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Improving Annual Fixed Wing Maintenance Cost Estimates through Cost Estimating Relationships

Kirsten Bunecke

IMPROVING ANNUAL FIXED WING MAINTENANCE COST ESTIMATES THROUGH COST ESTIMATING RELATIONSHIPS

THESIS

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THROUGH COST ESTIMATING RELATIONSHIPS

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Abstract

The Air Force executes its mission primarily through the use of fixed-wing aircrafts. Maintaining these aircrafts represents approximately one-third of annual Operating and Support costs; which in turn, make up the majority of Life Cycle Costs. The current approach to estimating aircraft maintenance costs does not take into consideration programmatic data available in the Air Force Total Ownership Cost (AFTOC) database. The four maintenance cost subcategories researched in this thesis are Consumable Materials and Repair Parts, Depot Level Repairables (DLRs), Depot Maintenance, and Contractor Logistic Support. Each of these cost categories must first be standardized to be able to compare costs across years and across airframes. Through regression, this research attempts to determine cost drivers within maintenance cost subcategories and build predictive models for annual maintenance costs. Upon validating the models, they did not prove to provide better estimates than the currently used method of applying a 2% increase factor. They do however, provide a framework for further research into possible cost driving variables maintained outside of AFTOC.

Acknowledgments

I would like to acknowledge all my committee members for providing valuable insight and guidance along this path. Completion of this thesis alone would not have been possible or pleasant. Thank you to my classmates and friends for sharing in my struggles; together we reached the finish line. Most importantly, I want to acknowledge my wonderful wife for pretending to understand what I was talking about and for keeping me sane during this process.

Kirsten Bunecke

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I. Introduction

Background

Given the Air Force's mission and its push for air superiority, the service's operations are centered around aircraft, specifically those with fixed wings. A current hot issue in the news and on the mind of Congress is the rising price tag of the F-35. But, the costs don't stop once an aircraft is ordered; that is merely the beginning. Considering the entire acquisition lifecycle of major weapon systems, the Operation & Support (O&S) phase is the costliest and comprises on average 72% of a program's overall cost (Defense Systems Management College, 1997). Of a program's O&S costs, roughly a third of is used by maintenance (OSD, 2014). Aircraft maintenance costs are a considerably large portion of annual costs and getting these estimates more accurate will both support program managers and enhance the mission of the Air Force.

Research Approach

The Air Force Total Ownership Cost (AFTOC) Management Information System tracks annual aircraft maintenance costs for the Air Force. The database was developed in response to a call by the Secretary of Defense in the year 2000, to provide more visibility into the life cycle cost of weapon systems (Brown, 2010). In addition to cost data, the system extracts information from a number of sources to also include manning numbers, flying hours, inventory data and other aircraft specific programmatic information. As quoted by SAF/FM in the system's introduction document found on AFTOC's homepage, "The AFTOC system, when fully implemented, will be the authoritative source across the Air Force for financial, acquisition, and logistics information." Data in AFTOC dates back to 1996 for some aircraft and includes recent data from the present year, 2017.

The Air Force Cost and Performance (AFCAP) tool is a user-friendly macros-enabled pivot table tool built in Microsoft Excel that pulls data directly from AFTOC and other databases and allows for easy extraction, manipulation and conversion of all O&S costs at varying levels of detail. Consistent with the Office of the Secretary of Defense (OSD) O&S Cost Estimating Guide, the O&S Maintenance cost category is divided into subcategories as follows: 3.1) Consumable Materials and Repair Parts, 3.2) Depot Level Repairables (DLRs), 3.3) Intermediate Maintenance (external to Unit-Level), 3.4) Depot Maintenance, and 3.5) Other Maintenance. Within each of the subcategories follows more detailed distinction. As with any database, AFTOC and the AFCAP tool have their limitations and so it is necessary to build a custom dataset to accommodate the analysis performed for this research.

With a dataset that has been standardized across aircraft and fiscal year to adjust for the effects of inflation and usage, the program JMP Pro 12.0.1 is used to perform regression analysis on the annual aircraft maintenance costs in hopes of developing predictive models. Programmatic variables available in the AFCAP tool are tested to determine if any of the currently tracked variables are predictive of annual aircraft maintenance costs. Determining the cost drivers provides insight into what factors have the ability to influence the overall annual maintenance cost. Cost estimating models are developed at the maintenance cost subcategories as detailed in the O&S Cost Estimating Guide. Finally, a subset of the data will be set aside to perform model validations.

Ultimately, the coefficients of any predictive models are not set in time. As aircrafts age, as technology get more advanced, as more data becomes available, models will need updating, but the overall process is repeatable to accommodate changes in data. The aforementioned process of building regression models differs from the current approach to estimating annual

maintenance costs. To estimate an annual maintenance cost, the previous year's maintenance cost is adjusted according to the most current Office of the Secretary of Defense (OSD) inflation table and adding an additional 2% for escalation (Ronning, 2017). The current process for estimating aircraft maintenance costs does not take into account any programmatic or aircraft mission specific data. This thesis works towards determining cost estimating relationships and cost estimating models to improve upon the accuracy of annual fixed-wing aircraft maintenance cost estimates.

Research Questions

1. What variables maintained within AFTOC are major cost drivers of annual fixed-wing aircraft maintenance costs?
2. What predictive models for aircraft maintenance costs can be derived from determined cost drivers?
3. At what aircraft classification level (M/D/S) can these models be developed for maximum accuracy?

Summary

The current technique for estimating Air Force aircraft maintenance costs utilizes overly general and simplistic analogies. The same index is applied without any regard to other factors specific to the aircraft. The Air Force owns and maintains a plethora of data in AFTOC but it's possible that this data is not being used to its fullest capabilities. AFTOC extracts both cost and programmatic data from various data sources as a way to increase the visibility of the total cost of a weapon system and ultimately make the decision maker more informed. Regression analysis is useful in determining the major cost drivers of annual maintenance costs that can be used to build a predictive model to create more accurate estimates.

Developing cost estimates for large weapon systems is a complex undertaking given the amount of information and variation present in so many of the variables. Annual cost estimates are used to help determine annual budgets. Thus, estimates that grossly over or under estimate the actual cost have impacts on other Air Force programs. Improving O&S cost estimates has been a new focus since the enactment of the Weapon System Acquisition Reform Act in 2009. While lots of time and effort was placed into developing cost estimates in the early phases of the acquisition life cycle, O&S estimates were comparatively an afterthought despite these costs ranging from roughly 60% - 80% of the total life cycle cost.

Chapter One of this thesis introduces the problem at hand and sheds light on the scope of this work. Chapter Two explores previous work in this field and educates the reader on the previous lack of focus on O&S costs but indicates the desire and importance of future research on the topic. This chapter also reviews potential techniques to develop predictive equations for aircraft O&S maintenance costs. Chapter Three details the systems used to retrieve data, the techniques used to transform the data and the methodology implemented to answer the research questions and develop predictive equations. Chapter Four acts as a standalone article that briefly recounts the task at hand and delves into the analyses and the results from techniques described in the previous chapter. Lastly, Chapter Five speaks to the implications for the research findings, provides potential follow on topics and summarizes the entirety of this thesis.

II. Literature Review

Chapter Overview

The review of previous work and studies accomplished as presented are meant to guide the reader to an understanding of the importance of providing better estimations for aircraft maintenance costs. Aircraft maintenance costs are not stand alone cost figures but rather are a fraction of weapon systems' costs that are, at the highest level, all-encompassing dollar figures. The "cost" for the newest joint strike fighter, the F-35, has been a hot issue in current news. It is important to understand what the definition of "cost" encompasses in the numbers that are being reported. As reported by Mizokami (2017) the overall estimated cost for the requested 2,456 F-35 aircrafts is $406.5 billion. This cost includes research and development, testing and evaluation, the actual purchase of the aircrafts, and building new facilities to support the aircrafts.

The dollar figure currently associated with the F-35, however, includes none of the costs that will be required for operating and maintaining this fleet of aircraft for its useable lifetime. A short introduction to the definition and components of a weapon system's total life cycle cost will provide the basis of knowledge to then begin to breakdown costs at more specific levels for further in-depth and detailed analysis. Within the life cycle cost structure lies specific cost categories that make up the operating and support costs of a weapon system. It is in the operating and support cost category that we drill down to the lower levels of cost to include maintenance costs, which again contain further subcategories of costs. An understanding of the intricacies of these maintenance cost subcategories is necessary before attempting to determine estimates and relationships between annual aircraft maintenance costs and potential explanatory variables.

Life Cycle Costs

The life cycle cost (LCC) of a system accounts for an all-inclusive and exhaustive dollar amount the government incurs from "cradle to grave" or from the initial concept of a system to the end of a system being phased out. In regard to defense systems, the LCC is also referred to as the Total Ownership Cost (Life-Cycle Costs, 2008). The Government Accountability Office (GAO) Cost Estimating and Assessment Guide identifies the four major cost categories that make up the LCC: research and development costs, procurement and investment costs, operations and support costs, and disposal costs (2009).

The research and development phase includes costs associated with a system's design, development, evaluation, test equipment and startup. Procurement and investment costs are comprised of production, deployment, and initial and repair parts for the prime system. All direct and indirect costs incurred from the use and maintenance of the system falls under the operating and support (O&S) costs. This includes subcategories such as manpower, fuel, repairs and sustaining engineering. Finally, disposal costs encompass demilitarization and the breakdown of a system after its useful life (GAO, 2009). While all services use this cost category structure, there are slight differences in where some costs are placed.

The LCC structure of four cost categories is used to develop an estimate, the Life Cycle Cost Estimate (LCCE). This LCCE is important not only for tracking the progress of a system but also for developing budgets. Additionally, an LCCE might be used by decision makers to determine if it is an appropriate expenditure and fiscally responsible to taxpayers to continue along the acquisition process of a system. The importance of getting an LCCE as accurate as possible is clear; however, as indicated by Ryan, Jacques, Colombi and Schubert (2009) there is often very little confidence placed in these estimates.

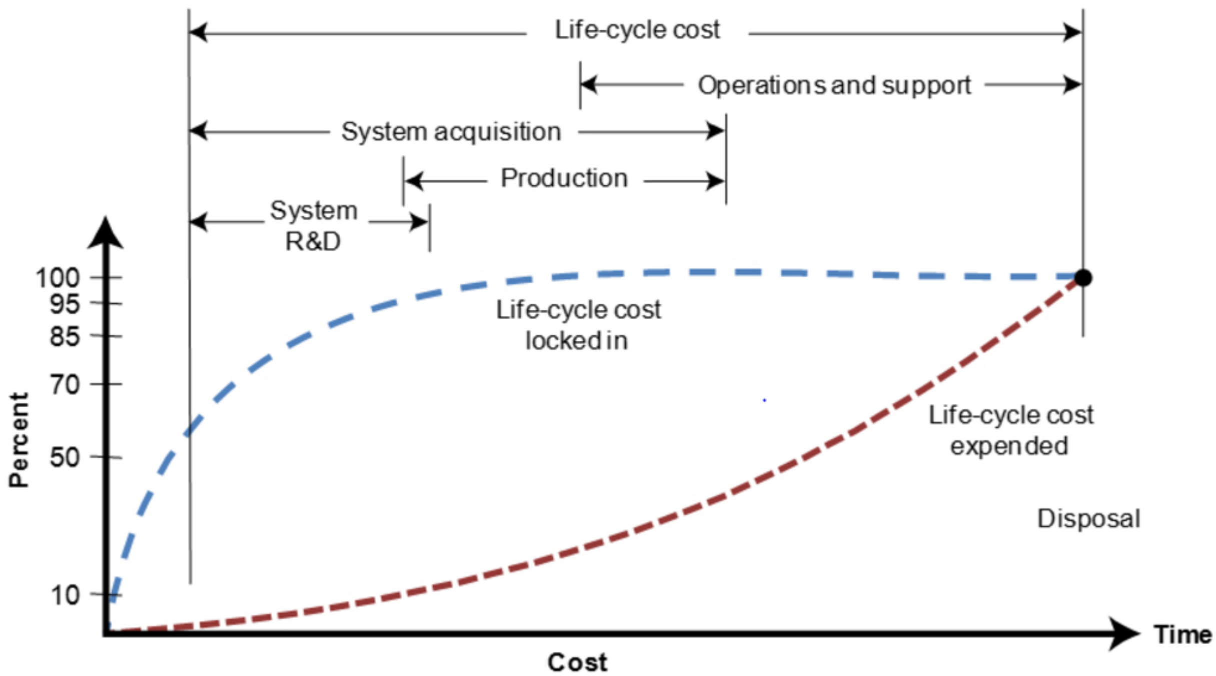

Figure 1. Relationship Between Cost and Life Cycle Phase

The disposal cost of a system can almost be considered negligible when compared to the first three cost categories. Of these remaining categories, both research and procurement costs can be considered acquisition costs; money that is used to physically acquire the weapon system. Thus, a system's LCC can be described as the sum of the acquisition costs and the remaining category of O&S costs. The acquisition phase of a system is relatively shorter and under tighter control as compared to the O&S phase of a system; however, it is often the decisions made early in the system's life cycle that drive the total LCC (Defense Standardization Program Office, 2016). Figure 1 illustrates this relationship of LCC spent and committed along the timeline of the acquisition phases of a system (Defense Standardization Program Office, 2016). Not until recently has the Department of Defense (DoD) placed more emphasis on improving life cycle cost estimates and according to Ryan et al. (2009), a good LCC estimate must first stem from robust knowledge on the accuracy of a program's O&S costs.

Operating & Support Costs

As previously mentioned, operating and support costs encompass the amount of money that the government spends to use and maintain a weapon system over its lifespan. Operating and support cost estimates are not a one-time requirement but rather, are useful along various stages on the acquisition process and the total life cycle. Initial estimates may be used in trade-off studies, analysis of alternative decisions, and affordability analysis. As a program matures, the O&S costs estimate should be updated with newly available data and actuals from previous fiscal years. This is necessary as both a tracking tool for past performance and as a basis for future estimates, which are then translated into annual budgets. Developing an appropriate O&S cost estimate, according to the O&S Cost-Estimating Guide, consists of the following top-level approach: 1) develop an analytical approach based on requirements and with a documented set of assumptions, 2) collect and validate data, 3) develop an estimating model, 4) identify risk areas, 5) estimate costs, 6) conduct sensitivity analysis, and 7) continually document results so estimates can be replicated (OSD, 2014). This arduous and meticulous process was once thought of as a near afterthought along the life cycle of a system (Jones, White, Ryan & Ritschel, 2014). It was not until recently that O&S cost estimates became an important piece of the equation (United States Congress, 2009).

