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IMPROVING ACQUISITIONS IN SCIENCE AND TECHNOLOGY PROGRAMS: CREATING UNIQUE COST FACTORS TO IMPROVE RESOURCE ALLOCATION DECISIONS

Technical Report prepared for the Naval Postgraduate School Acquisition Research Program (F20-039)

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Abstract

Cost factors are a common technique employed in Major Defense Acquisition Program (MDAP) cost estimating. The extant suite of available factors, however, primarily consists of development factors from the Engineering and Manufacturing Development (EMD) phase of the life cycle. This study expands the set of factors available to analysts by producing cost factors germane to programs early in the life cycle (i.e. Science and Technology (S&T) programs) and also creates factors for the Production phase of the life cycle.

Cost factor development in S&T programs provides unique challenges due to non-standard reporting requirements. To meet these challenges, this study first mapped S&T cost data to create a new, suggested Work Breakdown Structure (WBS) that mirrors the WBS structure utilized in MDAPs via Mil-Std-881. From this, it was determined that two cost factors commonly utilized in MDAP estimates, Systems Engineering/Program Management (SE/PM) and Systems Test and Evaluation (ST&E) could be derived for the S&T programs.

The creation of factors for the production phase of the life cycle resulted in 1033 new cost factors from a multitude of diverse programs. Factors were developed by *commodity type* (aircraft, missile, UAV, space, and ship), *contract type* (various), *contractor type* (prime and sub), and *Service* (Air Force, Army, and Navy). Combining the results of the previous EMD factors developed (Markman et al., 2019) with the two new phases developed here (S&T; Production) results in a robust cost factor toolkit across the acquisition life cycle spectrum.

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Introduction

Program management success is not measured solely by technical achievement. Rather, a defense acquisition program's success is evaluated through the triad of cost, schedule, and performance. Technologically successful programs that are significantly over budget or behind schedule garner scrutiny and are often the subject of legislative reform or media attention. As a result, congressionally mandated reforms and internal DOD policies such as the 2011 implementation of "will-cost and should-cost management" are introduced (Carter, 2011). These types of initiatives emerge because the demands for program resources exceed the constraints imposed through appropriated budgets. This tendency for programs to exceed budgetary targets manifests in cost growth and a crowding-out of additional programs. As shown by the works of Bolten et al. (2008), the reasons behind the cost growth are numerous. Bolten et al. (2008) found decisions by managers (e.g. changes in requirements post-project implementation) bear much of the blame, but the role of *inaccurate cost estimates* is also evident. Thus, improving the toolkit of the cost estimator is imperative for achieving more accurate estimates and thereby better resource allocation.

Cost models for acquisition programs are typically built through a multitude of estimating techniques to include parametric, engineering build-up, analogy, and cost factors (Miskick & Nussbaum, 2015). This study's focus is on expanding and improving the current state of cost factors. While current practices utilize published cost factors, there are still large gaps in the types of cost factors currently available. As such, this research employs a **two-phased approach** to closing the knowledge gap and improving the cost analyst's toolkit. The first phase analyzes those programs that occur prior to the Engineering and Manufacturing Development (EMD) phase of the life cycle. These are typically smaller Science and Technology (S&T) programs that encompass applied research (Budget Activity [BA] 2), advanced technology development (BA3), or advanced component development and prototypes (BA4). See Figure 1. These activities serve to expedite technology transition to operational use, proving component maturity prior to integration in subsequent major acquisition programs. The Cost Analysis Directorate at the Air Force Research Lab (AFRL) has identified this as a deficiency area, where little-to-no research has been conducted to develop cost factors in these types of programs.

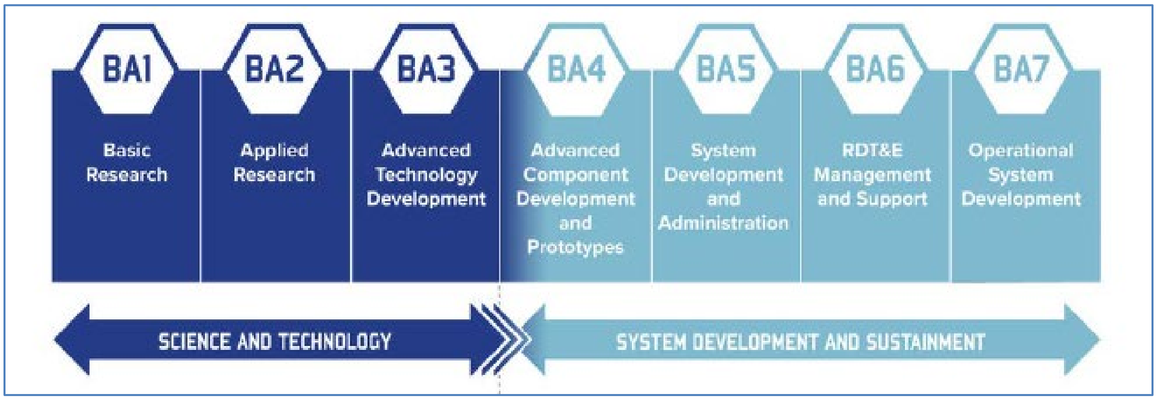

Figure 1: Definition of Science and Technology within the Overall Spectrum of Air Force Research, Development, Test, and Evaluation Activities

The second phase of the research develops cost factors for a wide range of common work breakdown structure elements [e.g. systems engineering, training, data, etc.] in the *Production phase* of the Major Defense Acquisition Program (MDAP) life cycle. This second phase expands upon previous factor development conducted under the Acquisition Research Program (ARP) that developed and analyzed factors in the same common work breakdown structure elements, but solely for the *EMD phase* of the life-cycle (Markman et al., 2019). Combining the results of the previous EMD effort (Markman et al., 2019) with the two new phases developed here (Science and Technology; Production) will result in a robust cost factor toolkit across the acquisition life cycle spectrum.

Research Objectives

The purpose of this paper is to investigate the current state of S&T and Production cost factors, refine existing standards where available, and develop and publish new cost factors for operational use by defense cost analysts in an array of project types. Furthermore, the conclusions from this paper help determine where future efforts should be focused towards gathering new data and/or refining existing factors. The specific questions this research aims to address are as follows:

1. 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?
2. What new standard cost factors can be produced through analysis of a diverse set of S&T project types?
3. How do the newly created S&T cost factors compare to published EMD factors?
4. What new standard cost factors can be produced through analysis of a diverse set of MDAPs in the Production stage?
5. What statistically significant differences are found in the newly created Production cost factors by commodity type, contract structure or program characteristic?

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Background

Cost-Estimating Methodologies

The *Air Force Cost Analysis Handbook* (AFCAH) and the Government Accountability Office (GAO) *Cost Estimating and Assessment Guide* (2009) provide and define the primary cost estimating methodologies which are utilized not only by the Air Force, but by the Department of Defense (DOD). These publications assist in setting a baseline for program offices and cost analysts to craft credible and consistent cost estimates, as well as an overarching legal requirement for the DOD to have policies in place to safeguard the billions of taxpayer dollars afforded to defense programs each year (GAO, 2009). While the documents define the acceptable estimating methodologies, they do not represent an all-encompassing guidebook, as every defense program presents its own unique challenges. The four methodologies outlined in the AFCAH are: Analogy and Factor, Parametric, Build-up (Engineering), and Extrapolation from Actuals (Department of the Air Force, 2007).

Each method represents a unique approach to cost estimating with corresponding strengths and weaknesses. However, best practices in cost estimating recommend the utilization of multiple methods to garner greater confidence in the element being estimated. The introduction of more than one estimating method provides cost analysts with the ability to triangulate a point estimate that considers levels of detail not fully captured by individual methods or estimates. Using multiple methods also serve as a cross-check to the primary technique employed.

Figure 2 from the AFCAH details the four cost estimating methods and shows the progression over the program life cycle.

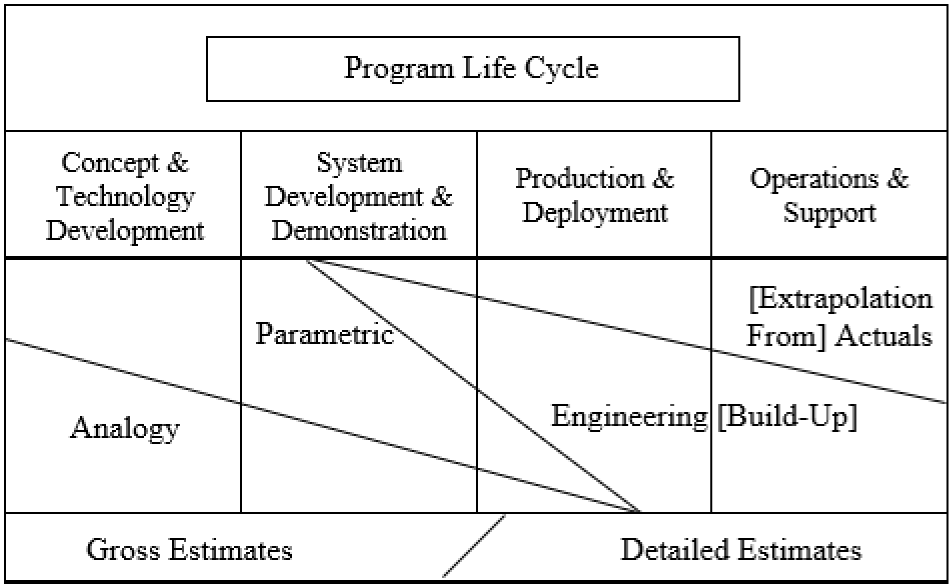

Figure 2. Selection of Methods (AFCAH, 2007)

The analogy method of cost estimating takes historical data from existing similar programs or systems and applies a scaling factor (or range of factors) to account for differences in the new system and arrive at a feasible estimate (Mislick & Nussbaum, 2015). The scaling factor(s) represent disparities between the old and new programs in the context of size, performance, technology, complexity, and many others, and set an initial estimate given the early stage of the program's life cycle (GAO, 2009).

