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A MODEL FOR ESTIMATING DEPOT
 MAINTENANCE COSTS FOR AIR FORCE
 FIGHTER AND ATTACK AIRCRAFT

THESIS

Michael P. Waker

AFIT/GSM/LSQ/87S-36

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A MODEL FOR ESTIMATING DEPOT MAINTENANCE COSTS
FOR AIR FORCE FIGHTER AND ATTACK AIRCRAFT

THESIS

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology
Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Systems Management

Michael P. Waker, B.S.

September 1987

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Preface

This study was conducted for two reasons. The first was to provide the cost analysts concerned with Operating and Support (O&S) costs with another tool for estimating depot maintenance costs for Air Force fighter and attack aircraft. The second purpose was to "put to work" the Weapon Systems Cost Retrieval System that is run at HQ AFLC. This system is providing more data on maintenance costs for Air Force aircraft than any system in the past. However, generating data is not an end in itself. Being able to use this data for a worthwhile purpose is the final measure of the data's worth.

The study used the most recent WSCRS' (FY 75 - FY 86) cost data for developing the CERs for depot maintenance. The physical, performance, and technical characteristics of the aircraft that are the independent variables for the CERS should be readily available early in the aircraft's design process. Simplicity of use was a goal for the CERs. The physical parameters chosen are easy to describe as goals of the design (e.g. a high thrust-to-weight ratio, and light weight), and follow most common sense guides as to how the cost reacts when a parameter is changed. The heavier aircraft, with a longer combat range, and very high thrust-to-weight ratio is going to be more expensive to maintain than an aircraft that is a light weight air combat fighter.

I would like to extend many thank-you wishes to all the people who helped me through this effort. My faculty ad-

visor, Ms Jane Robbins, who patiently listened to my philosophical debates on every subject but the thesis was always there to keep me pushing to complete this study. Also, I must thank Mr. Richard Murphy, who lit the spark to my interest in doing a study like this. Rich, also unlocked some of the doors to completing this study by pointing me in the right way and suggesting good ideas to find the relationships that made this study work.

Above and beyond it all, I would like to thank AFLC for having the faith in me to send me to this program. Mr. Henry Ring and Mr. Lou Schmiot had to live without me during the time I spent in AFIT. And finally I would like to thank all my instructors and friends who helped me through the program. Somewhere along the line I hope everyone realizes that you can teach an old dog new tricks.

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Abstract

The model developed in this study has two cost estimating relationships (CERs) for estimating depot maintenance costs in its two categories: depot maintenance cost per Primary Authorized Aircraft (PAA); and, depot maintenance cost per flying hour. The data source used for depot maintenance costs is the Weapon Systems Cost Retrieval System (WSCRs) as developed by HQ AFLC.

The CERs developed used empty weight of fighter and attack aircraft to predict the cost of depot maintenance per PAA. For depot maintenance cost per flying hour, the variables used were combat radius, thrust-to-weight ratio, and empty weight.

The study found that the F-111 was a significant outlier with respect to the data set, but even when included in the data base the F-111 was not distorting the results of model. Indeed, inclusion of the F-111 enhanced the values of the statistics for the model and improved the ability of the model to predict.

The relationship found for depot maintenance cost per PAA in the CER developed, was not as strong a predictor as was the CER developed for depot maintenance cost per flying hour. This conclusion agrees with previous studies that have tried to determine significant relationships between depot maintenance costs and those costs attributed to the number of PAA.

A MODEL FOR ESTIMATING DEPOT MAINTENANCE COSTS
FOR AIR FORCE FIGHTER AND ATTACK AIRCRAFT

I. Introduction

General Issue

Cost analysts in the Air Force Logistics Command (AFLC) are required to provide estimates for depot maintenance costs to support cost and economic analysis studies. These studies are prepared in response to direction from the Office of the Secretary of Defense (OSD), Headquarters United States Air Force (USAF), and HQ AFLC, or when requested by other Major Commands and Operating Agencies. The estimates for depot maintenance are often used in Independent Cost Analyses (ICAs) (6:2) supporting major program acquisition or budget decisions.

Depot maintenance costs are part of the Cost-of-Ownership aspects of a weapon system's total life cycle cost (LCC), and are considered when acquiring new weapon systems or when making decisions to modify existing weapon systems. With the increasing emphasis on competition and budget constraints the ability to estimate every component of the total life cycle cost of an aircraft is very important.

The current model used by analysts in AFLC to estimate aircraft depot maintenance costs is the Logistics Support Cost (LSC) model. The LSC model is a "built up" type model which requires inputs regarding weapon system maintenance in-

formation for Line Replaceable Units (LRUs) and Shop Replaceable Units (SRUs) that have been identified as potential cost drivers. "Built-up" models usually disaggregate the weapon system to its lowest levels (the system's LRUs and SRUs) and then attempt to estimate costs at these levels. Once estimates are made at these levels then the costs are summed to a total weapon's system cost.

Generating and collecting this data requires a great deal of resource expenditures. It usually involves the cooperation of representatives of the weapon system's prime manufacturer, the weapon system's program office (SPO) (especially personnel from the Deputy for Logistics Management (DPML) office and Engineering and Supporting functions), and from the five Air Logistics Centers' (ALCs) Maintenance and Material Management functions. A large amount of time is required for the cost analysts to collect and process the data and then run the LSC model on microcomputers.

Specific Problem

The LSC model is good for providing detail for depot maintenance cost estimates. At the LRU and SRU level of detail it is easy to do sensitivity analyses in response to different configurations and aircraft usage scenarios. However, there are two times when the use of the LSC model is either impractical or impossible. First, when a very quick turnaround time is required; and, second when the aircraft

being considered is in the conceptual or early development stage and the relevant maintenance data necessary to run the LSC model are not available.

In the first case, quick turnaround estimates are usually used by the Air Staff to prepare future budgets or to do trade-off studies between different designs. Required with many of these estimates is an update of the total life cycle costs of a new weapon system(s) being considered. Often the response time is so short that running an LSC model (or any type of built-up model) which requires many data inputs is not feasible.

The F-16/F-17 source selection was an example of the second reason why an LSC model can not always be run. At the time of the source selection there was not enough data available to run a LSC model because there was very little physical description of the individual LRUs and SRUs on the two competing aircraft systems. (After the source selection, data were provided by the manufacturer that enabled the running of the LSC model.) Yet AFLC was still requested to provide an estimate for depot maintenance costs for each of the competing systems.

During the source selection an important aspect in the decision to select the F-16 was its lower Life Cycle Cost (LCC). (15:1) The F-16 had a single engine that was also used in the F-15. The F-17 had twin engines that were not common to any Air Force fighter. Besides the obvious ac-

quisition savings the cost study emphasized the Operating and Support (O&S) savings due to commonality in procurement of spare parts and test equipment, fuel savings and depot and base level maintenance repair costs. To develop the estimate for depot maintenance costs, the AFLC cost analyst used a model employing Cost Estimating Relationships (CERs) developed specifically for this source selection. A brief description of a CER follows:

A CER relates cost as the dependent variable to one or more independent variables. It is expressed as a mathematical equation and once established is fairly simple to use. A relationship may compare cost-to-cost or cost-to-non-cost. A cost-to-cost example is using manufacturing hours (independent variable) to estimate quality assurance hours (dependent variable). A classic example of a cost-to-non-cost CER is estimating manufacturing cost (dependent variable) by using system weight (independent variable). In essence, the estimator utilizes top-level actual data to estimate future costs. CERs allow the estimator to provide quick estimates without a great deal of detailed information (4:3-22).

The requirement for a good CER existed then just as it does now to help provide a decision-maker with the insights necessary to determine the most cost-effective plan to follow.

Research Objective

This model is being developed to be used:

1. as a timely estimating tool for situations where fast turnarounds to what-if questions are required;
2. early in a program's life when the data to run a detailed, built-up model are not available; and,

3. as a crosscheck of other estimates developed using different methodologies.

Using depot maintenance cost data for fighter and attack aircraft from the Weapons Systems Cost Retrieval System (WSCRS) a Cost Estimating Relationship will be developed. WSCRS is a subset of the Air Force's Visibility and Management of Operating and Support Costs (VAMOSOC) data system, and it contains historical depot maintenance costs for aircraft for fiscal years 1975 through 1986.

The objective of this model will be to generate suitable estimates for use by the cost analysts of AFLC when using the LSC model is not feasible or practical.

Limitation of Study

This model will address only fighter and attack aircraft produced for the United States Air Force. The source of cost data will come from the WSCRS systems as reported in the VAMOSOC system.

The model will address depot maintenance costs as prescribed by Air Force (7:3) in the following categories: aircraft depot maintenance costs per flying hour, and depot maintenance costs per primary authorized aircraft (PAA).