The recent shift of focus to O&S costs means that there are relatively few published works that focus on purely O&S costs. The Weapon Systems Acquisition Reform Act (WSARA) of 2009 formally brought a new set of mandated requirements along with a shift in emphasis to O&S estimates. The WSARA highlights the necessity for analyzing, reporting, and attempting to reduce operating and support costs for major weapon systems throughout the Department of Defense. Section 304 of the Act lays out the expectation for the Comptroller

General to review and report on O&S costs. In addition to monitoring actual O&S costs and rates of growth in O&S costs for all major weapon systems (United States Congress, 2009), this publication requires that active measures are taken by the DoD to reduce O&S costs. This set of requirements and others detailed in the WSARA have led to an increase into the time and resources spent on not just collecting O&S cost data but also on using this newly available data to estimate these same costs for the future.

While the DoD has taken a step in the right direction with WSARA, it may still yet be some time before its benefits are evident. In addition to the requirement of valid data of actual costs and predicted costs, enough time has to lapse for a large number of programs to have this data and a methodology needs to be established to be able to adequately perform quantitative analysis. Ryan et al. (2009) proposes one possible methodology in an attempt to measure the accuracy of O&S estimates against actuals. He suggests comparing annual unitized O&S costs (converted to a standard base year) for actuals and estimates but recognizes a few concerns with this approach (Ryan et al., 2009). One such concern addressed by the GAO (2010) is that significant program changes, such as a decrease in flying hours or total number of aircraft, often occur after initial production costs estimates are developed. This makes it difficult to perform comparisons between actual and estimated costs and it brings to light the unfortunate reality that O&S estimates are not updated with information from the most recent actuals as often as they should.

The Operating and Support Cost-Estimating Guide identifies the same four LCC categories as previously explained and provides a visual representation of the relative magnitude of each category (OSD, 2014). Figure 2, although merely an illustrative rather than a quantitative graphic, clearly depicts the sizeable difference in the portion of O&S costs as

compared to the other three LCC cost categories. From this graphic, it can be stated that O&S costs account for the majority of a system's LCC (OSD, 2014). Additionally, the guide does indicate that the percentage of O&S costs varies based on the type of system. Jones, et al. (2014) also indicate the previous statement holds true in their analysis. It breaks out major weapon systems into seven categories: fixed wing aircraft, rotary wing aircraft, unmanned aerial vehicles (UAV), ground systems, surface ships, submarines, and space systems. For all categories except space systems, the average percentage of O&S costs ranges from 55% in the UAVs category to 69% for surface ships (OSD, 2014). For fixed wing aircraft, the average is 63%. Pie charts of each type of system and the percentage breakout of each cost category can be seen in Appendix A. Besides indicating that these percentages were derived from recent Selected Acquisition Report (SAR) data, there is no further indication of how these numbers where derived.

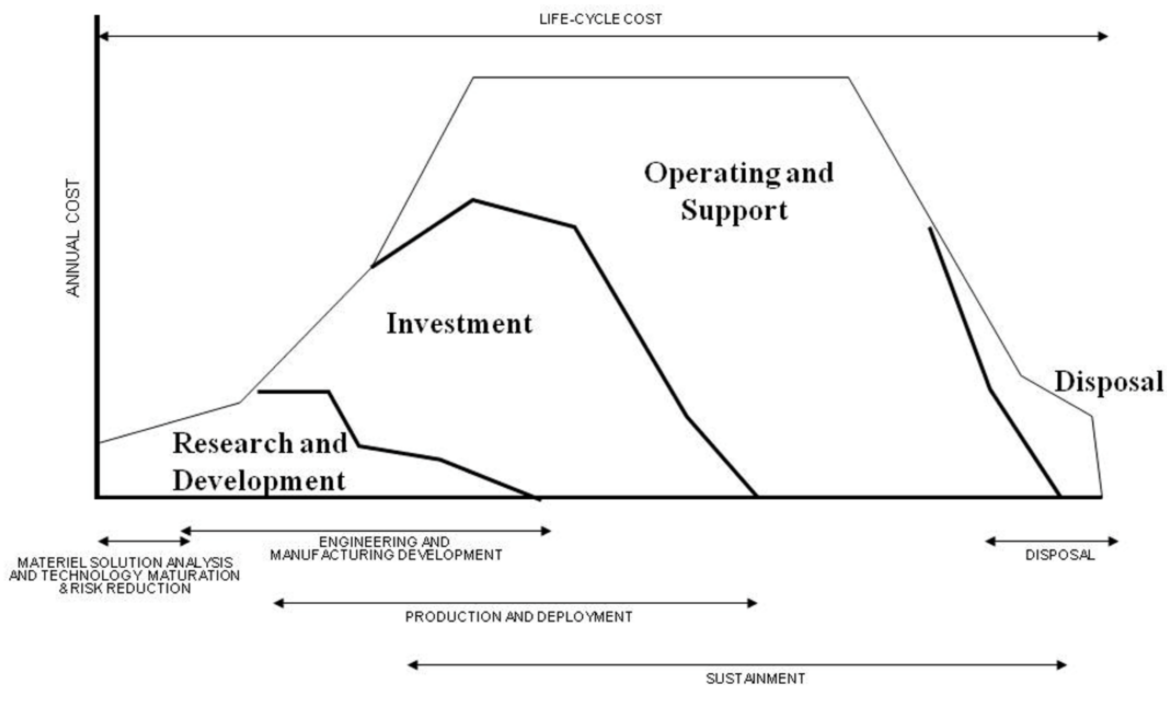

Figure 2. Illustrative Depiction of Life Cycle Costs

In an attempt to determine an appropriate percentage to represent the average percentage of O&S costs to the total LCC, Jones et al. (2014) challenge the ratio of 70% O&S costs that has become a "rule-of-thumb" in the cost community. Most interesting to note, is that Jones was unable to determine a source that indicated when or why 70% became the standard percentage used when describing O&S costs in relationship to LCCs. Jones et al. (2014) looked at a number of sources that assessed the portion of the LCC that is comprised of O&S costs and a summary of his findings can be found in Appendix B. Using both defense related and non-military sources, the O&S percentage ranged from a low of 24% to a high of 90%. His analysis indicated that it's inappropriate to use a standard across all weapon systems and his results show quite a variance based on system type (Jones et al., 2014).

Table 1. Summary of O&S Percentage of LCC from Jones et al. (2014) Analysis

System	Mean	Median
Ships	48.21%	51.12%
Ships – No Submarines	53.26%	51.46%
Fighter Aircraft	52.99%	51.46%
Cargo/Tanker/Bomber Aircraft	65.15%	61.73%
C/T/B – No KC-135R	59.94%	59.55%
Missiles	8.35%	6.56%
Rotary Wing Aircraft	70.73%	70.13%
Unmanned Aerial Vehicles	71.56%	71.56%
Electronic Equipment	15.53%	15.53%
Tilt Rotor Aircraft	65.03%	65.03%

His initial analysis into a more accurate representation of O&S costs sets up further analysis to create a better model to more accurately predict O&S costs. His findings resulted in a mean O&S percentage of 49.88% and a median of 54.09% of all systems combined together (Jones et al., 2014). His results, broken out by system type, can be seen in Table 1. As only two of the total ten categories have a mean or median near 70%, it's clear that the 70% typically used

and quoted by the acquisition community is inappropriate and typically an over estimation. Jones et al. (2014) suggest considering the variability in weapon systems due to things like mission capabilities, size and acquisition techniques.

While it's true that the WSARA sparked the increase into research on O&S costs, there have still yet been a surprisingly small number of studies that have been performed on the topic. One such study by Hildebrandt and Sze (1990) analyzed fixed-wing aircraft O&S cost data available in the Visibility and Management of Operation & Support Cost (VAMSOC) system from 1981-1986. This is a dated study, thirty-plus years, but the cost relationships that were discovered in this study may prove to still hold true in some form with the data that is currently available. At a bare minimum, they can provide insight in cost relationships for aircraft O&S data. Many things have changed in thirty years so it is unlikely that magnitudes of relationships are equivalent or similar but the possibility that this cost estimating approach is still applicable. Hildebrandt and Sze (1990) stated the following in the report summary:

> In an environment of declining defense budgets, obtaining the appropriate balance among the components of U.S. military posture—force structure, modernization, readiness, and sustainability—will be extremely challenging and require careful analysis of the cost reduction alternatives. (p. *v*)

Had the reader been oblivious to the date of this study, this statement could easily be mistaken for a description of recent fiscal concerns. If researchers thirty years ago felt budget constraints and recognized the importance of getting O&S estimates correct initially, their findings may be relevant to current cost concerns. Using a log-linear regression approach to predict an aircraft's O&S costs, the researchers were able to determine relationships among aircraft O&S costs, flyaway costs, total aircraft and design age (Hildebrandt & Sze, 1990).

Although Hildebrandt and Sze (1990) used a relatively small sample of data (approximately four hundred observations of fixed wing aircraft from six years of data) the researchers determined cost estimating relationships with strong explanatory results but did not test prediction accuracies. That is, no analysis was performed on the equations' ability to use those relationships to closely predict future O&S costs. Multiple models made use of the following variables: Fighter/Attack, Cargo, MDS year, Flying Hours, Number of Aircraft, Flyaway cost, and MD age. Bottom-line numbers of their research showed that assuming all other things equal, a one-year increase of an aircraft will bring an approximate 1.7% increase to the total O&S costs. Limitations from this analysis include the age of the data, the tight-knit group of aircraft, and an unknown quantitative factor in how technology has advanced since the eighties.

Just as life cycle costs can be broken up into categories, operating and support costs can also be further subdivided into like cost categories as seen in Table 2 (OSD, 2014) along with their respective average percentage. Unit-Level Manpower includes costs of the operator, maintenance, and support manpower that is typically based on personnel grades and skill categories of active and reserve military, government civilians and contractors. Unit Operations costs are comprised of operating material and support services for use in support of the primary system. This can include materials such as electricity and munitions and temporary duty or travel costs incurred by the unit. Maintenance costs include both parts and labor that are required to keep the primary system operational. Sustaining support costs are composed of costs incurred for system specific trainings and other support functions not already included in previous categories. Continuing System Improvement costs include modifications and upgrades to the system and lastly Indirect Support encompasses any costs that cannot be tied directly to the

unit or the personnel that utilize the primary system (OSD, 2014). More detailed descriptions of each of these cost categories can be found in the current O&S Cost Estimating Guide.

Table 2. Aircraft Cost Category Breakdown

Aircraft Cost Category	%
1.0 Unit-Level Manpower	30.8%
2.0 Unit Operations	21.4%
3.0 Maintenance	32.7%
4.0 Sustaining Support	1.4%
5.0 Continuing System Improvement	9.1%
6.0 Indirect Support	4.6%

Maintenance Costs

As evident from Table 2, maintenance costs comprise roughly one-third of aircraft O&S costs and represents the largest cost category. Estimating annual maintenance costs for an aircraft might initially seem like a small portion of the budget or LCCE but when considering annual maintenance costs for all aircraft owned and operated by the United States Air Force over the entire life of those aircraft, one begins to realize that aircraft maintenance cost can become a sizeable amount of money quickly. Keep in mind maintenance costs constitute roughly 30% of O&S costs (OSD, 2014) which in turn are approximately 72% of life cycle costs (Defense Systems Management College, 1997).

Recent estimates as reported to the public have indicated that the most current F-35 estimate for long term operations and support sits at $1.1 trillion if the aircraft is flown until the projected 2070 (Capaccio, 2017). One such reason for such a high O&S cost is because just four years into their service life, F-35 aircrafts are anticipated to need approximately 50 maintenance man-hours per flying hour; that is about three times more maintenance man-hours than the majority of the fighter aircraft flown by Western air forces (Briganti, 2016). If aircraft

maintenance is such a large portion of defense spending, then it is imperative to get the cost estimates as close to accurate as possible.

Breaking down the cost categories from Table 2 once more, we see that within O&S maintenance costs, there are 5 subcategories: 3.1) Consumable Materials and Repair Parts, 3.2) Depot Level Repairables (DLRs), 3.3) Intermediate Maintenance (External to Unit-Level), 3.4) Depot Maintenance, and 3.5) Other Maintenance. There are also three additional categories, all related to contractor support, that the Air Force tracks within AFTOC: 3.6) Interim Contractor Support, 3.7) Contractor Logistic Support, and 3.8) Other Contractor Support. There is little insight into the specifics of these categories through AFTOC as the data in these categories simply tracks an annual cost.

Consumable Materials and Repair Parts include the cost of items used to support maintenance of the primary system. These costs include not only the item but also transportation, storage, and overhead costs. DLR costs are those that the unit incurs when the system is repaired at a depot, which again includes the cost of the part, transportation, storage, direct labor, and overhead. Intermediate Maintenance consists of costs that are incurred at intermediate maintenance locations and could be for materials, parts, or labor. Depot Maintenance consists of costs for labor and materials when major overhauls are performed on the primary system. These overhaul activities are often based on schedules established to ensure proper and safe operations, similar to that of a 100,000-mile maintenance check-up on a car. Lastly, the Other Maintenance category is used for any maintenance cost that is not already captured by a previous cost category (OSD, 2014).

Maintenance costs across all airframes are most often standardized for comparison purposes by flying hours. This makes logical sense because an aircraft that is flown more will

naturally need more maintenance. Rather, the amount of maintenance necessary for an aircraft is a product of how much it is flown. The only subcategory in which flying hours are not an entirely logical standardizer is Depot Maintenance because as mentioned, maintenance operations performed in this category are often scheduled occurrences. However, for consistency and understanding purposes flying hours is still used to standardize this cost category. Accounting for flying hours per aircraft and otherwise standardizing maintenance cost data allows for more thorough analysis of what factor affect these costs. Knowledge on the cost drivers can then be applied to the cost estimating process.

Albeit a dated study, Marks and Hess (1981) explored cost estimating relationships for five different subcategories of specifically aircraft depot maintenance costs. While their analysis is one level deeper into the maintenance category than the analysis of this study and their results were less than favorable, their multiple regression technique and some explanatory variables provide a backbone. Their analysis can be scrutinized for having a rather small sample size as they used aircraft depot maintenance cost and programmatic data spanning only three fiscal years from 1975 through 1977. Marks and Hess (1981) also indicated that the focus of their study was to study estimating relationships for aircraft depot maintenance costs and attempt to develop accurate estimates for aircraft approaching the acquisition Milestone B and not for determining annual budgets.

Factors that Marks and Hess (1981) showed to be influential on depot maintenance cost include aircraft age, environment in which the aircraft is operated, aircraft mission and whether the aircraft is flown by active duty flyers or reservists and national guard members. Marks and Hess (1981) used a logarithmic form because it allows for the assumption that a normal distribution of error will lead to predictive equations with constant percentage error. Their

results did not produce one single equation, but rather a series of equations for each subcategory of depot maintenance activity where one equation over another may be more applicable or appropriate given certain aircraft or maintenance parameters. Similarly, Ronning (2017) challenged the current aircraft O&S maintenance cost estimating techniques and attempted to develop predictive equations. However, the results all had large standard deviation values and large Variance Inflation Factor (VIF) scores. His results indicated that there were several variables that exhibited multicollinearity and it seems that more standardization of the data is necessary to achieve equations that are more adequately predictive (Ronning, 2017). This thesis works to improve upon the groundwork laid out by Ronning.

