6.5 years after MSB a program sustains about 91% of the total program cost growth. Additionally, the first spike in percent of total cost growth occurs at FF, 35 months or ~3 years.

All of the information on percent of total cost growth, percent of program completion, and time from MSB can tie to a median CGF at the specific review. Table 13 identifies the mean and median CGFs at each review and appropriation. This table allows us to put a median CGF to a program at each review. With future programs, the information on median CGF, percent of total cost growth, and percent of program completion can all contribute to creating more accurate estimates as a program moves toward completion.

2. *Identify predictors of cost growth at program reviews.*

Using Fisher's Exact Test, we identified significant predictors of cost growth at the four reviews, CDR, FF, DTE, and IOC. FF identified the most (x) variables as predictors, 10. CDR and IOC both identified 9 (x) variables as predictors of cost growth. DTE End only identified 1 (x) variable as a predictor of cost growth. Bomber, Prototype, and Weapon Type Aircraft displayed the most importance as they were significant (5/12), (5/12), and (4/12) respectively. Bomber aircraft tend to have less cost growth compared to other airframes. If a program has prototypes, the program is likely to experience more cost growth compared to programs without prototypes. Significant results for prototypes agree with the past results of Dresner et al. (1993), White et al. (2004), and Tyson et al. (1994) where they identified prototyping as a predictor of cost growth. Lastly, we found aircraft are more likely to experience cost growth compared to aircraft electronic systems upgrades. Identifying upgrades as a significant predictor agrees with Brown et al. (2015) where they identified *upgrade characteristics* as a predictor variable for their distribution parameters

3. ***Graphically display trends of cost growth along an aircraft's schedule based on program reviews.***

Figure 4 through Figure 6 display cost growth trends along an aircraft's schedule for development, procurement and total appropriations. The major findings from the cost growth trends are presented earlier in this chapter under Research Goal 1.

Limitations

In our analysis of cost growth in DoD aircraft programs the major limitation was the lack of reported program reviews. We were only able to gather data for four significant program reviews, CDR, FF, DTE End, and IOC. Ideally, the study would consider additional dates, [Preliminary Design Review (PDR), Operational Test and Evaluation (OTE), Fully Operational Capability (FOC)] but the data was not there to support deeper analysis. SARs do not include all program dates, and the AFCAA database did not include additional dates. Compiling a database directly from weapon system program offices would allow for complete analysis and potentially generate additional significant results or an implementable model.

Recommendations for Future Research

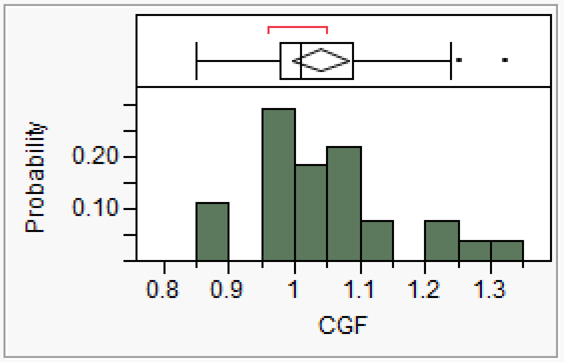
We recommend several areas for future research. First, our study included 30 aircraft programs. This research started with a specific platform, but the research could expand to include other platforms: Space, Ship, Land, Missile, and other DoD systems. Expanding the field of study could provide valuable information on the differences between DoD platforms in terms of how the programs experience cost growth throughout their lifecycle. Second, as stated in the limitations section, our study used program reviews in analyzing cost growth. Collecting program office data could allow for the inclusion of additional dates in the analysis. Lastly, we recommend a longitudinal study of cost growth. Foreman (2007) conducted a longitudinal study to identify how a program behaved over time. His study along with the dataset and results from our study provide a starting ground to analyze how programs behave overtime. Some potential research questions for longitudinal studies are: If a programs sustains x% cost growth at CDR, what does the cost growth % look like at subsequent reviews? Will cost growth continue or is there any chance for recovery? Is there a point where the program can expect extreme cost growth (greater than 50%)? We believe both future research topics provide paths to discovering significant results to combat cost growth in the DoD.

Last Words

Our research identified CGFs and percent of total cost growth at program reviews. In past research, we do not find any research which directly validates our findings using CGFs at different reviews along a program's schedule. However, there is significant research on total CGFs in different appropriations. Arena et al., (2006) found total CGFs for development, procurement, and total to be 1.58, 1.44, and 1.46 respectively and

Dresner et al., (1993) found total CGFs for development, procurement and total to be 1.25, 1.18, and 1.20 respectively. Additionally, Christensen, (1993), uses EVM data to identify cost overrun beginning as early as 10% of program completion. Our research identifies total cost growth at CDR, which occurs at 12% program completion. Our research ties to the finding of Christensen (1993). Brown et al., (2015) presented several models to predict the percent of expenditures occurring at 50% program completion. Our findings, along with the findings of Christensen (1993), Dresner et al., (1993), Arena et al. (2006), and Brown et al. (2015), contribute to creating more accurate cost models in the future.