The parametric estimating technique represents an approach based upon a statistical relationship drawn between historical costs and certain characteristics (program, physical, and performance), also referred to as cost drivers (GAO, 2009). A Cost Estimating Relationship (CER), where cost is directly proportional to a single independent variable, is known as a cost factor.

The build-up method of cost estimating consists of an exhaustive collection of lower-level program element estimates followed by a roll-up of each estimate to arrive at the total program cost (Department of the Air Force, 2007). Often referred to as the engineering approach, this technique is based largely on in-depth engineering data and requires a great deal of labor and material cost information to produce a reliable estimate.

Elements of the Work Breakdown Structure

A Work Breakdown Structure (WBS) provides a consistent and visible framework for defense material items and contracts within a program (DOD, 2018). It contains uniform terminology, definitions, and placement in a product-oriented family tree structure (DOD, 2005). By decomposing a project into smaller, more manageable components the WBS becomes a management blueprint for the product (Mislick & Nussbaum, 2015). Military Standard (MIL-STD) 881D mandates and governs the WBS, ultimately fulfilling broader requirements set forth in DOD Instruction 5000.2 (Under Secretary of Defense, 2013); the publication's purpose is to achieve a consistent application for all programmatic needs including performance, cost, schedule, risk, budget, and contractual (Mislick & Nussbaum, 2015). The 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) (DOD, 2018).

The WBS consists of three primary hierarchical levels, with a fourth and fifth sometimes included in expanded forms; for this study only the top three levels are addressed. Level one represents the entire system or material item such as an aircraft, ship, space, or surface vehicle system (Mislick & Nussbaum, 2015). The second level captures major elements subordinate to the system identified by level one and consists of prime mission products, including all hardware and software elements. Level two also includes combinations of system-level services applicable to the program including the following elements common to most programs: integration and assembly, System Test and Evaluation (ST&E), Systems Engineering/Program Management (SE/PM), Common Support equipment (CSE), Peculiar Support Equipment (PSE), training, data, operational/site activation, and initial spares and repair parts (DOD, 2018). These system-level combinations are then further deconstructed into the level three elements, which consist of more detailed components of the level two major elements of the program, including hardware, software, and services (DOD, 2005). Figure 3 displays a generic version of the WBS with varying amounts of detail as viewed from left to right, as published in MIL-STD-881D (DOD, 2018).

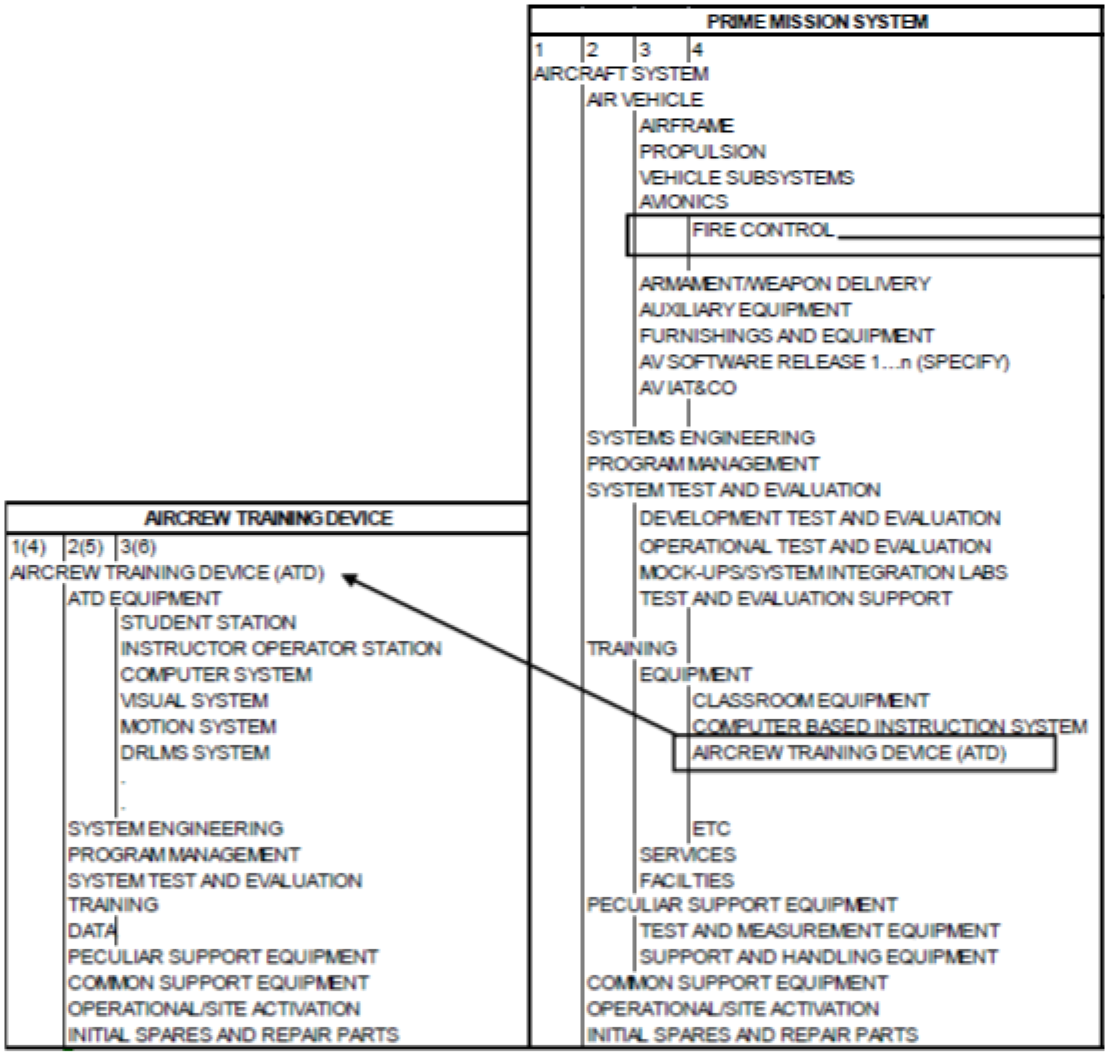

Figure 3. Work Breakdown Structure Matrix (Contract WBS) (DOD, 2018)

The aforementioned “common” elements at level two of the WBS are the focus for developing factors in phase two [recall phase two focuses on cost factors in the production phase of the life cycle] of this study. The mandated MIL-STD-881D structure enables the normalization of data and information across a variety of commodity types and DOD agencies (DOD, 2018). This allows not only for factor development, but also statistical testing of differences between characteristics such as commodity type to answer the proposed research questions.

Phase one of the study [recall phase one focuses on cost factors in S&T programs that are pre-EMD] is more problematic. 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 (DOD, 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. For phase one it will therefore be necessary to first determine a WBS construct germane to the unique nature of S&T programs and then delineate which "common" WBS elements are candidates to develop cost factors.

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Literature Review

Previous Cost Factor Research

Cost factors are a common cost estimating method, but extant research has primarily focused on the EMD phase of the life cycle. The first factor studies for United States Air Force aircraft were developed in the 1980s. The 1988 Blair Study consisted of 24 aircraft EMD avionics programs that created cost factors for various level two WBS elements such as ST&E, SE/PM, Data, and Training. The limited nature of the Blair Study proved useful for specific purposes at the Aeronautical Systems Center (ASC) at Wright-Patterson Air Force Base (WPAFB) for a period of approximately 10 years but ultimately became outdated (Wren, 1998).

A subsequent study by Wren (1998) utilized the Blair Study as a starting point and included an additional 20 programs, but again only in the realm of aircraft avionics and for the primary purpose of utilization by the ASC at WPAFB (Wren, 1998). Seventeen year later, Otte (2015) conducted a factor study aimed at updating and expanding the outdated cost factors utilized by many Air Force Life Cycle Management Center (AFLCMC) personnel. Otte's work developed factors for both the EMD and Production phase of the life cycle, but little was studied beyond clean sheet design aircraft. Markman et al. (2019) analyzed 102 Major Defense Acquisition platforms and created over 400 new cost factors for use in the EMD phase of the acquisition life cycle. Their study encompassed a broad range of development programs and included statistical testing of factor differences by commodity type, contractor type, contract type, developer type, and Service.

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, 2021). 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 often comprises 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 standard factors makes it possible to conduct more effective and extensive analysis at a variety of levels to construct credible cost estimates, especially in programs early in their life cycle or with limited information regarding the central task (Mislick & Nussbaum, 2015). While significant progress has been made in EMD cost factor research, the pre-EMD phase and production phases of the lifecycle are sparse. Creating cost factors for those phases of the life cycle will provide DOD analysts the tools needed to more effectively formulate credible, defensible estimates for both MDAPs and S&T programs.

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Methods/Design

Data

The data gathered in this study comes from two sources. The phase one S&T data was obtained from the AFRL cost and economics division at Wright Patterson AFB. The dataset consists solely of the 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 phase of the study. 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 final 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 MDAPs are traditionally developed from level two 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. That mapping will also help in suggesting a WBS structure germane to the unique nature of S&T programs.

The phase two data is collected from the Defense Automated Cost Information Management System (DACIMS), which exists within the Cost Assessment Data Enterprise (CADE) system. DACIMS contains cost data summary reports, often referred to as 1921s, which contain the necessary cost data to establish factors for the MDAPs targeted for this study. The 1921 data corresponds solely to the production phase of the life cycle as previously discussed. The CADE data set consists of 75 programs spanning from 1953 to 2018, representing a broad range of programs across numerous commodity types and services.

While 202 programs are available within CADE, only 75 of those programs fit the criteria for inclusion in the final data set. Table 1 depicts the exclusion criteria and accompanying number of programs utilized for this research.

