3-2020

Improving Acquisitions in Science and Technology Programs through Factor Development and Program Analysis

Eric A. Plack

IMPROVING ACQUISITIONS IN SCIENCE AND TECHNOLOGY PROGRAMS THROUGH FACTOR DEVELOPMENT AND PROGRAM ANALYSIS

THESIS

Eric A. Plack, Master Sergeant, USAF

AFIT-ENV-MS-20-M-234

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENV-MS-20-M-234

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THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Cost Analysis

Eric A. Plack, BA

Master Sergeant, USAF

March 2020

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-20-M-234

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THROUGH FACTOR DEVELOPMENT AND PROGRAM ANALYSIS

Eric A. Plack, BA

Master Sergeant, USAF

Committee Membership:

Dr. Jonathan D. Ritschel
Chair

Dr. Edward D. White
Member

Lt Col Clay M. Koschnick
Member

AFIT-ENV-MS-20-M-234

Abstract

This research involves a study of Air Force science and technology (S&T) programs which includes the creation of standard factors and a program analysis. There has been little prior cost research on S&T programs, which occur very early in the acquisition lifecycle. This leads the cost analyst to utilize estimating techniques such as analogy, factors, and parametric in order to develop budgets with minimal information. The absence of formal S&T cost reporting requirements and common cost elements necessitate a segregated two phased data analysis. The *Factor Development phase* accomplishes the development and creation of two new standard cost factors along with a new suggested Work Breakdown Structure. A comparison analysis between published development cost factors and the new S&T factors indicates similarities in some factors. This suggests the more robust development factor dataset could be used when developing cost estimates for S&T cost elements. The *Program Analysis phase* studies relationships through contingency table analyses between program characteristics and performance measures. The results suggest that aerospace programs are more likely to technologically mature and experience cost and schedule growth when compared to human system programs. Furthermore, results suggest that programs with mature technologies are more likely to experience above average cost growth but are less likely to experience schedule growth. The outcome of this research not only gives cost analysts more tools for estimating these early programs, but a better understanding of how these programs behave under different conditions in order to better predict program performance.

Dedication

This thesis is dedicated to my wife, son, and all of my family, friends, and mentors who have been a source of inspiration throughout my military and educational career.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Daniel Ritschel, for his guidance and support throughout the course of this thesis effort. The insight and experience were certainly appreciated. I would also like to thank Dr. Edward White for providing a robust statistical foundation which laid the groundwork for the analysis in this research. I would also like to thank Lt Col Clay Koschnick for his support, feedback, and guidance which led to a more rigorous exploration of the data. Finally, I would like to thank my sponsors, Mrs. Emily Duke and Mr. Jack Snyder, from the Air Force Research Laboratory for helping me understand the complexity of science and technology programs and also how intricate Excel can be.

Eric A. Plack

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IMPROVING ACQUISITIONS IN SCIENCE AND TECHNOLOGY PROGRAMS THROUGH FACTOR DEVELOPMENT AND PROGRAM ANALYSIS

I. Introduction

Background

The National Defense Strategy explains that a lethal, resilient, and rapidly innovating Joint Force will sustain American influence and ensure favorable balances of power (Department of Defense, 2018). The Air Force Science and Technology Strategy for 2030 aligns with the National Defense Strategy, allowing for Science and Technology (S&T) programs to develop and deliver warfighting capabilities rapidly and effectively (United States Air Force, 2019). Successful implementation of these strategies requires properly allocated resources. To achieve this, improvements in S&T cost estimating are needed.

The point estimate in a cost estimate is always going to be wrong. Properly constructed risk adjusted cost estimates provide a range, which should capture the true cost most of the time, but a defense acquisition program's budget is based upon a single number. This program can either come in, under, or over budget. The programs of the latter category are subject to the scrutiny of the media and receive negative congressional attention. Cost growth occurs as a result of numerous factors. Bolten et al. (2008) find decisions by managers (e.g. requirement changes during post project implementation) bear much of the blame for cost growth. Nonetheless, inaccurate cost estimates are also a contributing factor. Improvements in the cost estimator's toolkit to achieve more accurate S&T estimates are the topic of this study.

The four main cost estimating methods typically used by cost estimators include parametric, engineering build-up, analogy, and factors (Mislick and Nussbaum, 2015). The use of standard factors is a common practice and widely accepted in the cost estimating arena (Government Accountability Office, 2009). Factors are utilized in a number of ways to include cross-checking primary estimating methods or estimating costs early in a program's acquisition lifecycle (Mislick & Nussbaum, 2015). Thus, developing and refining factors provide estimators with a more robust toolkit, leading to a more accurate cost estimate.

The Air Force Research Laboratory (AFRL) is involved in programs that occur prior to the Engineering and Manufacturing Development (EMD) phase of the acquisition lifecycle. These programs are typically S&T programs, smaller than traditional Major Defense Acquisition Programs (MDAP), that develop and feed basic science or technologies to subsequent acquisition programs. These are also programs that develop new systems and technology. Little to no research has been conducted to develop cost factors in these types of programs. Once created, these factors will be applicable to a wide range of S&T projects across the Department of Defense (DoD).

Problem Statement

In order to allocate resources and provide thorough decision support, cost estimates need to be accurate and reliable. However, significant gaps exist in the development of cost factors relevant to DoD S&T programs that feed major defense acquisition programs. This effort represents the creation of unique cost factors relevant to these project types to improve cost estimates as well as an analysis on program outcomes given certain characteristics.

Research Objectives

With the purpose of creating unique cost factors for S&T programs, publishing them for operational use, and utilizing them for data analysis and estimate cross-checks, several questions are studied:

1. What are the program types and/or categories that comprise the S&T portfolio?

2. What are the salient work breakdown structure (WBS) characteristics of S&T programs? How should the WBS be structured in these programs? Which set of programs is a candidate for cost factor development?

3. What new standard cost factors can be produced through analysis of a diverse set of S&T project types?

4. How do the newly created S&T cost factors compare to published EMD factors?

5. What new insights can be garnered from an analysis of S&T program characteristics and program performance? How does the technology readiness level (TRL) affect S&T program performance?

Methodology

Data is collected and obtained from the AFRL cost and economics division. Specifically, Contract Performance Reports (CPR) and Funds and Man-Hour Expenditure Reports (FMER) are the primary data sources. In order to analyze the data for each of these categories, as well as the relationship(s) between them, several statistical techniques come into play. Factor development begins with descriptive statistics to develop the standard factors for each identified element. Establishing the mean, median, and standard deviation for each of the elements provides a starting point to identify trends in the data. Also, the identification of interquartile ranges amongst the individual elements allows for a thorough comparison analysis with published EMD factors.

For the behavioral analysis, a two-way contingency table analysis is conducted to summarize the relationship between two categorical variables. These categorical variables are created using data from both FMERs and each S&T program's Research Summary Reports. The contingency table analysis is a test for independence. If there is a failure to reject the null, the two variables are independent and are not statistically related to one another. If the null is rejected, then the variables are dependent, and a statistical relationship exists between them.

Scope and Limitations

Data collection relies upon the information contained in Contract Performance Reports (CPR), Funds and Man-Hour Expenditure Reports (FMER), and Research Summary Reports compiled from S&T programs at various periods of their respective lifecycle. The CPR provides contract cost and schedule performance data while the FMER documents the monthly costs of the contractor effort towards achieving the contract objectives. Research Summary Reports are generated at the start, periodically, and at the end of the program which includes general information such as the program title, lead technical directorate (TD), performance type, TRL, and start/end dates. These three reports contain comprehensive data dating back to 2007 and as recent as 2017. The data gathered from CPRs provides a common format and follows a WBS-like structure, loosely following the structure defined in MIL-STD-881D. The WBS elements that pertain to this analysis include Systems Engineering and Program Management (SE/PM) and System Test and Evaluation (ST&E). The data gathered from FMERs do not contain standard WBS cost elements like those found in MIL-STD-881D, but contain the contractor's expenditures to include labor, travel, and materials. The variables that pertain to the behavioral analysis include percentage of direct labor, TD, performance type, TRL, contract value, and cost/schedule growth.

There are several limitations to this research. The lack of formal reporting requirements for S&T programs contributes to the exclusion of several programs in this analysis. Reports for these programs do not have usable cost elements in which to derive cost factors and other information from. Additionally, informal WBS structures within these reports result in a very limited number of cost elements that are traditionally used in MDAP cost estimates. Finally, initial Research Summary Reports for several programs either were not provided or did not have a TRL within the report. As an important variable in the behavioral analysis, the initial TRL of a program is vital to the study of how an S&T program matures through its lifecycle.

Thesis Overview

The unique nature of the S&T programs under AFRL have little to no previous cost factor research. This inhibits the cost estimator's ability to accurately estimate the cost of these programs. The capability to develop and create standard cost factors is greatly dependent on the structure and content of the data. Due to the non-standardized structure and characteristics of each program, every element is required to be carefully analyzed. Compiling data from CPRs into a central database enables comparisons of not only the costs of the S&T programs, but the various types of the programs themselves. This structured database will facilitate the development and creation of new cost factors that cost analysts can use.

The distinct types of data contained in the reports lends to segregated analyses in two phases. The objective of Phase 1 is to create traditional cost factors for use in S&T estimates utilizing data contained in CPRs. The objective of Phase 2 is to understand the behavior in lower dollar value S&T programs, to include cost and schedule.

The rest of the thesis encompasses the process of developing cost factors and analyzing the behavior of these unique programs. This begins with a literature review in Chapter 2, examining other studies concerning the development, use, and application of standard factors in the field of cost estimating. This chapter also includes a background on S&T programs, review of the AFRL Science and Technology Strategy, and the state of S&T cost estimating. Chapter 3 provides an in-depth examination of the data (to include gathering the data, descriptive statistics, and statistical tests). This chapter describes how the data is utilized and tested in order for the results to be presented in the next chapter. Chapter 4, the results and analysis chapter, presents the determinations made from the dataset. This chapter also includes the conclusions drawn from both phases of this research. Lastly, the conclusion chapter answers each of the research questions and implements the findings to the role of standard factors in science and technology programs and how they can be utilized and improved upon in the future. This chapter also suggests a standardized reporting structure and provides a deeper understanding into the behavior of S&T programs.

II. Literature Review

Chapter Overview

"The men in charge of the future Air Forces should always remember that problems never have final or universal solutions, and only a constant inquisitive attitude toward science and a ceaseless and swift adaptation to new developments can maintain the security of this nation through world air supremacy."

- Dr. Theodore von Karman

The scientific and technical enterprise focuses on discovering new technology of Air Force relevance, identifying solutions to established Air Force mission gaps, maturing emerging technology into Air Force systems, and responding to urgent needs (United States Air Force, 2019). Air Force science and technology (S&T) is the initial phase of the acquisition process by which technologies are matured and, where appropriate, are transitioned for acquisition by the Air Force (Office of the Chief Scientist of the U.S. Air Force, 2010). The use of standard factors is common practice in these early milestone, ill-defined programs. (Mislick & Nussbaum, 2015). Furthermore, the Air Force obligates billions of dollars each year in S&T and even more in research and development (Department of the Air Force, 2018). Due to the recent focus on these immature programs and the vast amount of taxpayer dollars being used to fund their development, this research aims to expand on the analytical tools available, with respect to the development and utilization of standard cost factors, as well as analyze the behavior of various characteristics for the Air Force Research Laboratory's (AFRL) S&T programs.

To fully comprehend the importance of this research, a basic understanding must exist regarding the S&T background, strategy, state of cost estimating, technology readiness levels (TRL), cost estimating methodologies, elements of the Work Breakdown Structure (WBS), and previous research and utility of cost factors in the cost estimating field. The focus of this chapter is on the related literature and previous research with an emphasis on behavioral analysis and the usefulness of standard factors in cost estimating along with identifying the gaps this research aims to fill.

Science and Technology Programs

The AFRL was established in October of 1997. However, the vision to implement science and technology as the centerpiece of our nation's airpower strategy has been around since 1945 (Duffner, 2000). In order to appreciate the analysis of these unique types of programs, one must have an understanding of the S&T background, strategy, and current state of S&T cost estimating.

Background

Since the Air Force's inception, changing threats and advancements in technology have generated major shifts in the S&T strategy roughly once every decade. These efforts articulate a vision for the S&T advancements to enable the necessary capabilities to prevail against anticipated threats (Office of the Chief Scientist of the U.S. Air Force, 2010). In 1944, General H.H. "Hap" Arnold, Commanding General of the Army Air Forces, enlisted the aid of leading aeronautics scientist Dr. Theodore von Karman to lead the first of these efforts, recommending the creation of an agency devoted exclusively to aeronautical research and development, evolving to what AFRL is today (Gorn, 1995). Within two years after Dr. Karman's recommendation, the Air Force developed and flew the first supersonic flight demonstrator, the X-1, and later developed several fighter and bomber aircraft capable of flying supersonically (Aldridge, 2018). Examples of these S&T programs include Advanced Electronic Systems, Advanced Missile Seekers, Advanced Fighter Aircraft, Remotely Piloted Aircraft, Space Launch Capabilities, and Satellite Technologies (Office of the Chief Scientist of the U.S. Air Force, 2010). Today, AFRL is headquartered at Wright-Patterson Air Force Base (AFB) in Ohio. It is comprised of nine technology directorates in the continental United States and four locations overseas in Hawaii, United Kingdom, Chile, and Japan, as shown in Figure 1.

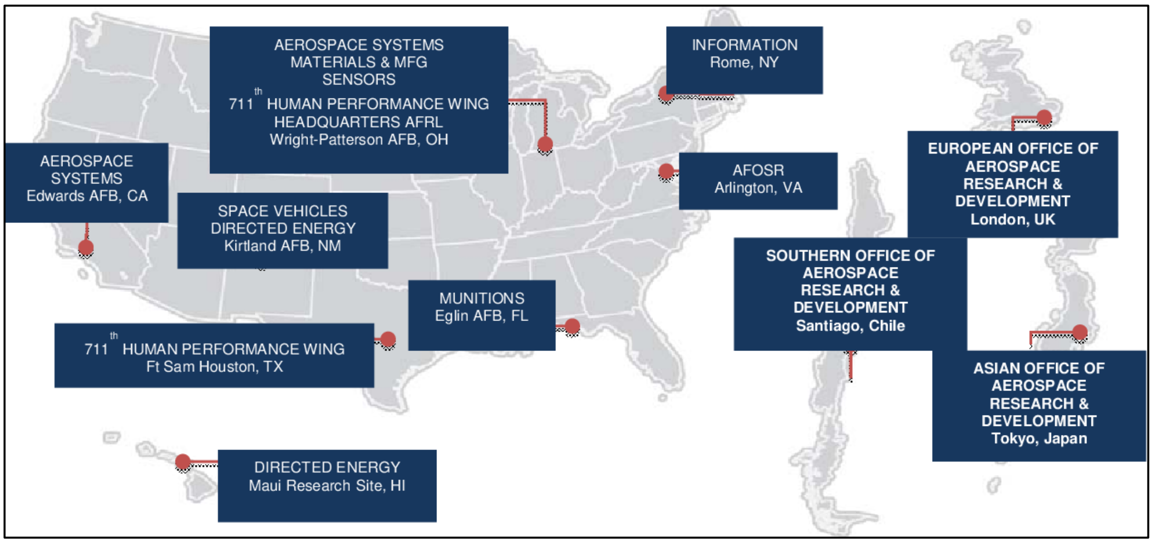


Figure 1. AFRL Locations and Major Offices

Each technology directorate focuses on the development and innovation of leading-edge technologies and are separated by technological capabilities. A list of AFRL’s technology directorates, their office symbol, and program descriptions are seen in Table 1.

Table 1. AFRL Technology Directorates

Technology Directorate	Symbol	Program Descriptions
Air Force Office of Scientific Research	AFOSR	Basic Research Manager for AFRL
711th Human Performance Wing	RH	Aerospace Medicine S&T, Human Sys Integration
Directed Energy Directorate	RD	Laser, Electromagnetics, Electro-Optics
Information Directorate	RI	Information Fusion, Exploitation, Networking
Aerospace Systems Directorate	RQ	Aerodynamics, Flight Control, Engines, Propulsion
Space Vehicle Directorate	RV	Space-Based Surveillance, Capability Protection
Munitions Directorate	RW	Air-Launched Munitions
Materials & Manufacturing Directorate	RX	Aircraft, Spacecraft, Missiles, Rockets
Sensors Directorate	RY	Sensors for Reconnaissance, Surveillance

Strategy

The global security environment is growing increasingly complex, characterized by overt challenges to the free and open international order and the re-emergence of long-term, strategic competition between nations (Department of Defense, 2018). The 2018 National Defense Strategy calls for a more lethal, resilient, and rapidly innovating Joint Force that will sustain American influence and ensure favorable balances of power that safeguard the free and open international order (Department of Defense, 2018). Released in 2019, the U.S. Air Force 2030 Science and Technology Strategy aligns with this call, putting its focus on S&T advances in order to drive transformational strategic capabilities (United States Air Force, 2019). This will involve a restructuring of the Air Force's S&T management processes to deliver advances in capabilities while sustaining a vigorous base of Air Force-critical science and technology that is enabling and enduring (United States Air Force, 2019). Meeting the calls of both strategies requires not only cost estimations for these new advanced programs but making sure these estimates are reliable and accurate in order to ensure the best use of taxpayer dollars.

State of Science and Technology Cost Estimating

The S&T enterprise encompasses basic research (Budget Activity [BA] 1), applied research (BA2), advanced technology development (BA3), and advanced component development and prototypes (BA4) (United States Air Force, 2019). These activities occur before the system development and sustainment phase of a program's lifecycle (see Figure 2). Attaining an understanding of the cost of developing technology is critical for those who perform technology research and technology development and to those who need to manage specific technology projects. Furthermore, an increased understanding of technology costs and estimating enhances decision making (Cole et al., 2013).

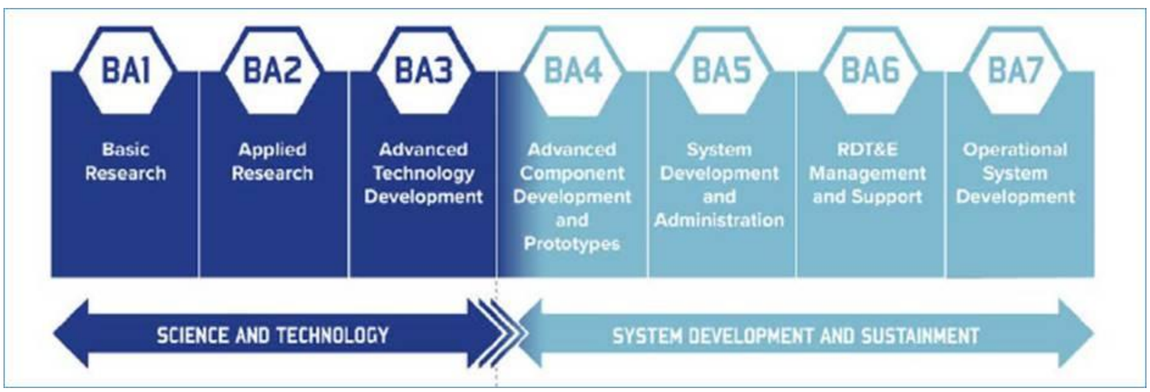


Figure 2. Overall Spectrum of AF RDT&E Activities (USAF, 2019)

Cost estimates for these nascent programs are often characterized by limited amounts of historical data available which constrains the estimation methods available to use. The use of parametric estimating [details on the parametric method is provided in a subsequent section] is prevalent in the S&T cost estimating literature. Cyr (1994) utilized parametric cost estimating methods for advanced space systems to develop a theoretical model which identified variables that drive cost such as weight, quantity, design inheritance and time. Thibault (1992) stated that parametric estimating techniques using cost-estimating relationships are an acceptable method for proposing costs on government contracts. Lastly, Cole et al. (2013) explained that parametric estimating is a preferred method when estimating technology with Technology Readiness Levels (TRL) between two and six given the need to perform analysis early in the project definition phase and possessing limited data. Parametric models can be organically developed or acquired from the commercial marketplace. Commercial parametric cost estimating and analysis tools, such as PRICE TruePlanning, offer robust cost knowledge bases and are driven by cost and schedule estimating relationships that can be highly tailored or calibrated to a particular application, platform, or environment (Alexander, 2018). However, the "black box" nature of the underlying data and algorithms of these commercial models are problematic for government estimators who require transparency and traceability for their estimates.