Appendix A: CGFs vs Probability of Occurrence



A 1: Development CDR

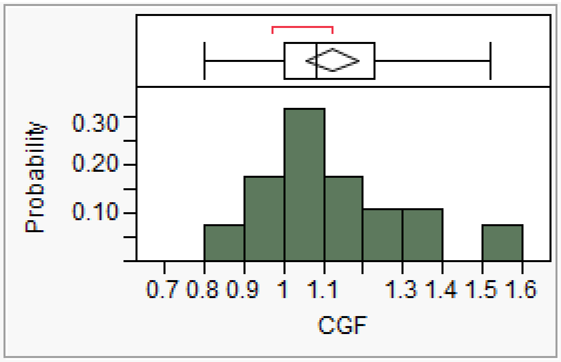


Figure A2: Development FF

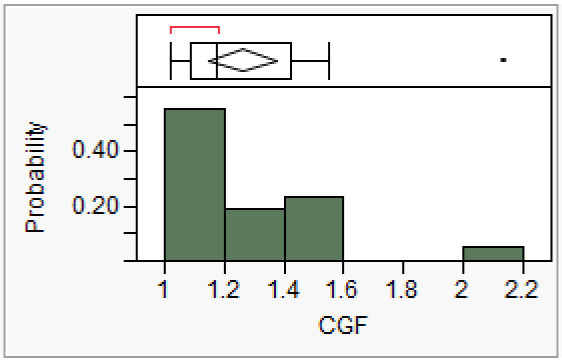


Figure A3: Development DTE

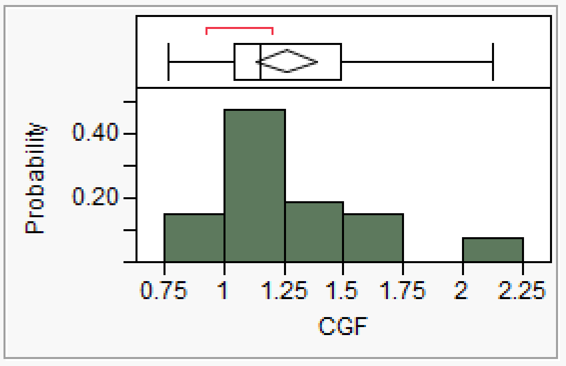


Figure A4: Development IOC

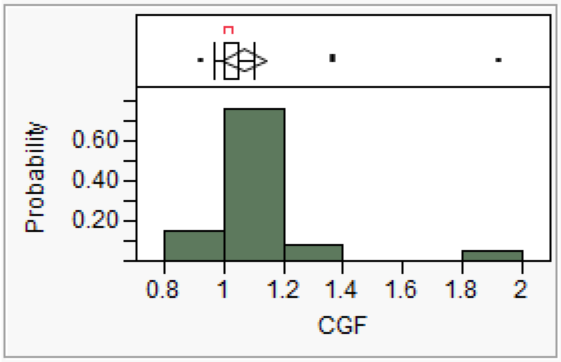


Figure A5: Procurement CDR

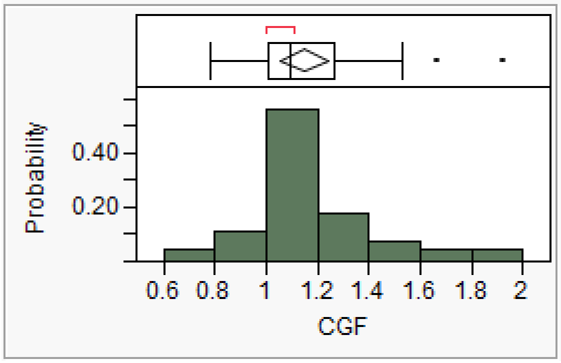


Figure A6: Procurement FF

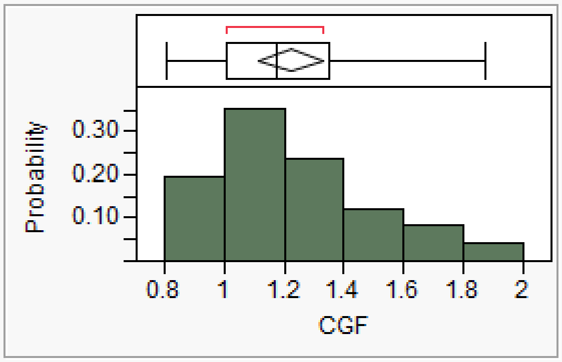


Figure A7: Procurement DTE

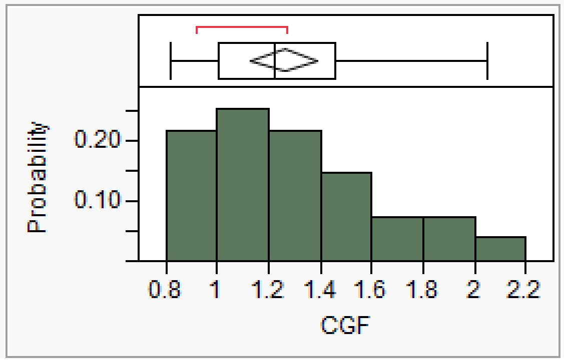


Figure A8: Procurement IOC

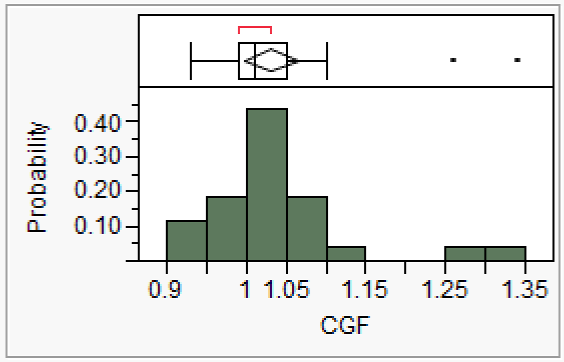


Figure A9: Total CDR

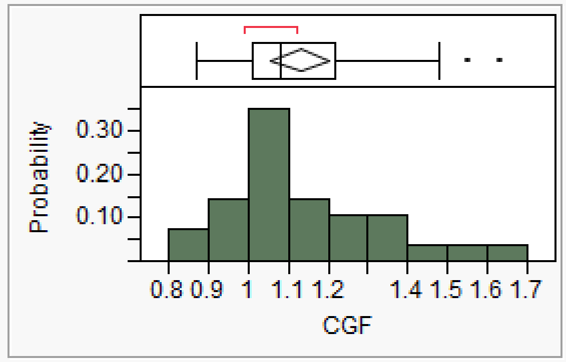


Figure A10: Total FF

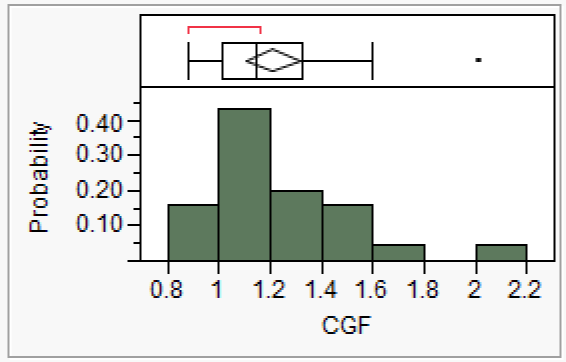


Figure A11: Total DTE

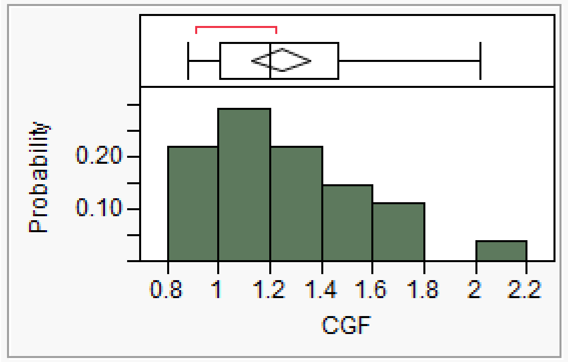
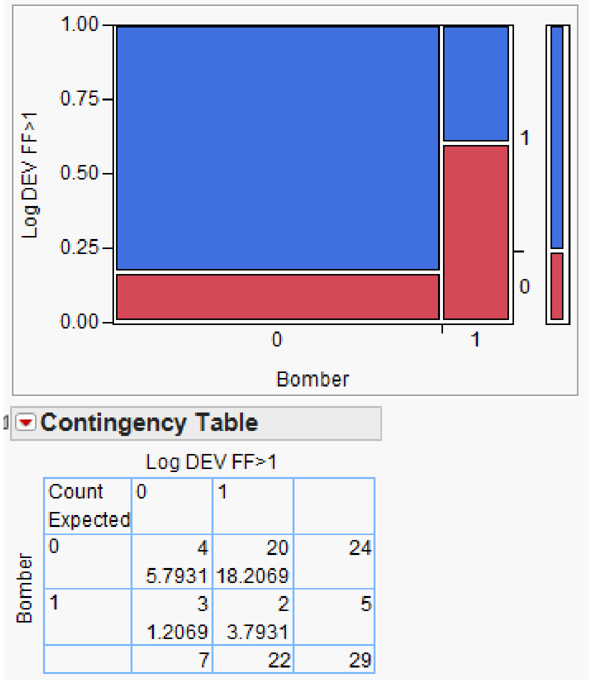