Table 1. CADE Data Set Exclusions

Category	Number Removed	Remaining Programs
Available Programs in CADE		202
Programs without Production Data	83	119
Excluded Commodity Types	44	75
Final Data Set for Analysis		75

Only final 1921s were used for data collection; programs solely containing initial or interim 1921s were excluded. This is because final 1921s contain the complete and accurate cost history of a program/subprogram. In total, 145 MDAPs were captured in the dataset; 75 from CADE which were added to the 70 MDAPs in the current AFLCMC cost factor database. A total of 1,033 cost factors (each 1921 corresponds with multiple factors) were created. See Table 2.

Table 2. Data Set Characteristics

Category	Total	Category	Total
Unique Factors Created	1033	**Contract Type**	
		FFP	313
Commodity Type		FPI	104
Aircraft	650	FPAF	22
Missile	357	CPIF	33
UAV	22	MC	53
Space	2	None Listed/Unknown	508
Ship	2		
		Service	
Contractor Type		Air Force	344
Prime	969	Army	172
Subcontractor	64	Navy (includes Marine Corps)	517

Factor Calculation

The methodological approach has two stages. The first stage is creation of individual factors. The cost element factors contained in this study are the ratio (percentage) of the individual level two WBS elements to a base cost. The base cost is represented by a program's Prime Mission Equipment (PME) value, which does not include the contractor's fee or miscellaneous expenses (general and administrative, undistributed budget, management reserve, facilities capital cost of money). The general form of the calculation is shown below:

$$\frac{WBS\ Level\ 2\ Element_{ij}}{PME_j}$$

where *i* = SE/PM, ST&E, Training, Data, PSE, CSE, and Spares; *j* = individual programs

After establishing cost factors for the level two WBS elements, it is possible to develop composite factors. Specific level two WBS elements can be examined in groupings to establish aggregate values that represent an average or percentage that can be used in formulating estimates. These groupings allow for analysis at commodity levels (e.g. fixed wing aircraft) or a specified contractor or their role (prime or sub). Many other combinations of categories exist to create the most useful factor given a specific scenario. Table 3 illustrates how a grouping of like programs is used to calculate an average cost factor. Using the data in this way reduces issues that may result from an estimate based on a single data point.

Table 3. Example Composite Cost Factor Calculation

	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%		

Once the factors were established for each program, the mean, median, and standard deviation values for the various program groupings were calculated. In addition, interquartile ranges were calculated to examine variability among factors. This allowed for descriptive analysis prior to statistical testing and analysis.

The second stage of analysis subdivided the cost factors into categories for statistical testing to aid the cost analyst in determining appropriate levels of aggregation for practical use. While many comparisons can be performed using the datasets, this study performed four major types with the production data: Service, commodity type, contractor designation, and contract type. Table 4 lists the categories and respective sub-categories compared in this study.

Table 4. Categories for Comparison Analysis

Categories			
Service	**Commodity Type**	**Contractor Designation**	**Contract Type**
Air Force	Aircraft	Prime	CPIF (Cost Plus Incentive Fee)
Army	Missile	Sub	FFP (Firm-Fixed Price)
Navy (includes Marine Corps)	Ship		FPI (Fixed-Price Incentive)
	Space		FPAF (Fixed-Price Award Fee)
	UAV		MC (Multiple Contract Types)

Statistical Tests

For each of the categorical comparisons, the hypothesis test in Equation 1 is utilized, where *x* and *y* represent subcategories from Table 4:

$$H_o: \Delta_x = \Delta_y$$

Equation 1

$$H_a: \Delta_x \neq \Delta_y$$

Initial statistical testing utilized the Shapiro–Wilk test for normality. Rejection of the Shapiro–Wilk null hypothesis necessitated the application of non-parametric tests in the analysis. Specific tests used include the Kruskal–Wallis and Steel–Dwass tests. The Kruskal–Wallis test is a rank-based nonparametric test to determine whether statistically significant differences exist between two or more groups of an independent variable on a continuous dependent variable. Because the Kruskal–Wallis test does not identify where within the subcategory comparison differences occur, the Steel–Dwass test was employed. The Steel–Dwass multiple comparison test identifies which rank orders of the tested groups are statistically different for each instance of subcategory comparison.

Results and Analysis

Phase 1: S&T Program Cost Factor Development

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 WBSs do not follow any formal structure such as those dictated for MDAPs 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 two WBS element from MIL-STD-881D. It was found that only two traditional cost factors could be created. These cost elements are SE/PM and 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. The final list of programs utilized in this phase's analysis can be seen in Table 5.

Table 5. S&T Program List

Program Title
Automated Collision Avoidance Technology – Fighter Risk Reduction (ACAT-FRRP)
Adaptive Engine Technology Development (AETD) – Pratt & Whitney
Adaptive Engine Technology Development (AETD) – General Electric
Aerial Reconfigurable Embedded System (ARES)
Autonomous Real-Time Ground Ubiquitous Surveillance Infrared System (ARGUS-IR)
Evolved Augmented Geostationary Laboratory Experiment (EAGLE
High Energy Endurance Laser
Hydrocarbon Boost
Integrated Vehicle Energy Technology (INVENT)
Laser Advancements for Next-generation Compact Environments (LANCE)
Laser Pod Research & Development (LPRD)
Supersonic Turbine Engine Long Range (STELLR) - Williams
Supersonic Turbine Engine Long Range (STELLR) – Rolls Royce
SHIELD Turret Research in Aero Effects (STRAFE)
Versatile Affordable Advanced Turbine Engine (VAATE)

S&T Factor Development & Descriptive Statistics – 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 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. The final factor calculations for SE/PM can be seen in Table 6.

Table 6. Final SE, PM, and SE/PM ST&E Factor Calculations

Program Title	Systems 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%	10.08%
Program E	7.69%	3.79%	11.48%
Program F	9.15%	14.33%	23.48%
Program G	3.01%	14.30%	17.31%
Program H		14.23%	14.23%
Program I			9.98%
Program J	16.95%	16.73%	33.68%
Program K		13.96%	13.96%
Program L		36.52%	36.52%
Program M	8.52%	16.34%	24.87%
Program N	4.30%	7.16%	11.46%

Figure 4 shows the distribution of the SE/PM values as well as the descriptive statistics. The SE/PM distribution consists of 14 programs with a mean of 0.178 and standard deviation of 0.095. The distribution 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 S&T Comparison Analysis section of this chapter.

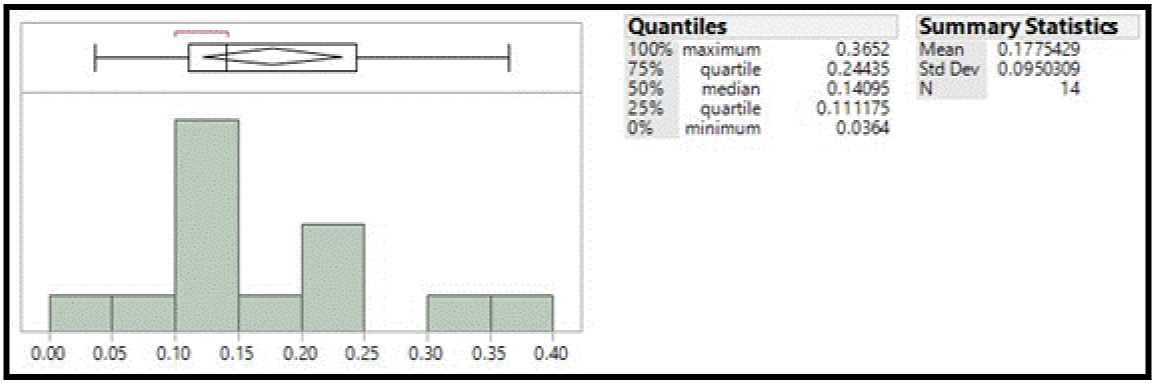


Figure 4. S&T SE/PM Descriptive Statistics

S&T Factor Development & Descriptive Statistics – 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 7.

Table 7. Final ST&E S&T Factor Calculations

Program Title	Systems 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 5 shows the distribution of the ST&E values as well as the descriptive statistics. The 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 right-skewed. These descriptive statistics for the ST&E element will be further discussed and compared to published EMD cost factors in the subsequent S&T Comparison Analysis section.

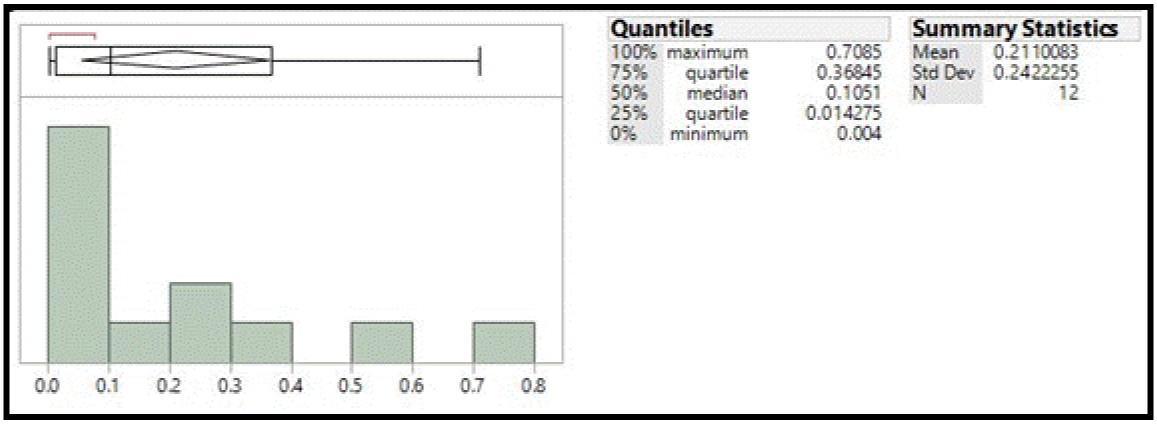


Figure 5. S&T ST&E Descriptive Statistics

Comparison Analysis: S&T Factors vs. Published EMD Factors

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, then the published EMD data could be used in conjunction with the S&T factors. This would results in a more robust dataset (i.e. a much larger n) 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. For this reason, the development type category of EMD cost factors was used for this comparison analysis.