Another key challenge to modeling S&T development programs is finding common system requirements, attributes, and parameters that drive cost and are readily available. Detailed and sometimes extensive technical design, configuration, performance, and complexity metrics are not generally available in initial development stages (Alexander, 2018). The program design may be vaguely defined, and the technology used is typically state-of-the-art or beyond which make cost estimating for conceptual programs very challenging (Cyr, 1994). This limited amount of data available for S&T programs is the foundation for many of the cost estimating challenges in this field. While the parametric estimating method is often implemented as the preferred approach, model selection depends upon the purpose and time constraints of the estimate process. The considerations made for selection must include what ultimate process is best for evaluating complex technologies, each with their own set of unique or potentially abstract conditions. Adding to the challenge are potential differences in the characterization of a technology, or from one technology to another, where the difference can be significant (Cole et al., 2013).

Despite these challenges and data limitation concerns, there are still numerous benefits from the cost research accomplished in this field. S&T research increases the confidence in technology costs and the capability to manage these technology costs (Cole et al., 2013). Analyzing factors that influence technology costs also assists in reducing overall cost and provides a dataset to better anticipate the resources needed to mature a technology. Conducting additional research can establish a dataset that addresses the gap in existing cost analysis methods for technologies and establish a framework for future data collection to further enhance estimating capabilities (Cole et al., 2013). Tracking technology in its early progressive stages along the path of development or where the early technology has branched to other areas would be a significant building block for better technology estimating (Cole et al., 2013).

Technology Readiness Levels (TRL)

Technology Readiness Levels (TRL) is a tool to measure the technology maturity of a system or subsystems using a 9-level ordinal scale (Department of Defense, 2011). TRL definitions, descriptions, and supporting information can be found in Appendix A. In an effort to reduce the risk associated with entering the EMD phase of the acquisition lifecycle at Milestone B, DoD Instruction 5000.02 requires technologies to obtain a TRL of at least 6 (Department of Defense, 2011). However, the U.S. Government

Accountability Office (GAO) recommends that all critical technologies should exhibit a TRL of 7 or greater before entry into Milestone B (Government Accountability Office, 1999). Despite multiple research efforts studying cost and schedule change, there are few that include information on technology maturity.

Dubos et al. (2008) analyzed the relationship between technology uncertainty and schedule slippage in the space industry. Their research resulted in the creation of TRL-schedule-risk curves, see Figure 3, which are intended to assist program managers make informed decisions regarding the appropriate TRL to consider when confronted with schedule constraints. The research of Dubos et al. (2008) suggested a close relationship between technology uncertainty and schedule risk and that the more mature a technology is (the higher the TRL), the less potential schedule slippage.

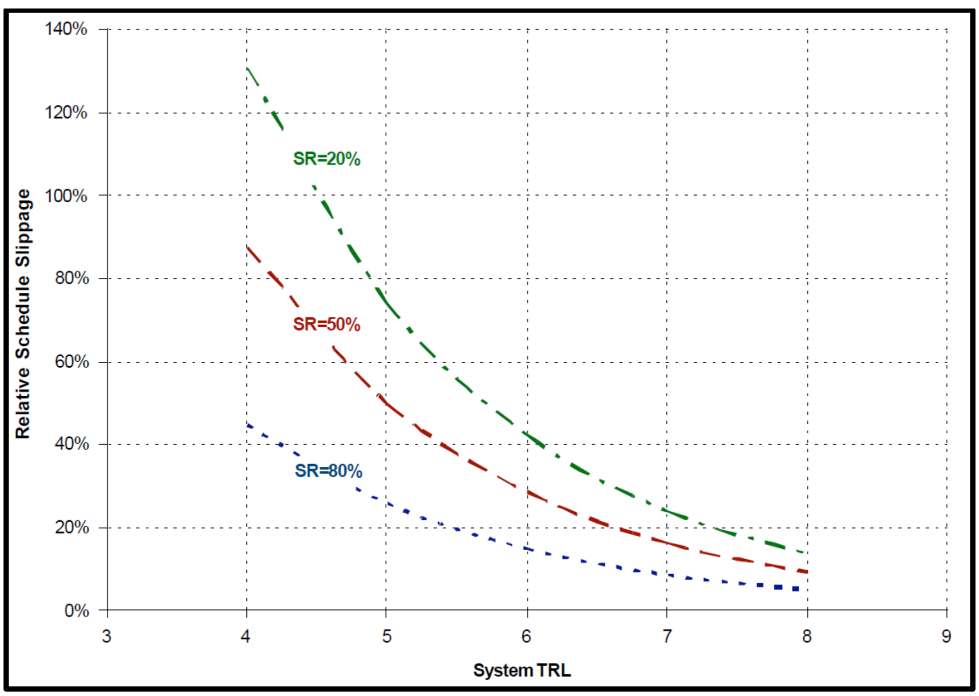


Figure 3. TRL-schedule risk curves (SR) (Dubos et al., 2008)

Katz et al. (2015) specifically studied the relationship of TRLs to cost and schedule change during the EMD phase. They found that weapon systems that achieved a TRL of 7 or greater at Milestone B had a lower probability of schedule slippage during the EMD phase than weapons systems that had a TRL of less than 7. While Katz et al. (2015) found evidence to suggest that technology maturity is related to schedule change, they did not find any for cost change.

Smoker and Smith (2007), however, found evidence that suggests costs vary exponentially across time as the system's technology progressed through each TRL. Similarly, Linick (2017) found that as the TRL increased throughout the development phase, the percentage of the development cost increased at an increasing rate as shown in Figure 4.

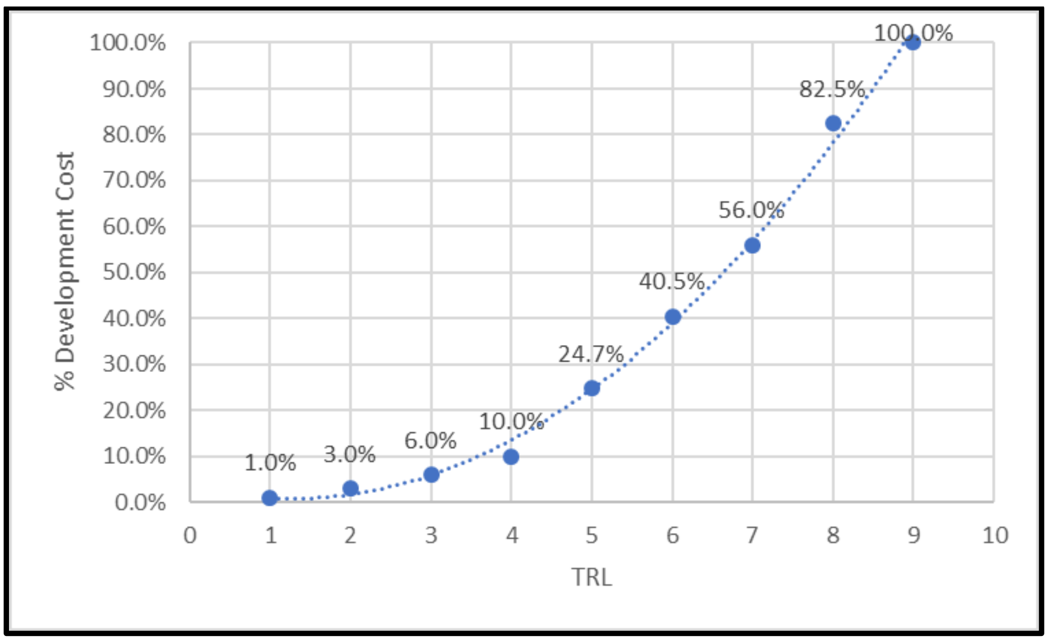


Figure 4. Percent Development Cost vs. TRL Average (Linick, 2017)

While TRLs have not been used to directly estimate the cost of an early S&T program, there exists evidence to suggest that these levels have a relationship with cost and schedule growth. The research leads the cost estimator to utilize TRLs as a useful factor with whatever cost estimating methodology is used.

Cost Estimating Methodologies

The Air Force Cost Analysis Handbook (AFCAH) and the Government Accountability Office (GAO) Cost Estimating and Assessment Guide provide and define the cost estimating methodologies which are utilized not only by the Air Force, but by the Department of Defense (DoD). The four methodologies outlined in the AFCAH are: Analogy and factor, Parametric, Build-up (Engineering), and Expert Opinion (Subject Matter Expert) (Department of the Air Force, 2007). It is important to note that these methods are not the only cost estimating methodologies and that there are more specialized estimating tools and approaches available. The estimating method used on a program depends on its current stage in the lifecycle with the analogy and factor method commonly used for programs that are early in development. Figure 5 shows how methodology selection varies depending on what stage of the acquisition lifecycle the program is in. Note that in addition to the analogy and factor method, analysts also rely on expert opinion (subject matter experts) during the early stages of a program when less detailed estimates are made (Department of the Air Force, 2007).

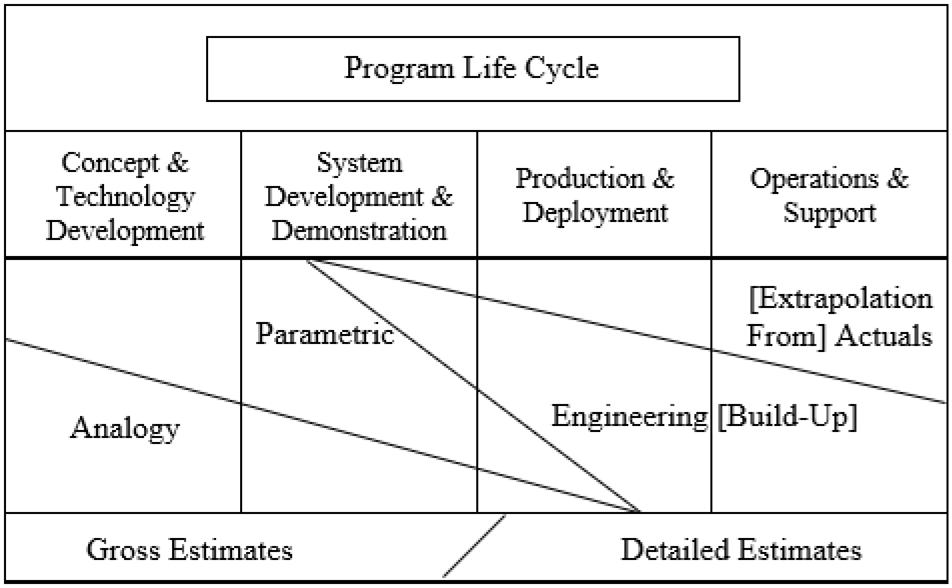


Figure 5. Selection of Methods (AFCAH, 2007)

Analogy and Factor

The analogy method uses actual costs from a similar program with a scaling factor to account for differences between the requirements of the existing and new systems. (Government Accountability Office, 2009). These factors account for differences in the relative complexities of the old and new elements, for example, in their performance, design, quantity, materiel selection, tooling concept, or operational characteristics (Department of the Air Force, 2007). A cost estimator typically uses this method early in a program's lifecycle, when insufficient actual cost data are available but the technical and program definition is good enough to make the necessary adjustments (Government Accountability Office, 2009).

The analogy and factor method provides a quick, low-cost technique which is easily understood, defensible if the analogy is strong, and used before detailed program requirements are known (Government Accountability Office, 2009). However, this method can be criticized for its simplicity due to the fact that the adjustment factors are derived from individual historical data points (Mislick & Nussbaum, 2015). Analogy and factors are often used as a cross-check for other estimating methods. Even when an analyst is using a more detailed cost estimating technique, an analogy or factor can provide a useful sanity check (Government Accountability Office, 2009). The reliability of the estimate depends on how similar the old and new items actually are, which is why this approach is used with new programs that can be somewhat compared to an existing system for which data is already available (Department of the Air Force, 2007).

Parametric

The parametric method, sometimes referred to as a top-down approach, uses cost estimating relationships (CER) that develop a statistical relationship between historical costs and independent variables such as technical and performance characteristics. This estimating method identifies characteristics, also referred to as cost drivers, such as weight, power, lines of code, test and evaluation schedules, and technical performance measures (Government Accountability Office, 2009). CERs are developed by correlating these technical/schedule/program parameters and costs for existing systems and applying them to the parameters of a new system. The CER relationships may range from simple arithmetic ones, such as hours per pound, to multi variable equations developed through a regression analysis (Department of the Air Force, 2007).

Parametric techniques can be used in a wide variety of situations, ranging from early planning estimates to detailed contract negotiations. Because parametric relationships are often used early in a program, when the design is not well defined, they can easily be reflected in the estimate as the design changes simply by adjusting the values of the input parameters (Government Accountability Office, 2009). An additional benefit is that when the parametric equations already exist, they allow the estimator to provide quick estimates and 'what ifs' for large portions of a total program. Parametric techniques are also useful both for primary and crosscheck estimates (Department of the Air Force, 2007). However, this estimating technique has some disadvantages. The underlying database must be consistent and reliable, which may result in the time-consuming task of normalizing data. CERs must also be relevant and updated to capture the most current cost, technical, and program data (Government Accountability Office, 2009). The analyst may not be able to break down a parametric estimate into its component costs. If successful in breaking down the estimate, the analyst would require extensive input and guidance from functional area program personnel in identifying, understanding, gathering, and adjusting the program parameters needed to drive CERs and parametric tools (Department of the Air Force, 2007).

Build-Up (Engineering)

Build up estimating, also known as engineering or grass roots estimating, provides a detailed basis of estimate for a program by estimating each low-level program element, then summing the estimates to calculate the total program cost (Department of the Air Force, 2007). An engineering build-up estimate is done at the lowest level of detail and consists of fully burdened labor and materials costs, in addition to quantity and schedule to capture the effects of learning (Government Accountability Office, 2009). Build up estimates typically are based on detailed engineering information about the system or item being produced. This detailed information includes at least some actuals from development and early production where the manufacturer has experience in building the product or end item (Department of the Air Force, 2007).

Outside of the cost estimating profession, many believe the engineering buildup method is the best cost estimating approach due to its great detail (Mislick & Nussbaum, 2015). The estimate is defensible and credible since it provides detailed insight into each component estimate (Department of the Air Force, 2007). The downside of the approach, however, is that it is very data intensive and time consuming and therefore expensive to produce (Mislick & Nussbaum, 2015). Product specifications must be well known and stable, small errors can grow into larger error during the summation, and some elements can be omitted by accident (Government Accountability Office, 2009). In fact, in most cases, this method typically underestimates the most probable cost (Department of the Air Force, 2007).

Expert Opinion (Subject Matter Expert)

When the other cost estimating tools are inadequate or not applicable, and/or when data is very scarce, such as during the development stage of a program, the analyst must rely on the information a subject matter expert (SME) can provide. This information includes the technical, programmatic, or schedule features of the cost element (Department of the Air Force, 2007). Because relying on expert opinion is by definition subjective, this method should be used sparingly and only as a sanity check (Government Accountability Office, 2009). Sometimes, though, the cost analyst must work with SMEs to directly estimate costs, or the limits on costs, using elicitation methods such as the Delphi technique, round-table discussions, and one-on-one interviews (Department of the Air Force, 2007).

The expert opinion method is easy to implement and takes minimal time once experts are assembled. Experts may provide different perspectives and/or identity facets the analyst may not have previously considered which could lead to a better understanding of the program (Government Accountability Office, 2009). This method is especially useful for filling gaps used to drive other estimating methods as well as being used as a cross-check method (Department of the Air Force, 2007). The disadvantages of the use of expert opinions are bias and credibility, which can lead to an inaccurate cost estimate and why this method is discouraged as a primary estimating method (Government Accountability Office, 2009).

Work Breakdown Structure

A Work Breakdown Structure (WBS) provides a consistent and visible framework for defense material items and contracts within a program (Department of Defense, 2018). It contains uniform terminology, definitions, and placement in a product-oriented family tree structure (Department of Defense, 2005). By displaying and defining the efforts to be accomplished, the WBS becomes a management blueprint for the product (Mislick & Nussbaum, 2015). Additionally, the WBS provides a basis for effective communication throughout the acquisition process and helps maintain program uniformity in definition and consistency (Department of Defense, 2018). Military Standard (MIL-STD) 881D mandates and governs the WBS for the purpose of achieving a consistent application for all programmatic needs including performance, cost, schedule, risk, budget, and contractual (Mislick & Nussbaum, 2015). This mandated WBS construct also forms the basis of reporting structures used for reports placed on contract such as Cost and Software Data Reporting (CSDR) and Cost Performance Reports (CPR) (Department of Defense, 2018).

The two fundamental and interrelated WBS sub-structures are the contract WBS and the program WBS. The Contract WBS is the Government-approved structure for program reporting purposes and includes all product elements extending from the Contract Statement of Work (SOW) (Department of Defense, 2005). The Program WBS encompasses an entire program, to include the Contract WBS, and is used by the Government program manager and contractor to develop and extend the Contract WBS (Department of Defense, 2005). A program WBS consists of at least three levels of the program starting with the entire material items (Level 1), such as aircraft, ship, space, or surface vehicle system (Mislick & Nussbaum, 2015). Next, are the major elements of the material items (Level 2), which include combinations of system level services such as integration and assembly, system test and evaluation (ST&E), systems engineering and program management (SE/PM), training, data, operational/site activation, and initial spaces and repair parts (Department of Defense, 2018). The subordinate elements to the Level 2 elements (Level 3) include hardware, software, and services (Department of Defense, 2005). Fourth and fifth levels are sometimes included in expanded forms of the WBS. By breaking the system into successively smaller pieces, system elements and enabling system elements are identified in terms of cost, schedule and performance goals, thereby reducing overall program risk in the process (Defense Acquisition University, 2017). Just as the physical system is defined and developed throughout its lifecycle, so is the WBS. The WBS is developed, maintained, and evolved based on the systems engineering efforts throughout the system's lifecycle. Figure 6 displays the WBS Evolution.

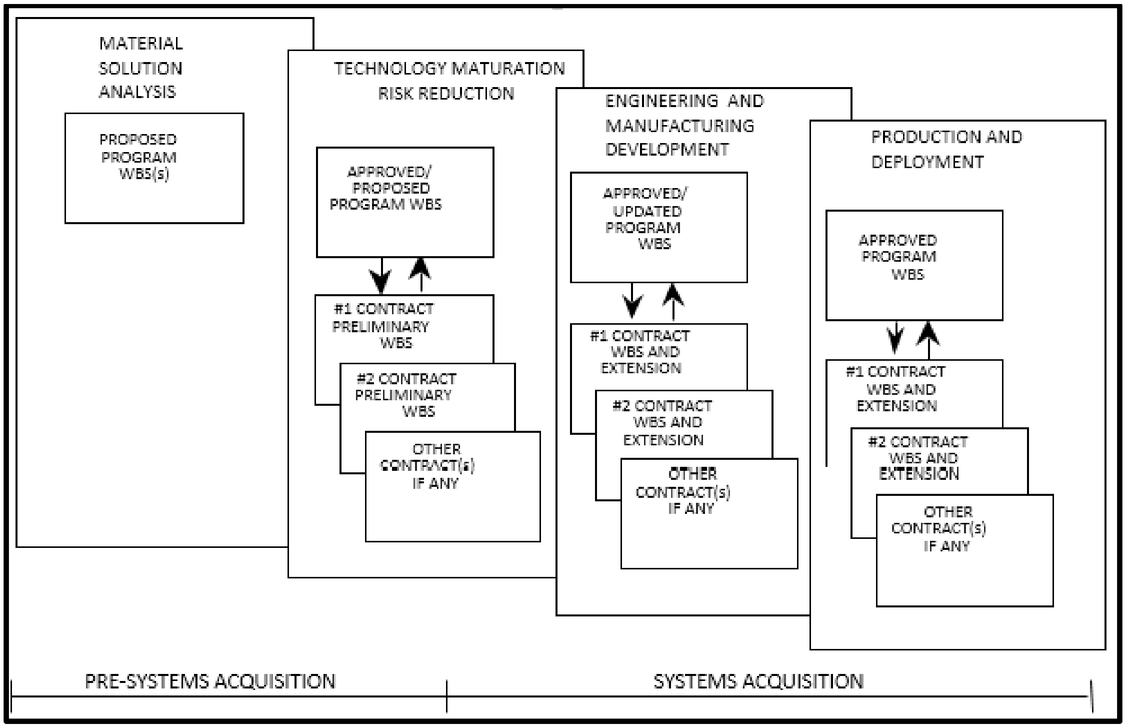


Figure 6. WBS Evolution (Department of Defense, 2018)

Developing a WBS presents some challenges. The primary challenge is to develop a WBS that defines the logical relationship between all program elements without constraining the contractor's ability to effectively execute the program (Department of Defense, 2005). A WBS should be sufficient to provide necessary program insights for effective status reporting and risk mitigation, facilitating the contractor's ability to effectively execute the program (Department of Defense, 2018). A secondary challenge is to balance the program definition aspects of the WBS with its data-generating aspects, remembering that the primary purpose of the WBS is to define the program's structure, and the need for data should not distort or hinder the program definition (Department of Defense, 2005).