Summary

To realize the magnitude of aircraft O&S maintenance cost, it is first imperative to trace those costs back up to the life cycle cost structure. Operating and supports costs are clearly the largest portion of LCCs, and similarly, maintenance costs are the largest portion of O&S aircraft costs. Focusing attention on improving estimates in this O&S cost category has the potential to have a large impact on annual budgets. Additionally, the WSARA of 2009 has called for an increased emphasis on not only lowing O&S costs but also creating better estimate techniques and models. Having an understanding for the structure of how aircraft maintenance costs are captured and what drives each maintenance cost category provides an opportunity to better estimate these costs. Chapter Three discusses details of the available aircraft O&S maintenance cost data and the methodology used to create corresponding cost estimating relationships and estimating models.

III. Methodology and Results

Chapter Overview

The purpose of this chapter is to provide a detailed approach to building a suitable database and lay out the steps necessary to perform analysis and build models that can predict annual fixed-wing maintenance costs in the established subcategories. Raw data is inspected and exclusion criteria is established to ensure that the resulting database is thorough and robust enough for analysis. The specific dependent and independent variables are outlined and assessed for appropriateness of potential inclusion. Because the data is from multiple years and multiple airframes, it is necessary to standardize the data to be able to appropriately compare values against each other. With cleaned and standardized data, a stepwise regression approach is applied to create predictive models, which are then assessed for fit and model assumptions. Results and implications from these models are presented in subsequent chapters.

Data Sources

Data from two different sources was used to create the database used in this research: Air Force Total Ownership Cost (AFTOC) accessed through the Air Force Cost and Performance (AFCAP) tool and Aircraft Maintenance Reports (AMREP) data provided by James Richards located at HQ AFMC/A4FI Life Cycle Management Branch. The AFTOC database is rather cumbersome to gather data in a usable format, so the AFCAP tool is used to organize the data in a manner that is more suitable for manipulation and standardization. AFCAP was designed in 2006 and pulls from five data sources to include AFTOC, Reliability and Maintainability Information System (REMIS), and the official database of historical USAF flying hour program information.

AFCAP version 9.1 is used in this analysis and includes complete data beginning in 1996 through the end of 2016. The advantage of using AFCAP rather than manually gathering the information from AFTOC, is that AFCAP makes use of pivot tables allowing users to output only the relevant information and it can apply a multitude of conversion factors. This is most useful in converting cost data originally reported in then-year dollars in AFTOC, into base-year dollars with a base year of 2016. Rather than using factors and applying formulas to a spreadsheet, AFCAP converts the data with a few selections from the main menu. Additionally, AFCAP is useful in gathering aircraft data at multiple aircraft levels and multiple O&S cost levels.

While the majority of the data used in this analysis is available through the AFCAP tool, additional information to build the database is acquired from AMREPs. These reports detail the depot maintenance for each aircraft tail number and are grouped into the categories of organic maintenance (planned and unplanned) and contracted maintenance (planned and unplanned). Because this data is listed by tail number, it is necessary to manipulate into yearly totals in each category to acquire information about the maintenance depot throughput of each aircraft. A limitation of this database is that data was only required to be maintained in this format starting in 2004. This limits the number of available years and data points to analyze depot maintenance in this research.

Exclusion Criteria for Database

The available AFTOC data in the AFCAP tool is the main source of data used to determine which airframes have enough viable data for analysis. The data from AMREP only limits the analysis of depot maintenance (cost subcategory 3.4) to the years of 2004-2016. The following is a list of exclusion criteria that was applied to achieve a useable dataset:

1. Aircraft is not manned and fixed wing
2. Aircraft is not currently operated and maintained by the Air Force
3. Cost data does not span at least ten years
4. TAI is less than ten for more than five years

The scope of this research is only on manned, fixed wing aircraft. While the Air Force has helicopters, unmanned crafts, and other aerial vehicles, fixed wing aircraft make up the majority of the inventory. Additionally, technology and design difference with these other aircrafts make it unsuitable to analyze alongside the manned, fixed wing aircrafts. Aircrafts that are no longer in operation are excluded from this analysis because the goal is to predict future costs. Additionally, it can be assumed that such aircrafts have been replaced with newer, more technologically-advanced aircraft. Including data from retired aircrafts might skew the data and would not accurately reflect the increased cost in the advanced technology used on current aircraft. Aircraft that did not have cost data for more than ten years is excluded because enough years of data is necessary to both perform analysis and to check the predictability of the resulting models. If an airframe has less than ten aircraft for more than five years in Total Available Inventory (TAI) it is excluded because it comprises such a small fraction of total maintenance costs and is such a small population size that a few data points can greatly affect the data. Applying these exclusion criteria to the AFCAP data resulted in twenty-one different airframes grouped together at the M/D level (A-10, F-16, etc).

Variables

Many variables for each airframe are tracked in AFTOC and the other databases that feed into AFCAP. Most importantly, the annual maintenance cost data is available for each airframe and can be easily categorized into the current Cost Assessment and Performance Evaluation

(CAPE) cost reporting structure used across the military. This data can be viewed in depth at four different levels. For the purpose of this research, the cost data is gathered at the second level which details how money is spent in each of the aforementioned maintenance cost subcategories. Along with the five maintenance subcategories detailed in the O&S Cost Estimating Guide: 3.1) Consumable Materials and Repair Parts, 3.2) Depot Level Repairables, 3.3) Intermediate Maintenance, 3.4) Depot Maintenance, and 3.5) Other Maintenance; three additional categories are used to track the money spent on contractor support. These categories are 3.6) Interim Contractor Support, 3.7) Contractor Logistic Support, and 3.8) Other Contractor Support.

The Air Force does not record costs in 3.3) Intermediate Maintenance and thus, there is zero cost data to analyze under this subcategory. This maintenance cost category is largely used by the other services. Subcategory 3.5) Other Maintenance is a catch-all (without explanation in AFTOC) for costs that don't apply to any of the other categories and it is used with little consistency throughout the dataset. For these purposes, 3.5) Other Maintenance cost data was removed from the dataset. Additionally, the majority of airframes have little to no data in 3.6) Interim Contractor Support and 3.8) Other Contractor Support. There is however, ample cost data recorded in 3.7) Contractor Logistic Support. For this research, analysis is not performed on the four subcategories that have very little data: 3.3) Intermediate Maintenance, 3.5) Other Maintenance, 3.6) Interim Contractor Support, and 3.8) Other Contractor Support.

Multiple programmatic variables are available through the AFCAP tool. Programmatic data includes the variables of TAI, fuel gallons, flying hours, sorties, landings, average aircraft age, maintenance manhours, total man power, and other variables that were thought to have little predictive qualities for annual aircraft maintenance. Just like the maintenance cost data, this

programmatic data is available yearly starting with data from 1996 through 2016. From the AMREP database, the following variables were created: Total Planned Organic, Total Unplanned Organic, Total Planned Contractor Logistic Support (CLS), and Total Unplanned CLS. From the database, totals were extracted for each airframe, for each year. These totals represent the total throughput of the aircraft maintenance depots. Again, the data related to depot maintenance is only available starting in 2004 through 2016.

Table 3. Distribution of Percentages of Annual Costs for Organic Airframes

Maintenance Subcategory	Mean	Lower 95%	Upper 95%
3.1	15.1%	8.2%	22.0%
3.2	42.6%	30.7%	54.4%
3.4	33.8%	20.3%	47.3%
3.5	0.0%	0.0%	0.0%
3.6	0.0%	0.0%	0.0%
3.7	6.3%	1.9%	10.7%
3.8	0.0%	0.0%	0.0%

Table 4. Distribution of Percentages of Annual Costs for Contractor Logistic Support Airframes

Maintenance Subcategory	Mean	Lower 95%	Upper 95%
3.1	1.0%	0.2%	1.7%
3.2	0.9%	-0.2%	2.0%
3.4	0.7%	-0.8%	2.2%
3.5	0.0%	0.0%	0.0%
3.6	0.0%	0.0%	0.0%
3.7	96.6%	93.0%	100.3%
3.8	0.0%	0.0%	0.0%

Using the available data, some additional variables can be extracted. Using the total maintenance costs to determine the percentage of money spent annually in each of the

maintenance subcategories, it is evident that an aircraft falls into one of two categories: organic maintenance or contracted maintenance. Those aircraft that had more than twenty percent of their annual maintenance costs spent in 3.7) Contractor Logistic Support are categorized as airframes maintained through contractor logistic support (CLS). Of the twenty-one airframes in this database, ten fall into this category: C-12, C-17, C-20, C-21, E-8, F-22, KC-10, T-1, T-6, and the U-2. The other airframes are maintained mostly organically and account from the remaining eleven airframes in the dataset: A-10, B-1, B-2, B-52, C-130, C-5, E-3, F-15, F-16, KC-135, and the T-38. Table 3 and Table 4 display the mean and 95% confidence intervals of the percentage of money spent in each maintenance subcategory when the airframes are categorized organic or CLS. For organic airframes, maintenance subcategories 3.1, 3.2, and 3.4 account for an average of 91.5% of annual maintenance costs and for CLS airframes, maintenance subcategory 3.7 accounts for 96.6% of annual maintenance costs. This distinction of organic or CLS determine which airframe to include in the predictive models for each of the maintenance subcategories.

Another variable that is added to the database is a binary variable to indicate if an aircraft is classified as stealthy. One of the measures of stealth for aircraft is the radar cross section (RCS), which is a measure of how detectable an object is to radar and typically has units of meters squared. Only two aircraft currently used by the Air Force were originally designed with stealth in mind, the B-2 and the F-22 with respective RCS measurements of $0.1m^2$ and approximately $0.0001m^2$, about the size of a marble (Richardson, 2001). For reference, the B-52 has an RCS of about $100m^2$. Through specific design features and upgrades, the B-1 and the F-15 have relatively small RCS measurements when compared to other bombers and fighters and can be considered stealthy (Grining, 2000). The variable of stealth is included in the database

because of the added technology that is required to make an aircraft stealthy. Using an extracted variable from AMREP, a new variable is created by dividing total planned depot maintenance by TAI. This variable expresses an annual percentage of aircraft that are expected to go through depot maintenance. Another independent variable was created by lagging the dependent variable of standardized annual cost by one year. Lastly, dichotomous variables are created to categorize airframes into their primary missions. The following categories are created: attack/fighter, bomber, cargo/tanker, reconnaissance, and trainer.

Standardization

To be able to compare cost data across multiple years, the first step to standardizing the data is ensure that all costs are adjusted for inflation. To transform the data, the AFCAP tool applies OSD inflation index for Operations and Maintenance (3400) to convert all data into base-year 2016 dollars. Due to the varying nature of each of the maintenance cost subcategories, they are analyzed separate from each other. Additionally, each of these categories will need to be standardized differently to reflect what is charged to each of the categories and so the cost data can be analyzed across airframes.

The first subcategory is 3.1) Consumable Materials and Repair Parts and is comprised of costs incurred by the operating unit for parts that are needed in maintenance of the aircraft. For this subcategory, cost data will be transformed into a cost per aircraft per flying hour. The airframe's annual TAI and flying hour data from AFCAP is used to calculate this cost variable. The 3.2) Depot Level Repairables subcategory consists of costs for parts that are sent to the depots to be repaired. The operating unit is then charged for the transport, storage, labor and material for the repairs. This cost category will also be standardized using values from each airframe's annual TAI and flying hours to create a cost per aircraft per flying hour. The

maintenance subcategory 3.4) Depot Maintenance is comprised of costs incurred from major maintenance events, usually of entire systems rather than smaller parts. This cost subcategory includes costs from both organic and contractor depot maintenance. Most depot maintenance is planned and follows a routine schedule, but depot maintenance can also be unplanned. Rather than standardizing this subcategory with TAI and flying hours, it will be standardized by the total planned (organic and CLS) depot maintenance or the throughput of the depots. The same values of annual TAI and flying hours used for subcategories 3.1 and 3.2 are used to standardize the final maintenance cost subcategory being analyzed, 3.7) Contractor Logistic Support. Because detailed information is not available on the maintenance performed by the contractors is can only be speculated that these values are appropriate for standardization.

Assumptions

Before performing the analysis, it's important to state some required assumptions. It's unlikely that every aircraft tail number has an equivalent usage rate and similarly, it's unfeasible that each tail number requires the same maintenance. However, to perform the analysis, it must be assumed that every tail number has equivalent usage and requires maintenance at the same rate. Each airframe represented in the database is a rollup of all the variants. Doing this reduces the number of different airframes represented in the database, but it also allows for more data points to be included. For example, some individual variants when not rolled up with their respective other variants, would have been excluded based on the previously established exclusion criteria. By lumping aircraft variants together, it must be assumed that each variant requires similar maintenance elements and will incur similar maintenance costs.

Methodology – Stepwise Regression

The main program used to perform the analysis is JMP, a statistical tool capable of performing regression analysis and producing graphics for large databases. To build models for each of the maintenance cost subcategories, stepwise regression is used to determine the variables that are predictive. Stepwise regression is a method of performing regression analysis that determines predictive variables based on prespecified criteria. Regression models built with a stepwise approach can be built starting with no variables in the model and adding the variables that create a better fit model, which is called a forward approach. A backward approach starts with a model that includes all variables and then removes variables to increase the fit of the model. A mixed, or bidirectional, approach makes use of both the forward and backward approaches at each step. This analysis makes use of the mixed approach to perform the stepwise analysis and determine the predictive variables. Inclusion and exclusion criteria of the variables in the model is based on a p-value threshold of 0.1.

In creating the models in JMP, the dependent variable is the standardized annual cost of the maintenance cost subcategories and the independent variables are any other variables that have been gathered in the database. Once JMP selects the predictive variables according the previously mentioned parameters (mixed approach with a p-value threshold of 0.1), the fit of the model is assessed and assumptions are checked.

Model Fit and Assumptions Check

First, the selected variables are checked to see if any multicollinearity is present. Analyzing the variance inflation factor (VIF) score provides insight into variables that may be correlated. Generally, a maximum value of 5 for VIF scores is desirable but lower values are preferred. Higher VIF scores indicate that two or more variables are correlated and thus one

needs to be removed from the model. The model is also checked for influential data points by plotting the Cook's Distance Influence values. Data points that fall above the generally accepted 0.5 threshold are overly influential and have too much effect on the p-values of the model's explanatory variable(s). Another check for outliers is performed by graphing a histogram of the studentized residuals. Data points that fall outside of three standard deviations from the mean have the potential to be outliers. Any outliers should be assessed to provide an explanation and may possibly be excluded from the database if appropriate.