Figure A12: Total IOC

Appendix B: Contingency Tables

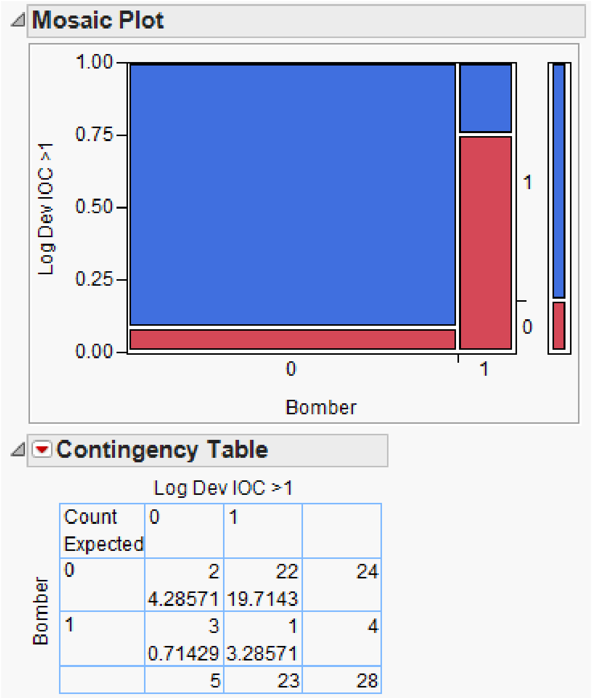


Contingency Table

Log DEV FF>1

	Count Expected	0	1	
Bomber	0	4 5.7931	20 18.2069	24
	1	3 1.2069	2 3.7931	5
		7	22	29

Figure A13: DEV FF > 1 vs Bomber

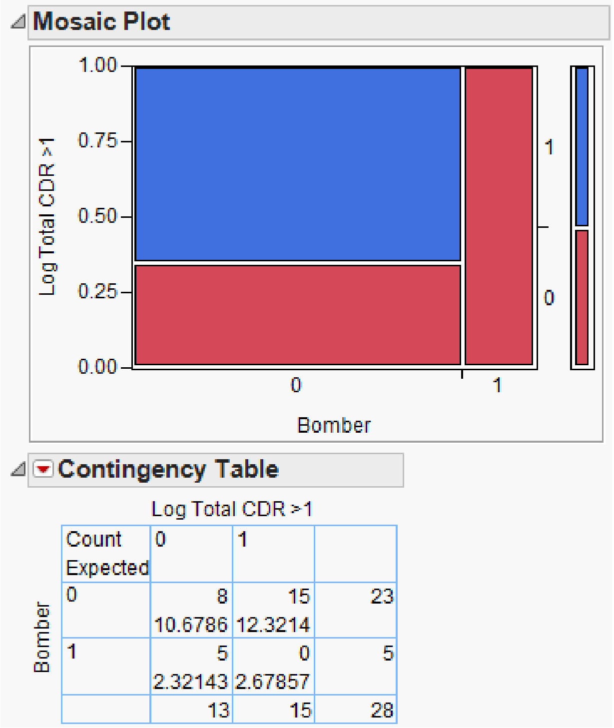


Contingency Table

Log Dev IOC >1

	Count Expected	0	1	
Bomber	0	2 4.28571	22 19.7143	24
	1	3 0.71429	1 3.28571	4
		5	23	28