Definition of Terms

Depot Maintenance Costs are the cost of personnel, material, and contractual services required to perform maintenance or modification of the defense system, its components, and support equipment at DoD centralized repair depots and contractor repair facilities or on site. Some depot maintenance actions occur at intervals ranging from several months to several years. As a result, the most useful method of portraying these costs is on an annual basis (for example, cost per defense system per year) or operating hour basis (13:19).

Depot Maintenance cost per primary authorized aircraft (PAA) is the cost associated with a particular Model Design Series (MDS) of aircraft (eg. F-4E). It is determined by adding the total airframe depot maintenance costs for the MDS to 35 percent of the total of the the aircraft's accessory depot maintenance costs (accessories include aircraft equipment, avionics, communication, navigation, and armament). To put on a PAA basis the the above costs are divided by the average monthly inventory for the aircraft (2:79).

Depot Maintenance cost per Flying Hour is the depot maintenance cost associated with an MDS's usage per year. It includes all engine costs (overhaul plus accessories) plus 65 percent of the aircraft's accessory depot maintenance costs (accessories include aircraft equipment, avionics, communication, navigation, and armament). To put on a flying hour basis the above total is divided by the total MDS's yearly flying hours (2:79).

II. BACKGROUND

General Background

Cost Estimating Relationships (CERs) were used as the primary estimating method for depot maintenance costs by AFLC cost analysts prior to the development and implementation of the Logistics Support Cost (LSC) model.

The use of the LSC was facilitated by the advent of easy accessibility to real time computing. The model requires that large amounts of data be manipulated. For example, on the original F-16 ICA, there were 57 variables related to the total weapon system's support (22 weapon system variables, 27 program variables, 8 support equipment variables), and 23 variables for each of the F-16's 368 major aircraft LRUs.

(1:19) Visibility into the lower indentured items (LRUs and SRUs) makes the model extremely useful for sensitivity analyses, trade-off studies, and other what-if studies such as those required for an ICA. However, because of the requirements for all the maintenance data necessary to run the LSC model, the model can not always be used. When the model can not be used, there is a need for CERs.

Related Studies

A review of published studies concerning depot maintenance costs as a part of the cost of ownership was conducted to determine if any available CERs have recently been devel-

oped that may suffice for the purpose of this effort. A brief description of those studies follows:

The RAND Corporation has been responsible for two efforts concerning estimating Operating and Support (O&S) costs for Air Force aircraft. In a report dated August 1981, "A New Approach to Modeling the Cost of Ownership for Aircraft Systems", the report, "illustrates estimation of support investment costs and recurring operations and support costs through a Model for estimating Aircraft Cost of Ownership (MACO)" (10:abstract). In MACO, "the basic LSC approach is expanded to provide fuller cost coverage and modified to improve depot maintenance cost component visibility". (10:46) The authors do not develop any new CERs for depot maintenance and thus the study does not provide any new insights into the specific problem addressed in this study. As a word of caution, the equations in the model do not conform to OSD CAIG standard cost elements, and this issue needs to be addressed when comparing estimates using the MACO model.

The second report from RAND was a study authored by Kenneth E. Marks and Ronald W. Hess that was released in July 1981. The report "Estimating Aircraft Depot Maintenance Costs", "Describes a series of parametric equations for use in estimating the depot maintenance cost of new Air Force aircraft. The equations are intended to provide cost estimates for Defense Systems Acquisition Review Council Milestone II." (11:v). This Rand study corresponds to effort

currently being accomplished in this study. In other words, the Rand study and this study are both trying to develop CERS for aircraft depot maintenance prior to final aircraft definition (conceptual or early development stages). The Rand study and this current effort both used as the primary source for depot maintenance cost data, the WSCRS system. According to the Rand study, "Data on the depot maintenance cost of most major USAF aircraft and aircraft engines for fiscal years 1975 through 1977 were obtained from the Air Force Logistics Command. The primary data source was the Weapon System Cost Retrieval System. (11:v) The WSCRS report is also being used for this study. The difference is that the RAND report used fiscal years 1975 through 1977. The current effort uses data for fiscal years 1975 through 1986. This expansion of the data base should provide more reliable estimates because the greater time span should erase any peculiar short term fluctuations that might have occurred (data smoothing), plus it also reflects more history on the two newest fighters in the USAF inventory, the F-15 and the F-16. The Marks' study also uses all the different USAF designs (fighter, attack, cargo, bomber) in the development of the estimating equations. The current effort attempts to limit the wide range of aircraft to only two closely related designs, the fighter and the attack aircraft. Another drawback of the Marks' model is data availability. Even though both efforts are for pre-production use, the Marks' model can not

be used in the real early theoretical planning period when some of the variables are not well defined.

Another effort was conducted for the Air Force Avionics Laboratory by the Westinghouse Electric Corporation. The study, "Predictive Operations and Maintenance Cost Model", was done in August 1979. The model developed is limited to estimating depot maintenance costs for Avionics only (17:iv). It also uses data that are pre 1979 which would mean that some of the data is no longer relevant. The data systems that were used (Logistics Support Cost Ranking Data System (K051) especially the Increase Reliability of Operational System (IROS) program within the K051 and the Air Force Maintenance Data Collection System per AFM 66-1) were not designed to provide historical cost data for estimating purposes. While the effort from the Westinghouse study is quite comprehensive in regards to avionics O&S costs, it lacks both validity and currency of data and it also is limited in its applications for current systems because of recent technological changes in avionics.

A fourth study surveyed was a handbook, Factors, Formulas, and Structures for Life Cycle Costing by Mary Eddins Earles. "This handbook is a compilation of factors, formulas, and structures useful in the conduct of Life Cycle Cost estimates and analyses". (8:iv) This is a compilation of equations from different sources especially in regards to the O&S area. For example, the the equations for avionics

are taken from the Westinghouse study which was previously noted. While there are many equations in this compilation, it does not address the same levels of depot maintenance costs as the current study, and the majority of equations are or have the same problem as the Westinghouse study; that is, currency of data and relevance of data.

Data Collection

Development of CERs requires a data base that is relevant to the weapon system or end-item that the CER is attempting to estimate. For the depot maintenance costs of fighter and attack aircraft the most relevant data base is that collected by the Weapon Systems Cost Retrieval System (WSCRS), which has a data systems designator of H036C.

The data for the dependent variable depot maintenance costs will be from the WSCRS data base as reported by HQ AFLC. There is data available for eleven years and there is consistency in the make-up of the data. This is considered the most complete and consistent data base available for depot maintenance costs. The following are the sources for the WSCRS data:

- D200 Requirements Data Bank (RDB)
- D041 Recoverable Consumption Item Requirements System
- H036B DMIF (Depot Maintenance Industrial Fund) Cost Accounting Production Report
- D043 Master Item Identification Control System

- H036C Office of Primary Responsibility Manual Inputs

WSCRS "is a management information system designed to support a variety of cost analysis functions. The primary objective of WSCRS is to provide visibility of depot maintenance and condemnation cost expenditures of major USAF aircraft and missile weapon systems" (3:1). It was developed by the Cost and Management Analysis office within AFLC to support in-house cost analysis projects. It "provides one central, consistent source of historical depot maintenance and condemnation cost data for most USAF aircraft, engines and missiles" (3:1).

Users of this system include not only AFLC and Air Force but other Majcoms, other branches of the service and outside activities such as weapon systems contractors, "think tanks" commercial consultants and educational institutions. It was selected to be the basis for the Depot Maintenance Cost Factors in AFR 173-13 for both budget projections and life cycle cost projections. The system became a formal AFLC data system in April 1983.

For the independent variables, the physical and performance characteristics, the source of the data was the "USAF Standard Aircraft/Missile Characteristics", Air Force Guide Number Two, (various dates) for the weapon system. There is a good deal of consistency between the data in these reports

because of the standardization of definitions and collection techniques.

It is important that all the fighter/attack aircraft possess the same characteristics and that they be described in the same way. Therefore, thrust in pounds must mean the same thing for an F-15 as it does for a new F-25.

III. METHODOLOGY

Model Identification

A four-step approach was used to determine the cost model. The overall objective was to develop a relatively simple model that used a few significant cost drivers to estimate fighter depot maintenance costs.

Model identification refers to the process whereby all the pertinent independent variables, in this case, the cost drivers of depot maintenance are identified and gathered for the purpose of predicting the dependent variable (depot maintenance costs). In the study of depot maintenance costs per PAA and depot maintenance costs per flying hour the most pertinent independent variables are from a collection of the weapon system's physical, performance, technological, and acquisition cost characteristics. The data gathered and analyzed were expected to describe the depot maintenance costs for all USAF fighter aircraft given their peculiar physical, performance or technological characteristics.

Model Specification

The second step specified the relationship of the potential cost drivers to the depot maintenance costs of fighters. All relationships were assumed to be linear unless data analysis revealed a strong nonlinear relationship. The only specification made was to determine if the costs increased as the potential cost driver increased or as the potential cost

driver decreased. The following table lists all the cost drivers thought to follow the criteria set forth in the model identification and specification processes. The table includes cost drivers for both models (i.e. depot maintenance cost per flying hour and depot maintenance cost per PAA).