Comparison Analysis: SE/PM (S&T vs. EMD Development Type Factors)

The comparison analysis of the SE/PM S&T factor against the SE/PM EMD Development Type factors can be seen in Table 8.

Table 8. 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	0.177	0.095	0.365	0.244	0.140	0.111	0.036	
EMD Modifications	124	0.348	0.256	1.319	0.495	0.285	0.154	0.004	
Absolute Percent Error		96.2%	169%	261%	103%	102%	38.4%	88.2%	122.5%
EMD New Design	131	0.474	0.347	1.466	0.658	0.376	0.219	0.005	
Absolute Percent Error		167%	265%	301%	169%	167%	97%	86%	178.9%
EMD Prototype	8	0.191	0.147	0.390	0.342	0.178	0.063	0.013	
Absolute Percent Error		7.4%	54.9%	6.8%	39.8%	26.5%	43.6%	65.4%	34.9%
EMD Subsystems	101	0.373	0.282	1.32	0.534	0.279	0.161	0.011	
Absolute Percent Error		110%	196%	263%	119%	98.2%	44.8%	71.2%	128.8%
EMD New MDS Des.	39	0.325	0.292	1.362	0.389	0.252	0.115	0.045	
Absolute Percent Error		83%	208%	273%	59%	79%	3.8%	22%	103.9%
EMD Comm. Derivative	3	0.184	0.101	0.268	0.268	0.213	0.072	0.072	
Absolute Percent Error		3.6%	6.4%	26.7%	9.5%	51%	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%). 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. Thus, 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.

Comparison Analysis: ST&E (S&T vs. EMD Development Type Factors)

The comparison analysis of the ST&E S&T factor against the ST&E EMD Development Type factors can be seen in Table 9.

Table 9. 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	0.211	0.242	0.709	0.369	0.105	0.014	0.004	
EMD Modifications	119	0.216	0.219	1.078	0.299	0.139	0.062	0.001	
Absolute Percent Error		2.1%	9.5%	52.1%	19%	32.8%	336%	67.2%	74.1%
EMD New Design	114	0.214	0.188	1.058	0.304	0.182	0.061	0.002	
Absolute Percent Error		1.6%	22.4%	49.3%	17.5%	72.9%	328%	59.6%	78.7%
EMD Prototype	9	0.267	0.103	0.456	0.325	0.282	0.179	0.118	
Absolute Percent Error		26.7%	57.6%	35.6%	11.8%	168%	1115%	2873%	618%
EMD Subsystems	89	0.174	0.188	0.852	0.238	0.104	0.043	0.001	
Absolute Percent Error		17.3%	22.3%	20.3%	35.5%	1.2%	199%	69.7%	52.3%
EMD New MDS Des.	39	0.293	0.228	0.944	0.429	0.246	0.098	0.008	
Absolute Percent Error		39%	5.8%	33.2%	16.4%	133%	591%	109%	132%
EMD Comm. Derivative	4	0.184	0.143	0.366	0.328	0.159	0.055	0.039	
Absolute Percent Error		14.5%	40.9%	48.4%	11%	50.8%	284%	880%	190%

The EMD development type subcategory, subsystem, has the lowest MAPE (52.3%). 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. The prototype subcategory cost factors, however, are the least comparable to S&T programs, as shown by the largest MAPE of 618%. These results suggest that the EMD factor dataset should *not* be used for the ST&E cost element. The practitioner completing an S&T estimate is thus advised to only include the S&T data in their analysis.

In summary, the results of the Phase 1 analysis led to the creation of two S&T 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 can be used for the ST&E element.

Phase 2: Production Cost Factor Development

Factor development using production data resulted in 1033 new, unique cost factors across the seven common level two WBS elements: SE/PM, ST&E, Training, Data, Common Support Equipment (CSE), Peculiar Support Equipment (PSE), and Spares. Individual results for each WBS element follow.

Production Factor – SE/PM

The SE/PM WBS element had the most available data of any level two WBS element. 749 of the 1,033 (72.5%) data points contained SE/PM values greater than zero. SE/PM values ranged from 0.1% to 1,066.8% of PME values. The extreme values may represent potential reporting flaws or other issues. In order to establish exclusion criteria, the distribution of all SE/PM values was analyzed using JMP software. This resulted in values above 197.1% of PME being removed from the dataset for the SE/PM analysis. The excluded values represented only 0.7% of the SE/PM dataset and were more than three standard deviations from the mean. These five data points were all under the missile commodity and part of sub programs with a total PME of less than $30.1K. Figure 4 shows the SE/PM distribution after exclusions and provides the descriptive statistics.

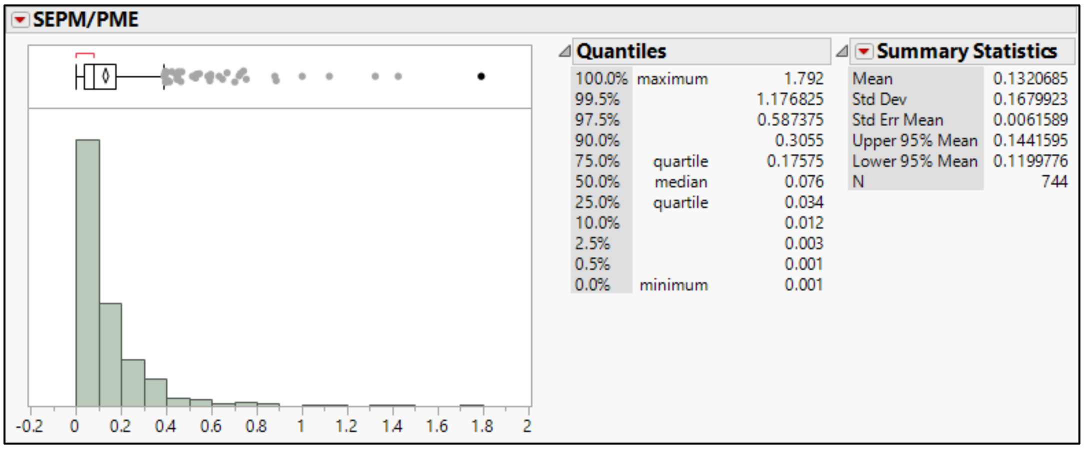


Figure 6. Production: SE/PM Element Descriptive Statistics

Table 10 displays an example of the individual distributions and descriptive statistics broken out by category for the SE/PM WBS element. Cost analysts can use these descriptive statistics to establish distributional forms and bounds for their SE/PM factor cost model. The detailed analysis displayed in Table 10 for subsequent WBS elements (ST&E, Training, Data, PSE, CSE, and Spares) can be found in Appendix A.

Table 10. Production: SE/PM Factor Table

SE/PM Summary Table								
	Mean	Std Dev	*N*	Max	75%	Median	25%	Min
Commodity Type								
Aircraft	0.0916	0.1135	427	0.742	0.115	0.054	0.024	0.001
Missile	0.1833	0.2094	291	1.792	0.245	0.132	0.05	0.001
UAV	0.1678	0.0769	22	0.345	0.225	0.147	0.115	0.012
Space	0.601	0.5657	2	1.001	1.001	0.601	0.201	0.201
Ship	0.441	0.4426	2	0.754	0.754	0.441	0.128	0.128
Contract Type								
FFP	0.0891	0.1135	237	0.729	0.1145	0.05	0.0205	0.001
FPI	0.1011	0.0949	75	0.399	0.138	0.069	0.027	0.005
FPAF	0.046	0.0486	21	0.23	0.059	0.027	0.022	0.009
CPIF	0.2401	0.245	29	1.001	0.336	0.155	0.0595	0.005
MC	0.0648	0.0601	48	0.265	0.0942	0.0515	0.0158	0.002
No Value	0.1752	0.2015	334	1.792	0.2403	0.1205	0.05	0.001
Contractor Type								
Prime	0.1297	0.1691	686	1.792	0.174	0.0735	0.032	0.001
Subcontractor	0.1604	0.1522	58	0.669	0.2358	0.1065	0.047	0.002
Service								
Air Force	0.1084	0.1297	262	1.001	0.143	0.0635	0.0248	0.001
Army	0.189	0.2188	155	1.792	0.263	0.143	0.048	0.012
Navy (Inc. Marines)	0.1241	0.1618	327	1.425	0.154	0.07	0.031	0.001

Production Factor - ST&E

ST&E contained 275 data points or 26.6% of the 1921s. The values ranged from 0.1% to 221.8% of PME, again indicating potential reporting issues in the extreme values. ST&E values above 70.8% of PME were excluded. These four data points represented 1.5% of the ST&E database and all fell under the missile commodity. PME values for the exclusions ranged from $2K to $30K, indicating smaller contracts. Figure 7 shows the ST&E distribution and its descriptive statistics. The graph suggests a lognormal distribution may be an appropriate distributional shape for modelling the fully aggregated ST&E cost factor. The individual descriptive statistics for ST&E broken out by commodity type, contract type, contractor designation, and service are located in Appendix A.