Figure A14: Dev IOC > 1 vs Bomber

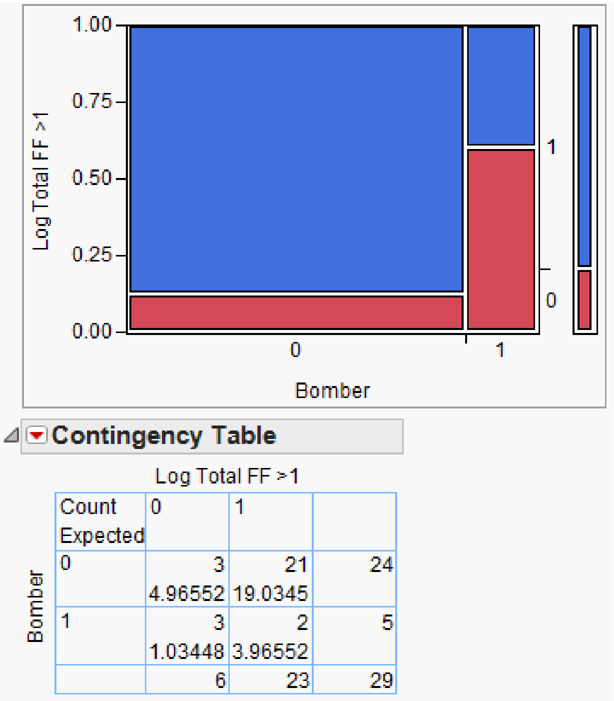


Log Total CDR >1

Bomber

Count Expected	0	1	
0	8 10.6786	15 12.3214	23
1	5 2.32143	0 2.67857	5
	13	15	28

Figure A15: Total CDR > 1 vs Bomber

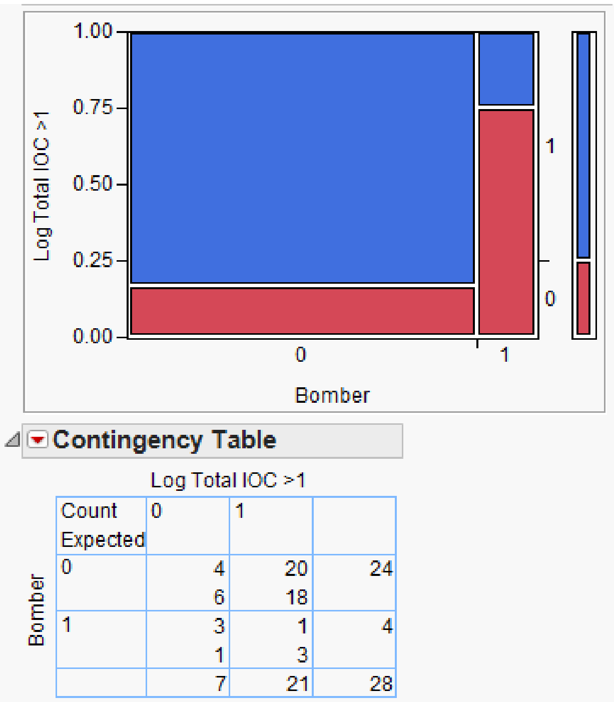


Log Total FF >1

Bomber

Count Expected	0	1	
0	3 4.96552	21 19.0345	24
1	3 1.03448	2 3.96552	5
	6	23	29

Figure A16: Total FF > 1 vs Bomber

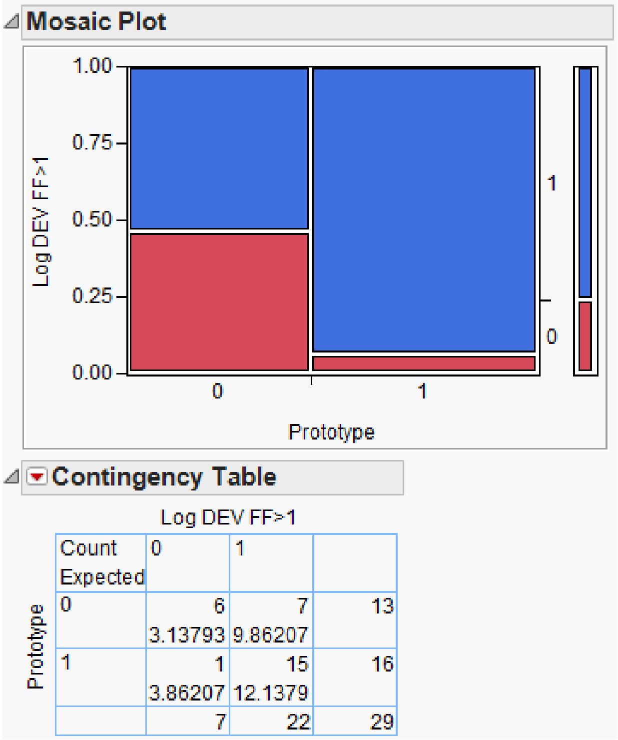


Contingency Table

Log Total IOC >1

Bomber	Count Expected	0	1	
	0	4 6	20 18	24
	1	3 1	1 3	4
		7	21	28

Figure A17: Total IOC > 1 vs Bomber



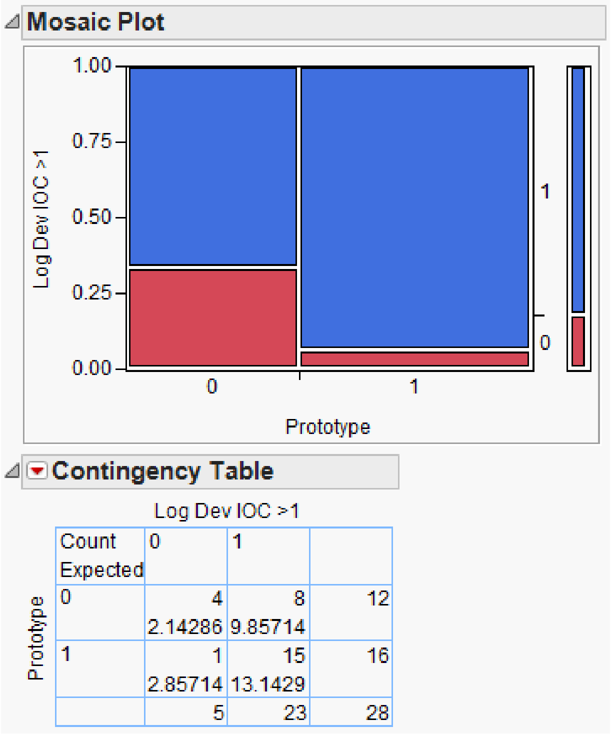
Mosaic Plot

Contingency Table

Log DEV FF>1

Prototype	Count Expected	0	1	
	0	6 3.13793	7 9.86207	13
	1	1 3.86207	15 12.1379	16
		7	22	29

Figure A18: Dev FF > 1 vs Prototype



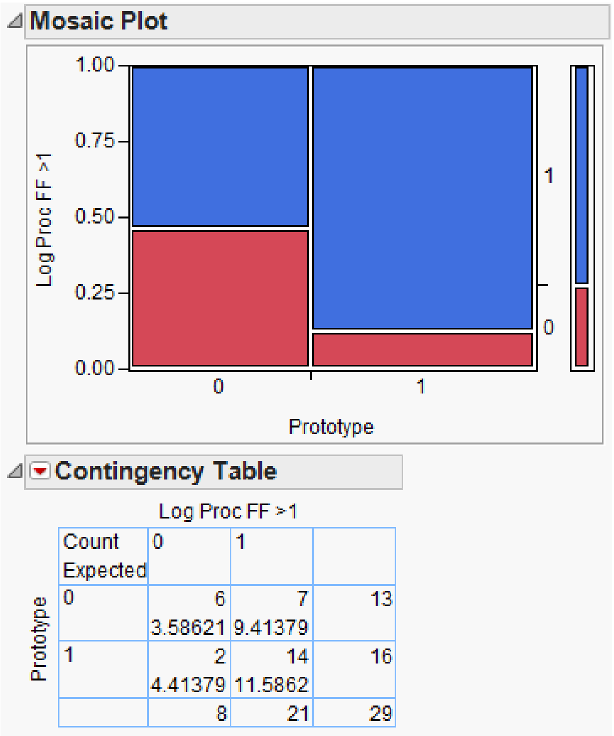
Contingency Table

Log Dev IOC >1

Prototype

Count Expected	0	1	
0	4 2.14286	8 9.85714	12
1	1 2.85714	15 13.1429	16
	5	23	28

Figure A19: Dev IOC vs Prototype



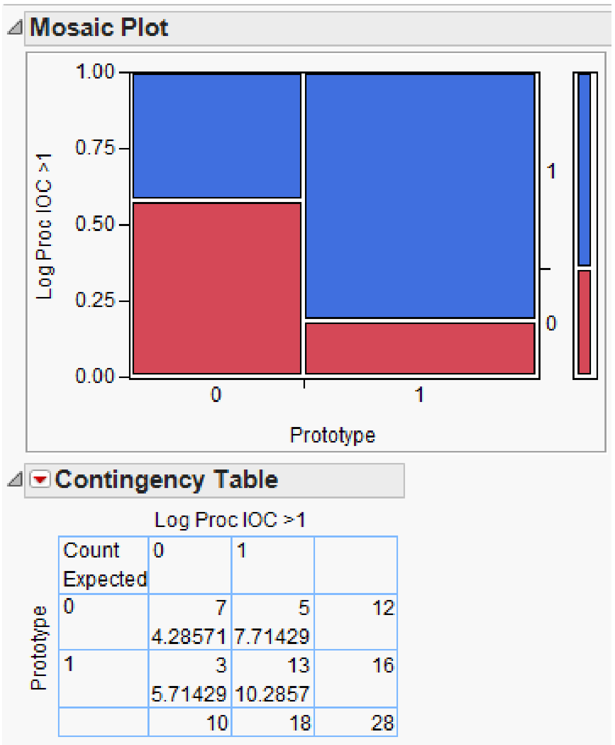
Contingency Table

Log Proc FF >1

Prototype

Count Expected	0	1	
0	6 3.58621	7 9.41379	13
1	2 4.41379	14 11.5862	16
	8	21	29

Figure A20: Proc FF > 1 vs Prototype

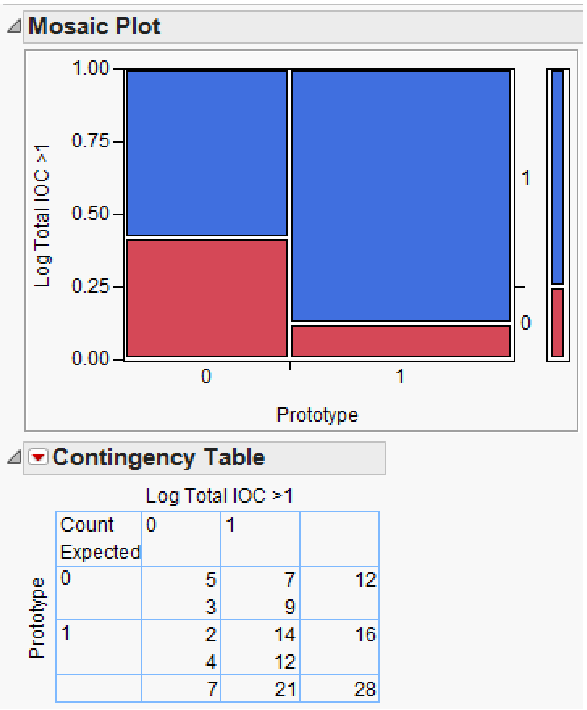


Contingency Table

Log Proc IOC >1

Prototype	Count Expected	0	1	
	0	7 4.28571	5 7.71429	12
	1	3 5.71429	13 10.2857	16
		10	18	28

