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THE USE OF COST ESTIMATING RELATIONSHIPS VERSUS ACCOUNTING MODELS FOR ESTIMATING MAINTENANCE AND REPAIR COSTS: A METHODOLOGY DEMONSTRATION

THESIS

Rajiv S. Verma First Lieutenant, USAF

AFIT/GSM/LSQ/87S-35

DEPARTMENT OF THE AIR FORCE

**AIR UNIVERSITY** 

AIR FORCE INSTITUTE OF TECHNOLOGY

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AFIT/GSM/LSQ/87S-35

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THE USE OF COST ESTIMATING RELATIONSHIPS VERSUS ACCOUNTING ACCOUNTING MODELS FOR ESTIMATING MAINTENANCE AND REPAIR COSTS: A METHODOLOGY DEMONSTRATION

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 Engineering Management

> Rajiv S. Verma, B.S., M.B.A. First Lieutenant, USAF

> > September 1987

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Rajiv S. Verma

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### AFIT/GSM/LSQ/87S-35

### Abstract

This thesis demonstrated a methodology of developing a Cost Estimating Relationship (CER) that is capable of generating nearly the same cost estimates as an accounting type of cost model. A cost model was first developed that estimated annual recurring maintenance and repair associated costs of a jet engine. This model used 51 input variables and 30 equations and represented an accounting approach to cost estimating with input requirements at low levels of detail. Using techniques of multiple linear regression, a CER was developed that used only seven aggregated variables to estimate the same cost at an acceptable level of accuracy.

The emphasis in this thesis is on the demonstration of a methodology that can be used to develop CERs. Both the accounting type cost model and the CER in this thesis are exclusively for the validation of a methodology and were developed using an artificially generated data base. As such they are not valid for any cost estimation purposes.

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### THE USE OF COST ESTIMATING RELATIONSHIPS VERSUS ACCOUNTING MODELS FOR ESTIMATING MAINTENANCE AND REPAIR COSTS: A METHODOLOGY DEMONSTRATION

### I. Introduction

### General Issue

Air Force Regulation (AFR) 800-11, Life Cycle Cost <u>Management Program</u>, defines life cycle cost (LCC) rather simply: "the total cost to the government for a system over its full life" (1:1). The life of a system can be divided into four distinct phases: (1) research and development (R&D), (2) acquisition or production, (3) operation and support, and (4) disposal (25:9).

Operation and support (O&S) costs often make up a substantial portion of LCC (22:1). While these costs are not incurred until the system is actually in the inventory, the decisions that determine these costs usually have to be made prior to production (24:1.2). Therefore, in order to make good acquisition decisions, it is very important to know what the life cycle cost implications of each alternative might be. This would require that one have some idea of what the O&S costs are under each alternative.

O&S cost estimation, often called life cycle costing, can serve a number of objectives (25:11): (1) to determine what the total costs are and what the expenditure profiles

look like so that one can assess the budget impact in the out years, (2) to determine economically feasible performance requirements, and (3) to provide design guidance to reduce O&S costs.

### Cost Estimating Methods

Within DOD, there are several generally accepted cost estimating techniques: detailed estimating, cost estimating relationships (CERs), expert opinion and estimating by analogy are some of them (5:9). No one method is the best; the appropriateness of any method depends on the situation. For instance if one is trying to cost a new system, something that perhaps represents a quantum leap in technology and for which there is no data base, one may be forced to develop the estimate by asking the opinion of people who are most knowledgeable about the system. This is the "Expert Opinion" approach where the cost analyst seeks, as the term suggests, the opinion of an expert or experts about the system being estimated. This method is purely judgmental and as such it involves a lot of subjectivity on the part of the "experts."

The method of estimating by analogy method is less subjective. According to this method, the cost analyst compares the new system to an already existing system that is most similar to it. Using the cost of the existing system as a starting point, the estimator then adjusts the cost based on the differences between the two systems.

Detailed cost estimating can further be divided into two categories: the engineering build-up method and accounting type cost models. The engineering build-up method builds a cost estimate by summing up costs of low levels of hardware breakdown and disassembly. This "bottom up" method uses the "sum of parts" approach to approximate the whole. Using a work breakdown schedule (WBS), the engineering build up method identifies components at a very detailed level and sums its way up to higher levels of aggregation.

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Accounting type of cost models are similar to the engineering build-up method in the amount of detail involved. However, while engineering build-up method concentrates on components, the accounting type of cost models are activity oriented. They account for cost by identifying activities at low levels and by summing the associated costs (9:17).

Cost estimating relationships (CERs) are statistical models which treat cost as a function of selected variables. These variables are called cost drivers; they drive cost in the sense that their influence on cost is rather substantial. Since the selection of input factors in CERs is rather discriminatory, i.e., the variables chosen have to be significant in terms of their impact on cost, CERs are not nearly as large as accounting models.

### Problem Statement

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Research seems to indicate that most O&S cost models are accounting type of models. These models try to estimate O&S cost by describing the operation and support process of the system itself. Consequently, they normally include a large number of variables that correspond to the many activities that make up the O&S cost effort. This property does have its advantages:

 Costs can be tracked more readily because they are more visible; this can lead to easier management of O&S dollars.

2. The amount of detail in the model lends itself to sensitivity analyses and tradeoff decisions.

However, accounting models require detailed information. During the early phases of the acquisition cycle, there is insufficient operational information on the new system to provide as much data as the accounting model needs. The use of an accounting model also requires having to estimate values for a large number of variables. This may require an amount of time that may not be available.

Assuming that the required time is available, estimating a large number of variables may inadvertently result in estimating errors. One could argue that in estimating a large number of variables, errors have a way of balancing out so that the overall estimate is still reasonably accurate. The underlying concept here is that an

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over-estimation of one variable may nullify the underestimation of another so that in totality things have a good chance of coming out even. The fallacy with this argument is that variables have different weights, i.e., their impact on cost could range from miniscule to very significant. Thus, an over-estimation of a very significant variable cannot be balanced out by an under-estimation of a variable that has minimal impact on cost and vice-versa.

Estimating errors may also be caused by a bias in the estimating process. In estimating a large number of variables, there is a tendency to estimate them in a normative manner, i.e., to estimate them as they should be. This kind of an optimistic approach tends to ignore the effect of problems and complexities that are a part of the normal operating environment and therefore may under-estimate actual costs.

During the early phases of the acquisition cycle, the purpose of an O&S cost estimate is primarily budgetary. At this point, the decision makers are more interested in an aggregate total O&S cost rather than a detailed breakdown of this cost among components and sub-components. If a model could estimate costs equally well while using a significantly lesser number of variables, the purpose would be served just as well. Cost estimating relationships can do just that. They do so by a careful identification of the input variables; if one variable can capture the effect that

several variables are having on cost, then it makes sense to only include that one variable and not the others if an aggregate cost estimate is what is desired.