Table I

Identification and Specification of Potential Cost Drivers

<u>Characteristic</u>	<u>Data Available</u>	<u>Potential Cost Driver</u>	<u>Specification</u>
Empty Weight	Yes	Yes	Increasing
Maximum Weight	Yes	Yes	Increasing
Combat Weight	Yes	Yes	Increasing
Maximum Engine Rating	Yes	Yes	Increasing
Military Engine Power Rating	No	Not Considered	---
Normal Engine Rating	Yes	Yes	Increasing
Maximum Speed	Yes	Yes	Increasing
Average Speed	Yes	Yes	Increasing
Service Ceiling	No	Not Considered	---
Number of Engines	Yes	Yes	Inconclusive
Maximum Rate of Climb	No	Not Considered	---
Combat Radius	Yes	Yes	Increasing
Thrust-to-Weight Ratio	Yes	Yes	Increasing
Acquisition Cost	Yes	Yes	Increasing
Dollars per Pound	Yes	Yes	Increasing

The model specifications depend on the variables chosen and their expected relationship to the dependent variable. If need be, interaction or indicator variables would be used to help define the model.

Interaction is the process of combining two or more variables within an equation. Interaction variables are used to explain that there is not always a one-to-one change in the dependent variable when a change occurs in the independent variable. If the effect that a change in speed has on cost is independent of the value of any other variable in the equation, there is no interaction effect. However, if the magnitude of the change in cost resulting from a change in speed depends on the values of one or more other independent variables, there is an interaction effect. For example, if the impact on cost of increasing speed from 400 knots/hour to 500 knots/hour is different for an aircraft weighing 25000 pounds than it is for an aircraft weighing 65000 pounds, there is an interaction effect between weight and speed. Interaction terms can be incorporated into a model to account for interaction effects.

An indicator variable is one of "many ways of quantitatively identifying the classes of a qualitative variable". (13:329) A qualitative variable could be specification of a fighter as a single engine or a dual engine, the primary mission as attack or interceptor, or the fighter as a swing wing or fixed wing.

Model Development

To develop the model several SAS regression procedures (PROC REG, PROC CORR, PROC STEP) were used. Multiple regression runs were made with logical combinations of the independent variable in an attempt to find the best model to describe the dependent variable.

The chosen model was the one which produced the best statistics given the logic described in Table I. Emphasis was put on the accuracy of the estimating capability of the model. This ability was judged using the coefficient of variation (C.V.) as the key indicator. An attempt to find the lowest C.V. was made, because the smaller the C.V. the tighter the prediction interval bounds at the center of the data.

Other goals in the model development phase were to use only significant variables to help describe cost; to develop the most significant model possible in terms of regression relationship; and, to develop the model with the highest possible Coefficient of Determination (R^2), while maintaining the previously mentioned goals. The R^2 can be manipulated by adding insignificant variables to the model, which will increase the value of the R^2 . While a high R^2 is desirable, adding independent variables was not done for the sole purpose of increasing this statistic.

Having chosen the variables that should be included in the model, the next step is to run the regression procedure

in SAS. The SAS Regression procedure uses the principle of least-squares-best-fit (LSBF) to develop estimates of the parameters (aka regression coefficients).

The only models considered were linear, and possess the properties of the least squares best fit criteria. The models considered are in the form of:

$$Y = B_0 + B_1X_1 + \dots + B_kX_k + E \quad (1)$$

where

Y = the value of the dependent variable;

X = the value of the independent variables;

B = the regression coefficient;

k = the number of independent variables in the model;

and,

E = the random error term (13:31).

This means that if a chosen variable is expected to be nonlinear (e.g. the variable causes cost to rise at an increasing rate), then a transformation of this variable may be required. A transformation of a variable is an attempt to describe the relationship between the independent variable and the dependent variable in mathematical terms which would make the data appear in a linear form. That is, a transformed variable may take the form of the independent variable raised to a power, (squared, cubed, square root function) or put in logarithmic terms.

The method of least squares considers the sum of the N squared deviations of Y from its expected value. For example:

$$\text{if, } Y = B_0 + B_1X_1 \quad (2)$$

the least squares method tries to minimize the following criterion (13:36) :

$$Q = (Y_i - B_0 - B_1X_1)^2 \quad (3)$$

According to this method, the estimators of the regression coefficients are those values that minimize the squared vertical deviations for a given sample. The least squares estimators are also maximum likelihood estimators, are unbiased, and have minimum variance among all unbiased linear estimators.

Once the variables were identified, the PROC CORR procedure of SAS was used to determine the amount of pairwise correlation between and among all the independent variables (the physical parameters) and the dependent variables (depot maintenance costs per flying hour and per PAA). Correlation is defined as "a causal, complementary, parallel, or reciprocal relationship, esp a structural, functional, or qualitative correspondence between two comparable entities" (5:162). Identification of correlated variables was important since in

building the model it was necessary to find the most significant independent variables that could describe the dependent variable. However, this does not imply that initially insignificant variables appearing in the pairwise correlation were discarded. These variables could still become significant when teamed with (more than one independent variable included in the model) other independent variables to describe cost.

PROC CORR also provided information to help determine the amount of correlation between independent variables, since introduction of two or more highly correlated independent variables in the model would probably result in one or more of the variables becoming very insignificant. For example empty weight and maximum takeoff weight are highly correlated, and the use of both in the model results in a very low confidence in the ability of maximum weight to predict depot maintenance costs.

Next SAS PROC STEP (a stepwise regression procedure) (16:101) was run to see which independent variables would combine with other independent variables to explain the dependent variables. The stepwise procedure adds variables one by one to the explanatory model in order of most significant variables when combined with the variable already in the model. In the first step the most significant independent variable is entered into the model, significance being based on the variable with the highest F statistic. In the second step the variable entered would be the most significant var-

iable when "teamed-up" with the variable already in the model. This continues until no variable meets the set significance level desired (for the purposes of this study the significance level was set at 85%). As each variable enters the model a check is made of the variables already in the model to see if any of these variables lose their significance. The check of remaining variables is performed at the 85% significance level, same as the criteria for entering the model. If a variable does not meet this criteria it is removed from the model. Using a stepwise method is most helpful when doing initial explanatory analysis, because it provides a good indication of the relationship between independent variables and dependent variables. The stepwise method does not, however, always produce the best model because it will continue to add or delete different variables based on bringing in the most significant variables. The logic of the model may be violated during the stepwise process, so checks for the sign of coefficients and multicollinearity must also be made to insure that the models built in the stepwise process are logical.

The fourth step involved the use of statistical analysis to evaluate the various models identified in step three. This analysis included tests for significance of the model, significance of each cost driver, outliers with respect to the range of the cost drivers and multicollinearity between the cost drivers. Tests for heteroscedasticity, autocor-

relation and non-normality of the data were not conducted because the small data base would not provide conclusive results for any of these tests.

Model Evaluation Criteria

In addition to the logic involved in testing the model, the behavior of the model and the model's coefficients were tested. The coefficients of the independent variables were closely examined to determine if the expected relationship occurred. The signs of the coefficients were inspected. The signs should be positive when costs are expected to increase because of a change in an independent variable.

Another test was performed to determine the impact of a coefficient of the independent variable on the dependent variable. The size of the regression coefficients in a multivariate model does not show the true strength of the regression coefficients. Therefore, to determine that, beta coefficients are used. Beta coefficients are standardized regression coefficients that show the mean response in the dependent variable given a change in an independent variable, while holding the other independent variables constant. The unit values for the beta coefficients are standard deviations. The interpretation of these values are for a one standard deviation change in an independent variable, the dependent variable will change by beta coefficient value number of standard deviations of the dependent variable. If the beta coefficient is .45 for an independent variable, then

this means that a one standard deviation change in the independent variable, will cause a 45% change in the standard deviation of the dependent variable. Thus the higher the beta coefficient for an independent variable, the more impact a change in that independent variable will have on the dependent variable.

t Test

The t test is used to determine the significance of the individual variables in explaining cost. A significance at the 80% confidence level or higher was considered good.

Hypothesis Test of an Independent Variable

1. $H_0 | B_1 = 0$
 $H_1 | B_1 \neq 0$
2. Level of Significance (alpha): .20
3. Students t distribution using the t statistic where

$$t_{table} = t(.80, n-p)$$

$$t_{calculated} = b_1 / s_{b1}$$

If $t_{table} \leq t_{calculated}$ reject H_0

If $t_{table} \geq t_{calculated}$ accept H_0

where

b_1 is the coefficient of the X_1 variable; and,

s_{b1} is the standard deviation of b_1 .