In addition to testing the fit of the model, it is also necessary to check two residual assumptions: normality and constant variance of model residuals. Normality is tested by running a Shapiro-Wilk test on the residuals. A model passes the normality test if the p-value associated with the Shapiro-Wilk test is greater than the established alpha of 0.05. The model is assessed for constant variance by viewing the residual by predicted plot or by calculating the Breusch-Pagan value. Again, a chart that appears to have random data points passes the assumption of constant variance. A chart that appears to have a triangle or diamond pattern means variance is not constant. Ideally, a good predictive model will be a good fit of the data and will pass all assumptions. This iterative process is executed for each of the maintenance subcategories with some additional exclusions made with each attempt at building a regression model.

Regression Results

The regression model for maintenance subcategory 3.1 starts with 198 possible data points from the eleven airframes categorized as organic from the years 1997 to 2014. The first year of data (1996) from each airframe is not used because of the effect from the lag variable of the dependent variable and the last two years of data (2015-2016) are not included in that analysis because they will be used to assess the predictive capabilities of the model. After an

initial run of the stepwise regression model, it is clear the B-2 data points are different from the other points. The standardized values of the B-2 are in the hundreds, while the standardized values of the other airframes mostly range from less than one to about twenty. Because of this difference with the B-2, it is excluded from the analysis and the model is rerun.

After a close look at the Cook's D influence scatterplot and an iterative process of running the model, excluding outliers, and rerunning the model; an additional thirteen data points are removed from the final model. Six rows from the B-1 and seven rows from the E-3. These data points fall under the generally accepted Cook's D Influence threshold of 0.5; however, they are values that stand out considerably from the rest of the data points. Upon inspection of these thirteen data points, it is evident that there are fluctuations in the raw cost values that are not explained through the information available in the dataset. A detailed list of excluded data points is available in Appendix C. The final model for maintenance subcategory 3.1 included 167 data points and Table 5 displays the summary of fit and parameter estimates for the model. The full JMP output of each of the models is shown in Appendix D. The only variable for maintenance subcategory 3.1 that the regression model flagged as significant was the lagged standardized cost.

Table 5. Regression Model Summary for Maintenance Subcategory 3.1

Summary		**Parameter Estimates**			
R Squared	0.981926	Term	Estimate	t Ratio	Prob > |t|
R Squared Adj	0.981817	Intercept	0.24331	1.36	0.1746
F Ratio	8964.297	Standardized Cost Lag 1	0.9979	94.68	<.0001
Prob > F	<.0001				

The data from the regression model for maintenance subcategory 3.2 initially has 198 data points from all eleven organically maintained aircraft from the years 1997 to 2014. Just like

with the previous regression model, the use of a lag variable of the response results in an inability to use the first year of available data from 1996. Additionally, the last two years of data are removed from the regression model to validate the model. A stepwise regression model is run with all the available independent variables and all 198 data points. Again, it is clear that the B-2 has much larger response values than the other ten airframes. Rerunning the regression model without the data points from the B-2 provides a clearer picture into potential outliers within the remaining ten airframes.

An iterative process of running the regression model, analyzing the Cook’s D Influence graph, and investigating data points for potential removal if they were thought to be outliers. This process highlights a few data points from the B-1, B-52, C-5, and E-3 that have the potential to be outliers. A total of 19 rows from the previously mentioned airframes are removed after looking into each data point for a potential explanation into why it flags as an outlier on the Cook’s D Influence chart. Appendix C contains a detailed list of the excluded data points. The remaining 161 data points are included in the regression model which returned three dependent variables as significant. Similar to the model for maintenance category 3.1, the lag variable of the standardized annual costs is the most significant variable for the 3.2 model. Additionally, the dichotomous variables for reconnaissance and bomber aircraft are significant. Parameter estimates and other model outputs are in Table 6 and the full model details are in Appendix D.

Table 6. Regression Model Summary for Maintenance Subcategory 3.2

<table>
<tr><th colspan="2">Summary</th><th colspan="4">Parameter Estimates</th></tr>
<tr><td>R Squared</td><td>0.987767</td><td>Term</td><td>Estimate</td><td>t Ratio</td><td>Prob > |t|</td></tr>
<tr><td>R Squared Adj</td><td>0.987534</td><td>Intercept</td><td>1.90255</td><td>2.77</td><td>0.0064</td></tr>
<tr><td>F Ratio</td><td>4225.882</td><td>Standardized Cost Lag 1</td><td>0.83333</td><td>56.92</td><td><.0001</td></tr>
<tr><td>Prob > F</td><td><.0001</td><td>Reconnaissance</td><td>11.2614</td><td>3.68</td><td>0.0003</td></tr>
<tr><td></td><td></td><td>Bomber</td><td>17.0021</td><td>6.51</td><td><.0001</td></tr>
</table>

The costs from maintenance subcategory 3.4 are the only response variables that are standardized by something other than flying hours and TAI. Rather, these costs are standardized using the total annual depot throughput. This data is only available beginning in 2004 through 2016 resulting in a smaller initial number of data points to include in the analysis. A total of 110 data points from eleven organically maintained airframes from 2005 to 2014 is reduced to 99 data points after the B-2 is again removed along with one data point from the E-3 that stands out on the Cook's D Influence chart after running the initial regression model. The final model consists of five variables with the lagged standardized cost being the most significant variable. The percentage of TAI that was planned to go through the depot along with dichotomous variables for trainer, fighter/attack, and reconnaissance are the remaining significant variables in the model. This model has a comparatively lower R Squared value to the previous two models and the following model as well. A summary and full details of the model are present in Table 7 and Appendix D, respectively.

Table 7. Regression Model Summary for Maintenance Subcategory 3.4

Summary		**Parameter Estimates**			
R Squared	0.750171	Term	Estimate	t Ratio	Prob > |t|
R Squared Adj	0.73674	Intercept	6913092	5.97	<.0001
F Ratio	55.851	Standardized Cost Lag 1	0.57957	7.9	<.0001
Prob > F	<.0001	Percent TAI in Depot	-12483067	-4.44	<.0001
		Fighter/Attack	-3077048	-3.44	0.0009
		Reconnaissance	3758084	3.04	0.0031
		Trainer	-4929644	-3.78	0.0003

The fourth and final model is the only model that attempts to predict cost for the ten airframes that are mostly maintained through Contractor Logistic Support. Using the same

iterative process of running a stepwise regression and using the Cook's D Influence chart to spot outliers for potential removal results in a continual process of new data points pulling away from the pack on the Cook's D Influence chart. A model with all initial 167 data points has a weak R Squared value and overall poor results. This model attempts to find a happy medium of excluding data points that flagged as clear outliers on the Cook's D Influence and maintaining enough data points to be able to conduct analysis and provide usable results.

Table 8. Regression Model Summary for Maintenance Subcategory 3.7

Summary		Parameter Estimates			
R Squared	0.902272	Term	Estimate	t Ratio	Prob > |t|
R Squared Adj	0.901149	Intercept	3.94719	1.86	0.066
F Ratio	803.23	Standardized Cost Lag 1	0.94154	28.34	<.0001
Prob > F	<.0001				

Nearly half of the data points are removed, including all data points from the E-8, F-22, and the U-2. The F-22 along with the T-6 are clearly phasing into operation and take a few years for costs to stabilize. Additionally, there is unexplained fluctuation in cost data in the C-12 and C-20 which each have a few data points that are removed from the final model. The removal of all these data points reduces the over usefulness of this model and limits its predictability to only those airframes not excluded from the model. The detailed list of removed variables for this model is available in Appendix C. The settled upon model in this case has a total of 89 data points from only six different airframes and the only variable that is significant is the lagged standardized cost. Table 8 shows a summary of the model for maintenance category 3.4 and Appendix D shows the full details of the model. The reader should note that while the process for removing potential outliers is an objective process heavily utilizing the Cook's D Influence chart, the point at which the researcher stops removing potential outliers is a subjective decision.

In this case, removing any more data points has the potential for degrading the model and diminishing its usefulness.

Model Fit and Assumption Results

Each model's fit is assessed and the assumptions are checked as the respective data points are removed. All four of the models have VIF scores lower than then the generally accepted standard five. This means that the variables chosen for each model don't exhibit any multicollinearity. None of the models have data points have Cook's D Influence values that are greater than 0.5. This standard is a good initial check, but this dataset requires additional scrutiny in the Cook's D Influence charts. Some values, while technically below the 0.5 threshold, have values much larger than the majority of values. Those data points that are thought to have too much influence on the models are removed to increase the predictability of the model. The Cook's D Influence values are the main indicator of potential outliers in this analysis. A histogram of the studentized residuals shows how many of the data points fall within +/- 3 standard deviations. The models for maintenance subcategories 3.1, 3.2, and 3.4 all have studentized residuals within +/- 3 standard deviations and the model for 3.7 has two points that fall outside of the boundaries. All four of the models fail the normality test; histograms of the residuals spike in the middle more than a normal curve. All models passed the test for constant variance.

Validation

Before any analysis is run and models are built, a subset of the data is set aside to test the predictive capabilities of each model. For this dataset, a subset of the last two years of data is used for the validation process. Predictive equations built from the parameter estimates of each model's significant variables provide the framework for calculating the standardized annual cost

in each of the four maintenance subcategories. The inputs for the model equations are all values that are available ahead of time to predict the following year's maintenance cost. The lagged standardized cost is taken from the previous year and the mission (bomber, trainer, reconnaissance) of the aircraft is also known. In the case of the model for 3.4, the percent of TAI in the depot is calculated using variables that should also be known ahead of time: planned number of aircraft to enter the depot and the Total Available Inventory.

The prediction estimate from each of the models is compared to the actual costs in each maintenance subcategory for years 2015 and 2016. The predictions and actuals are compared by calculating the absolute percent difference in the values. In addition to the model approach presented in this thesis, the actuals were also compared to the mean and median costs of each airframe and the status quo method of increasing the previous year's actuals by two percent. Table 9 shows the results of each method and highlights the best and worst approach for each of the categories. In no case did the models presented in this thesis predict the annual maintenance cost better than the status quo approach. For each maintenance subcategory, the mean and median cost approaches are farthest off the mark.

Table 9. Validation Results: Absolute Percent Difference of Actuals vs. Predictions

Maintenance Subcategory	3.1	3.2	3.4	3.7
Model Approach	11.60%	16.30%	46.80%	27.10%
Mean	36.10%	22.40%	43.60%	78.80%
Median	56.20%	27.50%	54.60%	135.70%
Status Quo (2%)	6.57%	11.01%	12.53%	16.35%

Summary

This chapter details the steps taken to create predictive models for four of the eight established cost subcategories that the Air Force uses to report their annual maintenance

expenses. To create a comprehensive database ready for analysis, exclusion criteria is applied, and the data is standardized to be able to compare the values across years and airframes. After assumptions are established, the program JMP is used to perform stepwise regression analysis creating models for each maintenance cost subcategory. These models are then critiqued on their fit and their assumptions are checked. Lastly, the models' predictions are then pitted against a subset of actual annual maintenance cost data to test their predictive capabilities. It's evident from Table 9 that each of the models do not do a better job at predicting annual maintenance cost than the status quo. Chapter Four acts as a standalone article that briefly highlights the main points of this thesis but focuses on the results of the analysis.

IV. Journal Article:

Evaluating Annual Fixed Wing Maintenance Costs

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Evaluating Annual Fixed Wing Maintenance Costs

Abstract

Maintaining Air Force fixed winged aircraft represents approximately one-third of annual Operating and Support costs. Of twenty-one different airframes grouped together at the Mission-Design Series (MDS), maintenance subcategories 3.1) Consumable Materials and Repair Parts, 3.2) Depot Level Repairables (DLRs), and 3.4) Depot Maintenance accounted for, an average, 91.5% of annual organic maintenance costs. For contractor maintained MDS, subcategory 3.7) Contractor Logistics Support (CLS) accounted for 96.6% of annual maintenance costs. A regression approach was investigated to identify possible cost drivers for each subcategory. After accounting for inflation, total available inventory, flying hours, and the total planned (organic and CLS) depot maintenance, the strongest driver of current year costs are last year's cost. The data suggests an overall maintenance year over year cost growth of 1.8%, with an increase of 2.5% and 3.8% year over year attributable to depot maintenance and DLRs, respectively.

Key Words: Operating and Support, Depot Level Repairables, Depot Maintenance, Contractor Logistic Support

Evaluating Annual Fixed Wing Maintenance Costs

Background

Given the Air Force's mission and its aim for air superiority, the service's operations are centered around aircraft, particular those considered fixed wing. A current hot issue in the news and on the mind of Congress is the rising price tag of the F-35. It is important to understand what the definition of "cost" encompasses in the numbers that are being reported. As reported by Mizokami (2017) the overall estimated cost for the requested 2,456 F-35 aircraft is $406.5 billion. This cost includes research and development, testing and evaluation, the actual purchase of the aircraft, and building new facilities to support this weapon system. However, this dollar figure does not include any of the costs that will be required for operating and maintaining this fleet of aircraft for its useable lifetime. The most current F-35 estimate for long term Operations and Support (O&S) sits at $1.1 trillion if the aircraft is flown until the projected year 2070 (Capaccio, 2017).

The F-35 is not alone in its high associated costs with respect to O&S. The life cycle cost (LCC) of a system accounts for an all-inclusive and exhaustive dollar amount the government incurs from "cradle to grave" or from the initial concept of a system to the end of a system being phased out. Thus, a system's LCC can be described as the sum of the acquisition costs and the remaining category of O&S costs plus disposal. The acquisition phase of a system is relatively shorter and under tighter control as compared to the O&S phase of a system; however, it is often

the decisions made early in the system's life cycle that drive the total LCC (Defense Standardization Program Office, 2016).

Considering the entire service life of a major weapon system, the O&S phase is the costliest and comprises approximately 72% of a program's overall cost (Defense Systems Management College, 1997). This percentage is an average and varies from system to system. In an attempt to determine an appropriate percentage to represent the mean percentage of O&S costs to the total LCC, Jones et al. (2014) used defense related sources to estimate this O&S percentage. Their findings indicate this percentage ranged from a low of 24% to as a high of 90%, depending on the weapon system. For fixed wing aircraft, these percentages ranged from 53% to 65%.

Because O&S costs are not a one-time requirement, but rather an ongoing yearly cost of maintaining a weapon system, one would think that such an expense would be heavily scrutinized. It was not until recently that O&S cost estimates became an important piece of the equation (GAO, 2010). The Weapon Systems Acquisition Reform Act (WSARA) of 2009 formally brought a new set of mandated requirements along with a shift in emphasis to O&S estimates. Section 304 of the Act lays out the expectation for the Comptroller General to review and report on O&S costs. In addition to monitoring actual O&S costs and rates of growth in O&S costs for all major weapon systems, this publication requires that active measures are taken by the Department of Defense (DoD) to reduce O&S costs.