There may be some apprehension that doing this increases the potential for estimating error, that is to say that since there are fewer variables and they are all significant in terms if their impact on cost, an estimation error in any one variable is likely to have a more serious impact on estimated cost. However, the task of estimating a much lesser number of variables means that more time can now be devoted to estimating each variable, thus increasing the opportunity to achieve greater accuracy. Besides, a variable that is significant in the CER is also likely to be one of the the more influential variables in the accounting type of model. Therefore, an error in its estimation would have a negative impact in either case.

### Some Myths about Detail and Accuracy

The following two phrases are often heard in connection with military cost analyses:

- 1. We must always strive for a high degree of accuracy in an absolute sense.
- 2. A higher degree of accuracy can be attained by going into a greater amount of detail [13:76].

In the context of long range planning, the possibility of accomplishing a high degree of accuracy in the absolute

sense is remote. This is so because of the characteristics of long range planning. These characteristics include uncertainties, lack of detailed information and data, and a wide range of alternatives. Under these conditions, highly accurate cost estimates are most unlikely. This is not critical because most long term planning efforts require relative comparisons between alternatives. If the cost estimates provide sufficient information to facilitate the best decision, then they have served their purpose. Analytical cost estimating techniques which treat alternatives consistently are better suited for comparative cost analyses.

It is important to understand these points because in the long-range planning context the analyst can waste much time and effort if he tries to pursue an objective as elusive (and perhaps as irrelevant) as a high degree of accuracy in an absolute sense [13:76].

The second statement, "a higher degree of accuracy can be attained by going into a greater amount of detail" is generally not true and particularly false in the context of long range planning. Under conditions of knowledge gaps and paucity of data, to force the analysis into a finer and finer grain of detail will force the analyst into essentially using fictitious numbers to fill in the categories that are overly detailed (13:76).

In such instances, concentrating the analytical effort at an appropriate (relatively high) level of aggregration and using carefully derived

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estimating relationships are the most likely means of producing fruitful results [13:77].

### Research Objective

Having established that accounting models are not really necessary nor suitable for O&S cost estimation during the early part of the acquisition cycle, the purpose of this research effort is to demonstrate the feasibility of using cost estimating relationships models to estimate O&S costs. The researcher will attempt to do this by by demonstrating that it is possible to develop a CER that is capable of generating nearly the same cost estimates as the accounting model.

### Scope

Both the accounting model and the CER estimate the annual recurring costs required to repair and maintain jet engines. However, the methodology demonstrated in this document is not limited to either jet engines or to the repair and maintenance element of O&S costs; it can be applied to any system or to any element of O&S costs.

The development of the CER is limited to those models that can be expressed as a linear function or as a transformed linear function. This allows the use of the Least Squares Best Fit method in determining the model parameters.

The CER will be evaluated within the context of the normal regression model.

### Research Questions

In order to accomplish the objective stated above, the following research questions will be addressed:

1. <u>Identification</u>: What new variables should be created from the inputs into the accounting model? What variables should be considered for inclusion in the CER?

2. <u>Specification</u>: What is the functional relationship of the dependent variable, cost, with the independent variables, the cost drivers?

a. Does cost increase or decrease with an increase or decrease in a particular variable?

b. Is this relationship linear? If not, can it be transformed into a linear relationship by transforming the independent variables?

3. <u>Model Description</u>: What is the nature of the relationship between cost and the cost drivers represented by the CER?

a. What is the influence of each independent variable on cost?

b. What are the standardized regression coefficients, and what do they mean?

4. <u>Model Statistics</u>: What are the statistical properties of the CER?

a. Does each individual variable make a significant contribution to the CER's ability to explain cost?

b. What is the overall statistical significance of the CER?

5. <u>Model Diagnostics</u>: How is each independent variable correlated with the other independent variables in the CER? Are any of the observations outliers, and if so, what is their impact on the analysis?

a. Do the error terms have a constant variance?

b. Are they normally distributed, and are they independent of each other?

6. <u>Predictive Ability of the Model</u>: How well does the CER predict cost?

a. How accurately does the CER predict the observations in the data set?

b. How wide are the prediction intervals in comparison to the magnitude of the predicted value?

### II. Background

Repair and maintenance costs are part of the operation and support costs which in turn are a significant portion of the total life cycle cost of a jet engine. Chapter I briefly introduced the idea of Life Cycle Cost (LCC). This chapter discusses the subject in greater detail, particularly in the context of defense acquisition.

### The Acquisition Cycle

In order to understand the importance of the LCC concept, it is first necessary to understand some basic concepts of the acquisition process of weapon systems. The literature suggests that the life cycle of a system is normally divided into four phases: (1) Research and Development (R&D), (2) Production, (3) Operating and Support, and (4) Disposal (25:9; 6:1; 16:2-1).

Research and development (R&D) can be further subdivided into the conceptual phase, the validation phase and the full scale development phase (25:9). Likewise, the first phase of the Operating and support is initial deployment. The three phases of R&D, Production, and the initial deployment phase of Operating and Support constitute the acquisition cycle, as shown in Figure 2.1.

1. <u>Concept Exploration</u>: A statement of need describes an operational deficiency or need and is initiated





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by HQ USAF or a major command (24:3.1). The concept exploration or conceptual phase is primarily concerned with substantiating the need, verifying capabilities and weighing possible alternatives. The end product of this phase is:

the data which, in the form of studies, analyses, test results and conceptual drawings and specifications, demonstrates that concepts exist which have a high probability of satisfying the mission at an affordable cost in a reasonable time [24:3.8].

Usually these outputs are developed by private firms under contract to the government. Successful completion of the conceptual phase starts the demonstration and validation phase (20:7).

2. <u>Demonstration and Validation Phase</u>: During the Demonstration and Validation phase, prototypes are designed, built and tested; program characteristics such as performance, cost and schedule are developed (1:6). If resources are sufficient, two or more contracts may be awarded for firms pursuing different concepts (24:3.9). Reducing technical, cost and schedule risks are the major objectives of this phase (24:3.9). By the end of this phase, a concept is selected, its operational need is verified and the process moves into full scale development.

3. <u>Full Scale Development</u>: During the Full Scale Development phase, the weapon system and the major subsystems are designed, fabricated, tested and evaluated. The

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purpose is to come up with a prototype that closely resembles the final weapon system (17:21). Much emphasis is placed on reducing the technical risks and developing a product that will meet the stated requirements.

Production and Initial Deployment: The produc-4. tion phase begins when the full scale development has demonstrated that the weapon system is ready for production. The system is produced and procured and support and training requirements are made available to facilitate deployment. Initial spare parts and most ancillary equipment are procured at this stage. A system is considered deployed when it is turned over to the using command (3:6). The point where Air Force Systems Command (AFSC) hands over the program to Air Force Logistics Command (AFLC) is known as Program Management Responsibility Transfer (PMRT). PMRT marks the end of the acquisition cycle and the beginning of the longest phase of a weapon system's life cycle (20:7). This phase is the ownership phase, also known as the operating and support phase (20:7). For jet engines, this time period generally lasts over 15 years.