Analysis of Variance

A discussion of the statistics used follows. To assist in an explanation of the statistics an Analysis of Variance (ANOVA) table is presented with an explanation of terms. The ANOVA table is helpful in determining the actual strengths of a regression model.

Table II

ANALYSIS OF VARIANCE

<u>Source of Variation</u>	<u>Sum of Squares</u>	<u>Degrees of Freedom (df)</u>	<u>Mean Sum of Squares</u>
Regression	$SSR = \sum (\hat{Y}_i - \bar{Y})^2$	$p-1$	$MSR = SSR/df$
Error	$SSE = \sum (Y_i - \hat{Y}_i)^2$	$n-p$	$MSE = SSE/df$
Total	$SST = \sum (Y_i - \bar{Y})^2$	$n-1$	$MST = SST/df$

where

\hat{Y}_i is the fitted values on the regression line;

\bar{Y} is the mean of the observations;

Y_i is the observed value;

p is the number of parameters in the model; and,

n is the number of observations.

SST is the variation of the dependent variable around its predicted value when the prediction is based on the mean (\bar{Y}). SSE is the variation of the dependent variable around its predicted value when the prediction is based on the esti-

mating equation (\hat{Y}). SSR is the difference between SST and SSE. It is a measure of the reduction in the estimating error accomplished by basing the estimate on the regression line as opposed to the mean of (\bar{Y}).

MSR and MSE are the sum of squares divided by their appropriate degrees of freedom. MST is the variance of the Y values around their mean (13:47,89,90).

The coefficient of determination (R^2) is the most commonly used statistic in determining the goodness of a model. R^2 measures the proportionate reduction in total variation associated with the fitted regression line. The formula for R^2 (13:396):

$$R^2 = SSR/SST \quad (4)$$

$$\text{or; } R^2 = (1-SSE) / SST \quad (5)$$

The adjusted R^2 is used as a test to insure that variables are not included in the model for the sole purpose of increasing the R^2 . The formula for the adjusted R^2 is:

$$\text{Adjusted } R^2 = (1 - SSE) / SST * (n-1 / n-p) \quad (6)$$

$$\text{or; Adjusted } R^2 = R^2 * (n-1 / n-p) \quad (7)$$

The adjusted R^2 formulae show that the adjustment to R^2 is made by multiplying by the degrees of freedom. It was conceived as a gauge to test whether as variables are brought

into the model the variables are significant. If a variable enters the equation that is not significant the adjusted R^2 will decrease, because of a loss of a degree of freedom.

F Test

The F test was used to determine whether or not there is a significant statistical relationship between cost and the independent variables (cost drivers). The null hypothesis is that the relationship is not statistically significant. In the expected equation, $Y = B_0 + B_1X_1 + B_2X_2$, the B values for the X_k s will be simultaneously tested to determine if they are zero. This hypothesis test will be conducted at the 90% confidence level.

Hypothesis Test for Regression Relationship

1. $H_0 | B_1 = 0 \text{ and } B_2 = 0$
 $H_1 | B_1 \neq 0 \text{ and/or } B_2 \neq 0$
2. Level of Significance (alpha): .10
3. F distribution using the F statistic where

$$F_{\text{table}} = F(.90, p, n-p)$$

$$F_{\text{calculated}} = \text{MSR/MSE}$$

If $F_{\text{table}} \leq F_{\text{calculated}}$ reject H_0

If $F_{\text{table}} \geq F_{\text{calculated}}$ accept H_0

In this study it was assumed that there must be a 90% confidence level that a regression relationship exists before accepting the model. Those models that were significant at the 90% confidence level or higher and had all independent variables significant at the 80% confidence level or higher were given further consideration.

Model Diagnostics

The next step was to run the model diagnostics. In model diagnostics, problems such as multicollinearity and outliers were explored.

Multicollinearity is a problem in regression models because it causes the estimates of the affected variables to be unstable. This instability is caused by the high standard errors of the independent variables. Multicollinearity occurs when an independent variable is nearly a linear combination of other independent variables in the model. VIF and COLLINOINT were used with the regression procedure in SAS to detect if multicollinearity existed and to determine how serious the problem was.

VIF stands for variance inflation factor. These factors measure how much the variances of the estimated regression coefficients are inflated as compared to when the independent

variables are not linearly related. The formula for VIF is:

$$\begin{aligned} (\text{VIF})_k &= 1 / (1 - R_k^2) \\ k &= 1, 2, \dots, p-1 \end{aligned} \quad (8)$$

where

R_k^2 is the coefficient of determination when X_k is regressed on the other independent variables in the model (13:391).

A VIF can take a value from one to infinity. A VIF of one indicates no multicollinearity. A VIF greater than one indicates an inflated variance for that regression coefficient. A VIF in excess of ten is often taken as an indication that multicollinearity is unduly influencing the least squares estimates (13:392). This is true when the R^2 is above 90%. However, if the model has an R^2 of 70% or above, a VIF value as low as 4 may indicate multicollinearity.

The COLLINOINT procedure computes the condition numbers. If there is no multicollinearity in the model all the condition numbers will equal one. The greater the degree of multicollinearity in the model, the larger the condition number. A condition number greater than five indicates that multicollinearity is unduly influencing the regression coefficients.

The CollinoInt option also computes the variance proportion for each regression coefficient in the model. The vari-

ance proportions for each variable in the model always sum to one. If there is no multicollinearity in the model there should be only one large variance proportion in each row. If there is more than one large variance proportion in any given row, the variables associated with the large variance proportions are involved in a multicollinear relationship. Therefore, a multicollinearity problem occurs when a row with a high condition number contains two or more large variance proportions.

To illustrate the concept of how to use the multicollinearity diagnostics in SAS, the results of a hypothetical model are presented (see Table II). As shown in the table, variable X_1 and X_2 have large variance proportions in row three. This means that there is a multicollinear relationship between these two variables. However, the condition number in row three is relatively small, which indicates that the multicollinear relationship is very weak. If the condition number had been 20 (vs. 2.8799), then it can be said that multicollinearity is a problem.

Table III

An Example of Multicollinearity Diagnostics

<u>Row</u>	<u>Condition Number</u>	Var Prop <u>X_1</u>	Var Prop <u>X_2</u>	Var Prop <u>X_3</u>
1	1.0000	.0476	.1435	.0740
2	1.3222	.0324	.5654	.1437
3	2.8799	.9400	.1526	.9073

Outliers are extreme observations in terms of the dependent or independent variables. Two methods were used to detect outliers. The first method is called the leverage factor. The leverage factor identifies outlying X observations (13:401-403). If the leverage factor is greater than twice the number of parameters divided by the number of observations ($2p/n$) or .80 for a small sample size then it can be considered an outlier with respect to X.

The second method is the studentized residuals (SRESID). SRESID identifies outlying Y observations (13:404-407) with respect to the regression line. The formula for the SRESID is:

$$\text{SRESID} = e_i / s(e_i) \quad (9)$$

where

e_i is the residual for the i^{th} trial; and,

$s(e_i)$ is the standard error of the residual for the i^{th} trial (13:405).

The formula for e_i is:

$$e_i = Y_i - \hat{Y}_i \quad (10)$$

where

Y_i is the observed value for the i^{th} trial; and,

\hat{Y}_i is the fitted value on the regression line for the i^{th} trial (13:405).

The formula for $S(e_i)$ is:

$$S(e_i) = [MSE(i-h_{ii})] \quad (11)$$

where

MSE is the mean squared error [Eq(xx)]; and,

h_{ii} is the leverage factor (13:405).

The SRESID value is compared to the t table at the 90% confidence level, $n-p$ degrees of freedom. If SRESID is greater than the t table value then it is considered an outlier with respect to Y.

Once these outliers were identified the Cook's distance measure (D_i) method will be used to identify which of the outliers are influential observations that have a substantial impact on the least squares regression fit. The equation for D_i is:

$$D_i = (SRESID)^2 * h_{ii} / \sum h_{ii} \quad (12)$$

where

SRESID is the studentized residual; and,

h_{ii} = the leverage value (13:408).

Notice from the above equation (12) that D_i depends on two factors: (1) the size of the SRESID, and (2) the leverage value h_{ii} . By reviewing the equation, there are three ways that an outlier can be influential: (1) a very large SRESID, (2) a very large leverage factor, or (3) SRESID and the lev-

erage factor are moderate. Though D_i does not follow the F Distribution, it has been useful to relate the D_i value to the corresponding F Distribution. Therefore, the D_i value is compared to the F Distribution table at the 50% confidence level, p , and $n-p$ degrees of freedom. If D_i is greater than the F Distribution table value, then the variable is considered an influential outlier.

An influential outlier should only be discarded if in fact the outlier observation resulted from a rare event. On the other hand, outliers may convey significant information, as when an outlier occurs because of the influence of another independent variable omitted from the model or reflects the new trend in technology.