Early in a program's lifecycle, as with S&T programs, the program WBS is ill defined. Since the system is mainly a concept at this point, it is not until the System Development and Demonstration (SDD) phase that the system is broken into its component parts and a detailed WBS is required to be developed (Department of Defense, 2005). As a result, CPRs for these early S&T programs are used to obtain individual contract cost and schedule performance information from the contractor which allocates the program's budget to WBS elements (Mislick & Nussbaum, 2015). Thus, the current WBS process for S&T programs is ad hoc and varies greatly from system to system. Filling this gap requires the creation of a WBS construct germane to the unique nature of S&T programs. This research aims to achieve those ends.

Previous Research on Factors in Cost Estimating

The use of cost factors is a common cost estimating method early in a program's lifecycle, but extensive research does not exist to utilize them efficiently. Factor studies for USAF aircraft, predominantly focusing on the Engineering and Manufacturing Development (EMD) phase, were first introduced in the 1980s. Subsequent studies were then built upon them, often after a significant period of time, updating factors with the use of recent program data. These periods between studies create gaps in the analyst's ability to use the technique effectively. Ms. Joan Blair was the first to conduct a major aircraft cost factor study, referred to as the "Blair Study," in 1988 (Wren, 1998). The study consisted of 24 aircraft avionics programs using data in the EMD phase and creating factors for various level 2 WBS elements such as ST&E, SE/PM, Data, and Training. These cost element factors are the ratio (percentage) of the individual level 2

WBS elements to a base cost, represented by a program's Prime Mission Equipment (PME) value (Wren 1998). The Blair Study was utilized for approximately ten years, at which estimates using these factors became suspect and questioned for their accuracy (Wren, 1998).

In 1998, building upon the Blair Study, Mr. Don Wren performed a factor study which included 20 additional programs using data in the EMD phase (Wren, 1998). Wren used data extracted from CPRs and Cost/Schedule Status Reports (CSSR) for the same type of avionics programs and the same WBS elements as Blair to remain consistent (Wren, 1998). Realizing the importance of having current factors available for cost estimating, Wren recommended annual updates to these cost factors as well as further research into factors beyond the EMD phase, to include the Production phase of the acquisition lifecycle (Wren, 1998). Despite Wren's recommendations, the next major study in cost factors was not conducted until 2015 by Mr. Jim Otte. Otte's research focused on both updating the previous studies and expanding the cost factors utilized by cost estimators. Otte used data pulled from DD Form 1921s to develop an additional set of factors in the EMD phase as well as the Production phase for Major Defense Acquisition Programs (MDAP) (Otte, 2015). While Otte's findings increased the utility of cost factors for level 2 WBS elements, little was studied beyond clean sheet design aircraft. Markman et al. (2019) later studied 102 MDAP platforms and created over 400 new cost factors for use in the EMD phase of the acquisition lifecycle across a broader range of development programs. This study also included statistical testing of factor differences by commodity type, contractor type, contract type, developer type, and Service. Despite the number of updates and expansion in the development of cost factors in recent years, many shortfalls remain. Of particular interest to this research effort, there is no prior research on cost factors for S&T programs.

Cost factor research is not limited to just acquisition programs. While the DoD governs each military branch with general guidance, each Service has their own Cost Factors Handbooks which demonstrates their differences in the field of cost estimation (Mislick & Nussbaum, 2015). The Naval Center for Cost Analysis (NCCA) routinely publishes and updates directives and guides to assist in the efficiency of cost analyses with the Navy (NCCA, 2019). Numerous other organizations derive their own cost factors for internal use (Mislick & Nussbaum, 2015). The Air Force uses Air Force Instructions (AFI) to publish cost factors which are utilized for predicting costs in logistics, personnel, and flying hour operations (Department of the Air Force, 2018). Additionally, Air Force organizations such as the Financial Management Center of Expertise (FM CoE) and The Deputy Assistant Secretary for Cost and Economics (SAF/FMC) conduct economic and business case analyses which utilize Area Cost Factors (ACF). These factors assist cost estimators to arrive at credible estimates for Military Construction (MILCON) projects (PAX, 2019). Research in cost factors, in the realm of acquisition and beyond, greatly enhances the utility of factors in cost estimating.

Utility of Factors in Cost Estimating

Analogy and factor cost estimation is a common approach in preparing a cost estimate for an early program when there is insufficient historical data or insufficient information, time, or resources to perform an engineering estimate (Shishko, 2004). The automotive, aerospace and defense industries often must estimate the cost of a program that contains significant amounts of new technology which requires considerable knowledge of previous projects, technology trends, or new developments in other industry sectors (Roy, Colmer, & Griggs, 2005). When programs are entirely new designs, analogous programs are developed as improved versions of previously successful designs. In developing the analogy cost estimate for a new program or sub-program, the analyst must develop and apply the appropriate adjustment, or factor (Shishko, 2004). The utilization of these cost factors in estimating improves the use of historical information (Riquelme & Serpell, 2013). The literature on analogy cost estimation is not voluminous and comprises mostly software projects. The focus of many of these articles is on empirical/statistical tests of alternative techniques for developing analogy cost estimates, and on quantifying the accuracy of those estimates (Shishko, 2004). Previous research has also examined the limitations of existing cost practices as they pertain to the early stages of a program to include a tendency to underestimate the cost growth. An effective and adaptive cost model is essential to successful mission design and implementation (Foreman, Moigne, & Weck, 2016).

A first step to any program budget is a representative cost estimate which hinges on a particular estimation approach, or methodology. However, new ways are needed to address very early cost estimation during the initial program research and establishment phase when system specifications are limited (Trivailo, Sippel, & Şekercioğlu, 2012). Early phases may require adaptations of existing engineering processes or development of entirely new approaches to design, manufacturing, integration and test (Foreman, Moigne, & Weck, 2016). A lack of historical data implies that using a classic heuristic approach, such as parametric cost estimation based on underlying CERs, is limited

(Trivailo, Sippel, & Şekercioğlu, 2012). With limited data available for analogy and factor cost estimation, it is likely that there are only a few good analogy projects. However, when the number of appropriate analogy projects in a database is found to be large the cost analyst can take advantage with an appropriate factor (Shishko, 2004). Some analysts have decided against utilizing CERs because the use of architectures for S&T programs is still relatively new, and as such the data set would be skewed significantly toward programs with low levels of experience and high implementation costs. Cost data is often competition sensitive and therefore not publicly available at the level of detail that would be required to establish high fidelity CERs (Foreman, Moigne, & Weck, 2016). The analogy and factor method, when properly utilized with early programs, aids in achieving an estimate that embodies completeness, reasonableness, and analytic defensibility (Mislick & Nussbaum, 2015).

The creation and utilization of factors allows the analyst to conduct more effective and extensive analysis at multiple levels to construct credible cost estimates, especially in programs early in their lifecycle and/or with limited data (Mislick & Nussbaum, 2015). New cost estimation methods and approaches for these programs need to be further investigated, developed, tested and validated (Trivailo, Sippel, & Şekercioğlu, 2012). Further, more experimentation, test cases, and data are needed to improve analogy and factor cost estimation (Shishko, 2004). With the creation of cost factors, cost analysts have yet another toolset to formulate accurate, reliable, and defensible estimates for S&T programs.

Chapter Summary

Estimating the costs of S&T programs proves difficult not only due to the lack of data and program structure, but also because these programs are early in the acquisition process. With billions of dollars being spent on S&T programs each year, being able to accurately estimate these costs is vastly important to the DoD and the taxpayer. Using historical information, cost analysts must utilize cost methodologies and understand the intricate workings of their estimate. This chapter introduced S&T programs and briefly discussed their background, unique strategy, technology maturity, and the current state of S&T cost estimating. Additionally, common cost estimating methodologies were examined along with their use, advantages, and disadvantages of each with an emphasis on early programs.

Knowledge of the WBS is required when using the analogy and factor method. This chapter proposed a thorough explanation of its structure, challenges, and the lack of a formal standardized format for S&T programs. Previous research on related cost factor studies were reviewed to comprehend the existing data and method used in developing cost factors. Finally, the utility of cost factors was studied to emphasize the importance of the analogy and factor method in S&T programs that have limited data and few analogous programs. The following chapter of this thesis explores the statistical methodologies employed to perform the analysis in order to accomplish the aims of this research.

III. Methodology

Chapter Overview

This chapter provides a description of the data used in the analysis and the methods used to analyze the data. Data obtained on S&T programs consisted of two different reporting types: Contract Performance Reports (CPR) and Funds and Man-Hour Expenditure Reports (FMER). The unique nature of the different types of data contained in the reports lends to segregated analyses in two phases. The objective of Phase 1 is to create traditional cost factors for use in S&T estimates utilizing data contained in CPRs. The objective of Phase 2 is to understand the behavior in lower dollar value S&T programs, to include cost and schedule. Phase 2 uses the FMER data to conduct this analysis through contingency tables.

Phase 1 – Factor Development

Data

The data gathered for this research was obtained from the Air Force Research Laboratory (AFRL) cost and economics division. It consists of the larger dollar value S&T programs which are traditionally reported in the form of CPRs. CPRs consist of five formats containing cost and related data for measuring a contractor's cost and schedule performance on acquisition contracts. The CPR is required on a monthly basis, unless otherwise stated in the contract, and submitted to the procuring activity. Format 1 provides data which measures cost and schedule performance by Work Breakdown Structure (WBS) elements. Format 2 provides this same data, only from the contractor's organizational structure, instead of a military WBS. Format 3 provides the budget baseline plan and Format 4 provides staffing forecasts. Finally, Format 5 is a narrative report used to explain any cost and/or schedule variances and other potential issues. Format 1 contains the necessary cost data needed to establish cost factors for this research. This data includes the WBS elements and their associated current and actual cumulative costs to date. Only the latest CPR available for each program is used for this analysis. This process ensures that only the most current data was utilized for the dataset. The dataset consists of CPRs for 16 S&T programs with contract start dates spanning from 2007 to 2017. The programs represent a wide range of contractors as well as four different AFRL technical directorates.

Observing each program's reported WBS within their respective CPR uncovers a potential limitation. The cost elements reported do not follow any structured, formal WBS as dictated in MIL-STD-881D. Cost factors for Major Defense Acquisition Programs (MDAP) are traditionally developed from level 2 elements found in the MIL-STD-881D formal WBS. These elements include Systems Engineering/Program Management (SE/PM), System Test and Evaluation (ST&E), Training, Data, and Common Support Equipment (CSE). Because of this limitation, the cost elements found in the CPRs are mapped to the traditional MIL-STD-881D structure to determine what types of traditional cost factors can be developed. This analysis will also help in suggesting a WBS structure germane to the unique nature of S&T programs.

Factor Calculation

The cost element factors created in this analysis are the ratio, or percentage, of the individual level 2 WBS element to the program's Prime Mission Equipment (PME) amount. PME is the cost of a program not including the contractor's fee or miscellaneous expenses (including general and administrative (G&A), management reserve (MR), cost of money (COM), and undistributed budget). An example of this calculation can be seen in Table 2.

Table 2. Cost Factor Calculation

	Prime Mission Equipment (PME)	Systems Engineering/Program Management (SE/PM)
Program X	$417.2K	$187.5K
Cost Factor = 187.5 ÷ 417.2K = 0.449 or 44.9%		

After the calculation of the WBS element(s) for each program, composite factors can be calculated. The WBS elements can be grouped together to create a percentage for all of the S&T programs in the dataset that can be used for cost estimations. Table 3 provides an example of how this averaged composite factor is calculated.

Table 3. Composite Cost Factor Calculation Example

	Prime Mission Equipment (PME)	Systems Engineering/Program Management (SE/PM)	Percentage
Program X	$450K	$180K	0.40
Program Y	$660K	$120K	0.18
Program Z	$265K	$80K	0.30
TOTAL:	$1,375K	$380K	0.88
Cost Factor = 0.88 ÷ 3 = 0.29 or 29%			

Comparison Analysis

Once composite factors are created for each WBS element, the mean, median, and standard deviation values are calculated. Interquartile ranges are also calculated to examine and compare the variability between the factors. These characteristics allow for a descriptive comparison analysis with previous cost factor studies on MDAP programs within the engineering, manufacturing, and development (EMD) phase of the acquisition lifecycle. More specifically, the newly created S&T factors from this research will be compared to the EMD factors from Markman et al. (2019). If similarities are found between these factors, then S&T cost estimators may consider incorporating the more robust EMD factor dataset when developing their estimates.

Phase 2 – S&T Program Behavioral Analysis

The S&T programs analyzed under Phase 2 are smaller than the programs in Phase 1, in terms of dollar amount. While reports obtained for these programs do not contain the cost elements necessary to develop standard cost factors, additional program data was acquired in order to study the program's characteristics and how they relate to each other. Finding significant relationships could shed light on how these programs behave under their unique conditions.

Data

The data gathered for this research was also obtained from the AFRL cost and economics division. In contrast to the Phase 1 dataset, this data consists of the smaller dollar value S&T programs which are traditionally reported in the form of FMERs. These reports provide the procuring activity visibility into the contractor's expenditures for labor, materials and parts, travel, subcontractors, and other charges. FMERs include these costs for the reporting period and cumulative costs to date. Like CPRs, these reports are required on a periodic basis from the contractor, usually monthly. Only the latest FMER available for each program is used for this analysis as this process ensures that only the most current data was utilized for the dataset. Unlike CPRs, FMERs do not report standardized cost elements like the ones found in MIL-STD-881D. The dataset consists of 165 S&T programs with contract start dates spanning from 2009 to 2017. The programs represent a wide range of contractors as well as six different AFRL technical directorates.

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

Of the 165 programs obtained from AFRL, 43 are included in the final dataset. Table 4 provides the exclusion criteria and associated number of programs remaining in the analysis.

Table 4. Dataset Exclusions

Category	Number Removed	Remaining Programs
Programs Obtained from AFRL		165
No Usable Cost Elements	64	101
Inadequate TD Sample Size	10	91
Less Than 92.5% Complete	48	43
Final Dataset for Analysis		43

As shown in Table 4, programs which did not have any usable cost elements are excluded. These 64 programs had their costs reported on the FMER in unique ways to include cost burn rates, earned value management graphs, total costs in phases, or simply an overall total cost or labor hours spent. These reporting methods lack the specific cost elements needed for this analysis to compute percentages of total cost which are used to observe the program's behavior. Of the 101 remaining programs, 10 programs fall under four different technical directorates (RD, RI, RX, and RY). Each technical directorate represents unique programs with different characteristics which precluded aggregation above the technical directorate level. Therefore, the small sample size in these directorates would likely skew the analysis results, especially when observing how these programs behave at the technical directorate level. Due to these reasons, these programs are excluded from the analysis. Finally, a program's completion percentage is computed using the total cost from the last available FMER to the program's contract value at that time. Previous research determined that a program with a completion percentage of 92.5% or greater accurately predicts the final cost of the program (Tracy & White, 2011). Therefore, programs with a completion percentage of less than 92.5% are excluded from the dataset, leaving the final number of programs in the dataset at 43.

Contingency Table Analysis

Since the nature of the dataset consists largely of qualitative variables, a two-way contingency table analysis is an appropriate test between two category classifications. This type of analysis is used to summarize the relationship between two categorical variables based on the data observed. The chi-square distribution is the test statistic used in order to consider inferences about the category probabilities. The contingency table analysis uses a 2 x 2 table to test for independence. For each test, the same hypothesis test will be utilized, as shown in Equation 1:

$$H_o\text{: The two classifications are independent}$$
$$H_a\text{: The two classifications are dependent}$$

Equation 1

If there is a failure to reject the null, the two variables are independent and are not statistically related to one another. If the null is rejected, then the variables are dependent, and a statistical relationship exists between them. The two-way contingency analysis examines the categorical variables, which can be seen in Table 5, with subsequent discussion on the rationale behind variable selection and categorization.

Table 5. Categorical Variables used in Contingency Table Analysis

Categorical Variables	
Technical Directorate	Cost Growth > 0%
Performance Type	Cost Growth > 33.7%
TRL Increase	Cost Growth > 44.1%
Last Known TRL ≥ 6	Cost Growth > 56.5%
Final TRL ≥ 6	Cost Growth > 60.5%
TRL 1 - 3	Cost Growth > 68%
TRL 4 - 5	Contract Value > $1M
TRL 6 - 7	Contract Value > $3M
TRL 8 - 9	% Direct Labor > 30%
Schedule Growth > 0%	% Direct Labor > 35%
Schedule Growth > 33%	
Schedule Growth > 63%	

Categorical variables for the technical directorate (TD), performance type, and TRL are obtained from the Research Summary Reports. The TD variable denotes which AFRL directorate is the lead on the program. For this dataset, the TD variable is either RH or RQ. The performance type represents the partnership method between AFRL and the contractor. This variable consists of Research, Development, Test & Evaluation

(RDT&E) and Small Business Innovative Research (SBIR) relationships. TRL data for the S&T programs are used in seven different categorical variables. TRL Increase indicates if the TRL increases at any point during the program's lifecycle. Last Known TRL $\geq$ 6 denotes the last reported TRL of the program while Final TRL $\geq$ 6 only analyzes programs that have a Final Research Summary Report. The decision to categorize based on TRL level 6 is due to the role this TRL level fulfills in the defense acquisition process. Specifically, a TRL of 6 is equivalent to demonstration in a relevant environment which is needed for a program to enter Milestone B (Department of Defense, 2011). Lastly, four variables were created grouping TRLs based on the maturity of the technology and the product's requirements, as seen in Figure 7.