### Cost Considerations

Before the idea of life cycle costing was fully accepted, system performance was often the only criterion considered in system design (1:10). Little or no consideration was given to the operating and support costs that would occur after deployment (3:3-5). Any cost consideration was

secondary to technological capability: things like speed, firepower, payload and other performance related factors took precedence over any cost considerations (1:10). Exclusive emphasis on performance often resulted in performance exceeding the requirements at the cost of sacrifice in reliability, a factor that contributed to the rapid escalation of O&S costs (20:18).

With time, awareness grew that O&S cost was a rather sizable proportion of a weapon's LCC and as such it required greater management attention. Procurement, RDT&E and other initial costs were found to represent only the proverbial tip of the iceberg. By some estimates, O&S costs are a full half of the total cost of the weapon system (22:1). O&S costs range from 10 percent for some electronic systems to an average of about 50 percent of LCC for aircraft (14:3). In a Rand report of March 1977, author J. R. Nelson stated that depot repair and overhaul costs alone can exceed procurement costs of a new jet engine over a 15 year life span (18:V).

These kinds of findings necessitate that one consider the LCC ramifications of buying a weapon system and not just the initial costs. A procurement process that places the emphasis on lowest bid price or highest technical performance may cause the government to incur a higher life cycle cost because operation and support costs were neglected. The objective of life cycle costing is to meet the

operational needs while achieving the optimum balance of performance, reliability, schedule and cost (14:3).

The military has come to realize that not only should life cycle costing be done in connection with acquisition but that it should be done early in the acquisition cycle because decisions concerning design greatly affect O&S costs (25:224). The idea of doing life cycle costing during the early stages of the acquisition cycle is absolutely necessary because majority of the LCC is already determined by the decisions that are made during the early phases. Figure 2.2 shows that up to 95 percent of life cycle costs are affected by the end of full scale development.

### Life Cycle Cost--Definition and Background

Definition: A typical definition of LCC is provided by Mr. Robert Seldon in his book on the same subject:

The life cycle cost of an item--its total cost at the end of its lifetime--includes all expenses for research and development, production, modification, transportation, introduction of the item into inventory, new facilities, operation, support, maintenance, disposal, and any other costs of ownership, less any revenue at the end of its lifetime [25:9].

History (41:1-1 to 1-10): The Logistics Management Institute (LMI) conducted the early studies in the area of life cycle costing. The LMI report, issued in 1965 and titled "Life Cycle Costing in Equipment Repair," concluded that O&S costs and purchase prices could vary significantly

# LCC CONTROL LEVERAGE



among different manufacturer's products. The report further stated that the use of predicted O&S costs is preferable to the traditional practice of ignoring them on the grounds that these predictions are uncertain. Based on these conclusions, the Assistant Secretary of Defense for Installation and Logistics (I&L), started trial procurements of certain items on a life cycle cost basis. Simultaneous to this event was the push for reduction of support costs. DoD directive 4100.35, issued in 1964, advocated minimization of the total life cycle cost of a system by employing the concept of Integrated Logistics Support.

In the late sixties, the growing public unwillingness to support growth in the defense budget resulted in several studies such as the Blue Ribbon Committee study and the Congressional Commission on Government Procurement study, among others. Common among the recommendations of these studies was that life cycle costing be applied to equipment and system acquisitions.

The seventies saw the issuance of several government regulations, directives and guidelines concerning LCC. Perhaps the most notable example is OMB circular A-109 which came out in April of 1976 and made the use of life cycle costing mandatory in the acquisition of major weapon systems.

### Resistance To Life Cycle Costing

Today, life cycle costing is required for the almost all major system acquisition. However, the implementation of life cycle costing has been sporadic. In the 82-83 winter quarter issue of AFIT AOG quarterly, Margaret A. Emmelhainz reported that while current military directives require that life cycle costs be considered in all acquisition decisions, the implementation of this policy has tended to focus on controlling acquisition costs rather than life cycle costs (12:8). The reasons, she went on to say, are funding constraints in the early years of the program, the inability to easily and accurately estimate operation and support costs and schedule considerations. These factors have hindered Air Force efforts to structure contracts that emphasize life cycle costs (12:8).

In his book, Life Cycle Costing: A Better Method of Government Procurement, Mr. Robert Seldon discusses five factors that further help explain the early resistance to life cycle costing (25:4-7):

1. <u>Separate Appropriations</u>--Appropriation of procurement funds is separate from appropriations for operating and maintaining (O&M) funds. By specifying the use of appropriated funds, the original intent of congress was to designate and control expenditures. Doing this, however, also separated the responsibility of the management of these different funds. As a result there is no institutional

incentive for the procurement funds manager to pay more now so that O&S costs can be saved later. Seldon wrote that Congress had begun to show flexibility in the area as it developed a greater appreciation for the issue (25:4-5).

2. Front End Loading--Mr. Seldon commented that LCC ran into political objections. The idea of higher initial costs in research, development and production in order to achieve later economies in operation and maintenance was politically not welcomed. This was so because politicians were influenced much more strongly by immediate budget stringencies than by projected savings in the future. The concern for politicians was that the public will judge them and the administration on current performance and not on possible future benefits. Seldon noted, however, that when scenarios were clearly presented, congress had often chosen lower total cost and not lower immediate cost (25:5).

3. <u>Past Procurement Policies that Resembled LCC</u>--Mr. Seldon cites examples of the C-5A transport aircraft, the short range air-launched missile (SRAM), the Cheyenne helicopter and the F-14 fighter plane. These were part of the "total package procurements" instituted during the sixties under the guidance of the then Secretary of Defense Robert S. McNamara. Total package procurement was an attempt to contract for the total cost of development and production early in the development cycle. These programs incurred heavy cost over-runs and were criticized widely.

Even though total package procurement did not concern itself with O&S costs, its perceived resemblance to life cycle costing caused skepticism about LCC (25:6).

4. Reluctance of Contractors--A significant percentage of a system's O&S costs are predestined by the decisions made during the design of the system. In order to get contractors to pay attention to the life cycle cost implications of their design decisions, some link must be created between a system's O&S cost and the contractor's compensation. Since actual O&S costs may not be known for many years, rewards or penalties must be based on estimated costs. However, many military contractors are skeptical about any cost estimate that stretches fifteen to twenty years out in the future. Furthermore, there are many factors that can influence O&S costs that are outside the control of the contractor. Consequently, contractors are not too enthusiastic about committing themselves to a target cost that they may miss entirely for unforeseeable reasons (25:8).