Just as a system's LCC can be partitioned into categories, O&S costs can also be further subdivided into a standard Cost Element Structure (CES). The CES delineated by the OSD Cost Assessment and Program Evaluation (CAPE) O&S guide is comprised of six top-level elements as shown in Table 10. According to the Office of the Secretary of Defense (OSD, 2014),

maintenance (CES 3.0), accounts for approximately a third of all O&S costs, with manpower (CES 1.0) accounting for the next highest at approximately 31%. Considering annual maintenance costs for all aircraft owned and operated by the United States Air Force (USAF) over the entire life of those aircraft, one begins to realize this maintenance cost can become a sizeable amount of money quickly. If aircraft maintenance is such a large portion of defense spending, then it is imperative to obtain accurate annual cost estimates. This increased accuracy could better support program managers and enhance USAF's mission.

[Insert Table 10]

While it's true that WSARA sparked the increase into research on O&S costs, there have still been a surprisingly small number of studies that have been performed on the topic. Ryan et al. (2012), Ryan et al, (2013), and Jones et al. (2014) have recently investigated O&S cost estimates, but a study by Hildebrandt and Sze (1990) analyzing fixed wing aircraft O&S cost is particularly relevant to this research. Obtaining available data from the Visibility and Management of Operation & Support Cost (VAMSOC) system from 1981-1986, they used a log-linear regression approach and concluded that assuming all other things equal, a one-year increase of an aircraft's age will bring an approximate 1.7% increase to the total O&S costs. Or comparably, the current O&S cost of an aircraft system increases from the previous year's by 1.7%.

Even though dated almost thirty years ago, this percent is very close to the anecdotal percentage of the current approach to estimating annual maintenance costs. The modern approach entails using the previous year's maintenance cost adjusted according to the most

current OSD inflation table and adding an additional 2% for escalation (Ronning, 2017). Our literature review did not find any archival journal or official guide that documents this method or percentage. Therefore, this article entails to empirically study and model the percentage increase of O&S costs for fixed wing aircraft from year-to-year and determine a more accurate percentage for practitioners to use.

Database and Methods

The Air Force Total Ownership Cost (AFTOC) Management Information System tracks annual aircraft maintenance costs for the USAF. The database was developed in response to a call by the Secretary of Defense in the year 2000 to provide more visibility into the life cycle cost of weapon systems (Mandelbaum and Pallas, 2001). In addition to cost data, the system extracts information from a number of sources to also include manning numbers, flying hours, inventory data and other aircraft specific programmatic information. Data in AFTOC dates back to as early as 1996 for some aircraft.

The O&S Cost Estimating Guide further subdivides the CES of Table 10 into sub-elements. For CES 3.0, maintenance, there are eight sub-elements. See Table 11. Consumable Materials and Repair Parts include the cost of items used to support maintenance of the primary system (including fuel). DLR costs are those that the unit incurs when the system is repaired at a depot. Intermediate Maintenance consists of costs that are incurred at intermediate maintenance locations. Depot Maintenance consists of costs for labor and materials when major overhauls are performed on the primary system. The Other Maintenance category is used for any maintenance cost that is not already captured by a previous cost category (OSD, 2014). Lastly, for the

contractor subcategories (Interim Contractor Support, Contractor Logistics Support, and Other Contractor Support), there is little insight into the specifics through AFTOC as the data in these categories simply track an annual cost.

[Insert Table 11]

Using AFTOC, annual maintenance cost data is available for each airframe and can be viewed down to the fourth cost element level. For the purpose of this article, the cost data is gathered at the second level (corresponding to Table 11) which details how money is spent in each of the aforementioned maintenance cost subcategories. With respect to 3.3) Intermediate Maintenance, the USAF does not record these costs since this maintenance category is used by the other services. Subcategory 3.5) Other Maintenance is a catch-all and is used inconsistently. Additionally, the majority of airframes studied have little to no data in 3.6) Interim Contractor Support and 3.8) Other Contractor Support. Consequently because of these reasons, analysis is not performed on the four subcategories that have very little data: 3.3) Intermediate Maintenance, 3.5) Other Maintenance, 3.6) Interim Contractor Support, and 3.8) Other Contractor Support. As shown in the results section, this had little affect on the outcome of the analysis.

The AFTOC system can be relatively cumbersome to gather requisite data, so the Air Force Cost and Performance (AFCAP) tool is utilized to extract the majority of data needed for analysis. AFCAP version 9.1 is used to pull AFTOC maintenance data spanning from 1996 through the end of 2016. While the majority of the data used in this analysis was available through the AFCAP tool, additional information was acquired from Aircraft Maintenance

Reports (AMREP). These reports detail the depot maintenance for each aircraft tail number and are grouped into the categories of organic maintenance (planned and unplanned) and contracted maintenance (planned and unplanned). Because this data is listed by tail number, it is necessary to aggregate into yearly totals in each category to acquire information about the maintenance depot throughput of each aircraft platform. A limitation of this database is that data was only required to be maintained in this format starting in 2004. This limits the number of available years and data points to analyze depot maintenance in this research.

Once all the data was acquired from either AFTOC via AFCAP or through AMREPs, data standardization is performed in order to account for inflation effects, flying hours, and throughput since these affect costs if left unaccounted. Using OSD's appropriation inflation tables, all dollar amounts are converted into base-year 2016 dollars. Due to the varying nature of each of the maintenance cost subcategories analyzed in this paper: 3.1, 3.2, 3.4, and 3.7, they are analyzed separately and are further standardized as follows. For subcategories 3.1, 3.2, and 3.7, base year costs are further standardized per aircraft per flying hour. The airframe's annual Total Available Inventory (TAI) and flying hour data from AFCAP are used for this conversion. For subcategory 3.4) Depot Maintenance, this includes costs from both organic and contractor depot maintenance. Rather than standardizing this subcategory with TAI and flying hours, it is standardized by the total planned (organic and CLS) depot maintenance or the throughput of the depots.

The scope of this research is only on manned, fixed wing aircraft. While the Air Force has helicopters, unmanned crafts, and other aerial vehicles, fixed wing aircraft make up the majority of the inventory. Fixed wing aircraft that are no longer in operation are excluded from this analysis; including data from retired aircraft might skew the data and would not accurately

reflect the increased cost in the advanced technology used on current aircraft. Aircraft that did not have cost data for more than ten years are also excluded in order to prevent a few years of data being extrapolated into longer patterns of maintenance costs. Lastly, if an airframe has less than ten aircraft for more than five years in TAI it is excluded because it comprises such a small fraction of total maintenance costs and is such a small population size that a few data points can greatly skew the results.

The analysis of the final cost database are broken into two sections: a descriptive analysis of the information broken into the respective subcategories to illustrate where the bulk of the maintenance costs are encountered, and secondly: a regression analysis using Ordinary Least Squares (OLS) is adopted to determine which variables appear to be statistically significant of the standardized cost data. For the OLS piece, a mixed stepwise procedure is adopted. A level of significance is set to 0.01 to determine initial predictive ability of an explanatory variable. From there, the preliminary selected variables are investigated to determine their practical effect on the respective model. If a particular explanatory variable is determined to have less than a 1% relative effect on a particular model's response, then that variable is excluded. This is done to minimize a variable being statistically significant but having little practical effect. All analysis in this article used JMP 12 Pro, Excel or R.

With respect to possible predictive explanatory variables to consider, many are obtained via AFTOC. For example, AFTOC contains programmatic data such as number of sorties, number of landings, average aircraft age, maintenance manhours, and total man power. Additionally, a dichotomous variable is included to determine if organically maintained versus contractor maintained has an affect on standardized cost. Those aircraft that had more than twenty percent of their annual maintenance costs spent in 3.7) Contractor Logistic Support are

considered as contractor airframes in comparison to less than twenty percent for organically maintained. Other explanatory variables considered include whether an aircraft is classified as stealthy, ratio of total planned depot maintenance to TAI, the previous year's standardized cost data, and lastly airframe categories such as attack/fighter, bomber, cargo/tanker, reconnaissance, and trainer.

As with any OLS analysis, the customary residual assumptions of normality and constant variance are tested by utilizing the Shapiro-Wilk test and the Breusch-Pagan test, respectively. Both are conducted at the 0.05 level of significance. Additionally, multicollinearity, outliers, and influential data points are investigated in order to prevent model bias. Variance Inflation Factors (VIF) highlight the linear relationship between independent variables and a VIF score higher than 5 suggests multicollinearity. Regarding outliers, any studentized residual greater than three standard deviations is categorized as an outlier and a possible source of concern. Lastly, Cook's Distance detects overly influential data points possibly skewing the results. Any value greater than 0.5 is investigated closely.

Before performing the analysis, it's important to state some required assumptions. It's unlikely that every aircraft tail number has an equivalent usage rate and similarly, it's unfeasible that each tail number requires the same maintenance. However, to perform the analysis, it must be assumed that every tail number has equivalent usage and requires maintenance at the same rate. Each airframe represented in the database is a rollup of all the variants. Doing this reduces the number of different airframes represented in the database, but it also allows for more data points to be included. For example, some individual variants when not rolled up with their respective other variants would have been excluded based on the previously established

exclusion criteria. By grouping aircraft variants together, it must be assumed that each variant requires similar maintenance elements and will incur similar maintenance costs.

Results

Applying the exclusionary criteria to the AFTOC database via the AFCAP tool, as previously aforementioned, resulted in twenty-one different airframes grouped together at the Mission-Design Series (MDS) level (A-10, F-16, etc). Table 12 highlights those programs incorporated in this paper's analysis. Of these twenty-one MDS, ten are maintained through Contractor Logistics Support (CLS), while the other eleven are maintained mostly organically. Tables 13 and 14 display the mean percentage of costs for each maintenance subcategory when the airframes are categorized as organic or CLS. For organic MDS, maintenance subcategories 3.1, 3.2, and 3.4 account, an average, 91.5% of annual maintenance costs and for CLS MDS, maintenance subcategory 3.7 accounts for 96.6% of annual maintenance costs. The percentages do not sum to 100%. To minimize the impact of outliers in maintenance costs, median percentages were first calculated for each MDS as a more robust measure of cost. Then, means were calculated across all the respective MDS.

[Insert Tables 12-14]

In order to investigate likely predictors of annual maintenance cost of organic MDS, individual OLS analyses are conducted for subcategories 3.1, 3.2, and 3.4. For CLS MDS, the only OLS analysis conducted is for subcategory 3.7. Starting with subcategory 3.1 (Consumable

Materials and Repair Parts), 231 points are initially available for analysis spanning years 1996-2016. However, because past annual cost may be a possible predictor of current annual cost, the first year of data (1996) for each MDS is lost due to lack of data for 1995. This reduction results in an effective sample size of 220 data points. The OLS assumptions of normality and constant variance of residuals were not initially satisfied until a natural logarithm transformation was conducted on the response, annual maintenance cost adjusted for inflation, flying hour, and TAI. Table 15 highlights the results from conducting the stepwise regression for subcategory 3.1. The dominant factor associated with current annual cost is last year's annual cost. The inflation adjusted price for a barrel of oil did not flag as significant for this category, despite 3.1 being often associated with fuel cost. Table 15, and subsequent tables, also includes R^2 (coefficient of determination) for the untransformed data as a comparison since the transformation to address OLS residual assumptions often artificially increases R^2 in the transformed case.

[Insert Table 15]

When investigating factors associated with subcategories 3.2, 3.4, and 3.7 maintenance costs, a similar logic to that conducted of subcategory 3.1 is adopted. That is, investigating prior year's maintenance cost results in losing the first year of data for each MDS (1996 for 3.2 and 3.7; 2004 for 3.4). Additionally, the natural logarithm transformation is required to alleviate issues due to non-normality and heteroscedasticity of OLS residuals. Table 16 highlights the results for subcategory 3.2 (Depot Level Repairables), Table 17 for subcategory 3.4 (Depot Maintenance), and lastly Table 18 for subcategory 3.7 (Contractor Logistics Support). Effective samples sizes consist of 220, 132, 186 points, respectively. Analyzing subcategory 3.4 resulted

in the smallest effective sample size due to AMREP data only available from 2004 onwards. With respect to subcategory 3.7, which involved CLS, only ten MDS were available instead of eleven for organically maintained. An additional fourteen points were unavailable due to missing data, notably seven for the F-22 and four for the T-6.

[Insert Table 16-18]

Similar to the results of Table 15 for subcategory 3.1, the previous year's standardized cost is the most predictive driver for current standardized cost. In other words, after accounting for inflation and then either flying hours and TAI for subcategories 3.1, 3.2, and 3.7 or total planned (organic and CLS) depot maintenance (or the throughput of the depots), no other explanatory variable effectively predicted annual maintenance other than the previous year's maintenance cost. On average, the analysis suggests an overall increase over time that does not appear to be attributable to aging aircraft or any other variable considered once accounting for prior year's cost. This also includes investigating how closely maintenance costs track with the overall DoD budget.

To assess the effect of how past maintenance cost is associated with current maintenance cost, the percent difference from last year's maintenance was calculated for each MDS for subcategories: 3.1, 3.2, 3.4, and 3.7. As before, all costs were standardized amounts for that respective subcategory. Since means can be extremely affected by even a single outlier for a year, median values were calculated instead. For 3.1) Consumable Materials and Repair Parts, the median percent increase from year to year is 1.6%. For 3.2) DLRs, this percent increases to 3.8%. For 3.4) Depot Maintenance, this percent drops to 2.5%. Lastly, for 3.7) CLS, the median

percentage increase is 0%. If investigated at a complete macro level at the 3.X maintenance level with no consideration of subcategories, and accounting for extreme values both large and small (approximately 2.3% of the data), the approximate median percentage is 1.8%, year over year.

Conclusion

This article's purpose was two-fold. One, empirically document and model the percentage increase of O&S costs for fixed wing aircraft from year-to-year and determine a more accurate percentage for practitioners to use. And secondly, to place into the archival realm another reference for other researchers to consider and from which to springboard other O&S topics to investigate. There are many published refereed articles regarding the acquisition of weapon systems, but little to date on the O&S side of the USAF. Within O&S costs, aircraft maintenance requires a sizeable budget and inaccurate estimates can have large impacts on the future of Air Force programs.