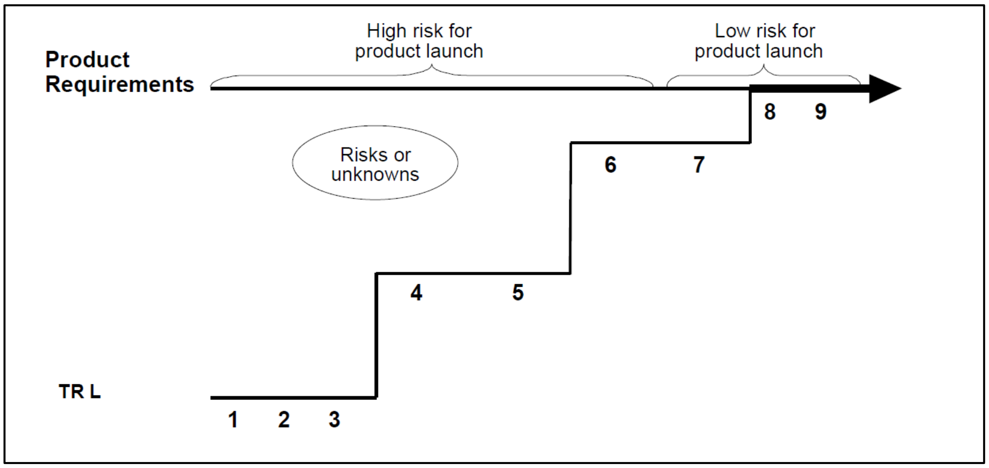


Figure 7. Using TRLs to Match Technology with Requirements (GAO, 1999)

Additional variables of interest created from the Research Summary Report contract information include schedule growth, cost growth, and contract value. These attributes are commonly studied for acquisition programs at all phases of their lifecycles. A variable for the percentage of a program's direct labor cost was also created in order to analyze the largest cost element obtained from the FMERs for these S&T programs.

The variables for cost growth, schedule growth, contract value and percent of direct labor have been converted from continuous variables to categorical variables, in the way of dummy variables, in order to be included in this type of analysis. Different variables with methodical break points were created in order to test the relationships at different locations. These breakpoints were derived from either the literature review or from descriptive statistics of the variable itself in the dataset with its mean and/or median. For example, the mean cost growth of the dataset was 68% which led to the creation of a dummy variable (Cost Growth > 68%) separating programs that are above and below this value. Likewise, Bolten et al. (2008) distinguished mean and median percentages of total Department of Defense (DoD) and Air Force acquisition program development cost percentages. A summary of the break points can be seen in Table 6.

Table 6. Break Point Summary

Category	Break Point	Reason	Source
Schedule Growth	0%	Any growth	Dataset
	33%	Median	Dataset
	63%	Mean	Dataset
Cost Growth	0%	Any growth	Dataset
	33.7%	DoD Development - Median	Bolten et al. (2008)
	44.1%	Air Force Development - Median	Bolten et al. (2008)
	56.5%	DoD Development - Mean	Bolten et al. (2008)
	60.5%	Air Force Development - Mean	Bolten et al. (2008)
	68%	Mean	Dataset
Contract Value	$1M	Median	Dataset
	$3M	Mean	Dataset
% Direct Labor	30%	Median	Dataset
	35%	Mean	Dataset

For significant results, the odds ratio and its associated confidence interval is observed. An odds ratio is a measure of association for a two-way contingency table and used to interpret the results for relatively moderate to large sample sizes. This ratio is the odds of an event occurring in one group to the odds of the same event occurring in another group. In other words, the odds ratio is the ratio of the probability of a property being present compared to the probability of it being absent. If the odds ratio is 1, the two events are independent.

Chapter Summary

This chapter discussed the methodological approach to both phases of this research. The discussion of the data in Phase 1 (Factor Development) gave a brief synopsis of the type of data available from CPRs and issues that could potentially arise in the development of standard cost factors. Furthermore, methods to calculate individual and composite cost factors were described as well as a comparison analysis process in an attempt to identify similarities with previously published factors. The discussion of the Phase 2 (S&T Program Behavioral Analysis) data provided insight into the types of costs reported on FMERs and Research Summary Reports. A description of the contingency table analysis introduced a statistical method to analyze the relationships between the numerous categorical variables in this dataset. The next chapter will provide a comprehensive look at the results and analysis of the factors and behavioral analysis developed from both datasets.

IV. Results and Analysis

Chapter Overview

This chapter provides the results and analysis from the methodology outlined in Chapter III. The chapter is segregated into the two phases, defined in Chapter III, due to the unique nature of the different types of science and technology (S&T) program data obtained. Phase 1 provides an overview of the dataset, calculations of each factor's descriptive statistics, and a comparison analysis with published engineering, manufacturing, and development (EMD) cost factors. Phase 2 provides an overview of its dataset along with a contingency table analysis exploring the relationships between multiple variables and how the S&T programs behave under various conditions.

Phase 1 – Factor Development

Data

The data for Phase 1 was obtained from the Air Force Research Laboratory (AFRL) in the form of Contract Performance Reports (CPR). With no mandated reporting requirement, the reported Work Breakdown Structures (WBS) do not follow any formal WBS such as those dictated for Major Defense Acquisition Programs (MDAP) in MIL-STD-881D. Rather, the WBS structure reported in the S&T CPRs is defined at the discretion of the respective program. A categorization of the CPRs was conducted by analyzing each cost element in each program's WBS and mapping it to a traditional MDAP level 2 WBS element. It was found that only two traditional cost factors could be created. These cost elements are System Engineering and Program Management (SE/PM) and System, Test and Evaluation (ST&E). Sixteen programs were available for this phase of the analysis. One program was excluded from the final dataset because it did not include any specific cost elements in the WBS within the CPRs. These programs were found to be in various stages of completion, but no programs were excluded solely based on completion percentage due to the small sample size. The final list of programs utilized in this phase's analysis can be seen in Table 7.

Table 7. Phase 1 Program List

	Program Title
1	Automated Collision Avoidance Technology - Fighter Risk Reduction (ACAT-FRRP)
2	Adaptive Engine Technology Development (AETD) - Pratt & Whitney
3	Adaptive Engine Technology Development (AETD) - General Electric
4	Aerial Reconfigurable Embedded System (ARES)
5	Autonomous Real-Time Ground Ubiquitous Survillance Infrared System (ARGUS-IR)
6	Evolved Augmented Geostationary Laboratory Experiment (EAGLE)
7	High Energy Endurance Laser
8	Hydrocarbon Boost
9	Integrated Vehicle Energy Technology (INVENT)
10	Laser Advancements for Next-generation Compact Environments (LANCE)
11	Laser Pod Research & Development (LPRD)
12	Supersonic Turbine Engine Long Range (STELR) - Williams
13	Supersonic Turbine Engine Long Range (STELR) - Rolls Royce
14	SHiELD Turret Research in Aero Effects (STRAFE)
15	Versatile Affordable Advanced Turbine Engine (VAATE)

Factor Development & Descriptive Statistics

The cost factors developed in this analysis are the ratio, or percentage, of the individual level 2 WBS element to the program's Prime Mission Equipment (PME) amount. PME is the cost of a program not including the contractor's fee or miscellaneous expenses (including general and administrative (G&A), management reserve (MR), cost of money (COM), and undistributed budget). For example, a cost factor for SE/PM is the dollar value of the SE/PM cost element divided by the program's PME dollar value.

Composite factors can also be calculated with multiple programs by adding the individual ratios and dividing by the total number of programs.

SE/PM

The Systems Engineering (SE) and Program Management (PM) cost elements were the most common WBS elements reported within the CPRs. Each program had at least one of these elements reported or the combined element, SE/PM. For those programs that reported SE and PM separately, these amounts were added together to form the SE/PM element amount. After the initial categorization and calculations, it was found that while every program either reported an amount for PM or SE/PM, not every program reported an SE amount. For instance, there were five programs that only reported a PM amount without the SE piece. The initial factor calculations can be seen in Table 8.

Table 8. Initial SE, PM, and SE/PM Factor Calculations

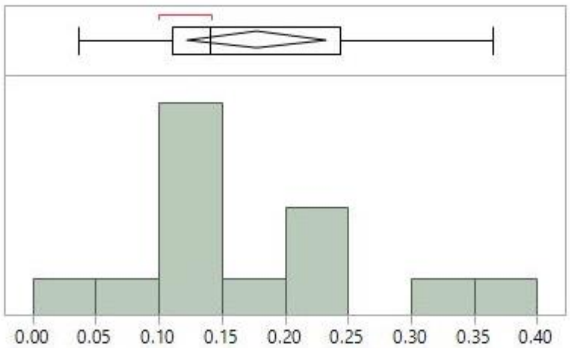
Program Title	System Engineering	Program Management	SE/PM
Program A		13.56%	
Program B		3.64%	
Program C			24.29%
Program D	6.98%	3.10%	10.09%
Program E	7.69%	3.79%	11.48%
Program F	9.15%	14.33%	23.49%
Program G	3.01%	14.30%	17.31%
Program H		14.23%	
Program I			9.98%
Program J	56.44%	40.96%	97.40%
Program K	16.95%	16.73%	33.68%
Program L		13.96%	
Program M		36.52%	
Program N	8.52%	16.34%	24.87%
Program O	4.30%	7.16%	11.46%

The informal WBS reporting in the CPRs for these programs, along with the common nature of reporting SE and PM as the combined element SE/PM, leads to the assumption that the SE amount for these five programs is contained within the reported PM amount. Therefore, the PM amount for these five programs is also mapped as SE/PM. An initial analysis of the SE/PM distribution resulted in a SE/PM value of 97.4% being removed from the dataset. A closer look at this program (Program J) revealed its latest CPR was six months after the contract award date with a reported cost to date being only 4.4% of its contract cost. Furthermore, this program's SE/PM value was more than three standard deviations away from the mean. Due to this program's early reported costs and outlier tendencies, it was removed from the SE/PM calculation. Considering the assumption and exclusion given above, the final factor calculations for SE/PM can be seen in Table 9.

Table 9. Final SE, PM, and SE/PM Factor Calculations

Program Title	System Engineering	Program Management	SE/PM
Program A		13.56%	13.56%
Program B		3.64%	3.64%
Program C			24.29%
Program D	6.98%	3.10%	10.09%
Program E	7.69%	3.79%	11.48%
Program F	9.15%	14.33%	23.49%
Program G	3.01%	14.30%	17.31%
Program H		14.23%	14.23%
Program I			9.98%
Program K	16.95%	16.73%	33.68%
Program L		13.96%	13.96%
Program M		36.52%	36.52%
Program N	8.52%	16.34%	24.87%
Program O	4.30%	7.16%	11.46%

Figure 8 shows the distribution of the SE/PM values as well as descriptive statistics utilized in the Comparison Analysis section of this chapter.



Quantiles		
100%	maximum	0.3652
75%	quartile	0.24435
50%	median	0.14095
25%	quartile	0.111175
0%	minimum	0.0364

Summary Statistics	
Mean	0.1775429
Std Dev	0.0950309
N	14

Figure 8. SE/PM Descriptive Statistics

Figure 8 shows the resulting SE/PM distribution consists of 14 programs with a mean of 0.178 and standard deviation of 0.095. The distribution is ranged from 0.036 to 0.365 and a median of 0.141 indicates it is right-skewed. These descriptive statistics for the SE/PM element will be further discussed and compared to published EMD cost factors in the Comparison Analysis section of this chapter.

Given the small sample size of the data, the jackknife procedure was performed on the cost factor descriptive statistics in order to identify outliers and bias in statistical estimates. This procedure is a resampling technique that is a special case of the bootstrap (Efron & Stein, 1981). A jackknife estimator of a parameter is found by systematically removing an observation from the dataset, calculating the estimate, and then finding the average of those calculations. For example, descriptive statistics were calculated for the 14 different datasets, all of which were composed of 13 programs. The mean, accompanying 95% confidence interval (CI), and minimum and maximum values were then calculated for each descriptive statistic. The results of the jackknife procedure can be seen in Table 10. A comparison of the jackknife means and the original descriptive statistics of the SE/PM cost factor are found to be similar with small confidence intervals. These results suggest the cost factor data for SE/PM is free of any outliers and bias.

Table 10. SE/PM Jackknife Procedure Results

	Mean	95% CI	Min	Max
Mean	0.1775	(0.1733, 0.1818)	0.1631	0.1884
Std Dev	0.0949	(0.0919, 0.0979)	0.0814	0.0989
Max	0.3632	(0.3588, 0.3676)	0.3368	0.3652
75%	0.2440	(0.2423, 0.2458)	0.2389	0.2458
Median	0.1410	(0.1401, 0.1418)	0.1396	0.1423
25%	0.1093	(0.1076, 0.1110)	0.1078	0.1147
Min	0.0409	(0.0311, 0.0507)	0.0364	0.0998

ST&E

System, Test and Evaluation (ST&E) was the second most common traditional WBS element reported within the CPRs. From the 15 programs in the final dataset, 12 of them displayed cost elements relating to ST&E. The three programs which did not have an ST&E cost element were removed from the ST&E analysis. The final factor calculations for ST&E can be seen in Table 11.

Table 11. Final ST&E Factor Calculations

Program Title	System Test & Evaluation
Program A	1.78%
Program B	
Program C	13.13%
Program D	70.85%
Program E	
Program F	0.40%
Program G	7.89%
Program H	3.76%
Program I	58.43%
Program J	
Program K	0.54%
Program L	28.94%
Program M	39.48%
Program N	1.31%
Program O	26.70%

Figure 9 shows the distribution of the SE/PM values as well as descriptive statistics utilized in the comparison analysis in the next section of this chapter.

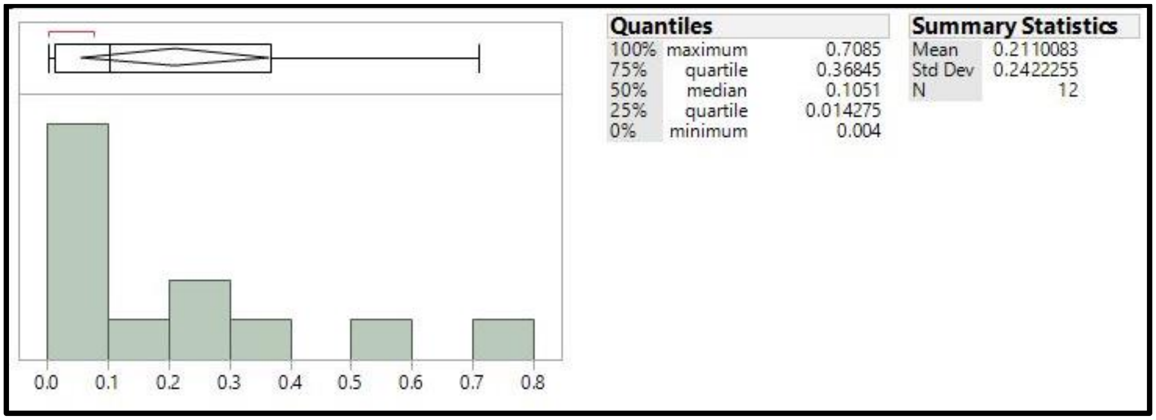


Figure 9. ST&E Descriptive Statistics

The resulting ST&E distribution has a mean of 0.211 and standard deviation of 0.242. The distribution ranged from 0.004 to 0.709 and a median of 0.105 indicates it is also right-skewed. These descriptive statistics for the ST&E element will be further discussed and compared to EMD cost factors in the next section of this chapter.

The jackknife procedure was performed on the ST&E cost factor descriptive statistics as well. The results can be seen in Table 12. A comparison of the jackknife means and the original descriptive statistics of the ST&E cost factor are found to be similar. However, the confidence intervals are found to be larger when compared to the SE/PM confidence intervals. This is largely contributed to the distance between the minimum and maximum values, specifically with the 75% quartile and maximum statistics. These results suggest the cost factor data for ST&E has some degree of variability and should be utilized with caution.

Table 12. ST&E Jackknife Procedure Results

	Mean	95% CI	Min	Max
Mean	0.2110	(0.1970, 0.2250)	0.1658	0.2298
Std Dev	0.2417	(0.2308, 0.2526)	0.1938	0.2534
Max	0.6982	(0.6754, 0.7209)	0.5843	0.7085
75%	0.3685	(0.3382, 0.3987)	0.2894	0.3948
Median	0.1051	(0.0877, 0.1225)	0.0789	0.1313
25%	0.0143	(0.0129, 0.0156)	0.0131	0.0178
Min	0.0041	(0.0039, 0.0044)	0.0040	0.0054

Correlation Analysis

The programs in this dataset are at various stages of completion. Because of this, the relationship between the factors and program completion percentage should be studied to further explore these cost factors. A multivariate correlation analysis was conducted on both sets of individual factors along with their respective program completion percentages. This analysis summarizes the strength of the linear relationships between each pair of variables. Results of this analysis can be seen in Table 13.

Table 13. SE/PM, ST&E, and %Complete Correlation Results

	SE/PM	ST&E	% Complete
SE/PM	1.0000	-0.3861	-0.3346
ST&E	-0.3861	1.0000	0.0904
% Complete	-0.3346	0.0904	1.0000

Correlations are found to be negatively weak between SE/PM vs. ST&E and SE/PM vs. %Complete, with values of -0.3861 and -0.3346 respectively. Further, there is very little correlation between ST&E vs. %Complete, with a value of 0.0904. These results indicate that there are little to weak linear relationships between the individual cost factors and program completion percentage as well as between the factors themselves.

Comparison Analysis

Once composite factors are created for SE/PM and ST&E, descriptive statistics are calculated to include interquartile ranges to examine and compare the variability between the factors. These characteristics allow for a descriptive comparison analysis with the published EMD factors from Markman et al. (2019). The EMD phase happens early in the acquisition lifecycle (pre-Milestone C) but after the Material Solution Analysis and Technology Maturation phases (pre-Milestone B). EMD occurs early enough where analogy and factor methods for cost estimating are commonly used, which makes the case for a comparison with S&T factors. If the EMD and S&T factors are comparable, it could provide a more robust dataset for S&T cost analysts to utilize.

Markman et al. (2019) used 102 MDAPs from the Cost Assessment Data Enterprise (CADE) to develop their cost factors. These factors were grouped into categories such as commodity type, contract type, development type, contractor type, and Service. Due to the unique nature of S&T programs, the development type subcategories (modification, new design, prototype, subsystem, new Mission Design Series (MDS) designator, and commercial derivative) are the most analogous with these programs. More specifically, the prototype and new design are found to be the similar subcategories when comparing to S&T programs. For this reason, the development type category of EMD cost factors was used for this comparison analysis.

SE/PM

The comparison analysis of the SE/PM S&T factor against the SE/PM EMD Development Type factors can be seen in Table 14.

Table 14. SE/PM – S&T vs. EMD Development Type Factor Descriptive Statistics

	N	Mean	Std Dev	Max	75%	Median	25%	Min	MAPE
S&T Programs	14	0.1775	0.0950	0.3652	0.2444	0.1409	0.1112	0.0364	
EMD Modification	124	0.3484	0.2555	1.3191	0.4954	0.2845	0.1539	0.0043	
Absolute Percent Error		96.2%	168.9%	261.2%	102.7%	101.9%	38.4%	88.2%	122.5%
EMD New Design	131	0.4738	0.3472	1.4655	0.6582	0.3759	0.2190	0.0053	
Absolute Percent Error		166.9%	265.4%	301.3%	169.3%	166.7%	97.0%	85.5%	178.9%
EMD Prototype	8	0.1906	0.1472	0.3900	0.3417	0.1783	0.0627	0.0126	
Absolute Percent Error		7.4%	54.9%	6.8%	39.8%	26.5%	43.6%	65.4%	34.9%
EMD Subsystem	101	0.3730	0.2816	1.3240	0.5343	0.2793	0.1610	0.0105	
Absolute Percent Error		110.1%	196.3%	262.6%	118.6%	98.2%	44.8%	71.2%	128.8%
EMD New MDS Designator	39	0.3249	0.2924	1.3619	0.3887	0.2517	0.1154	0.0445	
Absolute Percent Error		83.0%	207.7%	272.9%	59.1%	78.6%	3.8%	22.1%	103.9%
EMD Commercial Derivative	3	0.1840	0.1011	0.2676	0.2676	0.2128	0.0716	0.0716	
Absolute Percent Error		3.6%	6.4%	26.7%	9.5%	51.0%	35.6%	96.5%	32.8%

For each EMD development type subcategory, the absolute percent error between each EMD and S&T value was calculated. These percent errors are then averaged to compute the Mean Absolute Percent Error (MAPE) for each subcategory. The lower the MAPE is, the closer the comparison. Commercial derivative and prototype have the lowest MAPEs with commercial derivative being lowest. When only observing the MAPE of the mean and median percentage errors, prototype has the lowest MAPE (16.9% compared to 27.3%). Between these two subcategories, S&T programs are more closely analogous to prototypes, which are programs whose intent is to test an emerging capability for future utilization. The S&T and prototype values also lie within close proximity to one another within each descriptive statistic. These results suggest cost analysts may be able to use the more robust EMD factor dataset from the *prototype subcategory* when developing cost estimates for S&T SE/PM cost elements.