5. Accuracy and Reliability of Data and LCC Methodology--O&S costs typically include a wide variety of activities performed by many different organizations in multiple geographic locations. Consequently, the task of collecting O&S cost data is a formidable one. It is almost impossible to compile a complete and accurate picture of the true O&S costs for a given system. One of the problems that can be

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attributed partly to the lack of good data is the absence of a common methodology for estimating O&S costs. Mr. Seldon concluded:

Even within DoD it is hard to obtain cost data for past DoD procurements because of intraorganizational factionalism, fear of criticism, simple bureaucratic confusion, or the inherent complexity of multimillion dollar contracts spread over many years with changing requirements. Also, cost-estimating methods vary widely among analysts; there are no commonly accepted costing models (25:8).

However, he also noted that the situation is improving and solutions to many of the problems are slowly evolving over time.

### Life Cycle Cost Models

The literature review on the subject of LCC included an examination of some life cycle cost models. Some of these models are discussed below:

LSC model: The Air Force Logistics Command (AFLC) logistics Support Cost (LSC) model is an accounting type of cost model that is used to estimate support costs expected to be incurred by adopting a particular design for a weapon system. The model claims to be particularly useful in comparing and discriminating among design alternatives where relative cost difference is what is desired (7:4). The model has been in existence since the early 70s. In 1974, the team of Dover and Oswald reviewed this model as part of their MS thesis at the Air Force Institute of Technology. The model then had 88 data elements and 10 equations (9:20). Over the years, the model has been slightly modified, mostly to incorporate costing of software. It now has 109 data elements and 11 equations. Each equation represents a cost of resources necessary to operate the logistics system (7:Appendix 3):

Cost of first line unit (FLU) repairs
On equipment maintenance costs
Off-equipment maintenance costs
Inventory management cost
Cost of support equipment
Cost of personnel training
Cost of management and technical data
Facilities Costs
Cost of fuel consumption
Cost of spare engines
Software support cost

The model is exercised by summing the costs mentioned above. Each equation has a large number of input variables. This model is intended for application in three different areas:

1. To obtain an estimate of the different logistics support costs between the proposed design configuration of two or more contractors during source selection.

2. To establish a baseline for contractual commitments on certain aspects of operational supportability which will be subject to verification.

3. To use as a decision aid in discriminating among design alternatives during prototyping or full-scale development (7:4).

The Super Operating and Support Cost Model (SOSCM): SOSCM is intended to determine initial and recurring support cost for jet engines. The model was developed by the Jet Engine Systems Programming Office of the Aeronautical Systems Division, USAF, to allow consistent evaluations of engine offerings between different engine manufacturers. The input data to this model falls into three categories:

1. Yearly Input: This input consists of annual engine flight hour (EFH) build-up and the annual quantity of spare engines and cost of support equipment. A maximum of 40 years of data may be input including the fleet build-up and life cycle support period.

2. Ground rule input: This category of data includes repair cycle times, order and ship time, shipping cost per pound, labor rate and fuel consumption.

3. Reliability and maintenance and cost input by engine component: This category contains unscheduled and scheduled failure data for mode line items (8:3).

The number of data elements in the SOSCM model exceed 200. Efforts have also been made to estimate jet engine O&S costs through the use of Cost Estimating Relationships. Two such efforts are discussed below:

1. Rand Study: In a RAND corporation executive summary titled " Life-Cycle Analysis of Aircraft Turbine Engines," author J. R. Nelson discussed several CERs that computed sub-categories of LCC of jet engines. As an
example, the RAND CER for estimating "base maintenance cost per engine flying hour consumed (\$/BMCEFCHC)" is as follows:

 $\ln (BMCEFHC) = 3.50819 - 0.47457 \ln (MTBO) + 0.01299 OPSPAN + 0.56739 \ln (CPUSP)$ 

Where

BMCEFHC	=	base maintenance cost per engine flying hour consumed
MTBO	=	maximum time between overhaul in hours
OPSPAN	3	time since operational use began in quarters
CPUSP	=	Current unit production selling price

Nelson presented several other CERs that computed portions of LCC. Some of these categories included development cost, component improvement cost, and depot maintenance cost per engine flying hour. No more than six variables were used in any one particular CER (18:25).

2. Cox Model: In a 1985 master's thesis at the Air Force Institute of Technology, the author Brenda Cox developed the following CER for estimating partial jet engine O&S costs (24:58):

ADJC = -415350 + 184.307 TIT + 93565.729 SFC + 18.962133 WT + 0.049260 EFHRS

Where,

ADJC = Adjusted O&S cost TIT = turbine inlet temperature SFC = specific fuel consumption WT = weight of the engine EFHRS = annual engine flying hours

The literature review of O&S cost models showed that accounting type of cost models such as the LSC model or the SOSCM model are basically very large models that require voluminous amounts of data input. In contrast, CERs are rather compact models that use statistical techniques to estimate similar costs while employing the use of a few selected variables.

## III. Model-A

#### Introduction

Model-A is an accounting type of cost model that estimates annual recurring costs associated with the repair and maintenance of  $\underline{a}$  jet engine. The costs involved in this model can be put into three broad categories:

# 1. Costs to Perform Maintenance Directly on the Engine

- la. Labor costs associated with maintenance actions
- 1b. Cost of fuel to do engine trims and checks

## 2. Cost of Repairs

- 2a. Annual repair cost at base level
- 2b. Annual repair cost at depot level

# 3. Cost of Spares

- 3a. Cost of expendables associated with maintenance of the engine
- 3b. Cost of expendables associated with repair actions
- 3c. Cost of replacing condemned parts

#### Mean Time Between Failure

Through out the model, the word "failure" refers to the failure of the part that necessitates the removal of the engine from the aircraft. To use a very simplified example, if there are three such parts and their respective mean time between failures (MTBF) are 100 hours, 150 hours and 200 hours, then the maximum value that MTBF can take, as used in this model, is 100 hours. This is so because, starting from zero hour, the first failure would normally be expected around 100 hours which is the MTBF for part one. When part one fails, it will be either repaired or replaced. If nothing is done to the other two parts at this point, then the next failure would normally occur approximately 50 hours from this point or 150 hours from zero hour. Similarly part three would fail approximately 50 hours hence or 200 hours from zero hour. Under this kind of a scenario, one would experience three failures in 200 hours and the aggregrate MTBF would be 66.66 hours (200 divided by three).

If on the other hand, when the first part failed, maintenance was accomplished so that the other two parts were restored to zero hour also, then the next failure would occur about 100 hours from that point (the MTBF of part one). Under this scenario, part one would fail approximately every 100 hours and the other parts would be restored at the same time so that the aggregrate MTBF would never exceed approximately 100 operating hours.