Figure A21: Proc IOC > 1 vs Prototype

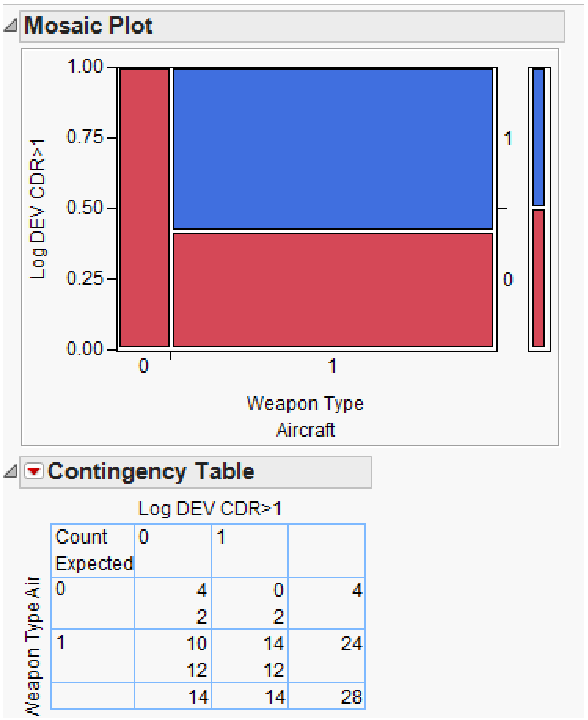


Contingency Table

Log Total IOC >1

Prototype	Count Expected	0	1	
	0	5 3	7 9	12
	1	2 4	14 12	16
		7	21	28

Figure A22: Total IOC > 1 vs Prototype

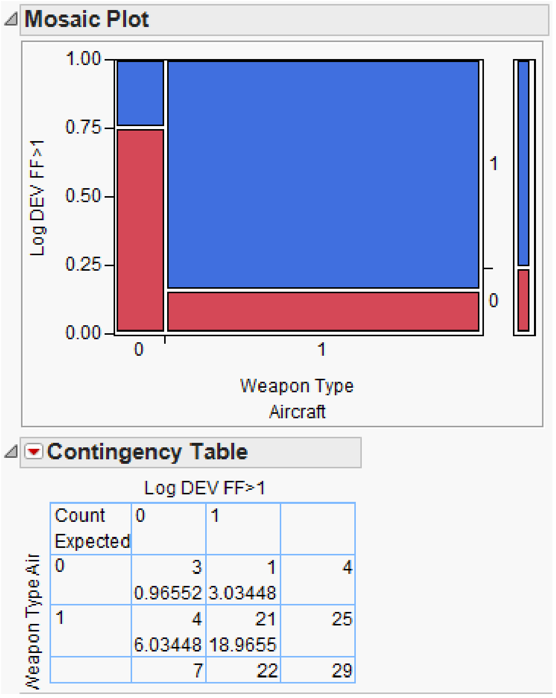


Log DEV CDR>1

Count Expected	0	1	
0	4 2	0 2	4
1	10 12	14 12	24
	14	14	28

Veapon Type Air

Figure A23: Dev CDR > 1 vs Weapon Type Aircraft

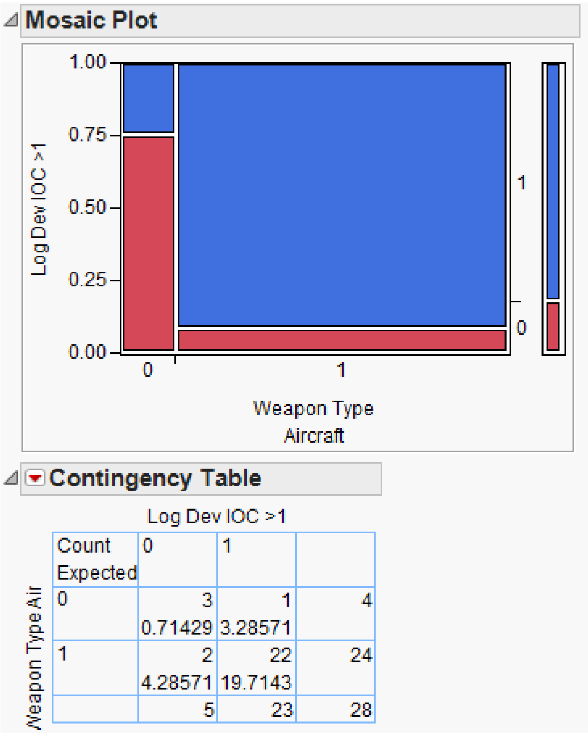


Log DEV FF>1

Count Expected	0	1	
0	3 0.96552	1 3.03448	4
1	4 6.03448	21 18.9655	25
	7	22	29

Veapon Type Air

Figure A24: Dev FF > 1 vs Weapon Type Aircraft

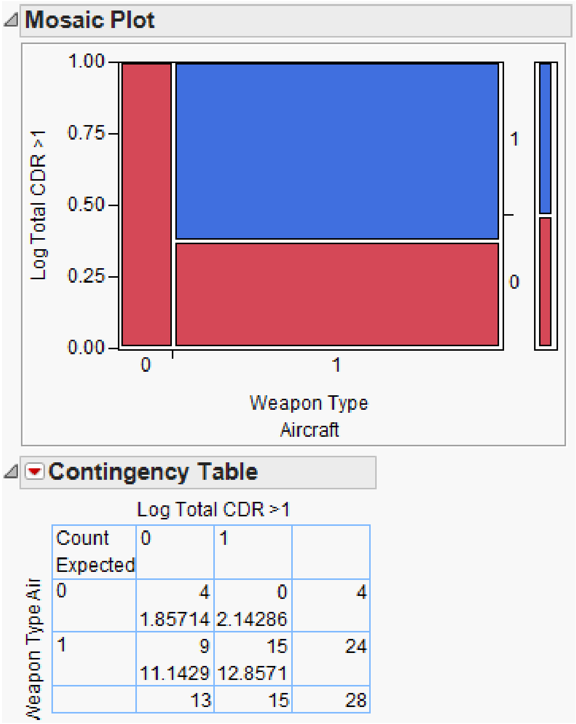


Log Dev IOC >1

Weapon Type Air

Count Expected	0	1	
0	3 0.71429	1 3.28571	4
1	2 4.28571	22 19.7143	24
	5	23	28

Figure A25: Dev IOC > 1 vs Weapon Type Aircraft

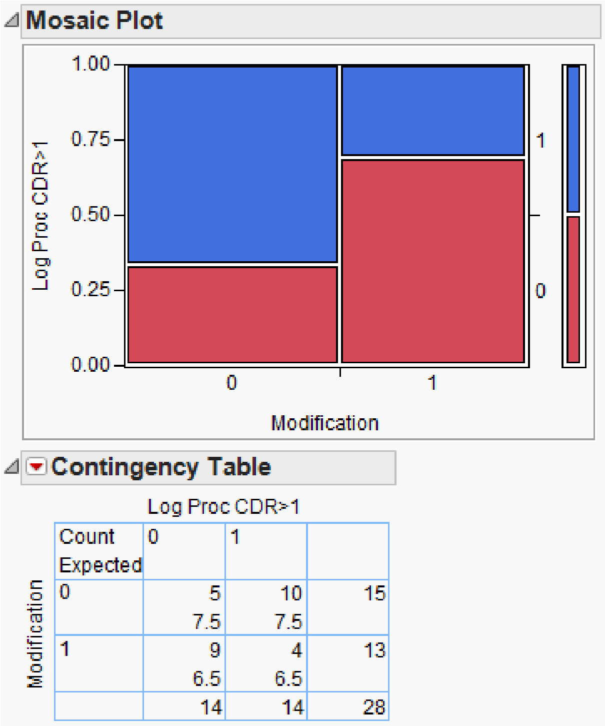


Log Total CDR >1