One caution to the conclusion that S&T and EMD prototype cost factors are similar warrants consideration. It is important to note that the sample size for both the S&T and EMD prototype programs (14 and 8, respectively) are small. This means that as new programs are added to either the EMD or S&T dataset, there is the potential for these new programs to have large effects on the descriptive statistics, thereby changing these results. In contrast, if the existing number of programs for S&T and EMD prototypes had been large, any additional program data would have smaller effects on the descriptive statistics. The recommended combination of the current S&T and EMD prototype data for cost analyst usage partially mitigates this concern.

ST&E

The comparison analysis of the ST&E S&T factors against the ST&E EMD Development Type factors can be seen in Table 15.

Table 15. ST&E – S&T vs. EMD Development Type Factor Descriptive Statistics

	N	Mean	Std Dev	Max	75%	Median	25%	Min	MAPE
S&T Programs	12	0.2110	0.2422	0.7085	0.3685	0.1051	0.0143	0.0040	
EMD Modification	119	0.2155	0.2193	1.0776	0.2986	0.1396	0.0623	0.0013	
Absolute Percent Error		2.1%	9.5%	52.1%	19.0%	32.8%	336.4%	67.2%	74.1%
EMD New Design	114	0.2143	0.1880	1.0575	0.3040	0.1817	0.0611	0.0016	
Absolute Percent Error		1.6%	22.4%	49.3%	17.5%	72.9%	328.0%	59.6%	78.7%
EMD Prototype	9	0.2673	0.1028	0.4561	0.3250	0.2820	0.1792	0.1177	
Absolute Percent Error		26.7%	57.6%	35.6%	11.8%	168.3%	1155.3%	2873.7%	618.4%
EMD Subsystem	89	0.1744	0.1883	0.8523	0.2378	0.1038	0.0428	0.0012	
Absolute Percent Error		17.3%	22.3%	20.3%	35.5%	1.2%	199.8%	69.7%	52.3%
EMD New MDS Designator	39	0.2934	0.2281	0.9436	0.4288	0.2456	0.0987	0.0083	
Absolute Percent Error		39.0%	5.8%	33.2%	16.4%	133.7%	591.4%	109.7%	132.7%
EMD Commercial Derivative	4	0.1804	0.1432	0.3659	0.3280	0.1585	0.0548	0.0388	
Absolute Percent Error		14.5%	40.9%	48.4%	11.0%	50.8%	283.9%	880.3%	190.0%

The EMD development type subcategory, subsystem, has the lowest MAPE. When only observing the MAPE of the mean and median percentage errors, subsystem still has the lowest difference, 9.3%, with modification being a close second at 17.5%. However, S&T programs are not functionally similar to modifications or subsystems. Rather, they are more closely aligned with prototypes and new designs. The prototype subcategory cost factors, however, are the least comparable to S&T programs, as shown by the largest MAPE of 618.4%. These results suggest that the EMD factor dataset should *not* be used for the ST&E cost element.

Phase I Summary

In summary, the results of the Phase 1 analysis led to the creation of two cost factors: SE/PM and ST&E. During the factor development process, it was found that S&T program reports do not contain many of the common WBS elements traditionally found in MDAPs. A comparison analysis of these S&T factors with published EMD factors determined that the prototype EMD subcategory may work as a proxy for the

SE/PM element. However, it was also determined that no EMD factors work for the ST&E element.

Phase 2 – S&T Program Behavioral Analysis

Data

The data for Phase 2 was obtained from AFRL in the form of Funds and Man-Hour Expenditure Reports (FMER) and Research Summary Reports. Much like the Phase 1 data obtained from CPRs, the reported cost elements on FMERs do not follow any formal WBS structure nor do they contain the traditional cost elements as found in MIL-STD-881D. Rather, the elements reported in the S&T FMERs include accounting elements such as direct labor, materials and parts, and travel. Since traditional cost factors cannot be developed from these elements, data from Research Summary Reports were analyzed in order to study S&T program characteristics. Of the 165 programs obtained, 43 contained the necessary data to study the behavior of S&T programs. These 43 programs are listed in Appendix C. Table 16 provides the exclusion criteria and associated number of programs remaining in the Phase 2 analysis.

Table 16. Dataset Exclusions

Category	Number Removed	Remaining Programs
Programs Obtained from AFRL		165
No Usable Cost Elements	64	101
Inadequate TD Sample Size	10	91
Less Than 92.5% Complete	48	43
Final Dataset for Analysis		43

Contingency Table Analysis

The dataset largely consists of qualitative variables. Therefore, a 2x2 contingency table analysis is employed to examine the relationships between the various variable combinations. Using the chi-square distribution as the test statistic, relationships are identified when Pearson's chi-squared test is significant at a p-value of less than 0.10.

The null hypothesis of Pearson's chi-squared test is that the two classifications are independent. If there is a failure to reject the null, the two variables are not statistically related to one another. If the null is rejected, then the variables are dependent, and a statistical relationship exists between them. For highly significant results (p-value < 0.01), the odds ratio and its associated confidence interval are analyzed. This ratio is a measure of association and used to interpret the results. It is important to note the possibility of spurious relationships. Spurious relationships occur when the two variables are associated, but not causally related, possibly due to an unknown mediating variable. With the sheer number of 2x2 tables generated in this analysis, spurious relationships are possible. Therefore, only highly statistically significant results (p-value < 0.01) will be studied in detail while the other significant variables are observed solely as potential findings.

The dataset consisted of 22 variables: two categorical qualitative variables and 20 categorical dummy variables. The two categorical qualitative variables, Technical Directorate (TD) and Performance Type, each consist of two different categories. The 20 categorical dummy variables were created with logical break values and percentages derived from the literature or from distributional analysis. Table 6 provides a summary of these breakpoints and Appendix D presents all contingency table analyses for TD, performance type, and technology readiness levels (TRL).

Technical Directorate (TD)

The TD categorical variable denotes which AFRL directorate is the lead on the respective program, which is either RH (Airman Systems) or RQ (Aerospace Systems). Analyzing the TD variable resulted in 21 contingency tables to be tested for significance. Three variables were significant at an alpha of 0.10 and three were significant at an alpha of 0.05. The full set of test results are provided in Table 17.

Table 17. Significant Contingency Tables for Technical Directorate

Variable	TD
Performance Type	
TRL Increase	**
Last Known TRL ≥ 6	
Final TRL ≥ 6	
TRL 1-3	
TRL 4-5	
TRL 6-7	
TRL 8-9	
Schedule Growth > 0%	
Schedule Growth > 33% (Median)	**
Schedule Growth > 63% (Mean)	*
Contract Value > $1.0M (Median)	
Contract Value > $3.0M (Mean)	
Cost Growth > 0%	*
Cost Growth > 33.7% (DoD Dev - Median)	
Cost Growth > 44.1% (AF Dev - Median)	
Cost Growth > 56.5% (DoD Dev - Mean)	
Cost Growth > 60.5% (AF Dev - Mean)	
Cost Growth > 68% (Mean)	
% Direct Labor > 30% (Median)	*
% Direct Labor > 35% (Mean)	**
Total Significant Contingency Tables:	6

Table Legend:
* p-value < 0.10
** p-value < 0.05
*** p-value < 0.01

TRL Increase is the only TRL variable type with a statistically significant relationship to Technical Directorate. This test suggests that it is more probable to have a program's TRL increase with RQ (Aerospace Systems) programs compared to RH (Airman/Human Systems) programs. The RQ programs are comprised primarily of engine and propulsion (hardware) system technologies. The ability to transition RQ through TRL levels may be due to the relationship of hardware versus software (human systems interactions). It is likely easier to make more distinct determinations on the state of hardware technologies as the testing, failures, and efficiencies may be more conclusive.

Similarly, the contingency table results suggest that RQ programs are more probable to have cost growth as well as schedule growth that is greater than 33% (the dataset's median) and 63% (the dataset's mean). This could be related to the maturing technology (increasing the TRL) of RQ programs. If the technology is maturing, a program office is more likely to increase funding and schedule to keep the maturation on track. If the technologies do not mature, it could be that the agile nature of S&T programs allow for early decision to cancel programs. Finally, contingency table results suggest that it is more probable to have a direct labor percentage greater than 30% (the dataset's median) and 35% (the dataset's mean) with RH programs. As discussed earlier, RH programs develop technologies that interface with the warfighter and optimize physical and cognitive performance. These types of programs could utilize more direct labor due to their human element than the RQ programs that deal with hardware such as rockets, compressors, and propulsion systems.

In summary, the results suggest that RQ programs are more likely to technologically mature, have cost growth, and have schedule growth (greater than 33% and 63%) when compared to RH programs. Furthermore, the results also suggest that RH programs are more likely to be compromised of direct labor (greater than 30% and 35%) than RQ programs.

Performance Type

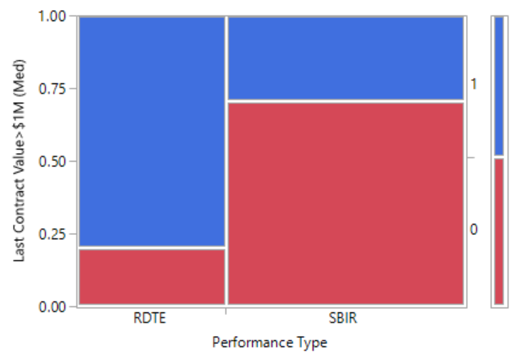
The performance type variable represents the partnership method between AFRL and the contractor, which consists of Research, Development, Test & Evaluation (RDT&E) and Small Business Innovative Research (SBIR) relationships. This variable formed 21 contingency tables to be tested for significance. One variable was significant at an alpha of 0.10, three variables were significant at an alpha of 0.05, and two variables were significant at an alpha of 0.01. The full set of test results is provided in Table 18.

Table 18. Significant Contingency Tables for Performance Type

Variable	Performance Type
TD	
TRL Increase	
Last Known TRL ≥ 6	**
Final TRL ≥ 6	**
TRL 1-3	
TRL 4-5	
TRL 6-7	
TRL 8-9	
Schedule Growth > 0%	*
Schedule Growth > 33% (Median)	
Schedule Growth > 63% (Mean)	
Contract Value > $1.0M (Median)	***
Contract Value > $3.0M (Mean)	***
Cost Growth > 0%	
Cost Growth > 33.7% (DoD Dev - Median)	
Cost Growth > 44.1% (AF Dev - Median)	
Cost Growth > 56.5% (DoD Dev - Mean)	
Cost Growth > 60.5% (AF Dev - Mean)	
Cost Growth > 68% (Mean)	
% Direct Labor > 30% (Median)	
% Direct Labor > 35% (Mean)	**
Total Significant Contingency Tables:	6

Table Legend:
* p-value < 0.10
** p-value < 0.05
*** p-value < 0.01

Table 18 test results suggest that an S&T program with an RDT&E performance type is more likely to have, and end up with, a TRL of at least 6. When compared to RDT&E, the SBIR programs are developed by small domestic businesses which provides potential to stimulate high-tech innovation. RDT&E programs are dominated by the larger, more experienced defense contractors. Perhaps these results suggest that the larger defense contractors obtain the contracts with the more mature technologies due to their capacity and ability to develop these technologies when compared to the SBIR businesses. Furthermore, the results suggest that it is more probable to have contract values greater than $1M (the dataset's median) with RDT&E performance types, as seen in Figure 10.



Contingency Table

Last Contract Value>$1M (Med)

Performance Type (Count / Expected)	0	1	Total
RDTE	3 7.69231	12 7.30769	15
SBIR	17 12.3077	7 11.6923	24
Total	20	19	39

Tests

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

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

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.102941	0.022042	0.480764

Figure 10. Contingency Table of Performance Type by Contract Value > $1M

Testing significance when the contract value is greater than $3M produces similar results, with an even smaller p-value. This could also be due to the differences in the types of contractors regarding RDT&E and SBIR programs. It suggests that the larger defense contractors obtain more funding because they are considered more established while the small businesses obtain lessor amounts. SBIR programs deal with uncertain and risky technologies that small businesses research so that AFRL can see which programs have the potential to develop into mature technologies. The uncertainty and risk of these programs contribute to lower contract values. In fact, the odds ratio indicates that given the program has a SBIR performance type, the odds of the contract value being less than $1M is 9.7 times higher than when the program has an RDT&E performance type.

The contingency test results also suggest that a program with a SBIR performance type is more likely to have schedule growth. With test results indicating that RDT&E programs are more likely to have higher TRL levels, the opposite could be said that SBIR programs are more likely to have lower TRL levels. Less is known about these immature technologies which could lead these small businesses to spend more time developing them, leading to schedule slippage. This result is consistent with the literature findings of Dubos et al. (2008). Lastly, contingency table results suggest that a program with a performance type of RDT&E is more likely to have a direct labor percentage greater than 35% (the dataset's mean). When considering the contractor differences between RDT&E and SBIR programs, these results could suggest that the larger defense contractors employ more expensive labor than the small businesses, and thus have a higher direct labor percentage.

In summary, the results suggest that an S&T program that has a performance type of RDT&E is more likely to have a TRL of 6 or more and a direct labor percentage greater than 35%. Furthermore, highly significant results points to evidence that a program that has a performance type of RDT&E is more likely to have a contract value greater than $1M. Lastly, the results suggest that SBIR programs are more likely to experience schedule growth.

Technology Readiness Level (TRL)

TRL data was utilized in the creation of seven different categorical dummy variables. TRL Increase indicates if the TRL increases during the program's lifecycle, Last Known TRL ≥ 6 denotes the last reported TRL of the program, and Final TRL ≥ 6 only analyzes programs that have a Final Research Summary Report, and thus a final TRL. For the six programs that had a last known TRL of at least 6, four of them provided a final TRL. Lastly, four dummy variables were created grouping TRLs based on the maturity of the technology and the product's requirements. These variables produced 91 contingency tables to be tested for significance. Seven variables were significant at an alpha of 0.10, four variables were significant at an alpha of 0.05, and one variable was significant at an alpha of 0.01. Even with significant Pearson p-values, the contingency table results for the seven variables significant at an alpha of 0.10 were found to be invalid. For all seven tests expected counts of two of the four cells were less than 5. This violates an assumption for a valid chi-squared contingency table test which states the sample size should be large enough so that the estimated expected count will be equal to 5 or more. As a further check, Fisher's Exact Test results were found to be non-significant for all seven tests. This was largely due to the small number of programs with a TRL of 6-7 (5) and a Final TRL of ≥ 6 (4). The full set of test results is provided in Table 19.

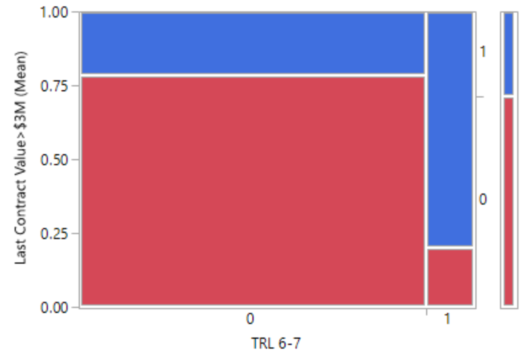
Table 19. Significant Contingency Tables for Technology Readiness Level

Variable	TRL Increase	Last Known TRL ≥ 6	Final TRL ≥ 6	TRL 1-3	TRL 4-5	TRL 6-7	TRL 8-9
Schedule Growth > 0%		**	$*_1$			$*_1$	
Schedule Growth > 33% (Median)							
Schedule Growth > 63% (Mean)							
Contract Value > $1.0M (Median)				**			
Contract Value > $3.0M (Mean)		**				***	
Cost Growth > 0%						$*_1$	
Cost Growth > 33.7% (DoD Dev - Median)						$*_1$	
Cost Growth > 44.1% (AF Dev - Median)						$*_1$	
Cost Growth > 56.5% (DoD Dev - Mean)						$*_1$	
Cost Growth > 60.5% (AF Dev - Mean)						$*_1$	
Cost Growth > 68% (Mean)						**	
% Direct Labor > 30% (Median)							
% Direct Labor > 35% (Mean)							
Total Significant Contingency Tables:	**0**	**2**	**1**	**1**	**0**	**8**	**0**

Table Legend:
$*_1$ p-value < 0.10, 50% of Expected Counts < 5, Non-significant Fisher's Exact Test
* p-value < 0.10
** p-value < 0.05
*** p-value < 0.01

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

Table 19 results also suggest that an S&T program is *more* likely to have contract values greater than $3M (the dataset's mean) with a TRL of 6 or greater and *less* likely to have contract values greater than $1M (the dataset's median) with a TRL of 1 thru 3. The explanation is consistent with the aforementioned cost growth finding. As the program's technology matures, additional investments are made, as shown in the contingency analysis results in Figure 11. In fact, the odds ratio indicates that given the program has a TRL of 6 or 7, the odds of the contract value being greater than $3M is 14.5 times higher than a program with a TRL other than 6 or 7.



Contingency Table

Last Contract Value>$3M (Mean)

TRL 6-7	Count / Expected	0	1	Total
0	Count	29	8	37
	Expected	26.4286	10.5714	
1	Count	1	4	5
	Expected	3.57143	1.42857	
Total		30	12	42

Tests

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

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

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
14.5	1.415167	148.5691

Figure 11. Contingency Table of TRL 6-7 by Contract Value > $3M

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

Growth Relationships

As previously shown, variables for TD, performance type, and TRL were tested for their relationships with cost growth, schedule growth, and contract value variables. An analysis was conducted with the latter variables to analyze their relationships to each other. This analysis produced 63 contingency tables to be tested for significance. Eight variables were significant at an alpha of 0.10, eleven variables were significant at an alpha of 0.05, and 22 variables were significant at an alpha of 0.01. The full set of test results is provided in Table 20.

Table 20. Significant Contingency Tables for Growth Relationships

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

Table Legend:
- * p-value < 0.10
- ** p-value < 0.05
- *** p-value < 0.01

The contingency table results suggest that it is more probable for S&T programs with larger contract values to experience cost growth. Observing cost growth relationships against the original two contract value variables (using the mean and median of the dataset) provided highly significant results. To fully explore this finding more, additional contract value variables were created with lower and higher breakpoints. This additional analysis found contract values greater than $0.9M to be the breakpoint, where only the cost growth greater than 0% (or, any cost growth) resulted in a significant p-value. As the contract value variable increased, additional cost growth variables displayed statistical significance until all were significant at a contract value of $3.0M. This suggests that cost growth and contract value have a positive correlation with each other.

Table 20 results also suggest that it is more probable for S&T programs with contract values greater than $0.9M to experience schedule growth above the median and mean (i.e. greater than 33% and 63%, respectively). This was the only contract value variable to result in significant p-values when tested with schedule growth variables. These results imply that programs with contract values less than $0.9M are less likely to experience schedule growth.

Finally, the results suggest that if S&T programs are experiencing schedule growth, it is more likely that they're also experiencing cost growth. This seems to contradict the findings that programs with mature technologies are more likely to experience cost growth while being less likely to experience schedule growth. But further analysis of these results suggests that programs with large schedule growth percentages are even more likely to experience cost growth at all amounts. This is because it is the immature technology programs that are experiencing both the schedule and cost growth.

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

Phase II Summary

The results of the Phase II analysis led to several potential findings through a contingency table analysis. Relationships with the technical directorate suggested that RQ programs are more likely to technologically mature, have cost growth, and have schedule growth greater than the median and mean. Additionally, RH programs are more likely to be compromised of direct labor. An analysis of the performance type suggested that RDT&E programs are more likely to have a TRL of 6 or more, contract value greater than $1M and $3M, and a direct labor percentage greater than the mean. Furthermore, programs with mature technologies are more likely to experience cost growth and have large contract values but are less likely to experience schedule growth. Also, the results suggest that programs with immature technologies are less likely to have larger contract values. Moreover, programs with larger contract values experience cost growth while programs with small contract values are less likely to experience schedule growth. Finally, programs with schedule growth are more likely to have cost growth.