#### Categories of Parts

All repairable parts have been placed in one of three categories. Every part in each category is treated as though it has the same MTBF, the same cost to repair, and the same cost to replace. Category L consists of all the parts that have a low MTBF. These parts are also the least

expensive to repair and replace. Category H consists of all the parts that have a high MTBF. These parts are also the most expensive to repair and replace. Category M consists of those parts whose MTBF, cost to repair, and cost to replace are between the two extremes.

#### Scheduled Maintenance Actions

Maintenance actions are scheduled at fixed intervals of operating hours. The interval of time between one scheduled maintenance action and the next one is the scheduled maintenance interval (SMI). The total number of scheduled maintenance actions per year is a function of total operating hours (annual flying hours) and SMI:

TSMA = AFH/SMI(1)

Where

Description & Bassission

TSMA	=	the total number of scheduled maintenance actions per year
AFH	=	total number of flying hours per engine
SMI	=	scheduled maintenance interval

For example, if the annual flying hours per engine equal 10,000 hours and there is maintenance action scheduled every 900 hours (SMI = 900), then the total number of scheduled maintenance actions would be a little over eleven as shown below:

 $TSMA = AFH/SMI = 10,000/900 \cong 11$ 

## The Probability of Failure

"P" is designated as the probability of a failure before a scheduled maintenance action (SMA). This probability is a function of MTBF and SMI. Theoretically, if one kept reducing SMI, that is if one scheduled maintenance at shorter and shorter intervals, one could almost guarantee no failure. The time between failure (TBF) is assumed to be exponentially distributed. This assumption stems from the fact that the number of failures in a given time interval follows a Poisson distribution. TBF, should then follow an exponential distribution. Therefore, in order to calculate the probability of a failure before a scheduled maintenance action, one must calculate the shaded area in Figure 3.1 presented below.



MTBF

SMI

Figure 3.1. An Exponential Distribution Whose Mean Is MTBF

Figure 3.1 represents an exponential distribution whose mean is MTBF. The shaded area represents the probability of a failure between zero hour and the SMI. The shaded area can be calculated by the following formula (15:199):

$$P = \int_{0}^{SMI} \lambda e^{-\lambda t} dt$$

Where

- P = the probability of a failure before a SMA
   (between zero hour and SMI)
- $\lambda$  = the reciprocal of MTBF = 1/MTBF
- e = the exponential constant, 2.718281828.....
- t = engine operating time in hours

Taking the integral of this formula from zero time to SMI should determine the probability of failure before SMI.

$$\int_{0}^{SMI} \lambda e^{-\lambda t} dt = 1 - e^{-\lambda SMI}$$

Since  $\lambda$  is = 1/MTBF, the Eq above transforms to

1 - e<sup>-SMI/MTBF</sup>

therefore,

$$P = 1 - e^{-SMI/MTBF}$$
(2)

For example, if MTBF equaled 900 hours and SMI was equal to 600 hours, the probability of a failure before a scheduled maintenance action would be:

$$P = 1 - e^{-600/900}$$

P = 0.4865

Following this procedure, one can determine the probability of a failure before a scheduled maintenance action. The probability of failure of a category L part before a SMA can be represented as:

$$PL = 1 - e^{-SMI/MTBFL}$$
(3)

where PL is the probability of failure of a category L part before a SMA and MTBFL is the MTBF of category L parts. The probably of failure associated with the other two categories can be similarly calculated.

$$PM = 1 - e^{-SMI/MTBFM}$$
(4)

and

$$PH = 1 - e^{-SMI/MTBFH}$$
(5)

Where PM and PH are the probabilities of failure before a SMA associated with categories M and H, respectively. MTBFM and MTBFH are the respective mean time between failures.

### Unscheduled Maintenance Actions

Each failure necessitates a maintenance action. The number of these maintenance actions can be estimated since the probabilities of failures are known. For example, if the probability of a failure before a SMA is 0.2 and there are 10 scheduled maintenance actions (TSMA) for the year, one could speculate that there will be two failures (10 x 0.2) during that year and therefore, two unscheduled maintenance actions. The number of unscheduled maintenance actions associated with each category are calculated below:

TUMAL	Ξ	PL	х	TSMA	(6	)	
					•		

$$TUMAM = PM \times TSMA$$
(7)

 $TUMAH = PH \times TSMA$ (8)

where

TUMAL	=	Total number of per year caused	unscheduled by failures	maintenance of category	actions L parts
TUMAM	=	Total number of per year caused	unscheduled by failures	maintenance of category	actions M parts
TUMAH	=	Total number of per year caused	unscheduled by failures	maintenance of category	actions H parts

The total number of unscheduled maintenance actions during the year then is simply the sum of these three.

$$TUMA = TUMAL + TUMAM + TUMAH$$
(9)

Where,

TUMA = the total number of unscheduled maintenance actions per year

Next, the total number of maintenance actions, scheduled and unscheduled, can be calculated:

NMA = TSMA + TUMA(10)

#### Where

NMA = total number of maintenance actions per year; it is simply the sum of the number of scheduled maintenance actions per year (TSMA) and the number of unscheduled maintenance (TUMA) actions per year

# 1. Costs to Perform Maintenance Directly on the Engine

As stated in the beginning of this chapter, this category of costs is further divided into: (1) labor costs associated with maintenance actions, and (2) cost of fuel to do engine trims and checks.

la. Labor Costs Associated with Maintenance Actions (TMALC)

 $TMALC = [(MHMA \times NMA) + (TSMA \times MHSMA) + (TUMA \times MHUMA)] \times CMH$  (11)

#### Where

MHMA = Manhours to do those maintenance activities that are common to both scheduled and unscheduled maintenance actions MHMA = MHRE + MHIE + MHTE + MHTB

- MHRE = Manhours needed to remove an engine, this includes transportation to the repair facility
- MHIE = Manhours needed to install an engine, this includes transportation back to the aircraft
- MHTE = Manhours needed to trim an engine
- MHTB = Manhours needed to do test the engine
- NMA = annual number of maintenance actions
- TSMA = annual number of scheduled maintenance actions
- TUMA = annual number of unscheduled maintenance actions
- MHSMA = Average number of manhours needed to perform "hands on" maintenance for a scheduled maintenance action
- MHUMA = Average number of manhours needed to perform "hands on" maintenance for an unscheduled maintenance action
- CMH = Average cost per manhour for personnel directly involved in maintenance/repair activity of jet engines; this cost represents not just an hourly wage rate but also an allocated overhead cost

Each maintenance action, whether it be scheduled or unscheduled, involves some common maintenance activities. This is represented by the term MHMA which has four components as described. However, there is a difference between scheduled and unscheduled maintenance actions when it comes to actual "hands on" maintenance. This is because while scheduled maintenance is routine and standard procedures are followed, each unscheduled maintenance is in

response to a problem or failure of some kind and would normally require a different kind of maintenance attention.