The standard error of the estimate (the square root of MSE) is the best indicator of the model's prediction capability. This capability is directly related to the size of the standard error of the estimate. In order to evaluate the size of the standard error of the estimate, a point of reference is needed. Since the model should be used to predict cost for systems that are similar to the observations used to develop the model, the mean of the dependent variable was used as the point of reference. The standard error of the estimate divided by the mean of the dependent variable, C.V.,

expresses the standard error of the estimate relative to this reference point. The formula for C.V. is:

$$\text{C.V.} = 100 * S_{yx} / \bar{Y} \quad (13)$$

where

S_{yx} is the standard error of the dependent variable;
and,

\bar{Y} is the mean of the observations of the dependent variable (16:127).

The residual, which is the difference between the predicted value and the observed value was used to determine the predictive capability of the model. In the analysis chapter the residuals are also expressed as a percentage of the observed value, to provide a sizing feel.

The prediction interval provides a cost analyst a range of values in which the next prediction should fall. The upper and lower bounds of the prediction interval have a probability equal to the level of the confidence. The higher the level of confidence, the wider the prediction interval bound; the opposite is true for the lower bound of the confidence interval. In SAS the default value for the prediction intervals is at the 95% level of confidence. The predictive capability of the models can be evaluated by examining the magnitude of the bound expressed as a percent of the predicted value which is included in the following chapter.

Meeting the Research Objectives

If the models can be developed that have the statistical properties described above, and use the potential cost drivers identified then the models will provide a good estimate of depot maintenance cost for fighter aircraft. The models will be useful in the earliest stages of the aircraft design when detailed information is not available, but when an accurate estimate is still necessary.

To be useful the model should meet the following criteria:

1. There should be a 90% confidence level that there is a linear relationship between the independent variables and depot maintenance costs (F test);
2. The coefficients of the independent variables must be significant at the 80% confidence level or higher (t test);
3. Multicollinearity should not be causing any problem within the model (multicollinearity diagnostics);
4. Outliers should not exist within the dependent variable data set; and,
5. The model should possess the best prediction capability possible (C.V. statistic).

IV. FINDINGS AND ANALYSIS

Overview

The model consists of two cost estimating relationships (each will be referred to as a separate model) that were developed for the two areas of depot maintenance: (1) The portion of depot maintenance attributable to flying hours, and, (2) the portion of depot maintenance related to inventory (per PAA) that occurs because of time and not use. Within the presentation of each of the models, significant findings fell into the following five areas. First, significant costs drivers were identified. Second, the models' significant statistical values are presented. Third, observations were identified as potential outliers. Fourth, the models' strengths and weaknesses are discussed.

There is also a section on the F-111, which gives some historical background about that aircraft. An analyst using this model may want to include or exclude the F-111 based on the relevance of the F-111 to the aircraft being estimated. The chapter concludes with some caveats on the use of the model and a section on how the model meets the objectives of this study.

Presentation of Models

The model for estimating depot maintenance costs consists of two models: (1) depot maintenance costs per flying hour; and, (2) depot maintenance costs per PAA. Their

actual construction and the strengths and weaknesses are discussed in the following sections.

Depot Maintenance Cost per Flying Hour

The formula for the model for depot maintenance cost per flying hour follows:

$$\text{CDF} = -499.314 + 1.204 \cdot \text{COMRAD} + 259.427 \cdot \text{TTWR} + .009 \cdot \text{EWT} \quad (14)$$

where

CDF = Depot Maintenance Cost per Flying Hour

COMRAD = Combat Radius for Typical Mission

TTWR = Thrust to Weight Ratio

EWT = Empty Weight

Significant Cost Drivers. For the first model, Depot Maintenance Costs per Flying Hour, three significant cost drivers were identified. They are Combat Radius, Thrust-to-Weight Ratio and Empty Weight. The combat radius depicts the ability of the fighter or attack aircraft to carry a full load of weapons and fuel on a typical mission. (Typical mission being the one the aircraft was primarily designed for.) It is a function of the aircraft's technical capability to fly on a certain amount of fuel. For an aircraft with an air-to-air intercept mission the technical parameters may be for a powerful engine with tremendous speed potential, a high service ceiling, and advanced radar capabilities, while

possessing limited loiter times on station and few provisions for carrying weapons other than air-to-air missiles.

The thrust-to-weight ratio (TTWR) is also a measure of the ability of the engine to put out maximum power in excess of the empty weight of the aircraft. Thus lighter weight aircraft with large engines will have a higher TTWR than an aircraft designed to be used in the attack role. The more complex the aircraft, the more the repair cost should be. Improved logistics may have been considered, but for the aircraft designed for maximum performance the amount of systems included within the aircraft is also larger than on the simpler attack aircraft.

Empty weight is a size factor that describes the aircraft sizing alone. Empty weight is defined as the weight of the aircraft itself plus the systems installed on the aircraft but does not include the weight of fuel or armament carried by the aircraft.

The cost drivers were evaluated based on the methodology discussed in Chapter III. First the signs of each independent variable were inspected to determine if the specifications for each followed expectations. In the case of the model for depot maintenance cost per flying hour, the signs are all positive which means that as an independent variable increases in size the depot maintenance cost will also increase.

A t test was conducted to determine if the coefficient for an independent variable is significant. The t test was performed on each independent variable's coefficient, i.e. the coefficients for combat radius, thrust-to-weight ratio, and empty weight. The result of the t test for all the coefficients showed at least an 80% confidence that the coefficient was different from zero (80% being the goal for acceptance of the test).

Table IV

t Values for Independent Variables

<u>Variable Name</u>	<u>Level of Confidence</u>
Combat Radius	99.9%
Thrust-to-Weight Ratio	99.9%
Empty Weight	98.6%

To determine the impact that a change in the coefficients of each individual independent variable has on the dependent variable, beta coefficients were calculated. The following table shows the beta coefficients for each independent variable.

Table v

Beta Coefficients for Independent Variables

Model: Depot Maintenance Cost per Flying Hour

<u>Variable Name</u>	<u>Beta Coefficient</u>
Combat Radius (COMRAD)	.7616
Thrust-to-Weight Ratio (TTWR)	.1938
Empty Weight (EWT)	.2514

Descriptive Statistics. The following ANOVA table contains the results of the statistical tests for the F test, the models coefficient of multiple determination and, an analysis of the model's prediction ability.

Table VI

ANOVA TABLE

Depot Maintenance Cost per Flying Hour

<u>F Value</u>	<u>R²</u>	<u>Adjusted R²</u>	<u>Coefficient of Variation</u>
312.117	.9957	.9926	6.05

An F test was performed to check the existence of a regression relationship. The F test uses the F statistic and the F distribution. For the model described the F value was 312.117. The results of this F test showed a 99% confidence of a regression relationship between depot maintenance

costs per flying hour, as the dependent variable, and combat radius, thrust-to-weight ratio, and empty weight, as the independent variables.

The coefficient of multiple determination, R^2 , measures the proportional decrease in the total variation of depot maintenance costs when combat radius, thrust-to-weight ratio and empty weight are present in the cost model. The value obtained (.9957) indicates that 99.57% of the total variation in depot maintenance costs per flying hour is explained by the model. An R^2 above .9 when three independent variables are used in the model is very good.

The adjusted R^2 is a check to insure that variables included in the model are significant and were not entered just to increase the R^2 . In the case of the model for depot maintenance cost per flying hour, when the third independent variable, empty weight is included, the adjusted R^2 increases from .9684 to .9926. This increase was considered sufficient enough to conclude that the variable empty weight has a significant impact on the model.

The coefficient of variation (C.V.), relates the standard error of depot maintenance costs per flying hour given combat radius, thrust-to-weight ratio and empty weight to the mean depot maintenance cost per flying hour as a percentage. The value of the C.V. for this model is 6.05%. This means that for estimates at the center of the data, the confidence range of that estimate is plus or minus 6.05%. This is a

very good predictor considering that a 10% estimating range is considered sufficient for most cost estimates.

Multicollinearity Diagnostics. The multicollinearity diagnostics are presented in the following table.

Table VII

Multicollinearity Diagnostics
(Variance Inflation Factors)

<u>Variable</u>	<u>Variance Inflation Factor</u>	<u>Potential Multicollinearity</u>
Combat Radius	3.44	Yes
Thrust-to Weight Ratio	1.03	No
Empty Weight	3.45	Yes

From the above table it appears that there could be a problem with multicollinearity. Further investigation into the potential problem is warranted. The next table presents the condition number and the variance proportions for all three independent variables.

Table VIII

Multicollinearity Diagnostics

<u>Row</u>	<u>Condition Number</u>	<u>Variance Proportion COMRAD</u>	<u>Variance Proportion TTWR</u>	<u>Variance Proportion EWT</u>
1	1.000	.079	.001	.079
2	1.352	.001	.962	.001
3	3.423	.919	.038	.920

From the analysis of the Variance Proportion numbers in the above table, there is a multicollinear relationship between combat radius and empty weight. However, further inspection of the Condition Number shows a very low number. Thus even though the multicollinear relationship does exist, it is a very weak one and does not cause any problems in using the model.