Weapon Type Air

Count Expected	0	1	
0	4 1.85714	0 2.14286	4
1	9 11.1429	15 12.8571	24
	13	15	28

Figure A26: Total DCR > 1 vs Weapon Type Aircraft

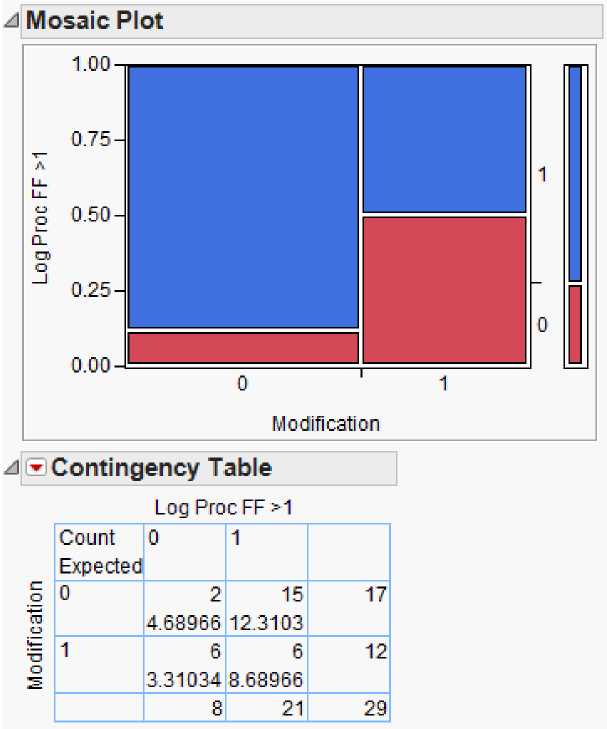


Log Proc CDR>1

Modification

Count Expected	0	1	
0	5 7.5	10 7.5	15
1	9 6.5	4 6.5	13
	14	14	28

Figure A27: Proc CDR > 1 vs Modification

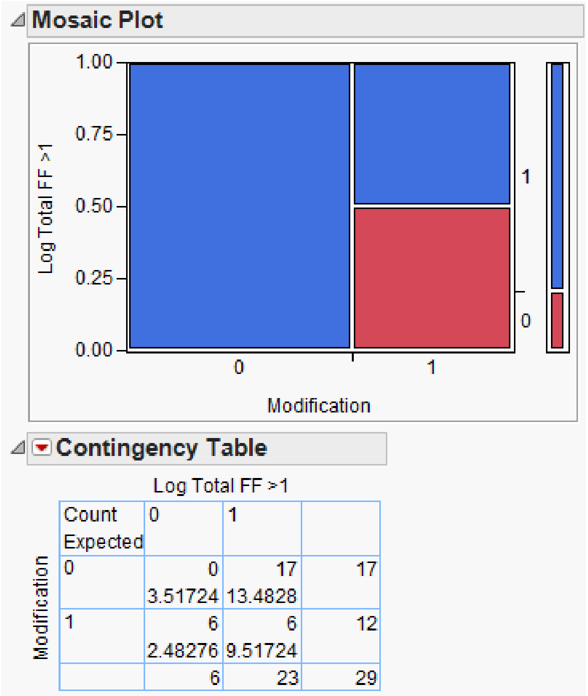


Log Proc FF >1

Modification

Count Expected	0	1	
0	2 4.68966	15 12.3103	17
1	6 3.31034	6 8.68966	12
	8	21	29

Figure A28: Proc FF > 1 vs Modification

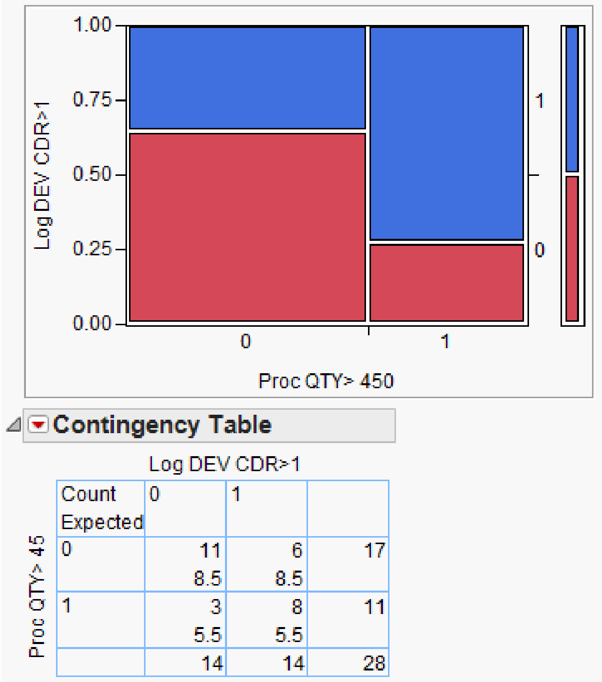


Log Total FF >1

Modification

Count Expected	0	1	
0	0 3.51724	17 13.4828	17
1	6 2.48276	6 9.51724	12
	6	23	29

Figure A29: Total FF > 1 vs Modification

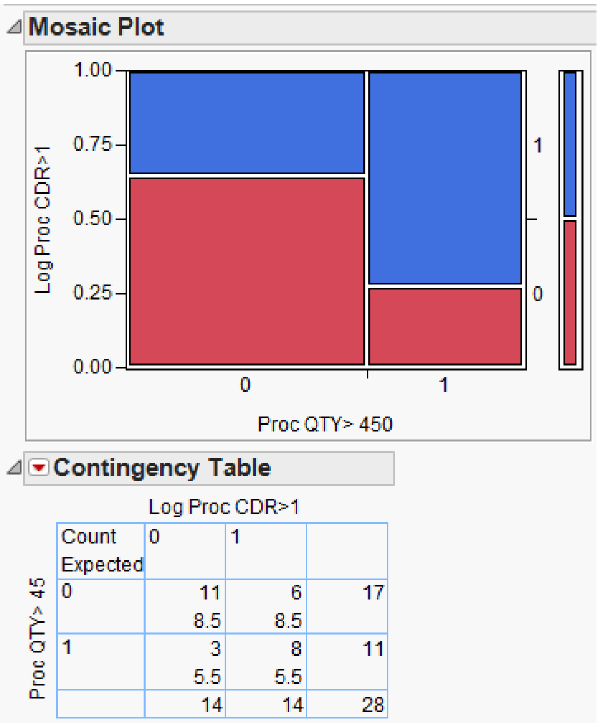


Log DEV CDR>1

Proc QTY> 45

Count Expected	0	1	
0	11 8.5	6 8.5	17
1	3 5.5	8 5.5	11
	14	14	28