Eq 11 takes the total annual number of maintenance actions, scheduled and unscheduled, and multiplies it by the manhours required to do the common maintenance activities (MHMA). Further, the total number of scheduled maintenance actions is multiplied by the manhours it takes to perform "hands on" maintenance for every scheduled maintenance action (MHSMA). Similarly, the total annual number of unscheduled maintenance actions is multiplied by the number of manhours it takes to perform "hands on" maintenance for each unscheduled maintenance action. The sum of these three products represents the total annual manhours associated with maintenance. Multiplying this sum by the average cost of manhour (CMH) yields the total annual maintenance

1b. Cost of Fuel to Do Engine Trims and Checks The following equation calculates the annual cost of fuel to trim a jet engine and also to test it after it has received maintenance action:

COSTFU = [NMA x (FUELTP + FUELTC)] x FUEL (12)

Where

COSTFU = the annual cost of fuel to trim a jet engine and also to test it after it has received maintenance action

- FUELTP = average number of gallons of fuel required to trim the engine while removed from the aircraft
- FUELTC = average number of gallons of fuel required to test the engine after repair
- FUEL = cost of fuel per gallon

Each maintenance action, scheduled or unscheduled, takes the same amount of fuel to trim and test an engine. This amount is represented by the expression "(FUELTP + FUELTC)." Multiplying this number by the annual number of maintenance actions (NMA) yields the total annual volume of fuel used to trim and test an engine. Multiplying the volume of fuel by the cost of fuel fields the annual cost of fuel (COSTFU).

## 2. Cost of Repairs

This category of costs is further broken down into two parts: (1) Repair cost at base level, and (2) repair cost at depot level.

#### 2a. Base Repair Total Cost (BRTC)

Base repair total cost represents the annual base level repair cost of parts removed from one engine. Eqs 13, 14, and 15 calculate this cost. Eq 13 calculates the base level repair costs stemming from scheduled maintenance actions; Eq 14 calculates base level repair costs arising from unscheduled maintenance actions and Eq 15 simply sums these two costs to come up with the total annual base repair cost.

### 2a.1. <u>Base Repair Cost Due To Scheduled</u> Maintenance Action (BRTCS)

BRTCS = TSMA x [(QPESL x RTSL x BURCL) + (QPESM x RTSM x BURCM) + (QPESH x RTSH x BURCH)] (13)

#### where

- BRTCS = Annual base repair cost due to scheduled maintenance actions
- TSMA = Annual number of scheduled maintenance actions
- QPESL = Average number of category L parts removed for repair during a scheduled maintenance action
- QPESM = Average number of category M parts removed for repair during a scheduled maintenance action
- QPESH = Average number of category H parts removed for repair during a scheduled maintenance action
- RTSL = That percent of parts removed from category L
  that is repaired at base level

- BURCL = Average base unit repair cost of a category L part
- BURCM = Average base unit repair cost of a category M part
- BURCH = Average base unit repair cost of a category H part

The unit repair cost of any category of parts reflects the labor cost as well as an allocated overhead cost. The term "(QPESL x RTSL x BURCL)" represents the average cost of repair, per each scheduled maintenance action, of parts from category L. Likewise, "(QPESM x RTSM x BURCM) and (QPESH x RTSH x BURCH)" are identical formulations which refer to average costs of repair, per scheduled maintenance action, of parts from categories M and H, respectively. The sum of these three elements of the equation,

"[(QPESL x RTSL x BURCL) + (QPESM x RTSM x BURCM) + (QPESH x RTSH x BURCH)]"

represents total base repair cost per scheduled maintenance action. Multiplying this quantity by the total number of scheduled maintenance actions per year (TSMA) yields the total annual base level repair cost due to scheduled maintenance actions (BRTCS).

# 2a.2. <u>Base Repair Total Cost due to Unscheduled</u> <u>Maintenance (BRTCU)</u>

Eq 14 calculates the annual base level repair cost due to unscheduled maintenance actions:

 $BRTCU = \{TUMAL x [(QPEUL x RTSL x BURCL)\}$ 

+ (QPESM x RTSM BURCM)

- + (QPESH x RTSH x BURCH)]}
- + (TUMAM x [(QPESL x RTSL x BURCL)
- + (QPEUM x RTSM x BURCM)

- + (QPESH x RTSH x BURCH)]}
- + {TUMAH x [(QPESL x RTSL x BURCL)
- + (QPESM x RTSM x BURCM)
- +  $(QPEUH \times RTSH \times BURCH)$  (14)

where,

- BRTCU = Annual base repair cost of unscheduled maintenance actions
- TUMAL = Annual number of unscheduled maintenance actions caused by problems with category L parts
- QPEUL = Average number of category L parts removed for repair during an unscheduled maintenance action which was caused by category L part(s)
- QPEUM = Average number of category M parts removed for repair during an unscheduled maintenance action which was caused by category M part(s)
- QPEUH = Average number of category H parts removed for repair during an unscheduled maintenance action which was caused by category H part(s)
- TUMAM = Annual number of unscheduled maintenance actions caused by problems with category M parts
- TUMAH = Annual number of unscheduled maintenance actions caused by problems with category H parts

In comparison to Eq 13, Eq 14 is much longer. This is so because unscheduled maintenance actions require removal of a different number of parts from that category that caused the unscheduled maintenance. For example, if unscheduled maintenance had to be accomplished due to a problem with a category L part, the number of category L parts removed will be different than if it were a scheduled maintenance (QPEUL as opposed to QPESL). The other two categories (in this case, categories M and H), will be treated as if it were a scheduled maintenance action. So, during a category L related unscheduled maintenance, QPESM and QPESH are the respective numbers of parts from categories M and H respectively, the same amount that is removed for scheduled maintenance actions. The underlined part of Eq 14 (presented again below) reflects this.

BRTCU = [TUMAL x [(QPEUL x RTSL x BURCL)]

- + (QPESM x RTSM x BURCM)
- + (QPESH x RTSH x BURCH)]]
- + [TUMAM x [(QPESL x RTSL x BURCL)
- + (QPEUM x RTSM x BURCM)
- + (QPESH x RTSH x BUTCT)]]
- + [TUMAH x [(QPESL x RTSL x BURCL)
- + (QPESM x RTSM x BURCM)

+  $(QPEUH \times RTSH \times BURCH)]$  (14)

The other two elements of Eq 14 follow the same logic with categories M and H related unscheduled maintenance actions.