Utilizing O&S maintenance data obtained from AFTOC and AMREPs for twenty-one MDS, the analysis convincing showed that the previous year's maintenance cost data for subcategories 3.1, 3.2, 3.4, and 3.7 is highly correlated with the current year maintenance cost data. All dollar amounts were standardized for inflation, flying hours, TAI, and depot throughput accordingly. For all categories, except 3.7, standardized costs rose year over year. For CLS, maintenance subcategory 3.7, the median percentage increase was 0%. This does not imply that the raw cost of CLS has not increased over time. Instead, the data for this study suggests that after accounting for inflation, flying hours, and TAI, CLS has remained constant in

the aggregate sense. At first glance, this does seem to contradict Boito, Cook, and Graser (2009) who suggest that although CLS costs and organic costs appear to be comparable, both are increasing over time. However, their analysis did not account for flying hours or TAI, just inflation.

Regarding subcategories 3.1, 3.2, and 3.4, after accounting for inflation and then either flying hours, TAI, or depot throughput, all have increased year every year. These standardized costs have risen, in the median sense, 1.6%, 3.8%, and 2.5%, respectively. Such sediment is also reflected by Boito, Cook, and Graser (2009) who further state in their findings that depot maintenance for aircraft and engines accounted for roughly 41 percent of CLS costs, while spare and repair parts accounted for another roughly 22 percent of CLS costs. Moreover, the percentile increase of 1.6%, 3.8%, and 2.5% are consistent with other past results, and in keeping with the USAF's anecdotal use of multiplying last year's maintenance costs with 2% (Ronning, 2017) for next year's estimates. In fact, the overall 3.X median increase for this study's database places this percentage slightly lower at 1.8% year over year. This closely aligns with Hildebrandt and Sze's (1990) percentage of 1.7%. These collective findings reflect a long-term consistent growth in O&S costs that are not accounted for by either flying hours, TAI, or depot throughput. An aging fleet would seem to be the likely driver, however, in none of the analyses for subcategories 3.1, 3.2, 3.4, and 3.7 did an MDS age appreciatively account for predicting current year's standardized cost.

The higher median percentile increase of 2.5% and 3.8% year over year are attributable to depot maintenance and DLRs, respectively. These percentages are similar to the findings of Ferry (2013) who determined that the Cost Growth Above Inflation (CGAI) in O&S costs in raw materials for USAF fixed winged aircraft appear to be approximately 3% year over year. It is

speculated that this annual increase might be due to replacing aircraft parts that are either becoming rare or obsolete. That is, the actual age of the aircraft itself is not causing this unaccounted for CGAI, but rather instead the escalating price of replacing rare if not impossible MDS parts on the open market. It is further speculated that perhaps investing in or determining the feasibility of utilizing 3D printing capability might help militate against year over year rising costs of depot related maintenance. This arena may be of interest for other researchers to investigate and to consider further.

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Table 10. OSD CAPE Cost Element Structures (CES)

CES	Name	Description
1.0	Unit-Level Manpower	Cost of operators, maintainers, and other support manpower assigned to operating units. May include military, civilian, and/or contractor manpower.
2.0	Unit Operations	Cost of unit operating material (e.g., fuel and training material), unit support services, and unit travel. Excludes material for maintenance and repair.
3.0	Maintenance	Cost of all system maintenance other than maintenance manpower assigned to operating units. Consists of organic and contractor maintenance.
4.0	Sustaining Support	Cost of system support activities that are provided by organizations other than the system's operating units.
5.0	Continuing System Improvements	Cost of system hardware and software modifications.
6.0	Indirect Support	Cost of support activities that provide general services that lack the visibility of actual support to specific force units or systems. Indirect support is generally provided by centrally managed activities that provide a wide range of support to multiple systems and associated manpower.

Table 11. Mainteance CES

CES	Name	CES	Name
3.1	Consumable Materials and Repair Parts	3.5	Other Maintenance
3.2	Depot Level Repairables (DLRs)	3.6	Interim Contractor Support
3.3	Intermediate Maintenance	3.7	Contractor Logistic Support
3.4	Depot Maintenance	3.8	Other Contractor Support

Table 12. Fixed wing Mission-Design-Series (MDS) included in the study's analysis, segregated by organic or Contractor Logistics Support (CLS) maintenance.

MDS	Organic / Contractor
A-10	Organic
B-1	Organic
B-2	Organic
B-52	Organic
C-130	Organic
C-5	Organic
E-3	Organic
F-15	Organic
F-16	Organic
KC-135	Organic
T-38	Organic
C-12	CLS
C-17	CLS
C-20	CLS
C-21	CLS
E-8	CLS
F-22	CLS
KC-10	CLS
T-1	CLS
T-6	CLS
U-2	CLS

Table 13. Mean percentages of median annual maintenance costs for all organic MDS by subcategory. Percentages rounded to one decimal place. Total percent does not add to 100% due to taking a mean of medians to remove affect of outliers.

Subcategory	Mean Percent
3.1	15.1
3.2	42.6
3.3	0.0
3.4	33.8
3.5	0.0
3.6	0.0
3.7	6.3
3.8	0.0

Table 14. Mean percentages of median annual maintenance costs for all CLS MDS by subcategory. Percentages rounded to one decimal place. Total percent does not add to 100% due to taking a mean of medians to remove affect of outliers

Subcategory	Mean Percent
3.1	1.0
3.2	0.9
3.3	0.0
3.4	0.7
3.5	0.0
3.6	0.0
3.7	96.6
3.8	0.0

Table 15. OLS analysis for maintenance subcategory 3.1. All values rounded to three significant digits. R^2 presented for both log transformed (natural log) and untransformed variables.

Analysis R^2	Variable	Estimate	P-value
Transformed: 0.992	Intercept	0.0481	0.0016
Untransformed: 0.929	Ln (Last Year's cost): Natural logarithm of last year's standardized cost	0.9870	< 0.0001

Table 16. OLS analysis for maintenance subcategory 3.2. All values rounded to three significant digits. R^2 presented for both log transformed (natural log) and untransformed variables.

Analysis R^2	Variable	Estimate	P-value
Transformed: 0.980	Intercept	0.140	< 0.0001
Untransformed: 0.832	Ln (Last Year's cost): Natural logarithm of last year's standardized cost	0.974	< 0.0001

Table 17. OLS analysis for maintenance subcategory 3.4. All values rounded to three significant digits. R^2 presented for both log transformed (natural log) and untransformed variables.

Analysis R^2	Variable	Estimate	P-value
Transformed: 0.867	Intercept	0.594	0.2401
Untransformed: 0.797	Ln (Last Year's cost): Natural logarithm of last year's standardized cost	0.961	< 0.0001

Table 18. OLS analysis for maintenance subcategory 3.7. All values rounded to three significant digits. R^2 presented for both log transformed (natural log) and untransformed variables. The untransformed R^2 is reported with 1 and 2 datapoints removed from the F-22 and E-8 respectively for the first few years of reporting. Values were exceedingly high.

Analysis R^2	Variable	Estimate	P-value
Transformed: 0.956	Intercept	0.154	0.0404
Untransformed: 0.876	Ln (Last Year's cost): Natural logarithm of last year's standardized cost	0.963	< 0.0001

V. Conclusions and Recommendations

Chapter Overview

The purpose of this chapter is to provide a summary of the research process followed for this analysis. It also explores some additional variables not originally included in the database. Sensitivity analysis is performed on the status quo approach used to estimate annual maintenance cost. This chapter outlines some broad conclusions and recommendations based on the findings and finally, it presents additional topics that warrant further research.

Additional Variables Considered

The discovery of relatively poor predictive models for the four maintenance cost subcategories invokes some thought on additional variables not contained in AFTOC or AMREP that have the potential to improve the models. One such variable is the price of a barrel of oil adjusted for inflation. This data was gathered from the United States Energy Information Administration and adjusted for inflation using Consumer Price Index (CPI) inflation tables. The same stepwise regression methodology detailed in Chapter Three is followed with this new variable included. The variable does not flag as significant when the lagged variable of the standardized cost is included as a variable. However, when the lagged variable is excluded, the variable for the price of a barrel of oil does flag as significant along with many other variables. The adjusted R Squared value of this model is lower than the model built with the lagged standardized variable and it is not better at predicting the actuals for 2015 and 2016. The full model output and the validation assessment can be seen in Appendix D. Lastly, the annual defense budget adjusted for inflation with a base year of 2016 is included as an additional variable; however, this variable does not flag as significant for any of the maintenance

subcategories. The annual defense budget values are found in the Office of Management and Budget's Table 5.2.

Table 19. Sensitivity Analysis on Predictive Capability of Status Quo on Total Annual Maintenance Cost (All 21 Airframes, Standardized by Flying Hours)

Percentage	Average % Diff	Avg (abs) % Diff
1.50%	0.43%	16.58%
1.60%	0.34%	16.59%
1.70%	0.24%	16.60%
1.80%	0.14%	16.61%
1.90%	0.04%	16.62%
2.00%	-0.06%	16.63%
2.10%	-0.15%	16.65%
2.20%	-0.25%	16.66%
2.30%	-0.35%	16.68%
2.40%	-0.45%	16.69%
2.50%	-0.55%	16.71%

Sensitivity Analysis

Because thesis's attempt to build predictive models that more accurately estimates annual maintenance costs with data available in AFTOC and AMREP was unsuccessful, an investigation into the status quo is conducted. Sensitivity analysis around the 2% multiplicative factor is performed for all 21 airframes in this dataset. Additionally, the analysis is performed for just the airframes that are characterized as organically maintained as there are unknown outside factors that influence the contracts for CLS airframes. To best capture the total annual maintenance costs, this sensitivity analysis is performed on 3.0) Maintenance, the rolled-up value of all the maintenance subcategories. Table 19 shows the mean percent difference and mean absolute percent difference between the calculated predictive value using each of the percent multipliers and the actuals from 2015 and 2016. It is interesting to note that the average percent

difference reaches zero between 1.9% and 2.0%. This indicates that at a top-level of budgeting and estimating, a multiplicative factor of 2% may be appropriate to estimate total annual maintenance costs for fixed wing aircrafts. Again, because airframes maintained on contract have unknown factors outside the scope of this thesis, the same analysis is performed for only the organic airframes in this dataset. Table 20 indicates that 2% may not be appropriate for just organic airframes as the mean percent difference reaches zero between 3.2% and 3.3%. Although it is important to indicate that Tables 19 and 20 are an average of all maintenance subcategories and that 2% may be an accurate percentage for some of the maintenance subcategories when assessed individually.

Table 20. Sensitivity Analysis on Predictive Capability of Status Quo on Total Annual Maintenance Cost (Organic Airframes only, Standardized by Flying Hours)

Percentage	Average % Diff	Avg (abs) % Diff
2.00%	1.19%	13.64%
2.10%	1.09%	13.64%
2.20%	1.00%	13.65%
2.30%	0.90%	13.66%
2.40%	0.80%	13.67%
2.50%	0.71%	13.67%
2.60%	0.61%	13.68%
2.70%	0.51%	13.69%
2.80%	0.42%	13.71%
2.90%	0.32%	13.72%
3.00%	0.22%	13.73%
3.10%	0.12%	13.75%
3.20%	0.03%	13.76%
3.30%	-0.07%	13.78%

Conclusions

The regression models presented in this thesis were not better at predicting annual maintenance cost than the current estimating method using a 2% multiplicative factor. This does

not indicate that a CER approach is not appropriate but rather, that more research into additional variables may prove valuable. AFTOC contains mostly cost data and a few programmatics but it is limited in detailed maintenance data. The main cost driver in each of the models is the standardized cost lagged one year. This indicates that a previous years cost instrumental in determining a future annual maintenance costs. The recommendation from this analysis alone is not to use the presented models; however, they may provide a foundation to continue to build and improve.

Future Research

The research presented in this thesis fell short of the goal; however, there is potential for improvement in the models. An investigation into detailed maintenance systems could provide additional variables that may be major cost drivers that are not tracked in AFTOC or AMREP. A comparison of aircraft maintenance performed in the private sector to military aircraft maintenance may provide insight into maintenance cost estimating or even cost saving techniques. Lastly, performing this analysis with a bottom-up approach that uses the lowest level of the cost estimating structure to create predictive models may improve upon the accuracy of estimates.

Summary

Any approach that challenges the status quo needs to perform at least just as good, if not better; or it should perform just as good but require less resources. Additionally, it should have significant research to support a change being worthwhile. Little research in O&S costs have been accomplished when compared to the tightly controlled acquisitions costs. Within O&S costs, aircraft maintenance requires a sizeable budget and inaccurate estimates can have large impacts on the future of Air Force programs. Standardizing cost data and applying regression

techniques to determine cost drivers from the data available in AFTOC did not result in better estimates than the status quo provided; however, the potential for improved models is ever present.