Chapter Summary

This chapter examined the statistical analysis conducted for both phases of this research. The analysis in Phase 1 (Factor Development) provided a brief overview of the dataset while presenting the factor development and descriptive statistics for the two standard cost factors created. A comparison analysis with published EMD factors was conducted to examine similarities for the potential use of a more robust dataset. Phase 2 (S&T Program Behavioral Analysis) provided results of contingency table analyses which observed significant relationships between multiple categorical variables. The next chapter will further discuss these results and provide the conclusions drawn from this research and analysis.

V. Conclusions

Chapter Overview

This chapter utilizes the analysis and results from the previous chapter to answer the initial research questions. Specific results and findings are presented for each phase of the analysis, if applicable. Finally, the limitations and potential future research are also discussed.

Research Questions Answered

1. What are the program types and/or categories that comprise the S&T portfolio?

An analysis of the complete set of S&T programs is shown in Table 21.

Table 21. S&T Program Category Distributions

TD		Performance Type		Last Known TRL		Report Type	
RD	6	CRDA	3	TRL 1	2	CPR	15
RH	60	CSAE	1	TRL 2	11	FMER	101
RI	1	RDT&E	60	TRL 3	30	Total:	116
RQ	40	SBIR	44	TRL 4	27		
RV	1	Total:	108	TRL 5	24		
RX	2			TRL 6	10		
RY	6			TRL 7	1		
Total:	116			TRL 8	3		
				TRL 9	0		
				Total:	108		

The analysis revealed several different program types, categorized by the lead AFRL technical directorate (TD), which can be seen in Table 1. These program types are largely dominated by RH (Airman Systems) and RQ (Aerospace Systems). S&T programs were also found to be categorized by performance type which represents the partnership method between AFRL and the contractor. S&T program performance types consisted of four different relationships: Research, Development, Test & Evaluation (RDT&E), Small Business Innovative Research (SBIR), Cooperative Research and Development Agreements (CRDA), and Contracted Studies, Analysis and Evaluations (CSAE). These S&T programs are largely comprised of RDT&E and SBIR programs. Each program also consisted of at least an initial, periodic, or final technology readiness level (TRL), which measures the maturity of the technology. The programs are primarily compromised of TRL 3, with the vast majority considered immature technology (TRL 1 – 5). Finally, S&T programs were found to be reported on Contract Performance Reports (CPR) or Funds and Man-Hour Expenditure Reports FMERs.

The reporting nature of the data led to the segregation of the analysis into different phases. Phase 1 (Factor Development) consisted of S&T programs that were reported by the contractor on Contract Performance Reports (CPR). Phase 2 (S&T Program Behavioral Analysis) consisted of S&T programs that were reported by the contractor on Funds and Man-Hour Expenditure Reports (FMER). Descriptive information for various categories can be seen in Table 22 for both of these phases.

Table 22. S&T Program Category Descriptive Information by Phase

	Phase 1	**Phase 2**
Report Type	CPR	FMER
Number of Programs	15	101
Mean Contract Value	$115M	$5M
Median Contract Value	$60M	$1.5M
Contract Value Range	$24M - $510M	$0.1M - $50M
Lead Technical Directorates	**RD**, **RQ**, RV, RY	RD, **RH**, RI, **RQ**, RX, RY
Performance Types	CRDA, **RDT&E**	CRDA, CSAE, **RDT&E**, **SBIR**
Mode(s) of Last Known TRL	5	3 & 4

There are many other differences between these two phases, not only in the program types, but the categories as well. Phase 1 S&T programs had a mean contract value of $115M and a median value of $60M, ranging from $24M to $510M. Phase 2 programs had a mean contract value of $5M and a median value of $1.5M, ranging from $0.1M to $50M. Phase 1 programs only consisted of S&T programs in which RD, RQ, RV, and RY were the lead technical directorates, mainly dominated by RD and RQ. Phase 2 included RD, RQ, and RY, but also RH, RI, and RX, mainly dominated by RH and RQ. S&T program performance type also has differences under each phase. Phase 1 programs are mainly the RDT&E performance type (with one CRDA program) while Phase 2 programs are mainly RDT&E and SBIR (with two CRDA programs and one CSAE program). Lastly, the mode(s) of last known TRLs for phase 1 and phase 2 were 5 and 3 & 4, respectively.

2. What are the salient work breakdown structure (WBS) characteristics of S&T programs? How should the WBS be structured in these programs? Which set of programs is a candidate for cost factor development?

Major Defense Acquisition Programs (MDAP) have a mandated WBS structure that ensures a consistent framework for contract reporting. This research finds S&T program reporting to be fundamentally different than MDAPs. Due to S&T programs occurring early in a program's lifecycle, the program WBS is ill defined. The data for phase 1 was obtained in the form of CPRs, which have no mandated reporting requirement. While most programs have a couple common cost elements, the reported WBS do not follow any formal reporting structure as seen in MIL-STD-881D. Rather, the reporting structure is primarily at the discretion of the respective program. Similar to the CPRs, the reported cost elements on FMERs under phase 2 do not follow any formal WBS structure nor do they contain any traditional cost elements found in MIL-STD-881D. FMERs include accounting elements such as direct labor, materials and parts, and travel. Due to a more standardized reporting vehicle (the CPR document), the CPRs contain a WBS structure that more closely aligned with the standard structure in the MIL-STD-881D. FMERs, however, share very little in common with the standardized reporting found in MIL-STD-881D.

Given the absence of a formal reporting WBS structure for CPRs, one should be recommended. Through a categorization process of all programs and mapping their respective cost elements to traditional WBS elements contained in the MIL-STD-881D, two level 2 WBS elements were consistently found: Systems Engineering and Program Management (SE/PM) and System Test and Evaluation (ST&E). These elements form the basis of the suggested S&T WBS structure. A comparison of a WBS found in MIL-STD-881D and the suggested S&T WBS can be seen in Table 23.

Table 23. MIL-STD-881D WBS and Suggested S&T WBS Comparison

MIL-STD-881D, Appendix A			**Suggested S&T WBS**			
WBS #	Level 1	Level 2	WBS #	Level 1	Level 2	Level 3
1.0	Aircraft System		1.0	S&T System		
1.1		Aircraft System, Integration, Assembly, Test, and Checkout	1.1		System, Integration, Fabrication, Build, Assembly, Test, and Checkout	
1.2		Air Vehicle	1.2		Design	
1.3		Payload/Mission System	1.3		Hardware	
1.4		Ground/Host Segment	1.4		Software	
1.5		Aircraft System Software Release	1.5		Systems Engineering/Program Management	
1.6		Systems Engineering	1.5.1			Systems Engineering
1.7		Program Management	1.5.2			Program Management
1.8		System Test and Evaluation	1.6		System Test and Evaluation	
1.9		Training				
1.10		Data				
1.11		Peculiar Support Equipment				
1.12		Common Support Equipment				
1.13		Operational/Site Activation by Site				
1.14		Contractor Logistics Support (CLS)				
1.15		Industrial Facilities				
1.16		Initial Spares and Repair Parts				

As shown in Table 23, the MIL-STD-881D structure includes many "common" level 2 WBS elements such as training, data, peculiar support equipment, common support equipment, etc. The majority of these elements are not found in S&T programs. Therefore, a streamlined WBS structure with only the salient level 2 WBS elements (SE/PM and ST&E) is recommended. It is important to note that not all WBS elements for a given S&T program would be found in the suggested S&T WBS. These programs are unique, complex, and come in various types as seen within each technical directorate.

3. What new standard cost factors can be produced through analysis of a diverse set of S&T project types?

Cost factors for MDAPs are traditionally developed from level 2 elements found in the MIL-STD-881D formal WBS. These common elements include SE/PM, ST&E, training, data, and common support equipment (CSE). The WBS elements contained in the phase 1 CPR data did not follow the traditional WBS structure and thus did not include many of the traditional level 2 elements. Consequently, cost elements found in the CPRs were mapped to the traditional MIL-STD-881D structure and it was determined that only the SE/PM and ST&E elements were common to both WBS structures and therefore candidates for factor development.

The cost factors developed are the ratio, or percentage, of the individual level 2 WBS element to the program's Prime Mission Equipment (PME) amount. The developed cost factors for SE/PM and ST&E, accompanied by their descriptive statistics, can be seen in Table 24.

Table 24. SE/PM and ST&E Factor Descriptive Statistics

Cost Element	N	Mean	Std Dev	Max	75%	Median	25%	Min
SE/PM	14	0.1775	0.0950	0.3652	0.2444	0.1409	0.1112	0.0364
ST&E	12	0.2110	0.2422	0.7085	0.3685	0.1051	0.0143	0.0040

4. How do the newly created S&T cost factors compare to published EMD factors?

Markman et al. (2019) researched 102 MDAPs and created over 400 cost factors for use in the engineering and manufacturing development (EMD) phase which included statistical testing of factor differences by commodity type, contractor type, contract type, development type, and Service. If S&T factors are comparable to these published EMD factors, cost analysts would have a much more robust dataset of programs to utilize in their estimates. Therefore, a comparison analysis between EMD and S&T factors was conducted. The comparison analysis of the SE/PM S&T factor against the SE/PM EMD development type factors can be seen in Table 25.

Table 25. SE/PM – S&T vs. EMD Development Type Factor Descriptive Statistics

	N	Mean	Std Dev	Max	75%	Median	25%	Min	MAPE
S&T Programs	14	0.1775	0.0950	0.3652	0.2444	0.1409	0.1112	0.0364	
EMD Modification	124	0.3484	0.2555	1.3191	0.4954	0.2845	0.1539	0.0043	122.5%
EMD New Design	131	0.4738	0.3472	1.4655	0.6582	0.3759	0.2190	0.0053	178.9%
EMD Prototype	8	0.1906	0.1472	0.3900	0.3417	0.1783	0.0627	0.0126	34.9%
EMD Subsystem	101	0.3730	0.2816	1.3240	0.5343	0.2793	0.1610	0.0105	128.8%
EMD New MDS Designator	39	0.3249	0.2924	1.3619	0.3887	0.2517	0.1154	0.0445	103.9%
EMD Commercial Derivative	3	0.1840	0.1011	0.2676	0.2676	0.2128	0.0716	0.0716	32.8%

As shown in Table 25, commercial derivatives and prototypes have the lowest Mean Absolute Percentage Errors (MAPE). However, it is not recommended to use commercial derivative data as these types of programs are fundamentally different from S&T programs. In contrast, the EMD prototypes are more analogous to S&T programs.

Additionally, when only observing the MAPE of the mean and median percentage errors, prototype has the lowest MAPE for any development type category. The S&T and prototype factor values lie within close proximity to one another within each descriptive statistic. These results suggest cost analysts may be able to use the more robust EMD factor dataset from the *prototype subcategory* when developing cost estimates for S&T SE/PM cost elements.

The sample size for both the S&T and EMD prototype programs are small, meaning as new programs are added to either dataset, there is the potential for large effects on the descriptive statistics, thereby changing these results. On the other hand, if the existing number of programs had been large, additional program data would have smaller effects on the descriptive statistics. A combination of the current S&T and EMD prototype data for cost analyst usage partially mitigates this concern.

The comparison analysis of the ST&E S&T factor against the ST&E EMD development type resulted in inconclusive findings. The ST&E EMD development type MAPEs can be seen in Table 26.

Table 26. ST&E – EMD Development Type MAPEs Compared to S&T

EMD Development Type	N	MAPE
Modification	119	74.1%
New Design	114	78.7%
Prototype	9	618.4%
Subsystem	89	52.3%
New MDS Designator	39	132.7%
Commercial Derivative	4	190.0%

For the ST&E factor, the MAPE for new design subcategory is third largest and the prototype subcategory is by far the largest which suggests that it is the least comparable to the S&T ST&E factor. The other development type subcategories, even with smaller

MAPEs, are not closely analogous to S&T programs. Thus, cost analysts should not use EMD factor data when developing cost estimates for S&T ST&E cost elements.

Similar to the SE/PM comparative results, the sample size for both the S&T and EMD prototype programs are small. It is recommended that this research should be completed again after more data has been collected for both datasets.

5. What new insights can be garnered from an analysis of S&T program characteristics and program performance? How does the TRL affect S&T program performance?

A 2x2 contingency table analysis was used to examine the relationships between variable combinations. Relationships were identified when Pearson's chi-squared test was significant at a p-value of less than 0.10. Contingency table results for TD, performance type, and various TRL variables are provided in Table 27.

Table 27. Significant Contingency Tables for TD, Performance Type, and TRLs

Variable	TD	Performance Type	TRL Increase	Last Known TRL ≥ 6	Final TRL ≥ 6	TRL 1-3	TRL 4-5	TRL 6-7	TRL 8-9	Total Significant Cont. Tables
TD										
Performance Type										**0**
TRL Increase	**									**1**
Last Known TRL ≥ 6		**								**1**
Final TRL ≥ 6		**								**1**
TRL 1-3										**0**
TRL 4-5										**0**
TRL 6-7										**0**
TRL 8-9										**0**
Schedule Growth > 0%		*		**	$*_1$			$*_1$		**4**
Schedule Growth > 33% (Median)	**									**1**
Schedule Growth > 63% (Mean)	*									**1**
Contract Value > $1.0M (Median)		***				**				**2**
Contract Value > $3.0M (Mean)		***		**				***		**3**
Cost Growth > 0%	*							$*_1$		**2**
Cost Growth > 33.7% (DoD Dev - Median)								$*_1$		**1**
Cost Growth > 44.1% (AF Dev - Median)								$*_1$		**1**
Cost Growth > 56.5% (DoD Dev - Mean)								$*_1$		**1**
Cost Growth > 60.5% (AF Dev - Mean)								$*_1$		**1**
Cost Growth > 68% (Mean)								**		**1**
% Direct Labor > 30% (Median)	*									**1**
% Direct Labor > 35% (Mean)	**	**								**2**
Total Significant Contingency Tables:	**6**	**6**	**0**	**2**	**1**	**1**	**0**	**8**	**0**	**24**

Table Legend:

- $*_1$ p-value < 0.10, 50% of Expected Counts < 5, Non-significant Fisher's Exact Test
- * p-value < 0.10
- ** p-value < 0.05
- *** p-value < 0.01

Analyzing the relationships with the technical directorates (RH and RQ), the results suggest that RQ programs are more likely to technologically mature, have cost growth, and have schedule growth greater than the median (33%) and mean (63%) when compared to RH programs. The results also suggest that RH programs are more likely to be compromised of direct labor than RQ programs. This could be due to the types of programs under each directorate. RQ (Aerospace Systems) programs are comprised primarily of engine and propulsion system technologies while RH (Airman Systems) programs are comprised of technologies interfaced with the warfighter. With more knowledge available with RQ programs, the technology matures faster, increasing the likelihood that a program office would increase funding and schedule to keep the maturation on track.

The results of the performance type analysis suggest that RDT&E programs are more likely to have a TRL of 6 or more, a contract value greater than $1M (median) and $3M (mean), and a direct labor percentage greater than the mean (35%) when compared to SBIR programs. However, SBIR programs are more likely to experience schedule growth due to limited knowledge with immature technologies. RDT&E programs are dominated by the larger defense contractors, which could be the reason why they obtain larger contracts with more mature technologies and employ more expensive labor to keep the technologies maturing.

The relationships with TRLs suggest that programs with mature technologies are more likely to experience above average cost growth and larger contract values while less likely to experience schedule growth. Additionally, the results suggest that programs with immature technologies are less likely to have larger contract values. As technologies mature, additional funds for investments are made which increases costs over their initial contract values. This is likely to happen when the program is met with new and unexpected challenges as the technology integrates into a demonstration effort (TRL 6-8). Linick (2017) found that as the TRL increased throughout the development phase, the percentage of the development cost increased at a faster rate as shown in Figure 12. This literature finding is in agreement with these results.

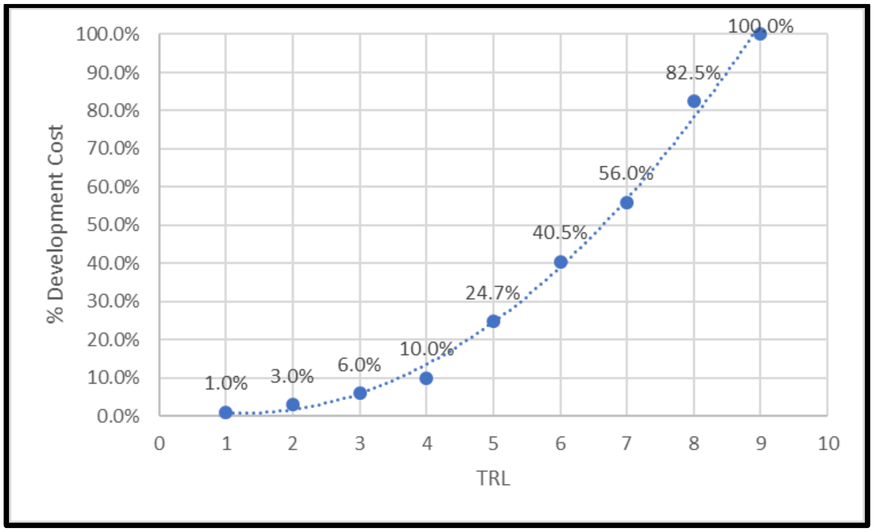


Figure 12. Percent Development Cost vs. TRL Average (Linick, 2017)

Conversely, as these technologies mature there is a broader knowledge base for its development, which increases the chance of meeting schedule requirements.

A contingency table analysis was also conducted with the "growth" variables (cost growth, schedule growth, and contract value) to analyze their relationships to each other. Results of this analysis are provided in Table 28.

Table 28. Significant Contingency Tables for Growth Relationships

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

Table Legend:
* p-value < 0.10
** p-value < 0.05
*** p-value < 0.01

The analysis results suggest that S&T programs with larger contract values experience larger cost growth at the same time programs with smaller contract values are less likely to experience schedule growth. Further analyzing the relationship between cost and schedule growth, the results suggest that programs with larger schedule growth are more likely to have larger cost growth as well. Deeper analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.

Limitations

The major limitation in this research is the reporting requirements, or lack thereof, for S&T programs. Within the datasets for both phases of this research programs had to be excluded for not having usable cost elements to derive factors and other information from. Phase 1 excluded one program for this reason while Phase 2 excluded 64 programs. Furthermore, the informal WBS structures within the CPRs severely limited the number of standard cost factors developed in this research. There are at least eight standard level 2 WBS elements in traditional MDAPs in which cost factors can be created for. This research was only able to develop two.

An important aspect of this research was observing the relationship between a program's TRL and other variables. For each program, Research Summary Reports were supplied at the initial, periodic, and final stages. For Phase 2, out of 43 programs, there were 21 programs that had an initial Research Summary Report, but the initial TRL was not given. Additionally, there were 13 programs in which an initial Research Summary Report was not supplied. In order to adequately study the relationships that TRLs have with other variables, observing the initial TRL is important, especially when determining how/if the TRL increases throughout the program's lifecycle.

Future Research

With the limited amount of previous research into S&T programs, the possibilities of future research are vast. One of the more surprising aspects of the data obtained for these programs was the reported TRL at various stages of the program's lifecycle. In order for a program to advance past Milestone B into the EMD phase, a program must have a TRL of 6 or greater. Further research into those S&T programs whose technology matured (TRL increased) could shed light on potential characteristics these programs have in common which allows for this technological maturity. With the large amounts of defense funding being allocated to research and development programs, finding ways to facilitate the technological maturity of S&T programs would lead to a more efficient use of the taxpayers' dollars.