Outliers. The data set and observations were analyzed to determine if any outliers existed with respect to the independent variables; or with respect to depot maintenance costs per flying hours, the dependent variable. Statistics used to identify potential outliers were: the leverage value, the studentized residual, and Cook's D. The following table contains results of these tests.

Table IX

Test for Outliers

<u>Observation</u>	<u>Leverage Value</u>	<u>Studentized Residual</u>	<u>Cook's D</u>
A-7	.580	-.037	.001
A-10	.387	.134	.003
F-4	.540	-.049	.001
F-5	.417	.978	.171
F-15	.574	1.670	.939
F-16	.453	-1.983	.813
F-106	.216	-.216	.003
F-111	.834	-.556	.389

The F-111 was identified as an influential outlier with respect to the other aircraft in the data base. In an effort to see what effect the F-111 had on this particular model, a model was developed without the F-111 in the data base. The same independent variables were found to be significant and the coefficients of these independent variables only changed slightly between the two models. This indicated that the two models were very closely related, and that the F-111 was not causing a significant variance between models. This study considers the model with the F-111 as the best model to be used. Statistics indicated that before the model is used the analyst should determine whether or not to include the F-111.

Predictive Capability of the Model. The predictive capabilities of the model are addressed next. The following table provides the point estimates, and the residuals for the model. The residual is a gauge of how far from the observed value (actual cost) the predicted value is. The last column shows that difference as a percent of the actual cost.

Table X

Predicted Values
(Point Estimate)

<u>Observation</u>	<u>Actual Cost</u>	<u>Predicted Value</u>	<u>Residual</u>	<u>Residual as % of Observed</u>
A-7	600	600.9	-.897	-.15
A-10	234	230.0	3.959	1.69
F-4	540	541.3	-1.245	-.23
F-5	223	194.9	28.101	12.06
F-15	941	899.9	41.032	4.36
F-16	403	458.2	-55.232	-13.71
F-106	491	498.2	-7.210	-1.47
F-111	1543	1551.5	-8.509	-.55

The prediction interval estimates are given in the following table. The prediction intervals (the lower and upper bounds) were set using a confidence level of 95%. This level of confidence would produce relatively wide intervals compared to a confidence level of only 70%. To determine how tight the prediction interval is above or below the predicted

value, the last column provides the percent of the range of a one-sided prediction interval divided by the predicted value.

Table XI
 Predicted Values
 (Interval)

<u>Observation</u>	<u>Predicted Value</u>	<u>Lower Bound</u>	<u>Upper Bound</u>	<u>Bounds as a % of Predicted</u>
A-7	600.9	469.6	732.2	21.85
A-10	230.0	106.9	353.1	53.52
F-4	541.3	411.6	670.9	23.94
F-5	194.9	70.5	319.3	63.83
F-15	899.9	768.9	1031.1	14.58
F-16	458.2	332.3	584.2	27.50
F-106	498.2	383.0	613.4	23.12
F-111	1551.5	1410.0	1693.0	9.12

Model Strengths. Three model strengths will be discussed.

1. The ability of combat radius, thrust-to-weight ratio and empty weight to explain a large portion of the variation in depot maintenance costs per flying hour. This is indicated by the large R^2 , which shows that 99.57% of the total variation in depot maintenance costs per flying hour is explained by the changes in combat radius, thrust-to-weight ratio and empty weight. This level of explanation is best shown through the reduction in standard error. Standard er-

ror of depot maintenance costs per flying hour using the averages of all the aircraft in the data base was 436.23. The standard error of depot maintenance costs per flying hour using the model with combat radius, thrust-to-weight ratio and empty weight in the model was 37.64. This means that estimating error can be improved by a factor of 11.6 (436.23/37.64).

2. The high degree of statistical probability that there is a linear regression relationship between depot maintenance costs per flying hour (dependent variable) and combat radius, thrust-to-weight ratio and empty weight (independent variables). The statistical probability is at least 99.99%.

3. The small prediction range when estimating at the center of data. With a C.V. of 6.05%, and a 95% prediction interval for the mean of depot maintenance costs is $621.9 \pm 12.1\%$ (or approximately 75.25). This is a very narrow range and indicates the large explanation of depot maintenance costs per flying hour by combat radius, thrust-to-weight ratio and empty weight with a high degree of confidence.

Model Weaknesses. Model weaknesses will now be discussed.

1. The amount of multicollinearity introduced into the model when empty weight is used in the model. Empty weight and combat radius are closely correlated (Pearson R of .8021). Thus using them in the same model is sure to create some multicollinearity. However, the model's statistics are enhanced

so much by this relationship that inclusion of empty weight was considered to be necessary to strengthen the model. The F Value almost tripled when empty weight is added to the model (from 108.125 to 312.117). Also, the R^2 increased from 97.74% to 99.57%, and the adjusted R^2 increased from 96.84% to 99.26%. While increasing statistics is important, it is best to note that this increase in the adjusted R^2 shows that adding empty weight helped the model in explanation of depot maintenance cost per flying hour variation and did not increase R^2 from 96.84% to 99.26% solely by adding another variable. The adjusted R^2 is a statistical measure that would penalize the model if the increase is based on adding another variable just to increase R^2 , and not taking into account the changing of the degrees of freedom in the model.

2. The F-111 is included in the observed data (the actual costs), when it is possible that the F-111 is an outlier with respect to this data. While this may not weaken the model as presented, it could interfere with future use of the model by an analyst whose next aircraft to predict is very unlike the F-111. For this study, the F-111 seemed to add so much to the statistics that it should not be left out. However, this may not be the case in follow on model use.

Depot Maintenance Cost per PAA

This section presents the model for depot maintenance cost per PAA. The format is the same as that used in the previous

model: presentation of the model, the statistics supporting the model, and model strengths and weaknesses.

The model for depot maintenance cost per PAA is:

$$\text{CDP} = -26055.6 + 4.218 * \text{EWT} \quad (15)$$

where

CDP = Depot Maintenance Cost per PAA

EWT = Empty Weight

Significant Cost Drivers. Only one variable could be considered a significant cost driver, Empty Weight. The probable reason for this is that in the case of depot maintenance per PAA the driving force for repair is not usage related but totally time related. Costs that are captured in this category are those of an overhaul kind. Rust inspection on a yearly basis, items that are marked rebuild or replace on a fixed time interval are examples of the type of costs captured in this category. Oil changes directed to occur at a fixed interval if operating time has not been exceeded are probably the most familiar type of activity. Since empty weight provides a sizing factor, it explains that the heavier the aircraft the costlier the repairs will be to it.

The cost drivers were evaluated based on the methodology discussed in Chapter III. First the signs of each independent variable were inspected to determine if the specifica-

tions for each followed expectations. In the case of the model for depot maintenance cost per PAA, the sign for empty weight is positive which means that as the independent variable increases in size the depot maintenance cost will also increase.

The t test determines if the coefficient for an independent variable is significant. A t test was performed on the independent variable's coefficient. The result of the t test for the coefficient showed at least an 80% confidence that the coefficient was different from zero.

Table XII

t Value for Independent Variable

<u>Variable Name</u>	<u>Level of Confidence</u>
Empty Weight	99.5%

To determine the impact that a change in the coefficient of the individual independent variable has on the dependent variable, a beta coefficient was calculated.

The following table shows the beta coefficient for the independent variable.

Table XIII
Beta Coefficient for Independent Variable

Model: Depot Maintenance Cost per PAA

<u>Variable Name</u>	<u>Beta Coefficient</u>
Empty Weight (EWT)	.8710

Descriptive Statistics. The following ANOVA table contains the results of the statistical tests for the F test, the models coefficient of multiple determination and, an analysis of the model's prediction ability.

Table XIV
ANOVA TABLE

Depot Maintenance Cost per PAA

<u>F Value</u>	<u>R²</u>	<u>Adjusted R²</u>	<u>Coefficient of Variation</u>
18.859	.7586	.7184	38.06

An F test was performed to check the existence of a regression relationship. This test uses the F statistic and the F distribution. For the model described previously the F value was 18.859. The results of this F test showed a 99.5% confidence that a regression relationship exists between de-

pot maintenance costs per PAA, (dependent variable), and empty weight, (independent variable).

The coefficient of multiple determination, R^2 , measures the proportional decrease in the total variation of depot maintenance costs when empty weight is the only independent variable in the model. The value obtained (.7586) indicates that 75.86% of the total variation in depot maintenance costs per PAA is explained by the model.

The adjusted R^2 is a check to insure that variables included in the model are significant and were not entered just to increase the R^2 . In the case of the model for depot maintenance cost per PAA, where there is only one independent variable the adjusted R^2 is not a consideration in determining the best model.