Figure A30: Dev CGF > 1 vs Proc QTY > 450

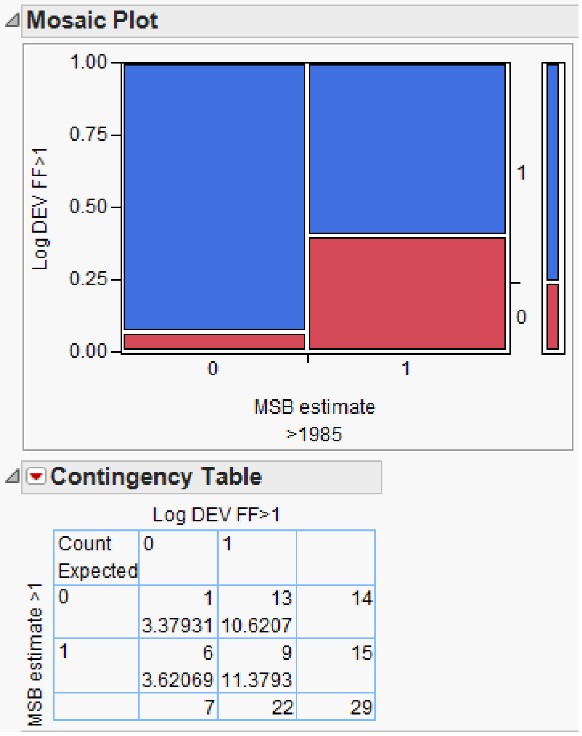


Log Proc CDR>1

Proc QTY> 45

Count Expected	0	1	
0	11 8.5	6 8.5	17
1	3 5.5	8 5.5	11
	14	14	28

Figure A 31: Proc CDR > 1 vs Proc Qty > 450

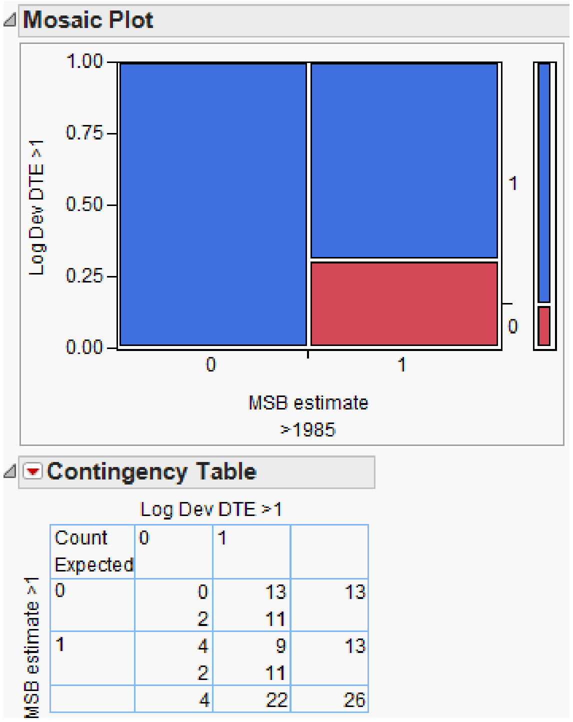


Log DEV FF>1

MSB estimate >1

Count Expected	0	1	
0	1 3.37931	13 10.6207	14
1	6 3.62069	9 11.3793	15
	7	22	29

Figure A32: Dev FF > 1 vs MSB estimate > 1985

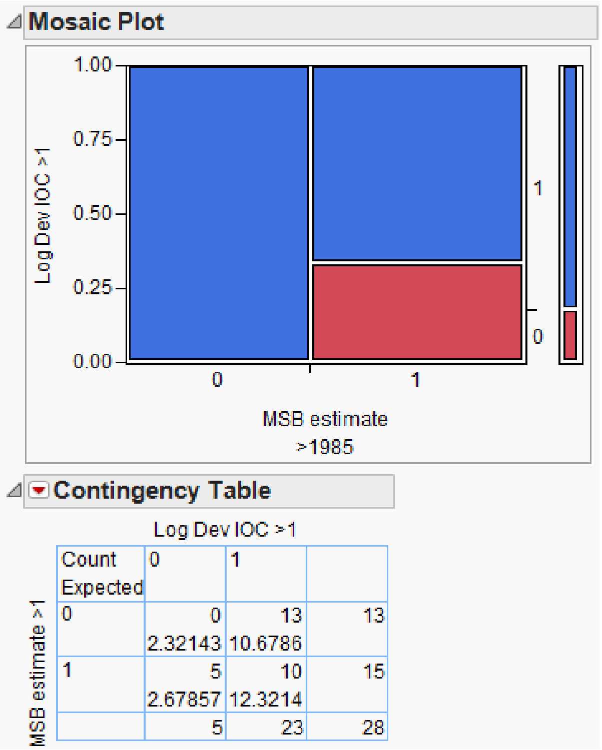


Log Dev DTE >1

MSB estimate >1

Count Expected	0	1	
0	0 2	13 11	13
1	4 2	9 11	13
	4	22	26

Figure A33: Dev DTE > 1 vs MSB estimate > 1985

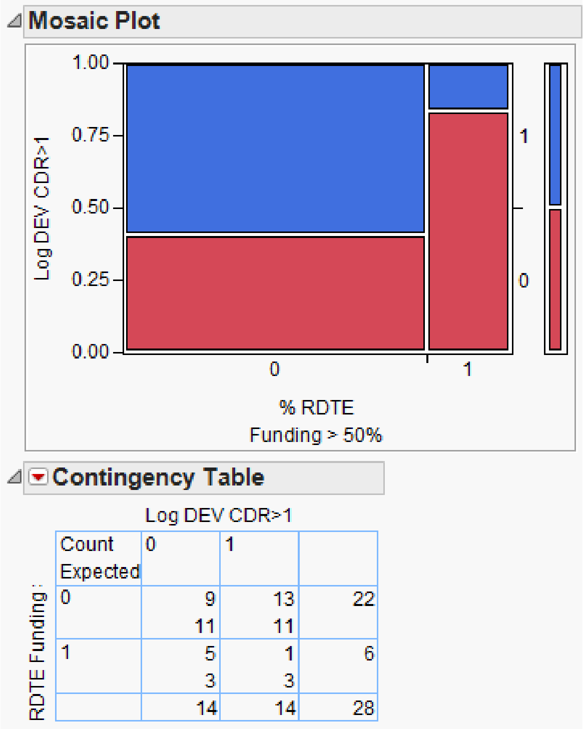


Log Dev IOC >1

MSB estimate >1

Count Expected	0	1	
0	0 2.32143	13 10.6786	13
1	5 2.67857	10 12.3214	15
	5	23	28

Figure A 34: Dev IOC > 1 vs MSB estimate > 1985

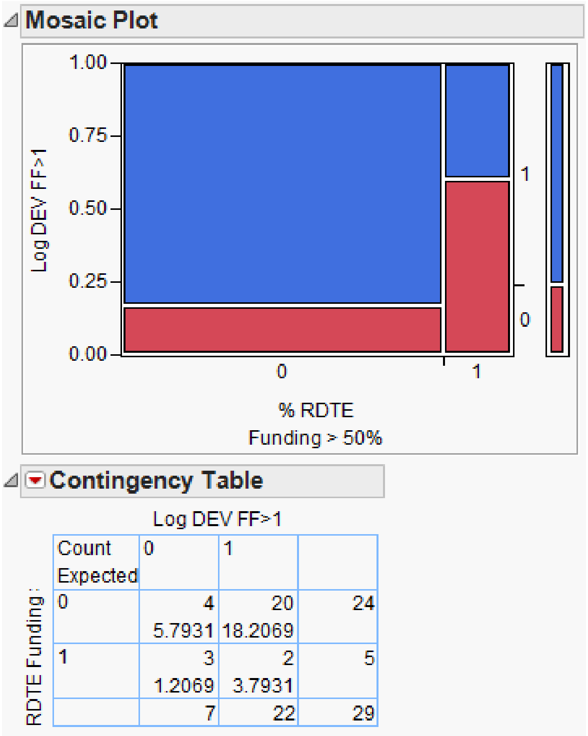


Log DEV CDR>1

RDTE Funding :