Final Thoughts

This research expanded knowledge in S&T programs through a two-phased analysis. Phase 1 used data obtained from cost reports to create two standard cost factors. One of these cost factors favorably compares to a published EMD development type subcategory which could open the possibility for cost estimators to utilize a more robust factor dataset when developing estimates. Furthermore, the analysis in this phase also provides a suggested WBS reporting requirement for future S&T programs. This recommended WBS structure can standardize S&T programs in order to provide effective status reporting, risk mitigation, and program structure. Phase 2 explored how various types of S&T programs behaved under certain conditions. This analysis provided insight into the relationships between variables such as AFRL technical directorate, performance type, TRL, cost growth, and schedule growth. The importance of research into S&T programs is crucial based on its early phase in the acquisition lifecycle. Not only is it important to develop new tools in order to accurately and efficiently estimate these programs, but it is equally important to study their characteristics in order to fully understand their behavior. The clearer the behavior is understood, the better grasp program offices have on the program's performance.

Appendix A – TRL Definitions, Descriptions, and Supporting Information

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

TRL	Definition	Description	Supporting Information
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	System/ subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?

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

Appendix B – Sample Research Summary Report

Research Summary Report

General Information

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

Work Unit Manager

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

DoD Required Information

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

Principal Investigator

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

Performing Mechanism

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

Performing Organization

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

WU Funding ($K)

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

Descriptive and Progress/Status

Objective/Restricted

MMM DD, YYYY
12:00:00 AM

Distribution C US Government Agencies and their Contractors only - C-CL Critical Technology (Export Controlled)
Page 1

Research Summary Report

Objective/Restricted
Approach/Restricted

Progress/Restricted From MM/DD/YYYY To MM/DD/YYYY

	MM/DD/YY

Technical Publication

Tech Pub #	Title	Final to DTIC	Final Tech Rpt
		MM/DD/YY	Yes/No
		MM/DD/YY	Yes/No

Research Summary Report

Approvals and Coordinations

Work Unit Manager: ______________________________ **Date:**__________

Branch Chief: ______________________________ **Date:**__________

Division Chief: ______________________________ **Date:**__________

Financial Management: ______________________________ **Date:**__________

Plans & Programs: ______________________________ **Date:**__________

Procurement: ______________________________ **Date:**__________

Other: ______________________________ **Date:**__________

Other: ______________________________ **Date:**__________

Appendix C – Phase 2 Program List

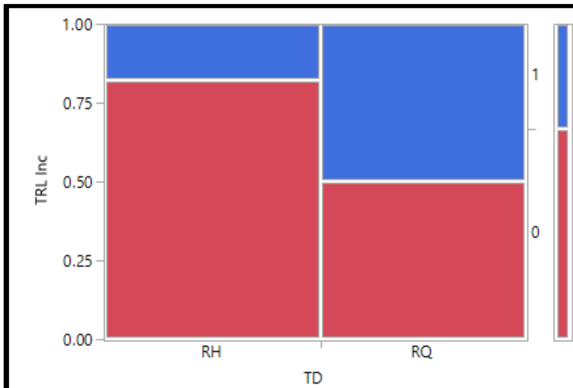
	Program Title
1	Adaptable Toolkit for the Assessment & Augmentation of Performance by Teams in Real Time (ADAPTER)
2	Alternative Aviation Fuels for use in Military Auxiliary Power Units (APU) and Engines
3	Air-Launched, Tube Integrated, Unmanned System (ALTIUS)
4	Guest-Host Liquid Crystal Dimmable Visor
5	Auditory Acoustic Research
6	Full Scale Small Engine Augmentor Development
7	Battlefield Air Targeting Man Aided kNowledge II (BATMAN II)
8	Cyber Operator Augmentation (COA)
9	R&D and Evaluation of Scramjet Concepts and Subsystems for Ignition and Transition (Cold Start for Scramjet)
10	Color Symbology in Helmet Mounted Visors & Heads up Displays
11	Improved Data and Power Transmission - Conductor and Shielding
12	Data fusion of Eddy Current, Ultrasonic, and Radiographic Data for Stealth Aircraft through Data Visualization
13	Efficient Manufacturing of Low Defect Density SiC Substrates using a Novel Defect Capped Planarization Assisted Growth (DC-PAG) Method
14	Enhanced Communications Research
15	Efficient Small Scale Propulsion (ESSP) Core Engine Demo
16	Framework for Adaptive Learning Content Management Delivery (FALCON)
17	Highly Energy Efficient Turbine Engine (HEETE) Compressor / Thermal Management System
18	High Range Resolution Radar for Flightline Boundary Surveillance
19	Rattan Holographic Lightfield 3D Display Metrology (HL3DM)

20	Stereo Binocular Head Mounted Display (HMD) Technology for Joint Strike Fighter (JSF) Aircraft & Simulation
21	Intelligent Course of Action Learning System (iCOALS)
22	Inspection Data Fusion for Large Aircraft
23	Integrated Power and Thermal Management System Development
24	Medium State Critical Components (MSCC) Common Rake Hardware Fabrication
25	Multi-Sensor Fusion Visualization
26	Optimizing Team Performance in Operational Environments
27	Predicting, Analyzing & Tracking Training Readiness & Needs (PATTRN)
28	Prognostic Health Management (PHM) of Electro-Mechanical Actuator (EMA) Systems for Next Generation Military Aircraft
29	Silcon Carbide Vertical Junction Field Effect Transistor (JFET) Power Electronics for More Electronic Aircraft (MEA)
30	System Acquisition Guidance from Expert Systems (SAGES II)
31	Digital Smart Glove Phase II
32	Sense & Avoid Postern Insect Eye/Neuromorphic (SAPIEN) Sensor Technology
33	Scalable One-Panel Liquid Crystal on Silicon (LCoS) System for 4k2k and 8k4k Resolutions
34	Software Suite for Integrated Design of Aerodynamic Shape, Structural Topology, Subsystem Topology, and Structural Sizing of Air Vehicles
35	Sensor Operations via Naturalistic Interactive Control (SONIC)
36	Solid State Electrical Distribution Unit (SSEDU)
37	Technical Knowledge Acquisition
38	TO3 Applied HEL Bioeffects
39	Adaptive Compliant Trailing Edge Flap Flight Demo
40	Unitized Composite Airframe Structures with Three Dimensional Preforms for Elevated Temperature Applications (Performance Polymer)

41	Wide Temperature, High Frequency Capacitors for Aerospace Power Applications
42	Wind Profiling Portable Radar (WiPPR) for Precision Air Drop
43	Zebra Holographic Video Display Phase II

Appendix D – Contingency Table Analysis Results

A contingency table analysis is used to study relationships between variables, identified when Pearson's chi-squared test is significant at a p-value of less than 0.10. This Appendix includes all significant contingency table tests for technical directorate (TD), performance type, and technology readiness levels (TRL) regardless of expected counts and Fisher Exact Test results.



Contingency Table

TRL Inc

TD	Count / Expected	0	1	Total
	RH	14 11.3333	3 5.66667	17
	RQ	8 10.6667	8 5.33333	16
	Total	22	11	33

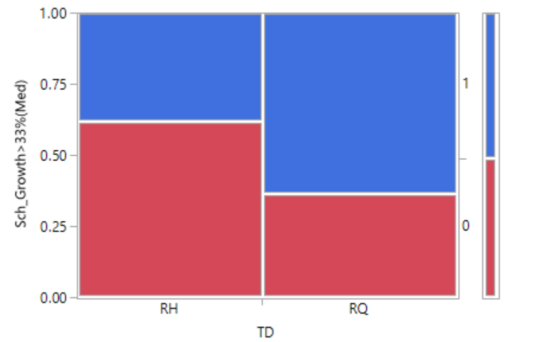
Tests

N	DF	-LogLike	RSquare (U)
33	1	1.9926253	0.0949

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	3.985	0.0459*
Pearson	3.882	0.0488*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9912	Prob(TRL Inc=1) is greater for TD=RH than RQ
Right	0.0540	Prob(TRL Inc=1) is greater for TD=RQ than RH
2-Tail	0.0707	Prob(TRL Inc=1) is different across TD

TRL Increase by TD



Contingency Table

Sch_Growth>33%(Med)

TD	Count / Expected	0	1	Total
	RH	13 / 10.2558	8 / 10.7442	21
	RQ	8 / 10.7442	14 / 11.2558	22
	Total	21	22	43

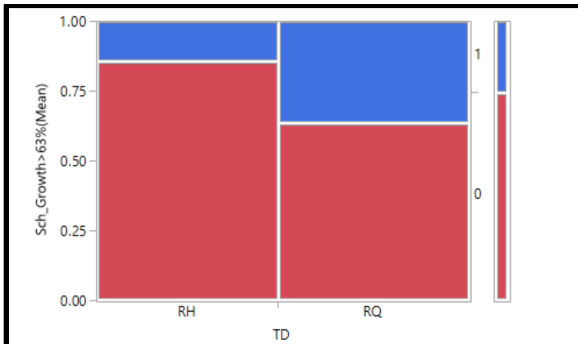
Tests

N	DF	-LogLike	RSquare (U)
43	1	1.4180036	0.0476

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.836	0.0922
Pearson	2.805	0.0940

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9767	Prob(Sch_Growth>33%(Med)=1) is greater for TD=RH than RQ
Right	0.0851	Prob(Sch_Growth>33%(Med)=1) is greater for TD=RQ than RH
2-Tail	0.1308	Prob(Sch_Growth>33%(Med)=1) is different across TD

Schedule Growth > 33% (Median) by TD



Contingency Table

Sch_Growth>63%(Mean)

TD	Count / Expected	0	1	Total
	RH	18 / 15.6279	3 / 5.37209	21
	RQ	14 / 16.3721	8 / 5.62791	22
	Total	32	11	43

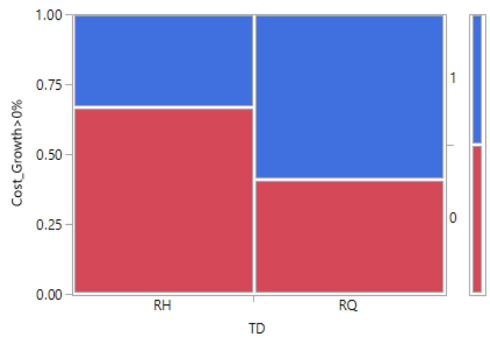
Tests

N	DF	-LogLike	RSquare (U)
43	1	1.4181664	0.0580

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.836	0.0922
Pearson	2.751	0.0972

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9794	Prob(Sch_Growth>63%(Mean)=1) is greater for TD=RH than RQ
Right	0.0946	Prob(Sch_Growth>63%(Mean)=1) is greater for TD=RQ than RH
2-Tail	0.1623	Prob(Sch_Growth>63%(Mean)=1) is different across TD

Schedule Growth > 63% (Mean) by TD



Contingency Table

Cost_Growth>0%

TD	Count / Expected	0	1	Total
	RH	14	7	21
		11.2326	9.76744	
	RQ	9	13	22
		11.7674	10.2326	
	Total	23	20	43

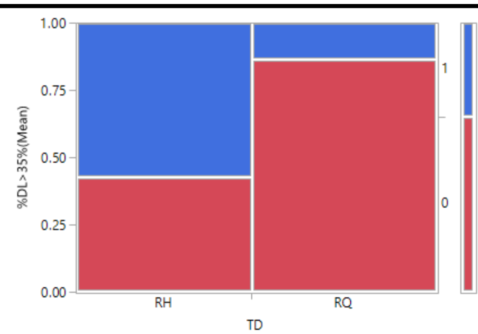
Tests

N	DF	-LogLike	RSquare (U)
43	1	1.4502239	0.0488

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.900	0.0886
Pearson	2.865	0.0905

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9778	Prob(Cost_Growth>0%=1) is greater for TD=RH than RQ
Right	0.0824	Prob(Cost_Growth>0%=1) is greater for TD=RQ than RH
2-Tail	0.1292	Prob(Cost_Growth>0%=1) is different across TD

Cost Growth > 0% by TD



Contingency Table

%DL>35%(Mean)

TD	Count / Expected	0	1	Total
	RH	9	12	21
		13.6744	7.32558	
	RQ	19	3	22
		14.3256	7.67442	
	Total	28	15	43

Tests

N	DF	-LogLike	RSquare (U)
43	1	4.7052990	0.1692

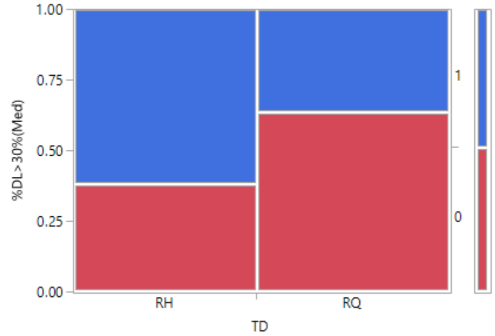
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	9.411	0.0022*
Pearson	8.953	0.0028*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0033*	Prob(%DL>35%(Mean)=1) is greater for TD=RH than RQ
Right	0.9997	Prob(%DL>35%(Mean)=1) is greater for TD=RQ than RH
2-Tail	0.0040*	Prob(%DL>35%(Mean)=1) is different across TD

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.118421	0.026604	0.527125

% Direct Labor > 35% (Mean) by TD



Contingency Table

%DL>30%(Med)

Count / Expected	0	1	Total
RH	8 10.7442	13 10.2558	21
RQ	14 11.2558	8 10.7442	22
Total	22	21	43

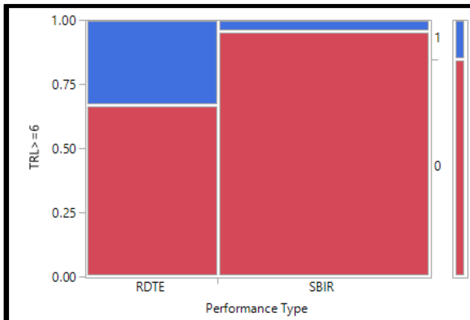
Tests

N	DF	-LogLike	RSquare (U)
43	1	1.4180036	0.0476

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.836	0.0922
Pearson	2.805	0.0940

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0851	Prob(%DL>30%(Med)=1) is greater for TD=RH than RQ
Right	0.9767	Prob(%DL>30%(Med)=1) is greater for TD=RQ than RH
2-Tail	0.1308	Prob(%DL>30%(Med)=1) is different across TD

% Direct Labor > 30% (Median) by TD



Contingency Table

TRL>=6

Count / Expected	0	1	Total
RDTE	10 12.6923	5 2.30769	15
SBIR	23 20.3077	1 3.69231	24
Total	33	6	39

Tests

N	DF	-LogLike	RSquare (U)
39	1	3.0389604	0.1815

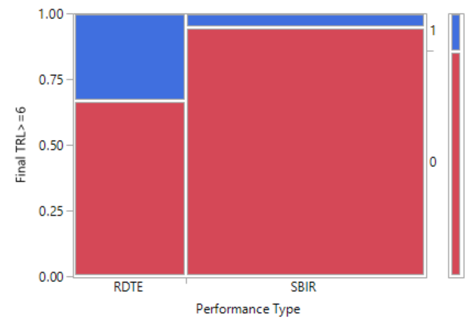
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	6.078	0.0137*
Pearson	6.032	0.0140*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0236*	Prob(TRL>=6=1) is greater for Performance Type=RDTE than SBIR
Right	0.9985	Prob(TRL>=6=1) is greater for Performance Type=SBIR than RDTE
2-Tail	0.0236*	Prob(TRL>=6=1) is different across Performance Type

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.086957	0.008968	0.843174

TRL ≥ 6 by Performance Type



Contingency Table

Final TRL>=6

Performance Type: Count / Expected	0	1	Total
RDTE	6 7.71429	3 1.28571	9
SBIR	18 16.2857	1 2.71429	19
Total	24	4	28

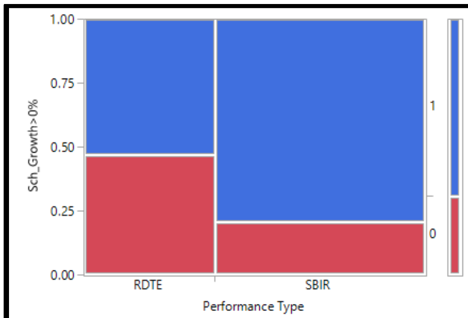
Tests

N	DF	-LogLike	RSquare (U)
28	1	1.8369804	0.1600

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	3.674	0.0553
Pearson	3.930	0.0474*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0841	Prob(Final TRL>=6=1) is greater for Performance Type=RDTE than SBIR
Right	0.9938	Prob(Final TRL>=6=1) is greater for Performance Type=SBIR than RDTE
2-Tail	0.0841	Prob(Final TRL>=6=1) is different across Performance Type

Final TRL ≥ 6 by Performance Type



Contingency Table

Sch_Growth>0%

Performance Type: Count / Expected	0	1	Total
RDTE	7 4.61538	8 10.3846	15
SBIR	5 7.38462	19 16.6154	24
Total	12	27	39

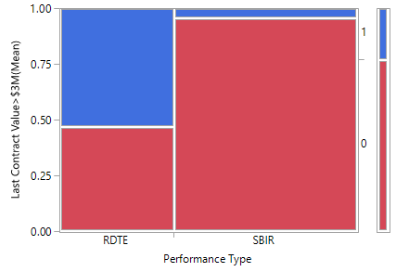
Tests

N	DF	-LogLike	RSquare (U)
39	1	1.4268176	0.0593

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.854	0.0912
Pearson	2.892	0.0890

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9797	Prob(Sch_Growth>0%=1) is greater for Performance Type=RDTE than SBIR
Right	0.0902	Prob(Sch_Growth>0%=1) is greater for Performance Type=SBIR than RDTE
2-Tail	0.1532	Prob(Sch_Growth>0%=1) is different across Performance Type

Schedule Growth > 0% by Performance Type



Contingency Table

Last Contract Value>$3M(Mean)

Performance Type: Count / Expected	0	1	Total
RDTE	7 11.5385	8 3.46154	15
SBIR	23 18.4615	1 5.53846	24
Total	30	9	39

Tests

N	DF	-LogLike	RSquare (U)
39	1	6.5471870	0.3108

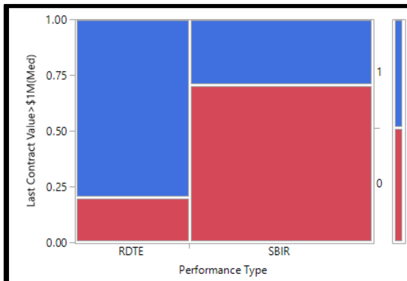
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	13.094	0.0003*
Pearson	12.570	0.0004*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0008*	Prob(Last Contract Value>$3M(Mean)=1) is greater for Performance Type=RDTE than SBIR
Right	1.0000	Prob(Last Contract Value>$3M(Mean)=1) is greater for Performance Type=SBIR than RDTE
2-Tail	0.0008*	Prob(Last Contract Value>$3M(Mean)=1) is different across Performance Type

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.038043	0.004032	0.35894

Contract Value > $3M (Mean) by Performance Type



Contingency Table

Last Contract Value>$1M(Med)

Performance Type: Count / Expected	0	1	Total
RDTE	3 7.69231	12 7.30769	15
SBIR	17 12.3077	7 11.6923	24
Total	20	19	39

Tests

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

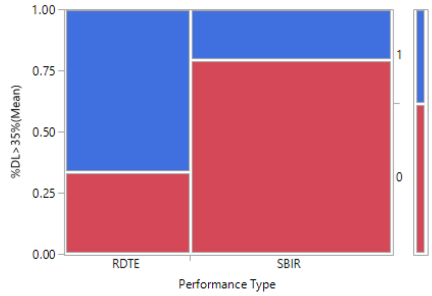
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	10.053	0.0015*
Pearson	9.547	0.0020*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0025*	Prob(Last Contract Value>$1M(Med)=1) is greater for Performance Type=RDTE than SBIR
Right	0.9998	Prob(Last Contract Value>$1M(Med)=1) is greater for Performance Type=SBIR than RDTE
2-Tail	0.0031*	Prob(Last Contract Value>$1M(Med)=1) is different across Performance Type