The coefficient of variation (C.V.), relates the standard error of depot maintenance costs per PAA given empty weight (as the only independent variable in the model) to the mean depot maintenance cost per PAA as a percentage. The value of the C.V. for this model is 38.06%. This means that for estimates at the center of the data, the confidence range of that estimate is plus or minus 38.06%.

Multicollinearity Diagnostics. Because there is only one independent variable in the model there is no problem with multicollinearity.

Outliers. The data set and observations were analyzed to determine if any outliers existed with respect to the independent variable; or with respect to depot maintenance costs per PAA, the dependent variable. Statistics used to identify potential outliers were: the leverage value, the studentized residual, and Cook's D. The following table contains results of these tests.

Table XV

Test for Outliers

<u>Observation</u>	<u>Leverage Value</u>	<u>Studentized Residual</u>	<u>Cook's D</u>
A-7	.149	-.230	.004
A-10	.148	-1.312	.149
F-4	.164	1.532	.230
F-5	.367	.979	.277
F-15	.139	-.950	.073
F-16	.211	-.607	.049
F-106	.125	.956	.065
F-111	.698	-.420	.203

The F-111 was identified as an influential outlier with respect to the other aircraft in the data base. In an effort to see what effect the F-111 had on this model, another model was built without the F-111 in the data base. The same independent variable was found to be significant and the coeffic-

ient of this independent variables only changed slightly between the two models. This indicated that the two models were very closely related, and that the F-111 was not causing a significant difference between the predictions of the two models. Consequently, this study considers the model with the F-111 as the best model to be used. Statistics indicated that before the model is used the question as to whether or not to include the F-111 should be resolved.

Predictive Capabilities of the Model. The predictive capabilities of the model are addressed next. The following table provides the point estimates, and the residuals for the model. The residual is a gauge of how far from the observed value (actual cost) the predicted value is. The last column shows that difference as a percent of the actual cost.

Table XVI

Predicted Values
(Point Estimate)

<u>Observation</u>	<u>Actual Cost</u>	<u>Predicted Value</u>	<u>Residual</u>	<u>Residual as % of Observed</u>
A-7	50977	57182	-6205	-12.07
A-10	22289	57701	-35412	-158.88
F-4	142844	101874	40970	28.68
F-5	37167	14389	22778	61.31
F-15	66290	92054	-25764	-38.87
F-16	23919	39689	-15770	-65.93
F-106	104964	78813	26151	24.91
F-111	166192	172939	-6747	4.06

The prediction interval estimates are given in the following table. The prediction intervals (the lower and upper bounds) were set using a confidence level of 95%. This level of confidence would produce relatively wide intervals compared to a confidence level of only 70%. To determine how tight the prediction interval is above or below the predicted value, the last column provides the percent of the range of a one-sided prediction interval divided by the predicted value.

Table XVII

Predicted Values
(Interval)

<u>Observation</u>	<u>Predicted Value</u>	<u>Lower Bound</u>	<u>Upper Bound</u>	<u>Bounds as a % of Predicted</u>
A-7	57182	0	133887	134.14
A-10	57701	0	134365	132.86
F-4	101874	24672	179077	75.78
F-5	14389	0	98048	581.41
F-15	92054	15669	168440	82.98
F-16	39689	0	118424	198.38
F-106	78813	2903	154724	96.32
F-111	172939	79699	266178	53.91

Model Strengths. The following points were considered to be model strengths.

1. The ability of empty weight to explain a large portion of the variation in depot maintenance cost per PAA. This is indicated by the R^2 , which shows that 75.86% of the total variation in depot maintenance cost per PAA are explained by the changes in empty weight. This level of explanation is also shown through the reduction in standard error. Standard error of depot maintenance cost per PAA using the averages of the aircraft in the data base was 55112. The standard error of depot maintenance cost per PAA using the model with empty weight was 29245. This means that esti-

mating error can be improved (decreased) by a factor of 1.9 (55112/29245).

2. The high degree of statistical probability that there is a regression relationship between depot maintenance cost per PAA (dependent variable) and empty weight (independent variable). The statistical probability is at least 99.5%.

Model Weaknesses. The model was considered to have the following weaknesses.

1. The wide prediction range when estimating at the center of data. With a C.V. of 38.07%, a 95% prediction interval for the mean of depot maintenance cost per PAA is $76830 \pm 76.14\%$ (or approximately 58498). This is a very wide range and indicates that even though there is a high degree of confidence in the explanation of depot maintenance cost per PAA by empty weight it may not be the best possible estimator.

2. Inability to find any other significant cost driver to enter into the model. This means that even though there is a statistically sound relationship between depot maintenance cost per PAA and empty weight, there is no other variable readily apparent that can help explain depot maintenance cost per PAA. As already noted, the predicting capability of empty weight, as seen by the value for C.V. is extremely poor.

Treatment of the F-111

The F-111 was identified as an outlier with respect to the other fighter and attack aircraft in the data base. Because of the technological innovations on the aircraft (swing wing, terrain following radar) it never was a successful fighter aircraft, but more resembled a long range attack or light bomber.

Some history on the F-111 program:

In 1960 the Department of Defense masterminded the TFX (tactical fighter experimental) as a gigantic programme (sic) to meet all the fighter and attack needs of the Air Force, Navy and Marine Corps, despite the disparate requirements of these services, and expected the resultant aircraft to be bought throughout the non-Communist world. In fact, so severe were the demands for weapon load and, in particular, mission range that on the low power available the aircraft had inadequate air-combat capability and in fact it was destined never to serve in this role, though it is still loosely described as a "tactical fighter". After prolonged technical problems involving escalation in weight, severe aerodynamic drag, engine/inlet mismatch and, extending into the early 1970s, structural failures, the F-111 eventually matured as the world's best long-range interdiction attack aircraft which in the hands of dedicated and courageous Air Force crews pioneered the new art of "skiing"--riding the ski-toe locus of a TFR (terrain-following radar) over hills, mountains and steep-sided valleys in blind conditions, in blizzards or by night, holding a steady 200ft. (91m) distance from the ground at high-subsonic speed, finally to plant a bomb automatically within a few metres (sic) of a previously computed target. (9:36)

Caveats

1. The strengths of this model are in its ability to predict the costs for depot maintenance costs per flying hour. The model does not do a "good job" on depot maintenance costs per PAA. However, the majority of depot

maintenance costs are directly related with flying hours. Before this model is used, the analyst must decide if it is acceptable to predict depot maintenance costs per PAA with a wider confidence bound than the one for depot maintenance costs per flying hour.

2. Multicollinearity between the cost drivers in the model and the other potential cost drivers that were considered for the model but were not included. Combat Radius is highly correlated with the weight variables and the acquisition cost of the aircraft. This relationship must be maintained in future aircraft systems when this model is used to predict the depot maintenance costs per flying hour for them.

3. Multicollinearity between empty weight and the potential cost drivers maximum takeoff weight and combat radius and acquisition cost. This multicollinearity restricts the use of the cost model. Now the relationship between empty weight and these other variables must be maintained in the final aircraft configuration for the estimate of depot maintenance cost per PAA to be valid.

Answering the Original Research Question

The models which have been developed will provide the cost analyst with the ability to estimate depot maintenance costs for fighter and attack aircraft. The models meet the research objectives of providing an estimating tool that:

1. can be used for estimates of depot maintenance costs when fast turnaround times are required, such as what-if

exercises;

2. can be used early in the development cycle of an aircraft when detailed data on actual maintenance and repair activities is not available; and,

3. will provide a crosscheck of estimates developed using other estimating techniques.

V. CONCLUSIONS AND RECOMMENDATIONS

Practical Implications

The two models developed provide the cost analyst with a tool to estimate depot maintenance costs for fighter and attack aircraft. The models use as the independent variables, physical, technical, and performance characteristics which usually are readily available in the conceptual and development timeframes. With these variables as the cost drivers, it is easy to differentiate depot maintenance costs between fighters or attack aircraft of different sizes. The ability of the model to do this is important since there may be some trade-offs possible based on the mission of an aircraft. In the very early stages of an aircraft's development, the USAF may not yet have determined the final role of the new aircraft. However, to be able to use this model, the Air Force planners only need to know if the aircraft is in the same configuration as an F-15, or an A-10.

The one caveat on the use of these models is that the aircraft they are intended to predict depot maintenance costs for must be in the universe of those that make up the data base from which the models were developed. If the depot maintenance costs for the new aircraft are actually different, a good case needs to be made as to how they're different. One explanation may be that new design parameters have

been employed, therefore the old data base is no longer sufficient for estimating costs.