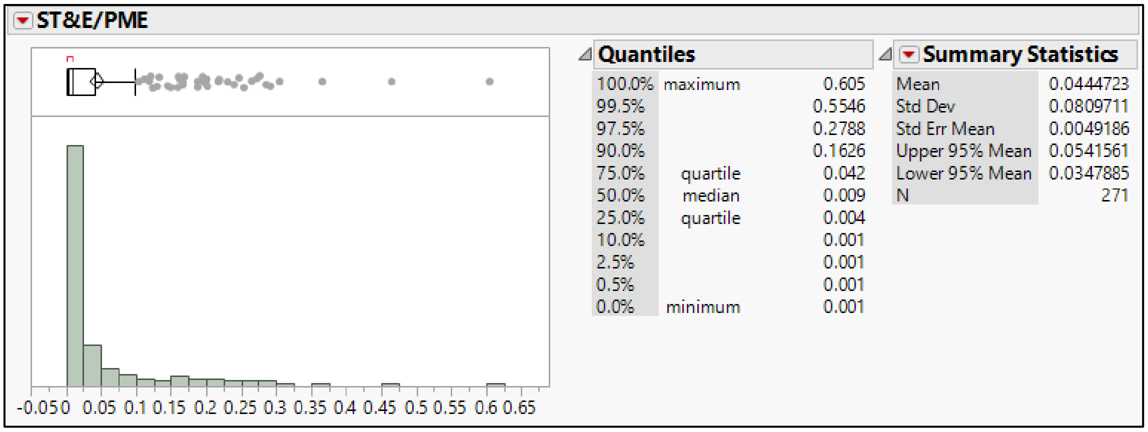


Figure 7. Production: ST&E Element Descriptive Statistics

Production Factor - Training

The Training WBS element had 242 data points. Three data points were removed representing 1.2% of the Training data; all missile commodity. These points were more than three standard deviations away from the mean and had PME values of under $1.3K. Figure 8 shows the distribution and descriptive statistics for the 239 values analyzed for the Training WBS element. The individual descriptive statistics for Training broken out by commodity type, contract type, contractor designation, and service are located in Appendix A.

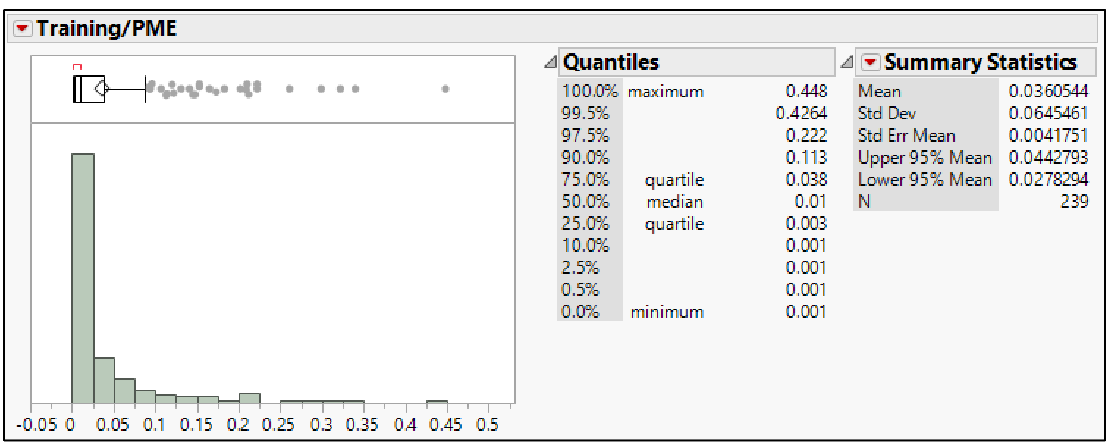


Figure 8. Production: Training Element Descriptive Statistics

Production Factor - Data

The Data WBS element contained 536 values, or 51.9% of the total available data. No data points were excluded from Data. Four points lie outside three standard deviations, but there were no other criteria met for exclusion such as low dollar values or irrelevant contract types. Figure 9 shows the descriptive statistics for the Data WBS element. The individual descriptive statistics for Data broken out by commodity type, contract type, contractor designation, and service are located in Appendix A.

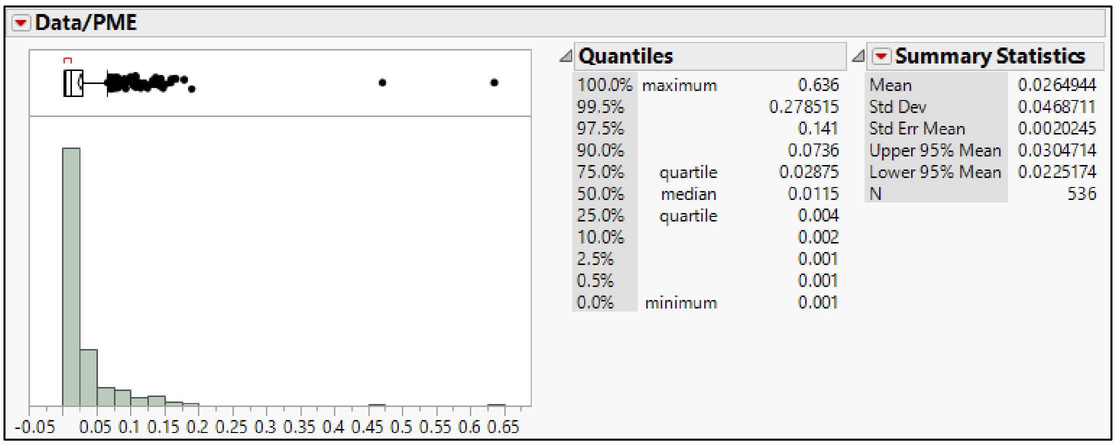


Figure 9. Production: Data Element Descriptive Statistics

Production Factor - PSE

Peculiar Support Equipment (PSE) contained 361 data points or 34.9% of the gathered data. Values ranged from 0.1% to 6,131%. The 6,131% value (from the missile commodity) was excluded as it was well above other values and the document had a PME value of just $123. After excluding this value, 11 more values remained outside three standard deviations of the mean. None of these values were excluded. Figure 10 shows the descriptive statistics for PSE. The individual descriptive statistics for PSE broken out by commodity type, contract type, contractor designation, and service are located in Appendix A.

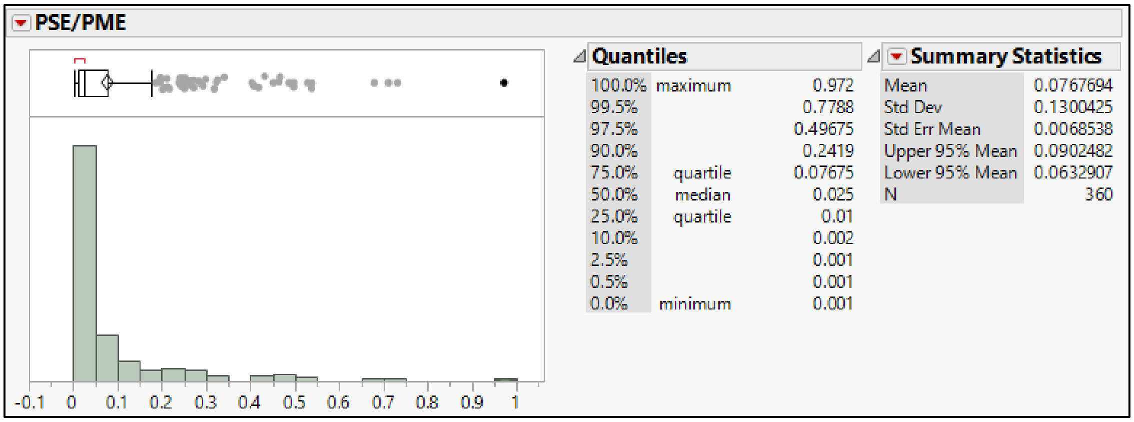


Figure 10. Production: PSE Element Descriptive Statistics

Production Factor - CSE

CSE had significantly less data points than other WBS elements at 68 (6.6% of database). No values were excluded from the CSE analysis. The descriptive statistics for the CSE WBS element are shown in Figure 11. The lack of distribution shape suggests the cost analyst must employ discretion when modeling the CSE factor. The individual descriptive statistics for CSE broken out by commodity type, contract type, contractor designation, and service are located in Appendix A.

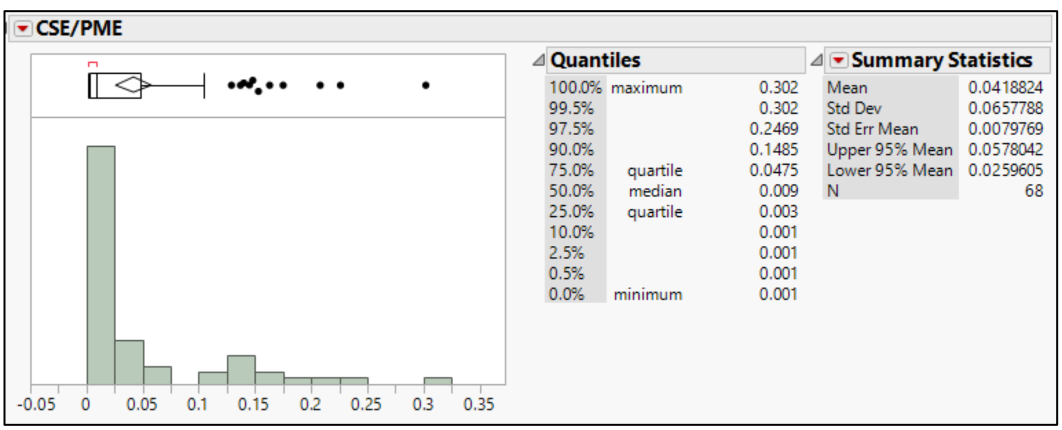
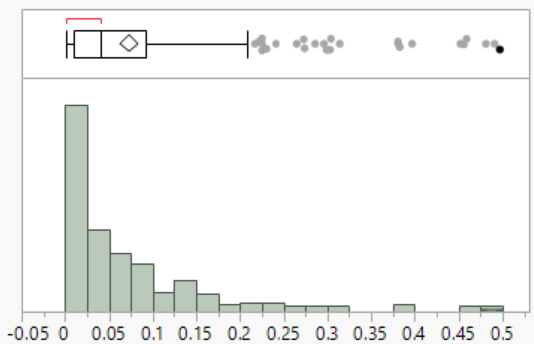


Figure 11. Production: CSE Element Descriptive Statistics

Production Factor - Spares

The Spares WBS element contained 322 values. The descriptive statistics and distribution for Spares is shown in Figure 12. Four values were more than three standard deviations away from the mean. An additional three values were greater than 50% factors (Spares/PME). All seven data points were removed to prevent documents from being included whose main purpose was to procure spares. The individual descriptive statistics for Spares broken out by commodity type, contract type, contractor designation, and service are located in Appendix A.