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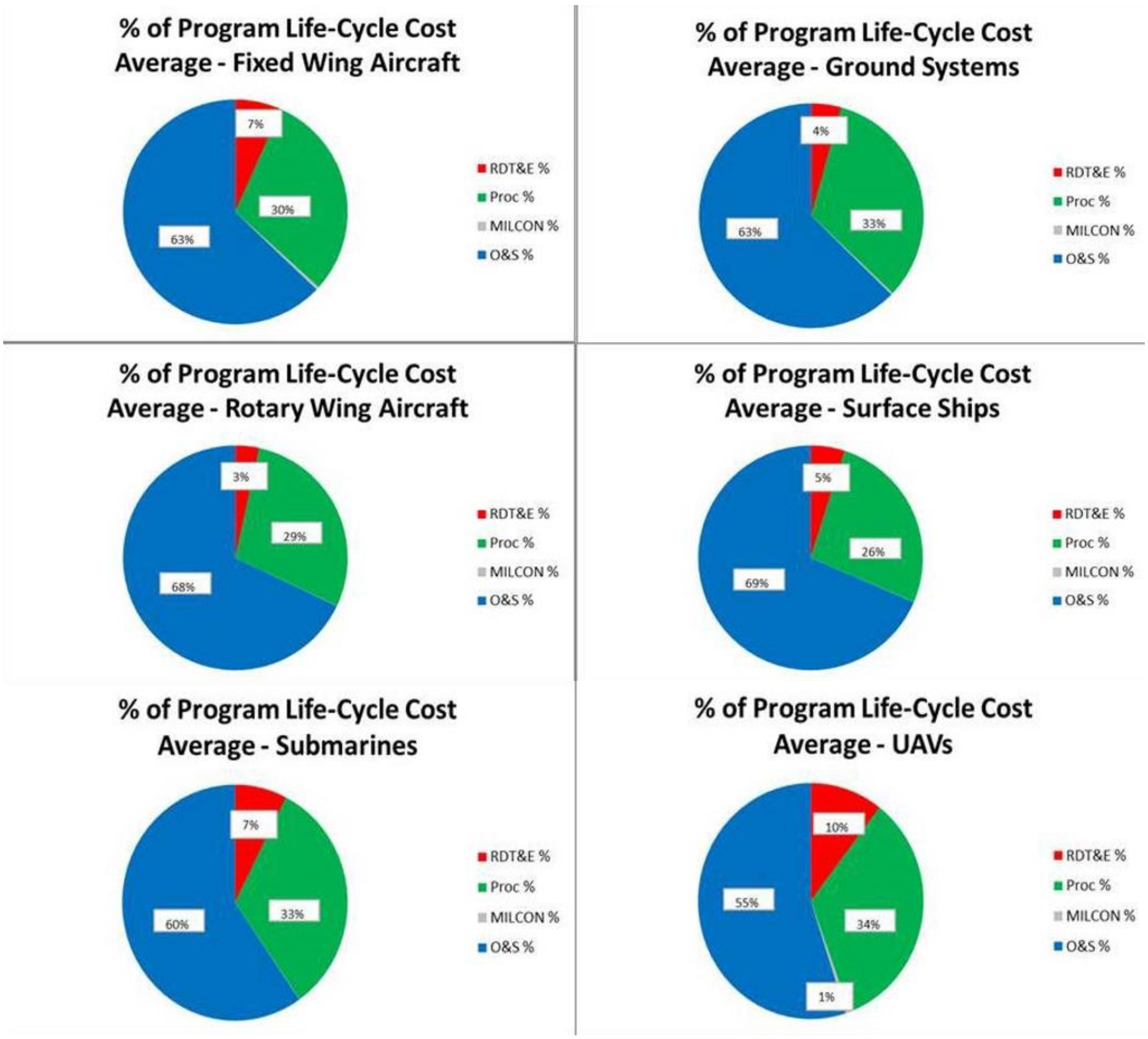
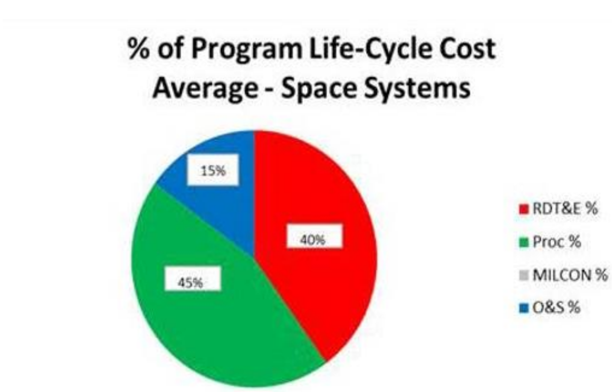
Appendix A

Percentage Breakdown of LCC by System Type (Office of the Secretary of Defense, 2014)





Appendix B

Summary of Findings from Jones et al. (2014) Literature Review

Source	O&S Portion of LCC
Sun Tzu, The Art of War, Sixth century B.C.	40%
Marco Fiorello, Getting "Real Data for Life-Cycle Costing, 1975	50%
T. W. Otto, Jr., Life Cycle Cost Model, 1975	24.4%
US GAO, O&S Costs of New Weapon System, 1977	42.2%
US GAO, Logistics Planning For The M1 Tank, 1981	70-90%
OSD CAIG, Operating and Support Cost Estimating Guide, 1992	78%, 84%
DSMC, Acquisition Logistics Guide, 1997	60-80%, 72%
IDA, Status of DoD's Capability to Estimate, 1999	Varies by Type
US GAO, Higher Priority Needed for Army O&S, 2000	60-70%
DoD, DoD Weapon System Acquisition Reform, 2009	60-75%
US GAO, Cost Estimating and Assessment Guide, 2009	Varies by Type
US GAO, Littoral Combat Ship, 2010	70%
US GAO, Improvements Needed to Enhance Oversight, 2012	70%
USD, ATL, Pentagon Efficiency Initiatives, 2011	70%
Dallosta & Simcik, Designing for Supportability, 2012	65-80%
Taylor & Murphy, OK, We Bought This Thing, 2012	45%, 60-80%

Appendix C

Exclusion criteria for each model

Model 3.1

- Exclusion: Airframes that are primarily CLS (10 airframes excluded)
- B-2: Any entirely different airframe than the rest… flagged all over the place. Exclude entirely
- Using Cook's D: B-1 and E-3 spike (under 0.5 but clearly stand out)
    - B-1: 6 rows excluded – 29, 30, 33, 35, 36, 38
        - Lots of fluctuation in raw costs
        - Draw down of TAI (95-67) over the course of 8 years
        - Continual decrease in sorties (~6000 to 3000)
        - In 2007, avg age hits 20
    - E-3: 7 rows excluded – 192, 193, 196, 200, 201, 205, 206
        - Fluctuation in raw costs with little to no change in TAI, flying hours, sorties
        - 4 different variants used by USAF
        - In 1999, avg age hits 20
- Total data points: 167

Model 3.2

- Exclusion: Airframes that are primarily CLS (10 airframes excluded)
- B-2: Any entirely different airframe than the rest… flagged all over the place. Exclude entirely
- Using Cook's D: B-1, B-52, C-5, & E-3 spike (under 0.5 but clearly stand out)
    - B-1: 9 rows excluded – 420 to 422, 426, 428, 431, 432, 436
        - Draw down of TAI (95-67) over the course of 8 years
        - Continual decrease in sorties (~6000 to 3000)
        - In 2007, avg age hits 20
    - B-52: 3 rows excluded - 458, 459, 472
        - Large increase in raw cost 96-97… used heavily in gulf war
        - In 1996, avg age is 35 (Last variant, B-52H, entered service in 1961!)
    - C-5: 3 rows excluded – 572 to 574
        - Large increase in raw cost without change in TAI or flying hours
    - E-3: 5 rows excluded – 591, 592, 596, 598, 607
        - Fluctuation in raw cost and flying hours
        - 4 different variants used by USAF
        - In 1999, avg age hits 20
- Total data points: 161

Model 3.4

- Exclusion: Airframes that are primarily CLS (10 airframes excluded)
- B-2: Any entirely different airframe than the rest… flagged all over the place. Exclude entirely
- Depot maintenance data only available from ’04-’16… years ’96-’03 (for each airframe) excluded from analysis… year ’04 excluded due to lag effect
- One data points excluded from flagging as an outlier bases on Cook’s D… row 1006 (E-3, 2013)
    - A few data points stuck out (from the E-3) but still under 0.5
- Total data points: 99

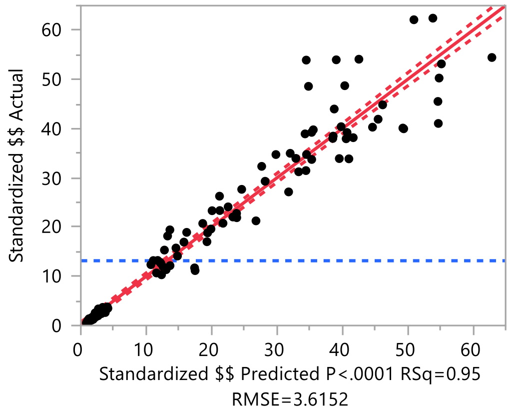
Model 3.7

- Exclusion: Airframes that are labeled as organic (excludes 11 airframes)
- Based on Cook’s D, the following points were excluded:
    - C-12: rows 1278-1281 – fluctuation in raw $$ right at about time aircraft hits avg age 20
    - C-20: all rows (1331-1349) – small TAI (~10) leading to fluctuation in stand $$
    - E-8: all rows (1407-1425) – airframe phasing in, small TAI, fluctuation in stand $$
    - F-22: rows 1464-1482 – airframe phasing in and hasn’t steadied out
    - T-6: rows 1559-1572 – airframe phasing in
    - U-2: all rows
- Total data points: 89
    - Not great results here… probably went through 100+ iterations of excluding/including data points based on Cook’s D; reality here is that aircraft maintained on contract are a black box to the AF

Appendix D

Whole Model (3.1)

Actual by Predicted Plot



Summary of Fit

RSquare	0.981926
RSquare Adj	0.981817
Root Mean Square Error	1.84718
Mean of Response	10.36138
Observations (or Sum Wgts)	167

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	30586.858	30586.9	8964.297
Error	165	562.992	3.4	**Prob > F**
C. Total	166	31149.851		<.0001*

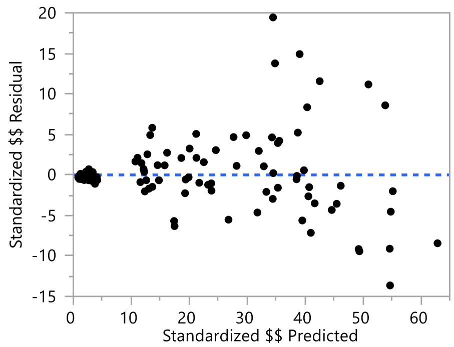
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	146	562.37328	3.85187	118.1937
Pure Error	19	0.61920	0.03259	**Prob > F**
Total Error	165	562.99248		<.0001*
				Max RSq
				1.0000

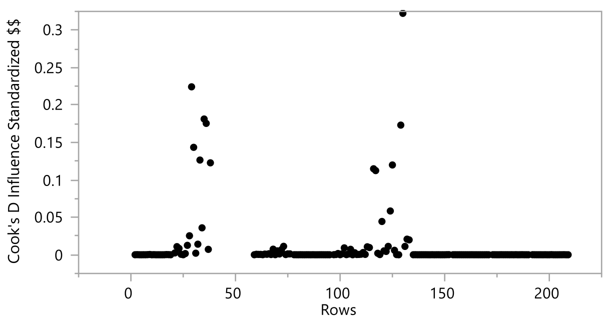
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2433108	0.178471	1.36	0.1746
Stand $$ Lag 1	0.9979017	0.01054	94.68	<.0001*

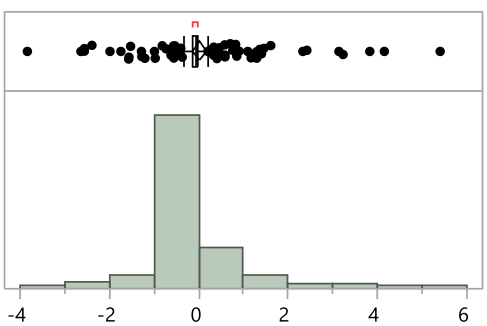
Residual by Predicted Plot



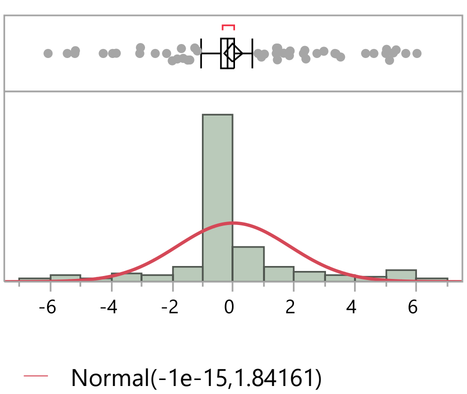
Overlay Plot Maint Cat=3.1, Organic/Contract=Organic



Studentized Resid



Residuals



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-1.07e-15	-0.281362	0.2813616
Dispersion	σ	1.8416083	1.6630195	2.0635067

-2log(Likelihood) = 676.878975944076

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.795846	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Sample Size	167
Model Degrees of Freedom	1
SSE	562.992
SSR	2777.632

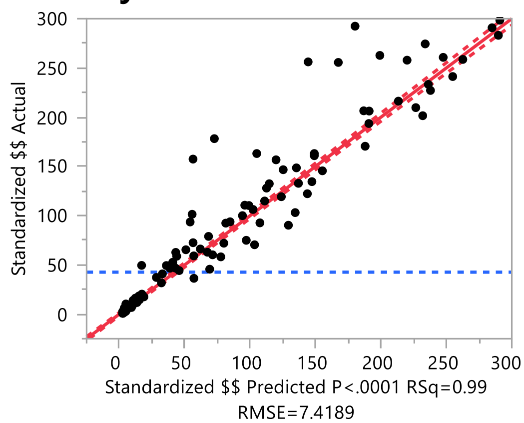
B-P Test Statistic	P-Value
122.2005628	2.08643E-28

Whole Model (3.2)

Effect Summary

Source	LogWorth	PValue
Stand $$ Lag 1	106.002	0.00000
Bomber Dummy	9.009	0.00000
Reconnaissance Dummy	3.493	0.00032

Actual by Predicted Plot



Summary of Fit

RSquare	0.987767
RSquare Adj	0.987534
Root Mean Square Error	7.41888
Mean of Response	42.57807
Observations (or Sum Wgts)	161

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	697774.86	232592	4225.882
Error	157	8641.25	55	Prob > F
C. Total	160	706416.11		<.0001*

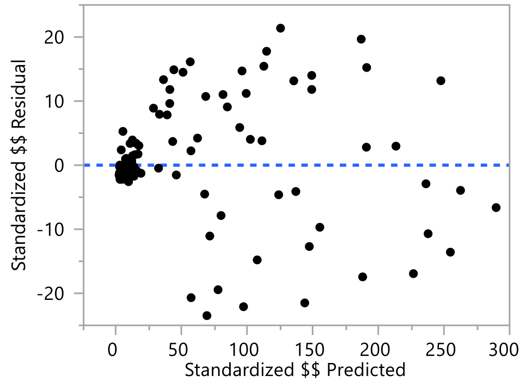
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	152	8639.2337	56.8371	141.1926
Pure Error	5	2.0127	0.4025	Prob > F
Total Error	157	8641.2464		<.0001*
				Max RSq
				1.0000

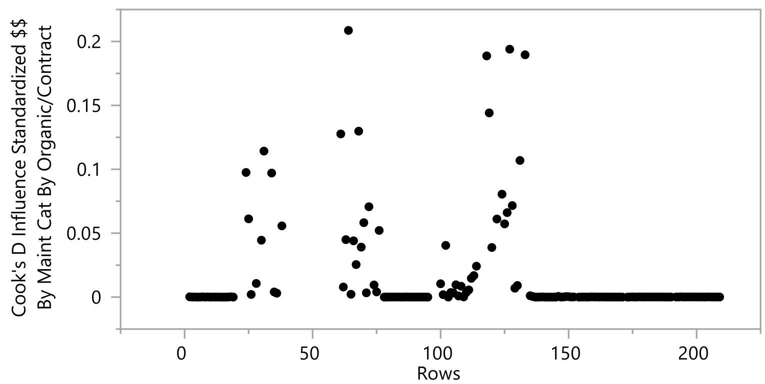
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	1.9025486	0.687794	2.77	0.0064*	.
Bomber Dummy	17.002148	2.613058	6.51	<.0001*	2.6198386
Reconnaissance Dummy	11.261374	3.061003	3.68	0.0003*	2.0343696
Stand $$ Lag 1	0.8333345	0.01464	56.92	<.0001*	3.2967009