The sum of base repair costs due to scheduled maintenance actions plus base repair costs due to unscheduled maintenance actions equal Eq 15. BRTC = Annual base level repair cost due to scheduled maintenance actions + annual base level repair costs due to unscheduled maintenance actions

BRTC = BRTCS + BRTCU(15)

## 2b. Annual Repair Cost at Depot Level (DRTC)

Depot repair costs are estimated in approximately the same manner as the base repair costs. Following is the formula for depot repair total costs arising out of scheduled maintenance actions (DRTCS):

# 2b.1. <u>Depot Level Repair Cost Due to Scheduled</u> Maintenance Actions (DRTCS)

DRTCS = TSMA x {[QPESL x NRTSL x (1-DCONDL) x DURCL] + [QPESM x NRTSM x (1-DCONDM) x DURCM] + [QPESH x NRTSH x (1-DCONDH) x DURCH]} (16)

Where

DRTCS =	Annual depot repair cost of scheduled maintenance actions
NRTSL =	That percent of "removed category L parts" that is sent to depot for repair
NRTSM =	That percent of "removed category M parts" that is sent to depot for repair
NRTSH =	That percent of "removed category H parts" that is sent to depot for repair
DCONDL =	That percent of NRTSL that is condemned at depot level
DCONDM =	That percent of NRTSM that is condemned at depot level
DCONDH =	That percent of NRTSH that is condemned at depot level

DURCL = Depot unit repair cost of a category L part
DURCM = Depot unit repair cost of a category M part
DURCH = Depot unit repair cost of a category H part

Once again, unit repair cost reflects labor cost and allocated overhead cost. Eq 16 is almost identical to Eq 13. Putting them together will illustrate this:

In Eq 13, the number of parts removed for repair (QPESL, QPESM, QPESH), were multiplied by the percent that are repaired at base level (RTSL, RTSM, RTSH). Eq 16 replaces the base repair rates in Eq 13 by the depot repair rates. The percent of parts repaired at the depot level is calculated by terms such as NRTSL x (1-DCONDL). This is because NRTSL represents that percent of QPESL that is sent to the depot for repair. However, a ceratin percent of NRTSL, on the average, is condemned at the depot (DCONDL). Therefore, the effective repair rate at the depot is "NRTSL x (1-DCONDL)" for category L parts. For category M parts, the equivalent expression would be "NRTSM x (1-DCONDM)."

2b.2. <u>Depot Level Repair Cost Due To Unscheduled</u> Maintenance Actions (DRTCU)

DRTCU = {TUMAL x [QPEUL x NRTSL x (1-DCONDL) x DURCL] + [QPESM x NRTSM x (1-DCONDM) x DURCM] + [QPESH x NRTSH x (1-DCONDH) x DURCH]} + {TUMAM x [QPESL x NRTSL x (1-DCONDL) x DURCL] + [QPEUM x NRTSM x (1-DCONDM) x DURCM] + [QPESH x NRTSH x (1-DCONDH) x DURCH]} + {TUMAH x [QPESL x NRTSL x (1-DCONDL) x DURCL] + [QPESM x NRTSM x (1-DCONDM) x DURCM] + [QPEUH x NRTSH x (1-DCONDM) x DURCM] + [QPEUH x NRTSH x (1-DCONDH) x DURCM] + [QPEUH x NRTSH x (1-DCONDH) x DURCM]

All the variables in this equation have been defined earlier. Eq 17 is simply an extension of Eq 16. Annual number of scheduled maintenance actions (TSMA) is now replaced by the three different kinds of unscheduled maintenance actions: TUMAL, TUMAM AND TUMAH (total number of unscheduled maintenance actions per year caused by problems with parts from categories L, M and H, respectively). Eq 17 is very similar to Eq 14 which calculated base repair total cost arising from unscheduled maintenance actions. Once again, since one is now dealing with depot, terms like RTSL and BURCL are replaced with their depot counterparts like NRTSL, DCONDL, DURCL and the like.

### Depot Repair Total Cost (DRTC)

$$DRTC = DRTCS + DRTCU$$
(18)

## 3. Cost of Spares

Since this model is only concerned with repair and maintenance costs, the pipeline spare costs are not included. Spares costs are divided into three categories:

- 3A. Cost of expendables associated with maintenance actions
- 3B. Cost of expendables associated with repair actions
- 3C. Cost of replacement of condemned parts

# 3A. Cost of Expendables Associated with Maintenance Actions (EXPM):

With every maintenance action, there is an expense associated with expendables. Expendables are items whose repair costs exceed their procurement cost; in other words it is cheaper to repaice them than to fix them. Normally these items are relatively inexpensive; however, cumulatively they may represent a significant cost. The next three equations calculate the cost of expendables. Once again, in keeping with the presentation format of the model, the cost of expendables is categorized by scheduled and unscheduled maintenance actions.

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3a.1. Cost of Expendables Associated with Scheduled Maintenance Actions (EXPMS):

Eq 19 calculates the cost of expendables associated with scheduled maintenance actions

EXPMS = TSMA x (EXPSL + EXPSM + EXPSH ) (19) Where

- EXPSL = the average cost of expendables associated with category L parts with each scheduled maintenance action
- EXPSM = the average cost of expendables associated with category M parts with each scheduled maintenance action

The sum of EXPSL, EXPSM and EXPSH yields the total cost of expendables associated with one scheduled maintenance action. Multiplying that number by the total number of scheduled maintenance actions per year (TSMA) gives one the total annual cost of expendables associated with scheduled maintenance actions.

3a.2. Cost of Expendables Associated with Unscheduled Maintenance Actions (EXPMU)

EXPMU = [TUMAL x (EXPUL + EXPSM + EXPSH)] + [TUMAM x (EXPSL + EXPUM + EXPSH)] + [TUMAH x (EXPSL + EXPSM + EXPUH)] (20)

Where

. . .

- EXPUL = the average cost of expendables that can be attributed to category L during each unscheduled maintenance action which is caused by a problem with category L parts
- EXPUM = the average cost of expendables that can be attributed to category M during each unscheduled maintenance action which is caused by a problem with category M parts

In keeping with the idea that the maintenance on parts of the category which is causing the unscheduled maintenance, is different than the maintenance on the other two sections which are treated as if it were a scheduled maintenance action, the cost of expendables also differs only for that category during an unscheduled maintenance action. For example, if the unscheduled maintenance is being caused by problems with category L parts section, then the maintenance action will generate a different cost of expedables associated with category L (EXPUL and not EXPSL as would be the case for a scheduled maintenance action). The other two sections in this kind of an unscheduled maintenance action (one caused by a category L part) would generate EXPSM and EXPSH respectively just as they would in a scheduled maintenance action. As a result, the total cost of expendables associated with a category L related unscheduled maintenance action would be equal to the sum of EXPUL, EXPSM and EXPSH. Multiplying this sum by the total number of such unscheduled

maintenance actions (TUMAL) would yield the total annual cost of expendables associated with unscheduled maintenance actions caused by a problem with category L parts. This can be represented as:

TUMAL x (EXPUL + EXPSM + EXPSH)

This notation is the underlined part of Eq 20 which is presented again below:

The other two elements are created by unscheduled maintenance actions caused by problems with category M and category H respectively. The final output of Eq 20 is the total annual cost of expendables associated with unscheduled maintenance actions (EXPMU). Eq 19 had earlier yielded the total annual cost of expendables associated with scheduled maintenance actions (EXPMS). The sum of the two simply aggregates the total annual cost of expendables associated with maintenance actions (EXPM):

$$EXPM = EXPMS + EXPMU$$
(21)

# 3B. Cost of Expendables Associated with Repair Actions (TEXPR)

Like maintenance actions, repair actions also use up expendables. The total cost of expendables associated with repair actions (TEXPR) can be broken down in four parts: (1) at base level due to scheduled maintenance actions, (2) at depot level due to scheduled maintenance actions, (3) at base level due to unscheduled maintenance actions, and (4) at depot level due to unscheduled maintenance actions.