Spares/PME



Quantiles

100.0%	maximum	0.497
99.5%		0.49352
97.5%		0.3844
90.0%		0.1886
75.0%	quartile	0.091
50.0%	median	0.04
25.0%	quartile	0.009
10.0%		0.002
2.5%		0.001
0.5%		0.001
0.0%	minimum	0.001

Summary Statistics

Mean	0.0725397
Std Dev	0.0949898
Std Err Mean	0.0053521
Upper 95% Mean	0.0830701
Lower 95% Mean	0.0620092
N	315

Figure 12. Production: Spares Element Descriptive Statistics

Production Factor Results by Category

This section employs nonparametric tests to identify differences in the four categories of data: commodity types, contract type, contractor type, and Service. As discussed in the methods section, each WBS dataset failed the Shapiro-Wilk normality test, necessitating a nonparametric approach. Nonparametric testing identifies similarities of locations in the data elements analyzed. Histograms of the data in this analysis reveal a consistent right-skewed profile. Due to the similarities in the shape of the histograms, the nonparametric tests can be considered to be testing medians (Hollander et al., 2014). Therefore, subsequent discussion of nonparametric results will discuss differences in the medians of the data.

Commodity Type

The first category analyzed is commodity type. The Kruskal-Wallis test identified statistically significant differences between the level two WBS element median values within the commodity category. These differences were identified in the SE/PM, Data, and Spares groups. Table 11 shows the Kruskal-Wallis test for each

WBS element by commodity, the associated p-values and whether or not the null hypothesis is rejected when compared to an alpha (α) of .05.

Table 11. Kruskal–Wallis Results (Commodity Type)

WBS Element	Alpha	Chi-Square	*P* value	Null Hypothesis Test Result	*N*
SE/PM	0.05	98.7633	<0.0001	Reject	744
ST&E	0.05	2.8587	0.4139	Do Not Reject	271
Training	0.05	2.9523	0.399	Do Not Reject	239
Data	0.05	37.139	<0.0001	Reject	536
PSE	0.05	2.913	0.2309	Do Not Reject	360
CSE	0.05	1.1554	0.5612	Do Not Reject	68
Spares	0.05	14.887	0.0006	Reject	315

Upon the discovery of statistically significant differences, the Steel-Dwass multiple comparison test was performed to identify which commodities exhibited them. Table 12 shows the significant differences that occurred for each WBS element by commodity type. The aircraft, missile, and UAV commodity types displayed statistically significant differences, while space and ship showed none. This could be because of the low N value of both the space and ship commodities; both with two data points each out of the total 1,033 data points. The test was rerun excluding space and ship commodities, but the results stayed the same. The differences in Table 12 show that analysts should consider filtering the data to include only that commodity type when creating factors for SE/PM, Data, and Spares.

Table 12. Commodity Differences Summary

	Aircraft	Missile	UAV	Space	Ship
SE/PM	2	1	1	0	0
ST&E	0	0	0	0	0
Training	0	0	0	0	0
Data	2	2	2	0	0
PSE	0	0	0	0	0
CSE	0	0	0	0	0
Spares	1	1	2	0	0

Contract Type

The Kruskal-Wallis test for the contract type category discovered one more statistical difference than the commodity type category. In addition to the SE/PM, Data, and Spares WBS elements, the PSE category also rejected the null hypothesis as shown in Table 13.

Table 13. Kruskal–Wallis Results (Contract Type)

WBS Element	Alpha	Chi-Square	*P* value	Null Hypothesis Test Result	*N*
SE/PM	0.05	96.748	<0.0001	Reject	744
ST&E	0.05	8.3239	0.1393	Do Not Reject	271
Training	0.05	1.5591	0.8161	Do Not Reject	239
Data	0.05	29.115	<0.0001	Reject	536
PSE	0.05	28.2742	<0.0001	Reject	360
CSE	0.05	6.4868	0.1656	Do Not Reject	68
Spares	0.05	27.312	<0.0001	Reject	315

Conducting the Steel-Dwass multiple comparison test across contract types revealed significant differences which are broken down by contract type for each element in Table 14. SE/PM (16) and PSE (12) record the most interactions with a combined 71.4% of total differences. One limitation with the data on this test is that contracts with no data listed (no value) accounted for 49.2% of the data. Running this test including that category makes the results difficult to interpret. However, in the SE/PM category, the No Value contracts showed statistical differences with FFP, FPI, FPAF, and MC contracts. This indicates that perhaps the contracts with no data were most similar to CPIF type contracts. These results show analysts may be able to use contract type (if known) to produce more accurate production factors in their cost estimates.

Table 14. Contract Type Differences Summary

	FFP	FPI	FPAF	CPIF	MC	No Value
SE/PM	2	2	2	4	2	4
ST&E	0	0	0	0	0	0
Training	0	0	0	0	0	0
Data	2	2	0	0	2	2
PSE	1	2	3	2	2	2
CSE	0	0	0	0	0	0
Spares	2	1	0	2	0	1

Contractor Type

The Kruskal-Wallis test by contractor type showed just three differences between WBS elements. Only the elements SE/PM, Training, and Data returned p-values less than the 0.05 alpha and led to a null hypothesis rejection. Table 15 summarizes the Kruskal-Wallis test results for contractor type.

Table 15. Kruskal–Wallis Results (Contractor Type)

WBS Element	Alpha	Chi-Square	*P* value	Null Hypothesis Test Result	*N*
SE/PM	0.05	6.1167	0.0134	Reject	744
ST&E	0.05	3.3601	0.0668	Do Not Reject	271
Training	0.05	7.899	0.0049	Reject	239
Data	0.05	19.378	<0.0001	Reject	536
PSE	0.05	0.3153	0.5744	Do Not Reject	360
CSE	0.05	0.9668	0.3255	Do Not Reject	68
Spares	0.05	3.5588	0.0592	Do Not Reject	315

Because there are only two designations (prime or subcontractor), there is no need to conduct a Steel-Dwass test (i.e. the Kruskal-Wallis results suffice). The results of this test suggest that analysts should filter by contractor type for the SE/PM, Training and Data categories in order to avoid basing estimates on statistically different groups of values.

Service

The Kruskal-Wallis test results for the Service category revealed the greatest amount (five) of statistically different median values for the WBS elements. These included SE/PM, Data, PSE, CSE, and Spares. Table 16 illustrates the p-values and resulting null hypothesis result for each element.

Table 16. Kruskal–Wallis Results (Service)

WBS Element	Alpha	Chi-Square	*P* value	Null Hypothesis Test Result	*N*
SE/PM	0.05	33.599	<0.0001	Reject	744
ST&E	0.05	0.3816	0.8263	Do Not Reject	271
Training	0.05	1.1936	0.5506	Do Not Reject	239
Data	0.05	77.674	<0.0001	Reject	536
PSE	0.05	16.947	0.0002	Reject	360
CSE	0.05	18.422	<0.0001	Reject	68
Spares	0.05	18.637	<0.0001	Reject	315

The Steel-Dwass test identified a total of 18 significant interactions. Table 17 shows how many interactions each Service had by WBS element. These results indicate that analysts should consider filtering the data to include only the relevant Service when creating cost factors for SE/PM, Data, PSE, CSE, and Spares.

Table 17. Service Differences Summary

	Air Force	Army	Navy
SE/PM	1	2	1
ST&E	0	0	0
Training	0	0	0
Data	2	2	2
PSE	1	1	2
CSE	0	1	1
Spares	1	0	1

Category Summary

Each of the four categories exhibited statistical differences in at least three, but no more than five, WBS elements. Descriptive statistics of each WBS element showed high standard deviations and coefficient of variation values which could have negatively impacted the power of the hypothesis testing performed. Low power in hypothesis testing results in a higher probability of a type II error—i.e. not rejecting a false null hypothesis. The high standard deviations in the data suggest that each MDAP has unique properties. Analysts must be familiar with these differences between programs to create data inclusion criteria when creating factors that result in accurate cost estimating. The realities of cost analysts possessing such knowledge are limited in most cases. For this reason, the generic cost factors calculated in this research represent a starting point for refinement based on the program being estimated and the knowledge of it. Given the analogy and factor method is typically used earlier in a program's lifecycle, it is appropriate that there is little knowledge or data of the MDAP being estimated. Under these circumstances broad datasets are suitable, but statistically different categories should be filtered out as more information becomes available.

Conclusions

Research Questions Answered

The first research objective sought to determine a requisite WBS structure germane to the unique nature of S&T programs. MDAPs have a mandated WBS structure that ensures a consistent framework for contract reporting. This study 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. S&T data is reported through the CPR construct, which has no mandated reporting requirement. While most programs have a couple common cost elements, the reported WBS does 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.

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 two 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 18.

Table 18. Suggested S&T WBS Compared to MIL-STD-881

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 18, the MIL-STD-881D structure includes many "common" level two 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 two 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 the data used for this study.

The second research objective was to develop new standard cost factors for S&T project types. Cost factors for MDAPs are traditionally developed from level two elements found in the MIL-STD-881D formal WBS. These common elements include SE/PM, ST&E, training, data, PSE and CSE. The WBS elements contained in the CPR data did not follow the traditional WBS structure and thus did not include many of the traditional level two 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 two 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 19.