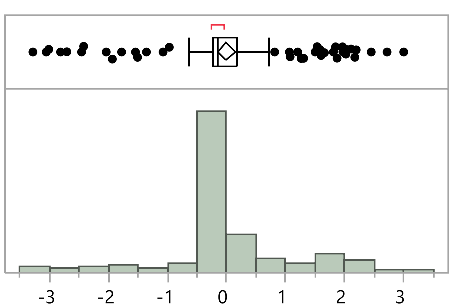
Residual by Predicted Plot



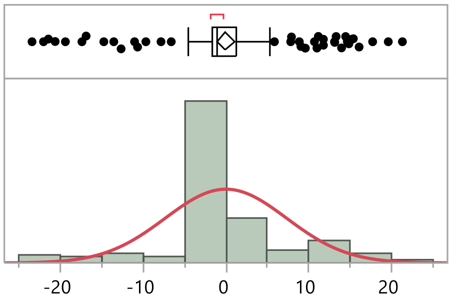
Overlay Plot Maint Cat=3.2, Organic/Contract=Organic



Studentized Resid



Residual Standardized $$ By Maint Cat By Organic/Contract



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-1.84e-14	-1.143828	1.143828
Dispersion	σ	7.3489993	6.6244319	8.2529391

-2log(Likelihood) = 1098.147863541

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.838246	<.0001*

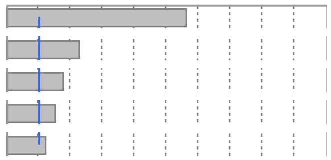
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

		B-P Test Statistic	P-Value
Sample Size	161		
Model Degrees of Freedom	3	125.6838626	4.60353E-27
SSE	8641.25		
SSR	724120.6		

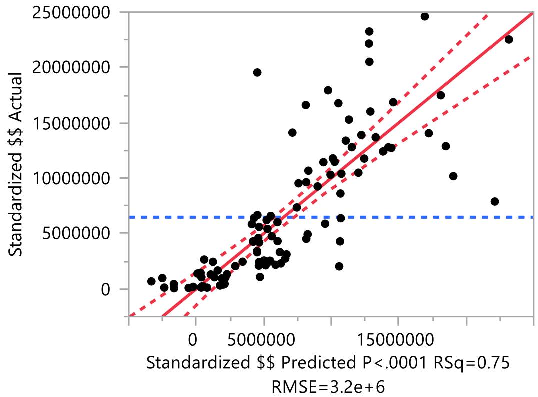
Whole Model (3.4)

Effect Summary

Source	LogWorth	PValue
Stand $$ Lag 1	11.259	0.00000
Total Planned/TAI	4.600	0.00003
Trainer Dummy	3.556	0.00028
Fighter/Attack Dummy	3.066	0.00086
Reconnaissance Dummy	2.508	0.00310



Actual by Predicted Plot



Summary of Fit

RSquare	0.750171
RSquare Adj	0.73674
Root Mean Square Error	3242648
Mean of Response	6475601
Observations (or Sum Wgts)	99

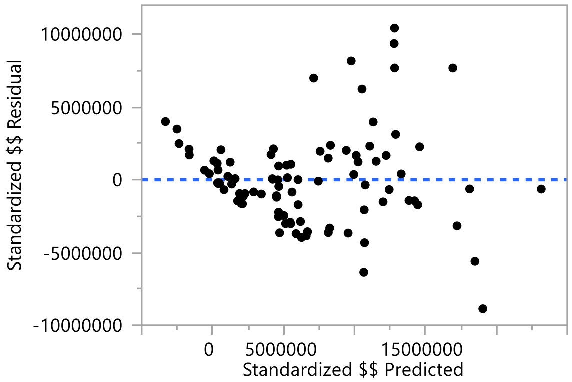
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	2.9363e+15	5.873e+14	55.8510
Error	93	9.7787e+14	1.051e+13	Prob > F
C. Total	98	3.9142e+15		<.0001*

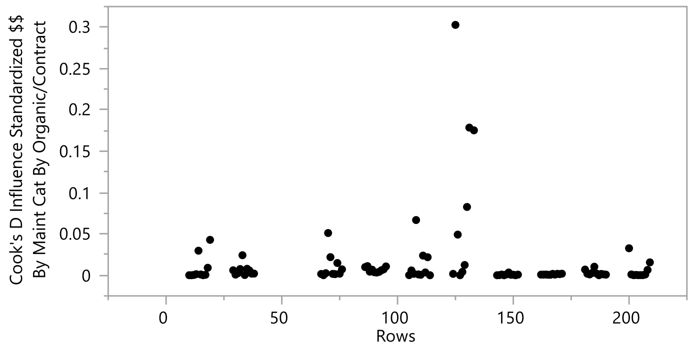
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	6913091.6	1157598	5.97	<.0001*	.
Stand $$ Lag 1	0.57957	0.073375	7.90	<.0001*	1.8478514
Total Planned/TAI	-12483067	2814254	-4.44	<.0001*	1.1324085
Fighter/Attack Dummy	-3077048	893249.8	-3.44	0.0009*	1.5866508
Reconnaissance Dummy	3758083.6	1237473	3.04	0.0031*	1.1915752
Trainer Dummy	-4929644	1304579	-3.78	0.0003*	1.4551104

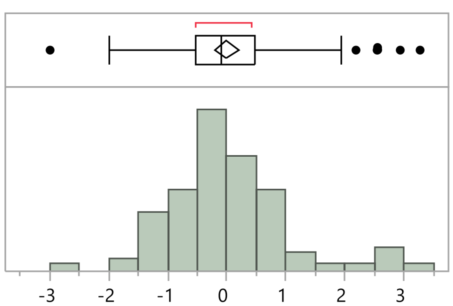
Residual by Predicted Plot



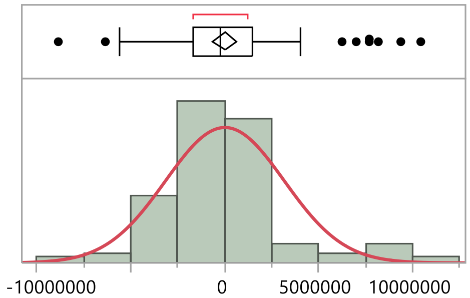
Overlay Plot Cook's D



Studentized Resid



Residuals



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-1.985e-9	-630020.5	630020.47
Dispersion	σ	3158844.7	2771773.2	3672565.1

-2log(Likelihood) = 3243.16178050181

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.937176	0.0001*

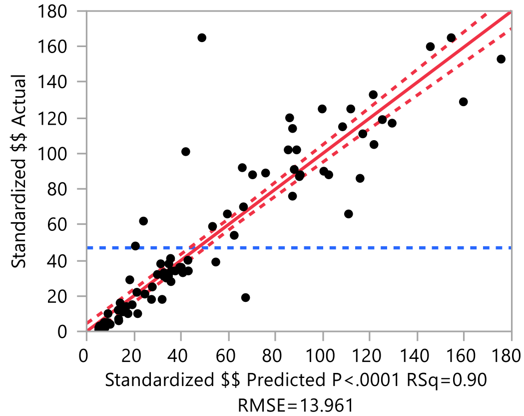
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Sample Size	99
Model Degrees of Freedom	5
SSE	9.7787E+14
SSR	6.7018E+27

B-P Test Statistic	P-Value
34.34548167	2.03213E-06

Whole Model (3.7)

Actual by Predicted Plot



Summary of Fit

RSquare	0.902272
RSquare Adj	0.901149
Root Mean Square Error	13.96086
Mean of Response	46.96629
Observations (or Sum Wgts)	89

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	156554.10	156554	803.2300
Error	87	16956.80	195	**Prob > F**
C. Total	88	173510.90		<.0001*

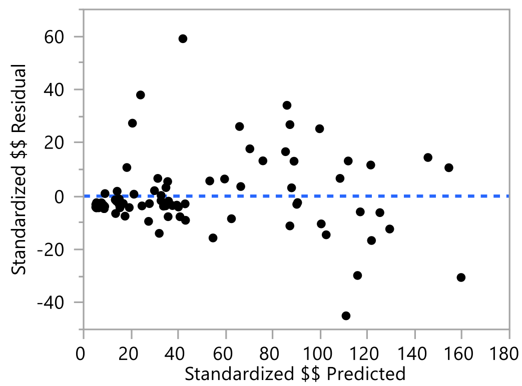
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	86	16956.795	197.172	.
Pure Error	1	0.000	0.000	**Prob > F**
Total Error	87	16956.795		.
				Max RSq
				1.0000

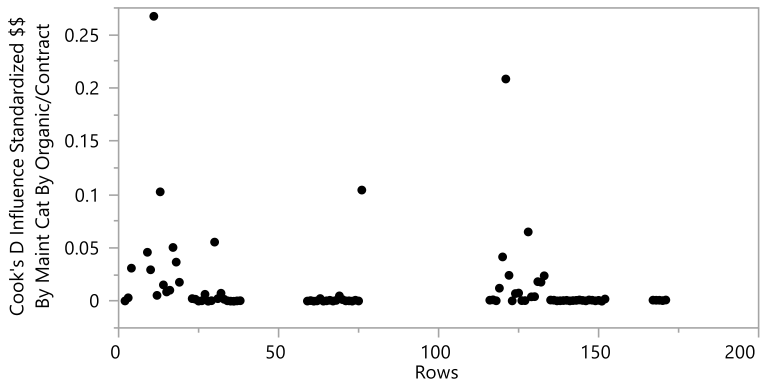
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.9471899	2.119895	1.86	0.0660
Stand $$ Lag 1	0.9415407	0.033221	28.34	<.0001*

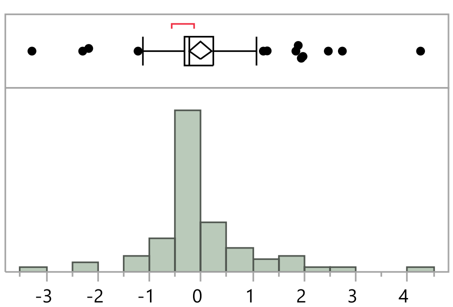
Residual by Predicted Plot



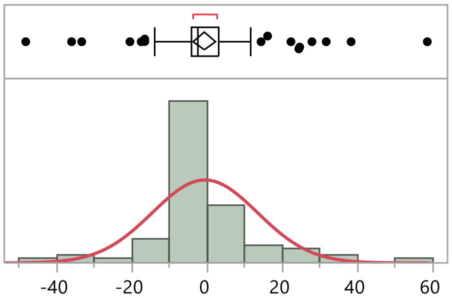
Overlay Plot Cook's D



Studentized Residuals



Residual Standardized $$ By Maint Cat By Organic/Contract



Normal(-0.5928,14.0075)

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-0.592834	-3.543553	2.3578843
Dispersion	σ	14.00753	12.208743	16.43287

-2log(Likelihood) = 721.418978680473

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.858572	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

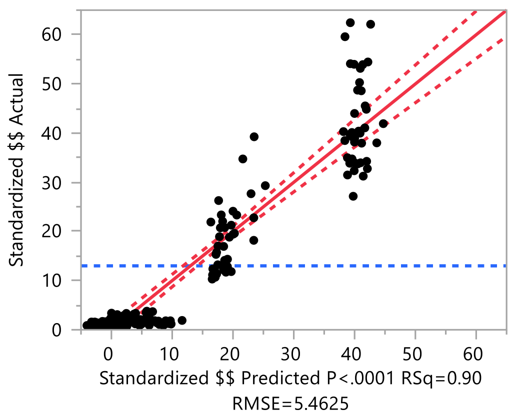
		B-P Test Statistic	P-Value
Sample Size	89		
Model Degrees of Freedom	1	25.28581416	4.94331E-07
SSE	16956.8		
SSR	1835755		

Whole Model (3.1 with Oil Price)

Effect Summary

Source	LogWorth	PValue
Fighter/Attack Dummy	30.372	0.00000
REMIS-Landings	24.903	0.00000
Reconnaissance Dummy	20.079	0.00000
Avg Age	16.462	0.00000
Inflation Adjusted (BY16) Crude Oil Price	9.993	0.00000
Secondary RCS	6.271	0.00000
Trainer Dummy	4.167	0.00007
Bomber Dummy	3.930	0.00012

Actual by Predicted Plot



Summary of Fit

RSquare	0.895946
RSquare Adj	0.891347
Root Mean Square Error	5.462456
Mean of Response	12.99953
Observations (or Sum Wgts)	190

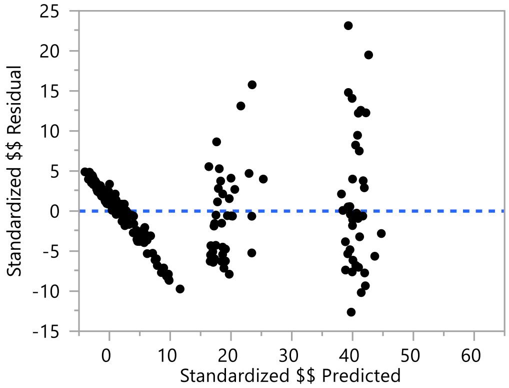
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	46502.724	5812.84	194.8106
Error	181	5400.755	29.84	**Prob > F**
C. Total	189	51903.478		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	30.738214	2.087809	14.72	<.0001*	.
Inflation Adjusted (BY16) Crude Oil Price	0.1104366	0.016083	6.87	<.0001*	1.4972601
Avg Age	-0.574734	0.061504	-9.34	<.0001*	2.8847621
REMIS-Landings	-7.947e-5	6.467e-6	-12.29	<.0001*	2.751103
Secondary RCS	8.0160805	1.541678	5.20	<.0001*	2.421502
Fighter/Attack Dummy	-17.02701	1.20317	-14.15	<.0001*	1.9357566
Bomber Dummy	6.855529	1.741227	3.94	0.0001*	3.088934
Reconnaissance Dummy	18.327994	1.724726	10.63	<.0001*	1.7047491
Trainer Dummy	6.8748606	1.685919	4.08	<.0001*	1.6288979

Residual by Predicted Plot



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14. ABSTRACT The Air Force executes its mission primarily through the use of fixed-wing aircrafts. Maintaining these aircrafts represents approximately one-third of annual Operating and Support costs; which in turn, make up the majority of Life Cycle Costs. The current approach to estimating aircraft maintenance costs does not take into consideration programmatic data available in the Air Force Total Ownership Cost (AFTOC) database. The four maintenance cost subcategories researched in this thesis are Consumable Materials and Repair Parts, Depot Level Repairables (DLRs), Depot Maintenance, and Contractor Logistic Support. Each of these cost categories must first be standardized to be able to compare costs across years and across airframes. Through regression, this research attempts to determine cost drivers within maintenance cost subcategories and build predictive models for annual maintenance costs. Upon validating the models, they did not prove to provide better estimates than the currently used method of applying a 2% increase factor. They do however, provide a framework for further research into possible cost driving variables maintained outside of AFTOC.			
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