Air Force planners who are responsible for making decisions such as this will need to be sensitive to the mission first, and then to the life cycle impacts that might occur in selecting an aircraft that can accomplish the mission. The models developed in this study will provide the cost analysts with the ability to estimate the depot maintenance costs once the aircraft sizing, thrust-to-weight ratio and combat radius are determined. The models will show the sensitivity to depot maintenance costs between two aircraft models if there are disparities between empty weight, thrust-to-weight ratio and combat radius by being able to produce estimates based on these characteristics.

The models also provide a good back-up estimating methodology that the cost analyst can use to crosscheck an estimate made using a different technique for estimating depot maintenance costs (such as the Logistics Support Cost Model). A parametric crosscheck, provided by the models developed in this study, is easy to use and provides a quick method to determine if, in regards to depot maintenance costs, the new aircraft is deviating from the historical trends of the aircraft in the data base. This is a particularly interesting tool for management, as any deviation discovered from the predicted value should be analyzed and explained.

Because the models do provide a quick turnaround capability, the cost analyst can use the models to answer what-if questions. Most what-if exercises require a fast turnaround response and the models can be run quickly to provide this response. The benefit of quick turnaround times may not be apparent when a major weapon system is just being considered. However, there are many trade-offs that take place in the early stages of development, and the decision maker often requires that the impacts on total life cycle cost should be provided. The models presented here can do this in a most economical way, especially in terms of manpower resources required and computer time expended.

Policy Implications for Management

The models provide the decisionmaker with timely estimates in the early stages of a program, plus quality answers to fast turnaround time estimate requirements. An extremely useful benefit of the models to management may be in the models' ability to provide a crosscheck of the depot maintenance cost estimates that are prepared using other techniques.

Another policy implication of these models is their ability to predict future costs containing the same cost content and allocation of costs as those costs captured in the depot maintenance cost accounting collection system. While knowing what the true cost is may or may not be important to a decisionmaker when development is just being started, the decisionmaker is usually most concerned that the chosen sys-

tem can perform the given mission best, and that the total life cycle cost is the most reasonable, of the systems competing for selection.

One of the more critical aspects in any management control system is the ability to track what was planned, what was budgeted, and what was spent to carry out the activity. The models have been developed using the data base from the depot maintenance cost accounting system. Thus estimates made by these models reflect the cost content and allocation of costs that are reported to Congress, and are similar in nature to the costs shown in AFR 173-13, "USAF Cost and Planning Factors".

For models not using the historical costs as the data base, they may or not be providing the management control information that is desired to be consistent with formal accounting reporting. For instance, in the case of fighter aircraft the depot maintenance estimating equations of the LSC model have never been validated (12:1) and consequently these equations may or may not be providing the true cost of depot maintenance repairs.

Recommendations for Follow-on Activities

The models developed in this study have verified that there exists a relationship between the variables as predictors of depot maintenance costs for fighter aircraft. This relationship should be further expanded to include other

types of aircraft such as bombers, tankers, cargo and trainers. Development of cost estimating relationships for all these aircraft types would provide the same benefits that the development of these two models has provided.

This work was accomplished at a high level of depot maintenance cost aggregation. It was done at the basic fighter and attack Model and Design (MD) level. Further investigation might find that the same results could be accomplished at a lower level of detail, such as the Model Design and Series (MDS) level. This would be useful for developing and assessing the impact on depot maintenance costs when the Air Force plans to change the actual mission of an aircraft within the original design constraints of the aircraft, e.g. making a reconnaissance version of the F-16.

There is data available within the WSCRS historical data base that provides visibility into the Work Breakdown Structure (WBS) of fighter and attack aircraft. An ability to predict depot maintenance costs at this lower level of indenture would make it easier to conduct various trade-off studies of systems such as propulsion, and electronics.

The final follow-on development effort suggested for these models using the WSCRS data base would be to develop models that could estimate costs at the Work Unit Code (WUC). WUCs identify specific items on an aircraft. For example on the F-15 , the APG 63 radar may have a WUC of 72A00, and the

boxes within the radar system may have WUCs of 72A01, 72A02 etc. By being able to identify costs to these specific WUCs, it will be possible, with the use of models developed as a follow-on to this study, for a cost analyst to provide better estimates (more sensitive to aircraft configurations) based on the configuration given by an aircraft designer/planner. If the designer/planner can say that a similar system will be on that type of aircraft, then the relationship between the historical cost and the future costs for depot maintenance can be estimated.

This study did not attempt to estimate depot maintenance costs at the lower levels of indentures because, while the ability in WSCRS to collect and allocate costs at the lower levels of indenture does exist, the cost analysts at AFLC do not recommend use of these lower indentured costs until the collection and allocation process is verified and validated. This is currently being accomplished within the purview of the VAMOSC office. Once developed a WUC/NSN dictionary will lead to better cost allocations making the historical data even more useful to cost analysts at AFLC.

This study has illustrated that there is a relationship between the actual data on depot maintenance cost being reported in the AFLC cost accounting system, and physical, technical, and/or performance characteristics of fighter and attack aircraft. A stronger relationship existed between depot maintenance costs per flying hour and the chosen physical

parameters then the relationship between depot maintenance cost per PAA and other physical parameters. On the strength of the relationship shown between depot maintenance costs per flying hour and the physical parameters chosen to describe this relationship, further efforts into using the WSCRS data as a predictor of depot maintenance costs should be accomplished.

Appendix: Variable Data

<u>Aircraft Model</u>	<u>Depot Maintenance Cost per Flying Hour</u>	<u>Cost per Paa</u>	<u>Empty Weight</u>	<u>Maximum Weight</u>	<u>Combat Weight</u>
A-7	600	50977	19733	39325	28200
A-10	234	22289	19856	46270	38136
F-4	540	142844	30328	61795	41487
F-5	223	37167	9588	21818	14588
F-15	941	66290	28000	68000	44630
F-16	403	23919	15586	35400	23810
F-106	491	104964	24861	41381	33570
F-111	1543	166192	47175	100000	62350

Depot maintenance costs are expressed in 1988 dollars.
Empty, maximum and combat weights are in pounds.

<u>Aircraft Model</u>	<u>Engine Power Rating</u>			<u>Speed</u>	
	<u>Maximum</u>	<u>Military</u>	<u>Normal</u>	<u>Maximum</u>	<u>Average</u>
A-7	14250	14250	12950	576	530
A-10	9065	7990	7335	389	376
F-4	17900	11870	11110	1221	506
F-5	5000	3500	3280	840	476
F-15	23900	15774	14197	1435	574
F-16	23900	15774	14197	1172	469
F-106	24500	16100	14300	1153	516
F-111	25100	14560	13170	1262	431

Engine power ratings are expressed in pounds of thrust.
Speed is in knots in level flight.

<u>Aircraft Model</u>	<u>Service Ceiling</u>	<u>Maximum Rate of Climb</u>	<u>Combat Radius</u>	<u>Thrust-to-Weight Ratio</u>
A-7	37000	8000	600	0.722
A-10	30500	5340	250	0.913
F-4	36000	41300	367	1.180
F-5	38500	28536	275	1.043
F-15	60000	50000	570	1.707
F-16	50000	50000	340	1.533
F-106	43500	43500	417	0.985
F-111	38050	43750	1096	1.064

Service ceiling is in feet.

Maximum rate of climb is in feet per minute.

Combat Radius is in normal configuration. It is not ferry range.

Thrust-to-weight ratio calculated as the maximum power (thrust multiplied times the number of engines, divided by empty weight).

<u>Aircraft Model</u>	<u>Acquisition Cost Dollars in Millions (FY 88 Dollars)</u>	<u>Acquisition Cost Dollars per Pound (FY 88 Dollars)</u>
A-7	8.2	415.5
A-10	8.2	413.0
F-4	9.4	310.0
F-5	4.3	448.5
F-15	27.3	971.4
F-16	14.4	923.9
F-106	21.3	856.7
F-111	33.5	710.1

Acquisition cost reflects flyaway costs normalized for inflation. Acquisition cost per pound is flyaway cost divided by empty weight.

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Abstract

The model developed in this study has two cost estimating relationships (CERs) for estimating depot maintenance costs in its two categories: depot maintenance cost per Primary Authorized Aircraft (PAA); and, depot maintenance cost per flying hour. The data source used for depot maintenance costs is the Weapon Systems Cost Retrieval System (WSCRS) as developed by HQ AFLC.

The CERs developed used empty weight of fighter and attack aircraft to predict the cost of depot maintenance per PAA. For depot maintenance cost per flying hour, the variables used were combat radius, thrust-to-weight ratio, and empty weight.

The study found that the F-111 was a significant outlier with respect to the data set, but even when included in the data base the F-111 enhanced the values of the statistics for the model and improved the ability of the model to predict.

The relationship found for depot maintenance cost per PAA in the CER developed, was not as strong a predictor as was the CER developed for depot maintenance cost per flying hour. This conclusion agrees with previous studies that have tried to determine significant relationships between depot maintenance costs and those costs attributed to the number of PAA.

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