Table 19. 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

The third research objective was to compare the newly created S&T factors from Table 19 to currently published EMD cost factors. Markman et al. (2019) researched 102 MDAPs and created over 400 cost factors for use in the EMD phase. 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 the previously published EMD and new developed 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 20.

Table 20. SE/PM Comparison (S&T vs. EMD)

	N	Mean	Std. Dev.	Max	75%	Median	25%	Min	MAPE
S&T Programs	14	0.177	0.095	0.365	0.244	0.140	0.111	0.036	
EMD Modifications	124	0.348	0.256	1.319	0.495	0.285	0.154	0.004	122.5%
EMD New Design	131	0.474	0.347	1.466	0.658	0.376	0.219	0.005	178.9%
EMD Prototype	8	0.191	0.147	0.390	0.342	0.178	0.063	0.013	34.9%
EMD Subsystems	101	0.373	0.282	1.32	0.534	0.279	0.161	0.011	128.8%
EMD New MDS Des.	39	0.325	0.292	1.362	0.389	0.252	0.115	0.045	103.9%
EMD Comm. Derivative	3	0.184	0.101	0.268	0.268	0.213	0.072	0.072	32.8%

As shown in Table 20, 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 21.

Table 21. EMD MAPE Compared to S&T

EMD Development Type	N	MAPE
Modifications	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.

The fourth research objective was to develop new standard cost factors for the production phase of the life cycle. This resulted in 1033 new cost factors created from a multitude of diverse programs. Factors were developed by *commodity type* (aircraft, missile, UAV, space, and ship), *contract type* (various), *contractor type* (prime and sub), and *Service* (Air Force, Army, and Navy). The average (mean) composite factors for the seven level two WBS elements are displayed in Table 22 with full summary factors provided in Table 10 and Appendix A.

Table 22. Production Factors by Type (Mean Values)

Standard Factors of Production							
	SE/PM	ST&E	Training	Data	PSE	CSE	Spares
Commodity Type							
Aircraft	0.0916	0.0391	0.0357	0.0295	0.0849	0.0707	0.0712
Missile	0.1833	0.0515	0.0374	0.0208	0.0584	0.0284	0.0497
UAV	0.1678	0.0073	0.0420	0.0021	0.0633	0.0210	0.2157
Space	0.601	N/A	N/A	N/A	N/A	N/A	N/A
Ship	0.441	0.002	0.002	0.058	N/A	N/A	N/A
Contract Type							
FFP	0.0891	0.0419	0.0263	0.0278	0.0733	0.0057	0.0510
FPI	0.1011	0.0430	0.0345	0.0362	0.0989	0.0040	0.1245
FPAF	0.046	0.0010	0.0071	0.0159	0.0083	N/A	0.0822
CPIF	0.2401	0.04	0.0273	0.0268	0.1165	0.0080	0.1269
MC	0.0648	0.0243	0.0403	0.0124	0.0145	0.0133	0.0818
None Listed	0.1752	0.0502	0.0461	0.0263	0.0804	0.0516	0.0605
Contractor Type							
Prime	0.1297	0.0450	0.0372	0.0275	0.0776	0.0410	0.0735
Subcontractor	0.1604	0.0381	0.0025	0.0068	0.0583	0.0700	0.0140
Service							
Air Force	0.1084	0.0383	0.0270	0.0220	0.0623	0.0859	0.0976
Army	0.189	0.0527	0.0241	0.0053	0.0578	0.1075	0.1312
Navy (inc. Marines)	0.1241	0.0438	0.0487	0.0343	0.0977	0.0105	0.0541

The final research objective sought to determine whether the four categories (i.e. commodity type, contract type, contractor type, and Service) exhibited statistical differences in the production phase cost factors. If differences are present, then the cost analyst should allocate more time and effort to refine their dataset in these areas. If differences are not detected, then the cost analyst can economize on refinement time and employ a more aggregated dataset when developing their estimate.

Specific findings from statistical testing indicated that differences in the Services exist. The Services category had the highest amount of statistical differences between the subcategories with Navy exhibiting the most. The analysis also showed that knowing the contract type is important when developing factors. While it would be most advantageous to develop composite factors based on the precise contract type (e.g., cost plus award fee), even broader classifications into the two general categories of cost-reimbursable or fixed-price contracts are useful. Differences were also found in the commodity type category and contractor type category, but to a lesser extent than Service and contract type.

Significance of Results

This study improves the cost analyst toolkit through the development of cost factors in S&T programs and MDAPs in the production phase. Combining the results of this study with Markman et al. (2019) work on EMD factors provides the cost analyst with a comprehensive set of cost factors that span all phases of a program's life cycle. The descriptive statistics for each WBS element and accompanying summary tables provide analysts the ability to create an initial estimate quickly with minimum program data. Upon establishing this initial estimate, the analyst can then perform statistical and practical analysis to generate a more accurate factor for their unique estimating scenario. This process can be repeated as more information or data becomes available to the analyst. Lastly, this study suggests a new WBS framework based on MIL-STD-881 for program managers and cost analysts to employ when working with S&T programs.

Future Research

There are several areas where this research can be expanded. The current set of cost factor studies has focused solely on S&T programs and MDAPs. The natural next step would be to develop factors for ACAT II and ACAT III programs. Additionally, the focus of the cost factors in this study were on the "common" elements of the level two WBS structure from MIL-STD-881. Other factors, outside of these common elements could be explored. The approach to both of these future research efforts would depend upon the availability of data.

Appendix A—Descriptive Statistics by WBS Element

SE/PM Summary Table								
	Mean	**Std Dev**	***N***	**Max**	**75%**	**Median**	**25%**	**Min**
Commodity Type								
Aircraft	0.0916	0.1135	427	0.742	0.115	0.054	0.024	0.001
Missile	0.1833	0.2094	291	1.792	0.245	0.132	0.05	0.001
UAV	0.1678	0.0769	22	0.345	0.225	0.147	0.115	0.012
Space	0.601	0.5657	2	1.001	1.001	0.601	0.201	0.201
Ship	0.441	0.4426	2	0.754	0.754	0.441	0.128	0.128
Contract Type								
FFP	0.0891	0.1135	237	0.729	0.1145	0.05	0.0205	0.001
FPI	0.1011	0.0949	75	0.399	0.138	0.069	0.027	0.005
FPAF	0.046	0.0486	21	0.23	0.059	0.027	0.022	0.009
CPIF	0.2401	0.245	29	1.001	0.336	0.155	0.0595	0.005
MC	0.0648	0.0601	48	0.265	0.0942	0.0515	0.0158	0.002
No Value	0.1752	0.2015	334	1.792	0.2403	0.1205	0.05	0.001
Contractor Type								
Prime	0.1297	0.1691	686	1.792	0.174	0.0735	0.032	0.001
Subcontractor	0.1604	0.1522	58	0.669	0.2358	0.1065	0.047	0.002
Service								
Air Force	0.1084	0.1297	262	1.001	0.143	0.0635	0.0248	0.001
Army	0.189	0.2188	155	1.792	0.263	0.143	0.048	0.012
Navy (Inc. Marines)	0.1241	0.1618	327	1.425	0.154	0.07	0.031	0.001

ST&E Summary Table								
	Mean	**Std Dev**	***N***	**Max**	**75%**	**Median**	**25%**	**Min**
Commodity Type								
Aircraft	0.0391	0.0622	139	0.292	0.046	0.009	0.004	0.001
Missile	0.0515	03098	128	0.605	0.041	0.009	0.004	0.001
UAV	0.0073	0.0085	3	0.017	0.017	0.004	0.001	0.001
Space	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ship	0.002	N/A	1	0.002	0.002	0.002	0.002	0.002
Contract Type								
FFP	0.0419	0.0642	75	0.273	0.052	0.008	0.003	0.001
FPI	0.043	0.0525	28	0.188	0.0528	0.0225	0.007	0.001
FPAF	0.001	N/A	1	0.001	0.001	0.001	0.001	0.001
CPIF	0.04	0.0846	8	0.247	0.031	0.0045	0.0013	0.001
MC	0.0243	0.0599	23	0.292	0.021	0.006	0.003	0.001
No Value	0.0502	0.096	136	0.605	0.0405	0.009	0.004	0.001
Contractor Type								
Prime	0.045	0.0836	251	0.605	0.041	0.008	0.003	0.001
Subcontractor	0.0381	0.0343	20	0.13	0.0518	0.035	0.0065	0.001
Service								
Air Force	0.0383	0.0643	78	0.292	0.0373	0.0105	0.003	0.001
Army	0.0527	0.104	69	0.605	0.044	0.007	0.003	0.001
Navy (Inc. Marines)	0.0438	0.0759	124	0.465	0.045	0.009	0.004	0.001

Training Summary Table								
	Mean	**Std Dev**	***N***	**Max**	**75%**	**Median**	**25%**	**Min**
Commodity Type								
Aircraft	0.0357	0.0644	169	0.448	0.036	0.01	0.002	0.001
Missile	0.0374	0.0662	68	0.34	0.045	0.009	0.004	0.001
UAV	0.042	N/A	1	0.042	0.042	0.042	0.042	0.042
Space	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ship	0.002	N/A	1	0.002	0.002	0.002	0.002	0.002
Contract Type								
FFP	0.0263	0.0454	75	0.212	0.03	0.007	0.002	0.001
FPI	0.0345	0.0609	33	0.222	0.0295	0.008	0.001	0.001
FPAF	0.0071	0.0059	7	0.017	0.012	0.005	0.001	0.001
CPIF	0.0273	0.0406	9	0.114	0.0505	0.002	0.001	0.001
MC	0.0403	0.0725	15	0.261	0.039	0.01	0.002	0.001
No Value	0.0461	0.0785	100	0.448	0.056	0.013	0.004	0.001
Contractor Type								
Prime	0.0372	0.0653	231	0.448	0.038	0.01	0.003	0.001
Subcontractor	0.0025	0.0013	8	0.004	0.004	0.002	0.0013	0.001
Service								
Air Force	0.027	0.0415	93	0.209	0.027	0.012	0.002	0.001
Army	0.0241	0.057	41	0.34	0.0155	0.006	0.004	0.001
Navy (Inc. Marines)	0.0487	0.0805	105	0.448	0.06	0.01	0.002	0.001