Count Expected	0	1	
0	9 11	13 11	22
1	5 3	1 3	6
	14	14	28

Figure A35: Dev CDR > 1 vs % RDTE funding > 50%

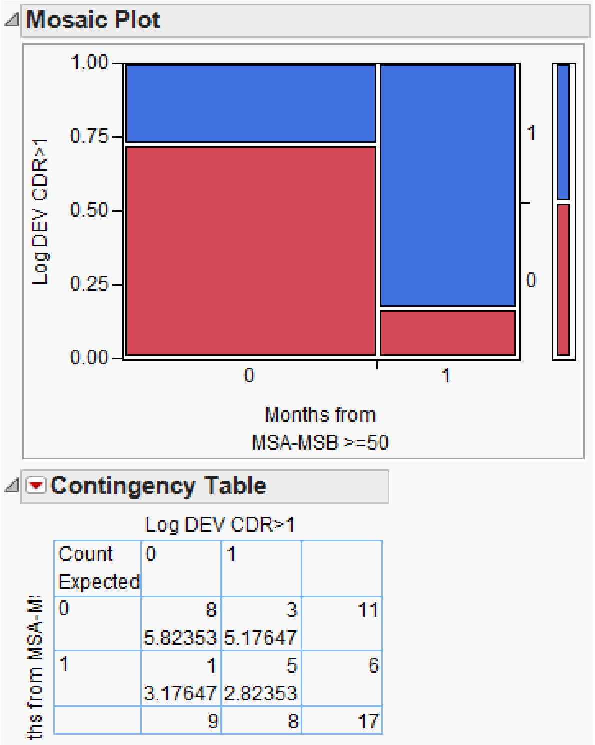


Log DEV FF>1

RDTE Funding :

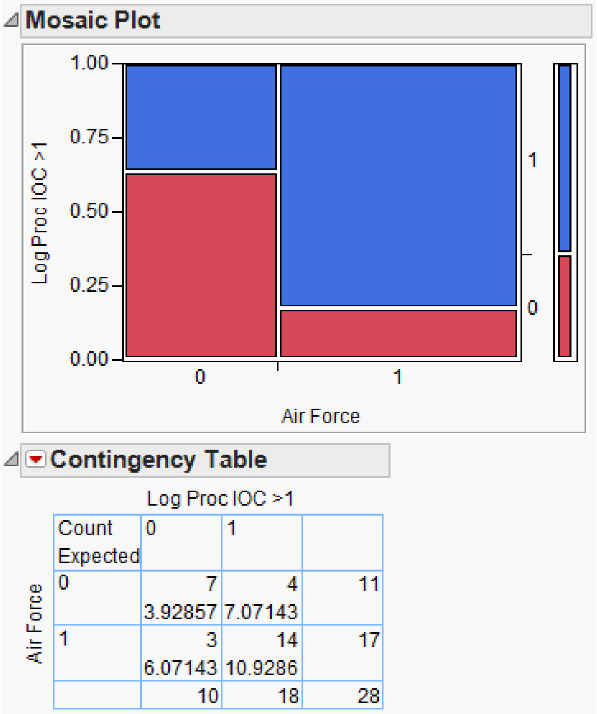
Count Expected	0	1	
0	4 5.7931	20 18.2069	24
1	3 1.2069	2 3.7931	5
	7	22	29

Figure A36: Dev FF > 1 vs % RDTE funding > 50%



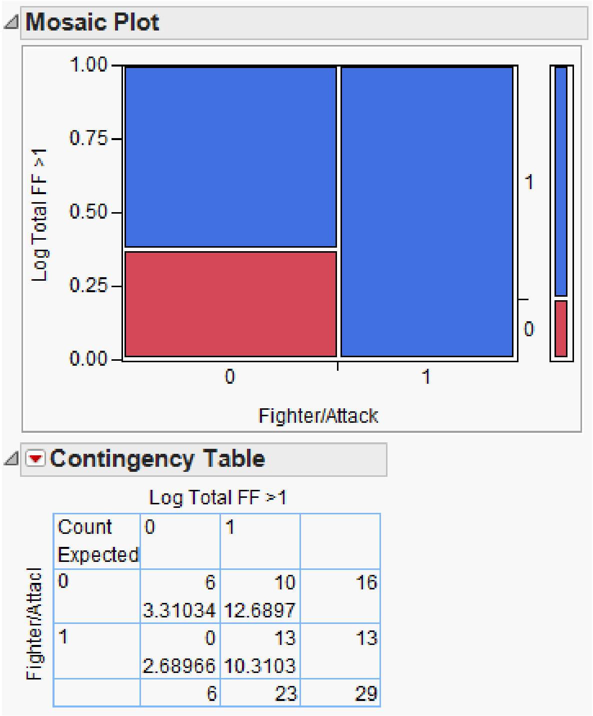
Count Expected	0	1	
0	8 5.82353	3 5.17647	11
1	1 3.17647	5 2.82353	6
	9	8	17

Figure A37: Dev CDR > 1 vs Months from MSA - MSB >= 50



Count Expected	0	1	
0	7 3.92857	4 7.07143	11
1	3 6.07143	14 10.9286	17
	10	18	28

Figure A38: Proc IOC > 1 vs Air Force



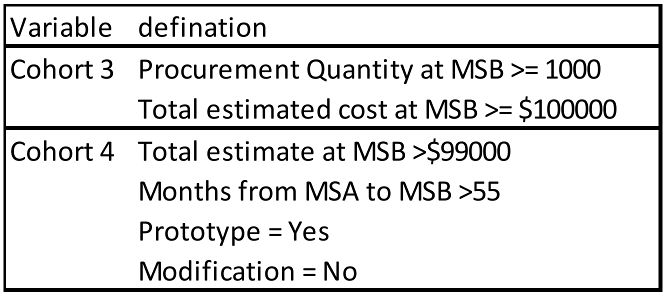
Contingency Table

Log Total FF >1

Fighter/Attacl	Count Expected	0	1	
	0	6 3.31034	10 12.6897	16
	1	0 2.68966	13 10.3103	13
		6	23	29

Figure A39: Total FF > 1 vs Figher/ Attack

Appendix C: Variables defined



Variable	defination
Cohort 3	Procurement Quantity at MSB >= 1000
	Total estimated cost at MSB >= $100000
Cohort 4	Total estimate at MSB >$99000
	Months from MSA to MSB >55
	Prototype = Yes
	Modification = No

Figure A40: Cohorts Defined

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Vita

Captain Scott J. Kozlak completed his undergraduate studies at the United States Air Force Academy, where he was awarded a degree in Management. Following the completion of his undergraduate degree, he was commissioned as an officer in the U.S. Air Force.

During his Air Force Career, Captain Kozlak gained a variety of acquisition experience across the spectrum of budget, cost and earned value management. Upon graduation from the Air Force Institute of Technology, he will be assigned to the Air Force Cost Analysis Agency, Andrews Air Force Base, Maryland.

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Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/ENY)
2950 Hobson Way, Building 640
WPAFB OH 45433-8865

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Air Force Life Cycle Management Center
1865 4th Street, Wright-Patterson AFB, OH 45433
937-656-5504 and shawn.valentine@us.af.mil
ATTN: Shawn Valentine

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14. ABSTRACT

Past research shows predicting cost growth is an important topic with DoD systems. Researchers have attempted to predict total program cost growth as well as identify predictors of program cost growth. Our research addresses this through examining cost growth at reviews and milestones along an aircraft's schedule. We assess cost growth factors at four major reviews, Critical Design Review, First Flight, Development Test and Evaluation End, and Initial Operating Capability.

The first portion of the analysis focuses on identifying cost growth factors and percent of total cost growth at the four program reviews. The second portion identifies predictors of cost growth at the four reviews. In our results, we present a spike in procurement cost growth first occurring around First Flight and we identify the median percent of total cost growth at IOC, or 48 percent of program completion to be 91%. The second portion of the results identifies the three most common predictors of cost growth at program reviews: Bombers, Prototyping, and electronic aircraft system upgrades.

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