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.102941	0.022042	0.480764

Contract Value > $1M (Median) by Performance Type



Contingency Table

%DL>35%(Mean)

Performance Type: Count / Expected	0	1	Total
RDTE	5 9.23077	10 5.76923	15
SBIR	19 14.7692	5 9.23077	24
Total	24	15	39

Tests

N	DF	-LogLike	RSquare (U)
39	1	4.1553850	0.1599

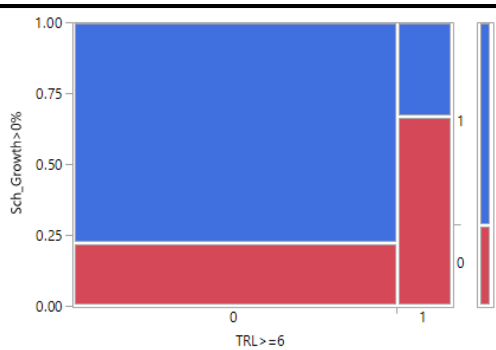
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	8.311	0.0039*
Pearson	8.193	0.0042*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0057*	Prob(%DL>35%(Mean)=1) is greater for Performance Type=RDTE than SBIR
Right	0.9994	Prob(%DL>35%(Mean)=1) is greater for Performance Type=SBIR than RDTE
2-Tail	0.0069*	Prob(%DL>35%(Mean)=1) is different across Performance Type

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.131579	0.030649	0.564889

% Direct Labor > 35% (Mean) by Performance Type



Contingency Table

Sch_Growth>0%

TRL>=6: Count / Expected	0	1	Total
0	8 10.2857	28 25.7143	36
1	4 1.71429	2 4.28571	6
Total	12	30	42

Tests

N	DF	-LogLike	RSquare (U)
42	1	2.2388145	0.0891

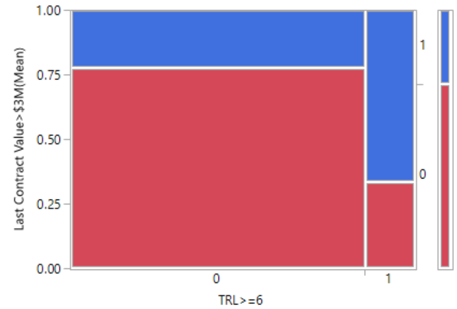
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	4.478	0.0343*
Pearson	4.978	0.0257*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0458*	Prob(Sch_Growth>0%=1) is greater for TRL>=6=0 than 1
Right	0.9953	Prob(Sch_Growth>0%=1) is greater for TRL>=6=1 than 0
2-Tail	0.0458*	Prob(Sch_Growth>0%=1) is different across TRL>=6

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.142857	0.022008	0.927289

Schedule Growth > 0% by TRL ≥ 6



Contingency Table

Last Contract Value>$3M(Mean)

TRL>=6 (Count / Expected)	0	1	Total
0	28	8	36
	25.7143	10.2857	
1	2	4	6
	4.28571	1.71429	
Total	30	12	42

Tests

N	DF	-LogLike	RSquare (U)
42	1	2.2388145	0.0891

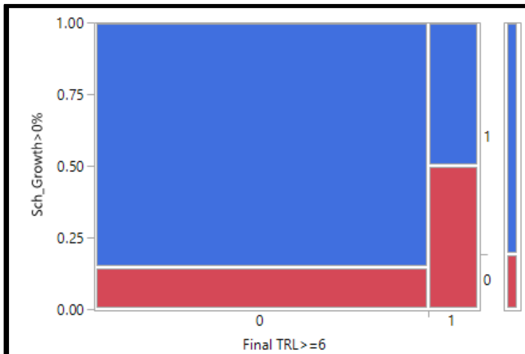
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	4.478	0.0343*
Pearson	4.978	0.0257*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9953	Prob(Last Contract Value>$3M(Mean)=1) is greater for TRL>=6=0 than 1
Right	0.0458*	Prob(Last Contract Value>$3M(Mean)=1) is greater for TRL>=6=1 than 0
2-Tail	0.0458*	Prob(Last Contract Value>$3M(Mean)=1) is different across TRL>=6

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
7	1.078412	45.43716

Contract Value > $3M (Mean) by TRL ≥ 6



Contingency Table

Sch_Growth>0%

Final TRL>=6 (Count / Expected)	0	1	Total
0	4	23	27
	5.22581	21.7742	
1	2	2	4
	0.77419	3.22581	
Total	6	25	31

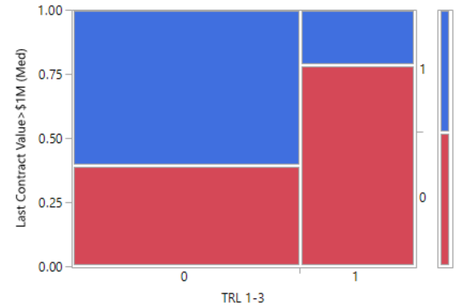
Tests

N	DF	-LogLike	RSquare (U)
31	1	1.1325112	0.0744

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.265	0.1323
Pearson	2.763	0.0965

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.1594	Prob(Sch_Growth>0%=1) is greater for Final TRL>=6=0 than 1
Right	0.9836	Prob(Sch_Growth>0%=1) is greater for Final TRL>=6=1 than 0
2-Tail	0.1594	Prob(Sch_Growth>0%=1) is different across Final TRL>=6

Schedule Growth > 0% by Final TRL ≥ 6



Contingency Table

Last Contract Value>$1M (Med)

TRL 1-3 (Count / Expected)	0	1	Total
0	11 14.6667	17 13.3333	28
1	11 7.33333	3 6.66667	14
Total	22	20	42

Tests

N	DF	-LogLike	RSquare (U)
42	1	3.0301753	0.1043

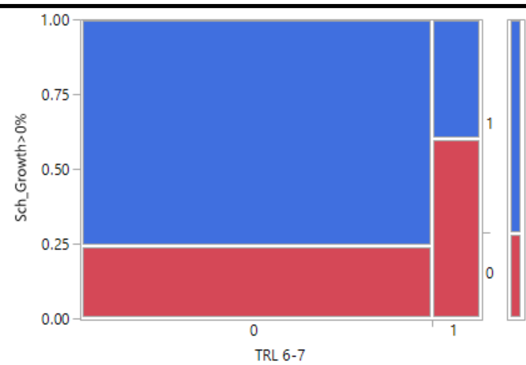
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	6.060	0.0138*
Pearson	5.775	0.0163*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.0177*	Prob(Last Contract Value>$1M (Med)=1) is greater for TRL 1-3=0 than 1
Right	0.9975	Prob(Last Contract Value>$1M (Med)=1) is greater for TRL 1-3=1 than 0
2-Tail	0.0232*	Prob(Last Contract Value>$1M (Med)=1) is different across TRL 1-3

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
0.176471	0.039975	0.779027

Contract Value > $1M (Median) by TRL 1-3



Contingency Table

Sch_Growth>0%

TRL 6-7 (Count / Expected)	0	1	Total
0	9 10.5714	28 26.4286	37
1	3 1.42857	2 3.57143	5
Total	12	30	42

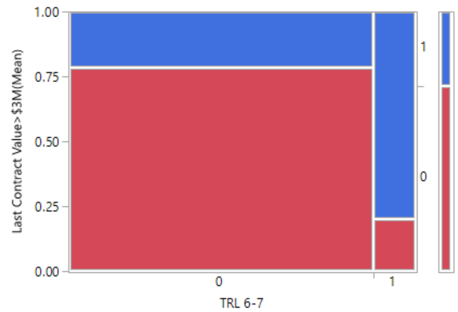
Tests

N	DF	-LogLike	RSquare (U)
42	1	1.2350491	0.0492

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.470	0.1160
Pearson	2.747	0.0974

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.1309	Prob(Sch_Growth>0%=1) is greater for TRL 6-7=0 than 1
Right	0.9816	Prob(Sch_Growth>0%=1) is greater for TRL 6-7=1 than 0
2-Tail	0.1309	Prob(Sch_Growth>0%=1) is different across TRL 6-7

Schedule Growth > 0% by TRL 6-7



Contingency Table

Last Contract Value>$3M(Mean)

TRL 6-7	Count / Expected	0	1	Total
	0	29	8	37
		26.4286	10.5714	
	1	1	4	5
		3.57143	1.42857	
	Total	30	12	42

Tests

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

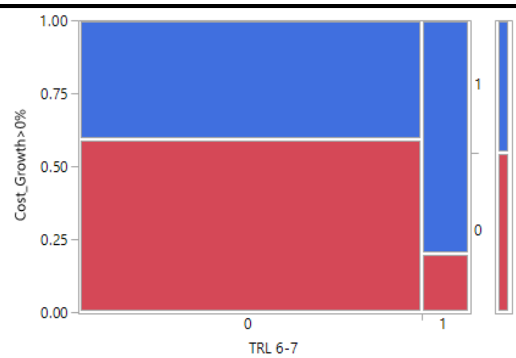
Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	6.617	0.0101*
Pearson	7.356	0.0067*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9991	Prob(Last Contract Value>$3M(Mean)=1) is greater for TRL 6-7=0 than 1
Right	0.0184*	Prob(Last Contract Value>$3M(Mean)=1) is greater for TRL 6-7=1 than 0
2-Tail	0.0184*	Prob(Last Contract Value>$3M(Mean)=1) is different across TRL 6-7

Odds Ratio

Odds Ratio	Lower 95%	Upper 95%
14.5	1.415167	148.5691

Contract Value > $3M (Mean) by TRL 6-7



Contingency Table

Cost_Growth>0%

TRL 6-7	Count / Expected	0	1	Total
	0	22	15	37
		20.2619	16.7381	
	1	1	4	5
		2.7381	2.2619	
	Total	23	19	42

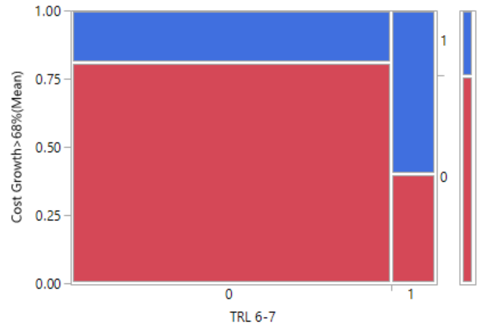
Tests

N	DF	-LogLike	RSquare (U)
42	1	1.4391285	0.0498

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.878	0.0898
Pearson	2.768	0.0961

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9863	Prob(Cost_Growth>0%=1) is greater for TRL 6-7=0 than 1
Right	0.1185	Prob(Cost_Growth>0%=1) is greater for TRL 6-7=1 than 0
2-Tail	0.1580	Prob(Cost_Growth>0%=1) is different across TRL 6-7

Cost Growth > 0% by TRL 6-7



Contingency Table

Cost Growth>68%(Mean)

TRL 6-7	Count / Expected	0	1	Total
	0	30 / 28.1905	7 / 8.80952	37
	1	2 / 3.80952	3 / 1.19048	5
	Total	32	10	42

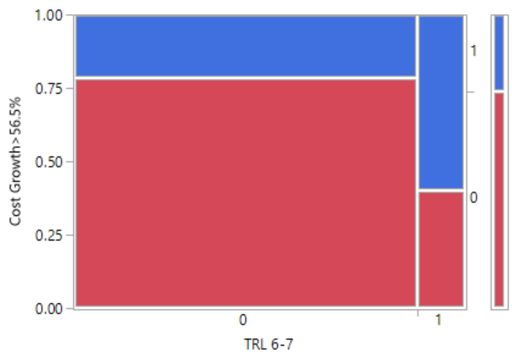
Tests

N	DF	-LogLike	RSquare (U)
42	1	1.7409955	0.0755

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	3.482	0.0620
Pearson	4.098	0.0429*

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9918	Prob(Cost Growth>68%(Mean)=1) is greater for TRL 6-7=0 than 1
Right	0.0782	Prob(Cost Growth>68%(Mean)=1) is greater for TRL 6-7=1 than 0
2-Tail	0.0782	Prob(Cost Growth>68%(Mean)=1) is different across TRL 6-7

Cost Growth > 68% (Mean) by TRL 6-7



Contingency Table

Cost Growth>56.5%

TRL 6-7	Count / Expected	0	1	Total
	0	29 / 27.3095	8 / 9.69048	37
	1	2 / 3.69048	3 / 1.30952	5
	Total	31	11	42

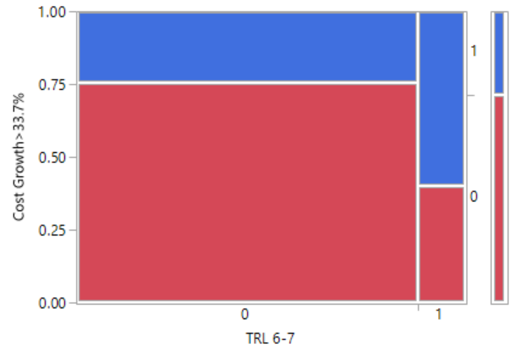
Tests

N	DF	-LogLike	RSquare (U)
42	1	1.4697629	0.0609

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.940	0.0864
Pearson	3.356	0.0670

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9874	Prob(Cost Growth>56.5%=1) is greater for TRL 6-7=0 than 1
Right	0.1028	Prob(Cost Growth>56.5%=1) is greater for TRL 6-7=1 than 0
2-Tail	0.1028	Prob(Cost Growth>56.5%=1) is different across TRL 6-7

Cost Growth > 56.5% by TRL 6-7



Contingency Table

Cost Growth>33.7%

TRL 6-7	Count / Expected	0	1	Total
	0	28 / 26.4286	9 / 10.5714	37
	1	2 / 3.57143	3 / 1.42857	5
	Total	30	12	42

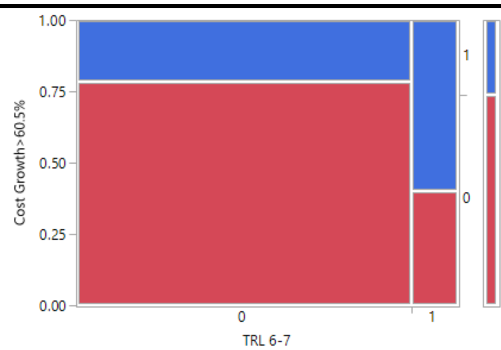
Tests

N	DF	-LogLike	RSquare (U)
42	1	1.2350491	0.0492

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.470	0.1160
Pearson	2.747	0.0974

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9816	Prob(Cost Growth>33.7%=1) is greater for TRL 6-7=0 than 1
Right	0.1309	Prob(Cost Growth>33.7%=1) is greater for TRL 6-7=1 than 0
2-Tail	0.1309	Prob(Cost Growth>33.7%=1) is different across TRL 6-7

Cost Growth > 33.7% by TRL 6-7



Contingency Table

Cost Growth>60.5%

TRL 6-7	Count / Expected	0	1	Total
	0	29 / 27.3095	8 / 9.69048	37
	1	2 / 3.69048	3 / 1.30952	5
	Total	31	11	42

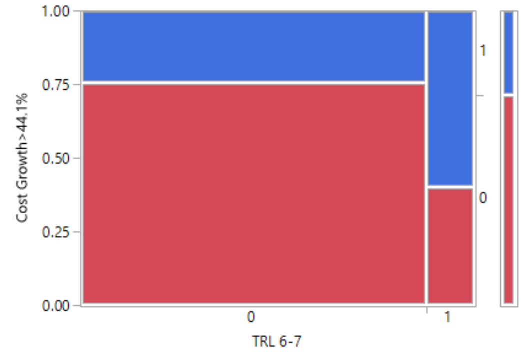
Tests

N	DF	-LogLike	RSquare (U)
42	1	1.4697629	0.0609

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.940	0.0864
Pearson	3.356	0.0670

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9874	Prob(Cost Growth>60.5%=1) is greater for TRL 6-7=0 than 1
Right	0.1028	Prob(Cost Growth>60.5%=1) is greater for TRL 6-7=1 than 0
2-Tail	0.1028	Prob(Cost Growth>60.5%=1) is different across TRL 6-7

Cost Growth > 60.5% by TRL 6-7



Contingency Table

Cost Growth>44.1%

TRL 6-7	Count Expected	0	1	Total
	0	28 26.4286	9 10.5714	37
	1	2 3.57143	3 1.42857	5
	Total	30	12	42

Tests

N	DF	-LogLike	RSquare (U)
42	1	1.2350491	0.0492

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	2.470	0.1160
Pearson	2.747	0.0974

Fisher's Exact Test	Prob	Alternative Hypothesis
Left	0.9816	Prob(Cost Growth>44.1%=1) is greater for TRL 6-7=0 than 1
Right	0.1309	Prob(Cost Growth>44.1%=1) is greater for TRL 6-7=1 than 0
2-Tail	0.1309	Prob(Cost Growth>44.1%=1) is different across TRL 6-7

Cost Growth > 44.1% by TRL 6-7

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Vita

Master Sergeant Eric A. Plack graduated from Lakota East High School in West Chester, Ohio. He entered undergraduate studies at Miami University in Oxford, Ohio where he graduated with a Bachelor of Arts degree in Mathematics and Statistics. Following the completion of his undergraduate degree, he enlisted into the United States Air Force.

His first assignment was at Randolph Air Force Base (AFB), Texas as a Financial Services Technician. After deploying to Al Dhafra Air Base, United Arab Emirates as an Accounting Technician, he was assigned to Osan Air Base, Republic of Korea as a Resource Advisor and Executive Officer for the 7th Air Force/A2. Sergeant Plack was then relocated to Nellis AFB, Nevada where he was assigned Non-Commissioned Officer in Charge of Customer Support. Following a deployment to Al Udeid Air Base, Qatar in support of United States Forces Afghanistan as a Budget Analyst, he was then assigned to the Financial Management Center of Expertise at Buckley AFB, Colorado as a Cost Analyst. He entered the Graduate School of Engineering and Management, Air Force Institute of Technology in August 2018. Upon graduation, he will be assigned under the Deputy Assistant Secretary for Cost and Economics (SAF/FMC) at the Pentagon.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
13-03-2020	Master's Thesis	March 2019 – March 2020

TITLE AND SUBTITLE

IMPROVING ACQUISITIONS IN SCIENCE AND TECHNOLOGY PROGRAMS THROUGH FACTOR DEVELOPMENT AND PROGRAM ANALYSIS

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Plack, Eric A., Master Sergeant, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)

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

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENV-MS-20-M-234

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AIR FORCE RESEARCH LABORATORY
1864 Fourth St, Bldg 15, WPAFB, OH 45344
937-904-7158 and emily.duke@us.af.mil
ATTN: Emily Duke

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/FMC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This research involves a study of Air Force science and technology (S&T) programs which includes the creation of standard factors and a program analysis. There has been little prior cost research on S&T programs, which occur very early in the acquisition lifecycle. This leads the cost analyst to utilize estimating techniques such as analogy, factors, and parametric in order to develop budgets with minimal information. The absence of formal S&T cost reporting requirements and common cost elements necessitate a segregated two phased data analysis. The *Factor Development phase* accomplishes the development and creation of two new standard cost factors along with a new suggested Work Breakdown Structure. A comparison analysis between published development cost factors and the new S&T factors indicates similarities in some factors. This suggests the more robust development factor dataset could be used when developing cost estimates for S&T cost elements. The *Program Analysis phase* studies relationships through contingency table analyses between program characteristics and performance measures. The results suggest that aerospace programs are more likely to technologically mature and experience cost and schedule growth when compared to human system programs. Furthermore, results suggest that programs with mature technologies are more likely to experience above average cost growth but are less likely to experience schedule growth. The outcome of this research not only gives cost analysts more tools for estimating these early programs, but a better understanding of how these programs behave under different conditions in order to better predict program performance.

15. SUBJECT TERMS

Science and Technology (S&T), Factors, Cost Estimating, Technology Readiness Level (TRL)

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. Jonathan Ritschel, AFIT/ENV
U	U	U	UU	122	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565, ext 4484 (jonathan.ritschel@afit.edu)

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