Data Summary Table								
	Mean	**Std Dev**	***N***	**Max**	**75%**	**Median**	**25%**	**Min**
Commodity Type								
Aircraft	0.0295	0.0478	361	0.363	0.033	0.014	0.005	0.001
Missile	0.0208	0.0454	167	0.471	0.021	0.006	0.002	0.001
UAV	0.0021	0.0011	7	0.004	0.003	0.002	0.001	0.001
Space	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ship	0.058	N/A	1	0.058	0.058	0.058	0.058	0.058
Contract Type								
FFP	0.0278	0.0359	172	0.165	0.031	0.015	0.0043	0.001
FPI	0.0362	0.0352	60	0.134	0.0553	0.0235	0.0063	0.001
FPAF	0.0159	0.0255	21	0.125	0.0135	0.01	0.0075	0.001
CPIF	0.0268	0.0239	18	0.082	0.045	0.0225	0.0048	0.001
MC	0.0124	0.0229	38	0.141	0.012	0.007	0.004	0.001
No Value	0.0263	0.0604	227	0.636	0.024	0.009	0.003	0.001
Contractor Type								
Prime	0.0275	0.0478	510	0.636	0.03	0.012	0.004	0.001
Subcontractor	0.0068	0.0106	26	0.052	0.007	0.0025	0.002	0.001
Service								
Air Force	0.022	0.0508	221	0.636	0.023	0.009	0.003	0.001
Army	0.0053	0.0062	51	0.027	0.006	0.003	0.001	0.001
Navy (Inc. Marines)	0.0343	0.0462	264	0.471	0.04	0.019	0.007	0.001

PSE Summary Table								
	Mean	Std Dev	*N*	Max	75%	Median	25%	Min
Commodity Type								
Aircraft	0.0849	0.1385	248	0.972	0.0885	0.002	0.009	0.001
Missile	0.0584	0.1115	101	0.711	0.0575	0.02	0.01	0.001
UAV	0.0633	0.056	11	0.217	0.098	0.042	0.021	0.011
Space	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ship	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Contract Type								
FFP	0.0733	0.1198	117	0.732	0.067	0.025	0.0095	0.001
FPI	0.0989	0.1096	57	0.452	0.147	0.051	0.0135	0.001
FPAF	0.0083	0.0046	12	0.017	0.0118	0.0085	0.004	0.001
CPIF	0.1165	0.151	11	0.497	0.217	0.042	0.025	0.002
MC	0.0145	0.0127	16	0.038	0.0253	0.013	0.0025	0.001
No Value	0.0804	0.1511	147	0.972	0.073	0.022	0.01	0.001
Contractor Type								
Prime	0.0776	0.1318	345	0.972	0.077	0.024	0.0095	0.001
Subcontractor	0.0583	0.0794	15	0.323	0.059	0.042	0.012	0.002
Service								
Air Force	0.0623	0.1206	143	0.972	0.051	0.021	0.009	0.001
Army	0.0578	0.1274	62	0.711	0.0568	0.0145	0.006	0.001
Navy (Inc. Marines)	0.0977	0.1371	155	0.732	0.116	0.034	0.016	0.001

CSE Summary Table								
	Mean	**Std Dev**	***N***	**Max**	**75%**	**Median**	**25%**	**Min**
Commodity Type								
Aircraft	0.0707	0.0893	22	0.302	0.1413	0.013	0.0025	0.001
Missile	0.0284	0.047	44	0.208	0.037	0.0085	0.003	0.001
UAV	0.021	0.0184	2	0.034	0.034	0.021	0.008	0.008
Space	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ship	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Contract Type								
FFP	0.0057	0.006	6	0.017	0.0095	0.004	0.001	0.001
FPI	0.004	0.0036	3	0.008	0.008	0.003	0.001	0.001
FPAF	N/A	N/A	N/A	N/A	N/A	N/A	N/A`	N/A
CPIF	0.008	0.0099	2	0.015	0.015	0.008	0.001	0.001
MC	0.0133	0.0144	4	0.034	0.0283	0.009	0.0025	0.001
No Value	0.0516	0.0716	53	0.302	0.085	0.012	0.003	0.001
Contractor Type								
Prime	0.041	0.0658	66	0.302	0.0445	0.0085	0.003	0.001
Subcontractor	0.07	0.0834	2	0.129	0.129	0.07	0.011	0.011
Service								
Air Force	0.0859	0.0925	18	0.302	0.147	0.0675	0.0025	0.001
Army	0.1075	0.0628	8	0.208	0.1593	0.099	0.0505	0.039
Navy (Inc. Marines)	0.0105	0.0124	42	0.052	0.0133	0.0065	0.002	0.001

Spares Summary Table								
	Mean	**Std Dev**	***N***	**Max**	**75%**	**Median**	**25%**	**Min**
Commodity Type								
Aircraft	0.0712	0.0932	228	0.497	0.0948	0.0425	0.007	0.001
Missile	0.0497	0.0517	73	0.225	0.0735	0.037	0.012	0.001
UAV	0.2157	0.165	14	0.481	0.385	0.1525	0.0623	0.022
Space	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ship	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Contract Type								
FFP	0.051	0.0743	107	0.456	0.064	0.02	0.003	0.001
FPI	0.1245	0.1419	39	0.481	0.16	0.074	0.02	0.001
FPAF	0.0822	0.0626	9	0.241	0.081	0.065	0.059	0.017
CPIF	0.1269	0.1026	20	0.383	0.19	0.1245	0.0333	0.001
MC	0.0818	0.1006	37	0.381	0.0955	0.056	0.0035	0.002
No Value	0.0605	0.0801	103	0.497	0.083	0.038	0.011	0.001
Contractor Type								
Prime	0.0735	0.0954	310	0.497	0.0923	0.0415	0.009	0.001
Subcontractor	0.014	0.0155	5	0.037	0.03	0.005	0.0025	0.002
Service								
Air Force	0.0976	0.1053	116	0.481	0.1363	0.0595	0.0223	0.001
Army	0.1312	0.1751	10	0.452	0.3173	0.0395	0.0058	0.003
Navy (Inc. Marines)	0.0541	0.077	189	0.497	0.074	0.027	0.007	0.001

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Bibliography

Bolten, J. G., Leonard, R. S., Arena, M. V., Younossi, O., & Sollinger, J. M. (2008). *Sources of weapon system cost growth* (MG-670). RAND Corporation.

Carter, A.B. (2011). *Implementation of Will-Cost and Should-Cost Management.* The Under Secretary of Defense, Acquisition, Technology, and Logistics.

Department of the Air Force. (2007). *Air Force cost analysis handbook*.

Department of the Air Force. (2018). *Financial Management: US Air Force Cost and Planning Factors.* AFI 65-503. Washington: HQ USAF, 13 July 2018.

Department of Defense (DOD). (2005). *Work Breakdown Structures for Defense materiel items* (MIL-HDBK-881A).

Department of Defense (DOD). (2018). *Department of Defense standard practice: Work breakdown structures for Defense materiel items* (MIL-STD-881D) [Standard].

Foreman, V.L., Le Moigne, J., & De Weck, O. (2016). *A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions*. Proceedings of the 18th Conference on American Institute of Aeronautics and Astronautics (AIAA) SPACE, 13-16 September 2016, Long Beach California. doi: 10.2514/6.2016-5245.

Government Accountability Office. (2009). *Cost estimating and assessment guide* (GAO-09-3SP). U.S. Government Printing Office.

Hollander, H., Wolfe, D. A., & Chicken, E. (2014). *Nonparametric statistical methods* (3rd ed.). John Wiley & Sons.

Markman, M.R., Ritschel, J.D., White, E.D. and Valentine S.M. (2019). *Developing Standard EMD Cost Factors for Major Defense Acquisition Program (MDAP) Platforms*, Proceedings of the 16th Annual Acquisition Research Symposium, 8-9 May 2019, Monterey, CA.

Mislick, G. K., & Nussbaum, D. A. (2015). *Cost estimation: Methods and tools.* John Wiley & Sons.

Naval Center for Cost Analysis. (2021). *NCCA.* Retrieved April 7, 2021, from https://www.ncca.navy.mil/references.cfm

Otte, J. (2015). *Factor study September 2015*. Air Force Life Cycle Management Center Research Group.

PAX. (2018, April 24). DoD area cost factors (ACF). *Programming Administration and Execution System Newsletters (PAX), 3*.2.1, 1–19.

Riquelme, P., & Serpell, A. (2013). Adding qualitative context factors to analogy estimating of construction projects. *Procedia—Social and Behavioral Sciences, 74,* 190–202. https://doi.org/10.1016/j.sbspro.2013.03.037

Roy, R., Colmer, S., & Griggs, T. (2005). *Estimating the cost of a new technology intensive automotive product: A case study approach*. International Journal of Production Economics, 97(2), 210-226. doi:10.1016/j.ijpe.2004.08.003.

Shishko, R. (2004). *Developing analogy cost estimates for space missions*. Proceedings of the AIAA Space 2004 Conference & Exhibition. Pasadena, CA. doi:10.2514/6.2004-6012.

Trivailo, O., Sippel, M., & Şekercioğlu, Y.A. (2012). Review of hardware cost *estimation methods, models and tools applied to early phases of space mission planning*. Progress in Aerospace Sciences, 53, 1-17. doi:10.1016/j.paerosci.2012.02.001.

Under Secretary of Defense for Acquisition, Technology, and Logistics. (2013, May 12). *Operation of the defense acquisition system* (Department of Defense instruction 5000.2). Department of Defense.

Wren, D. (1998). *Avionics support cost element factors*. Aeronautical Systems Center.

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