3b.1. Total Annual Cost of Expendables Associated with Repair Actions at Base Level Due to Scheduled Maintenace Actions (TEXPRBS)

TEXPRBS = TSMA x [(QPESL x RTSL x EXPRBL) + (QPESM x RTSM x EXPRBM) + (QPESH x RTSH x EXPRBH)] (22)

where the new terms are:

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- EXPRBL = the average cost of expendables associated with each base level repair action on a category L part
- EXPRBM = the average cost of expendables associated with each base level repair action on a category part
- EXPRBH = the average cost of expendables associated with each base level repair action on a category H part

During a scheduled maintenance action, the average number of parts removed for repair from the three categories are QPESL, QPESM, QPESH, respectively. QPESL for example is

the average number of parts removed for repair from category Multiplying this number by the average percent of these L. parts that is repaired at base level (RTSL), will yield the number of category L parts that on the average are repaired at base level with every scheduled maintenance action. Now, if "EXPRBL" is the cost of expendables associated with each repair action involving a category L part, then the cost of expendables associated with repair actions involving category L parts during a scheduled maintenance action at base level would be "QPESL x RTSL x EXPRBL." This is the underlined element in Eq 22. The other two elements of Eq 22 estimate the same cost for the other two categories. The sum of the three elements is multiplied by TSMA to calculate annual costs.

# 3b.2. Annual Depot Level Cost of Expendables Associated with Repair Actions Generated Due to Scheduled Maintenance Actions (TEXPRDS)

Eq 22 calculated the cost of expendables associated with scheduled maintenance actions at base level (TEXPRBS). Eq 23 calculates the same for depot level:

TEXPRDS = TSMA x [(QPESL x NRTSL x (1-DCONDL) x EXPRDL) + (QPESM x NRTSM x (1-DCONDM) x EXPRDM) + (QPESH x NRTSH x (1-DCONDH) x EXPRDH)] (23)

Where the new terms are:

- EXPRDL = the average cost of expendables associated with a depot level repair action on a category L part
- EXPRDM = the average cost of expendables associated with a depot level repair action on a category M part
- EXPRDH = the average cost of expendables associated with a depot level repair action on a category H part

The formulation is very similar to Eq 22; depot related terms have been substituted for base related terms. For example if QPESM is the average number of parts removed for repair from category M during a scheduled maintenance action and the number of parts repaired at base level in this kind of a scenario is QPESM x RTSM, then the depot level counterpart of this expression would be "QPESM x NRTSM x (1-DCONDM)."

3b.3. Annual Base Level Cost of Expendables Associated with Repair Actions Generated Due to Unscheduled Maintenance Actions (TEXPRBU)

TEXPRBU = {TUMAL x [(QPEUL x RTSL x EXPRBL) + (QPESM x RTSM x EXPRBM) + (QPESH x RTSM x EXPRBH)]} + (TUMAM x [(QPESL x RTSL x EXPRBL) + (QPEUM x RTSM x EXPRBM) + (QPEUH x RTSH x EXPRBM)] + (TUMAH x [(QPESL x RTSL x EXPRBL) + (QPESM x RTSM x EXPRBM) + (QPEUH x RTSM x EXPRBM) + (QPEUH x RTSH x EXPRBM)]} (24) All terms in Eq 24 have been defined previously. An unscheduled maintenance action caused by a problem with category L parts will generate the removal of parts that are QPEUL, QPESM and QPESH (had it been a scheduled maintenance action, the terms would have been QPESL, QPESM and QPESH). Multiplied by their respective base level repair rates (RTSL, RTSM and RTSH), and the respective costs of expendables (EXPRBL, EXPRBM and EXPRBH) yields a term like:

"(QPEUL x RTSL x EXPRBL) + (QPESM x RTSM x EXPRBM) + (QPESH x RTSH x EXPRBH)"

This term represents the cost of expendables associated with repair actions at base level due to one unscheduled maintenance action caused by problems with category L parts. Multiplying this number by the total annual number of unscheduled maintenance actions caused by problems with category L parts yields the total cost of expendables per year associated with repair actions that are generated by category L related unscheduled maintenance actions.

The remainder of Eq 24 deals with this kind of cost that stem from the other two causes of unscheduled maintenance actions, namely those caused by problems with category M parts and those caused by problems with category H parts.

## 3b.4. Annual Depot Level Cost of Expendables Associated with Repair Actions Generated by Unscheduled Maintenance Actions (TEXPRDU)

TEXPRDU = {TUMAL x [(QPEUL x NRTSL x (1-DCONDL) x EXPRDL) + (QPESM x NRTSM x (1-DCONDM) x EXPRDM) + (QPESH x NRTSH x (1-DCONDH) x EXPRBH)]} + {TUMAM x [(QPESL x NRTSL x (1-DCONDL) x EXPRDL) + (QPEUM x NRTSM x (1-DCONDM) x EXPRDM) + (QPESH x NRTSH x (1-DCONDH) x EXPRDM) + {TUMAH x [(QPESL x NRTSL x (1-DCONDL) x EXPRDL) + (QPESM x NRTSM x (1-DCONDM) x EXPRDM) + (QPESM x NRTSM x (1-DCONDM) x EXPRDM) + (QPEUH x NRTSH x (1-DCONDH) x EXPRDM) (25)

Eq 25 is identical to to Eq 24 with one exception. Terms standing for repair rates at base level like RTSL, RTSM and RTSH in Eq 24 have been replaced by their depot counterparts like NRTSL x (1-DCONDL), NRTSM x (1-DCONDM) and NRTSH x (1-DCONDH).

Eqs 22, 23, 24 and 25 respectively calculated the annual costs of expendables associated with repair actions: (1) at base level due to scheduled maintenance actions, (2) at depot level due to scheduled maintenance actions, (3) at base level due to unscheduled maintenance actions, and (4) at depot level due to unscheduled maintenance actions. Adding these four costs gives the annual cost of expendables associated with repair actions (TEXPR):

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TEXPR = TEXPRBS + TEXPRDS + TEXPRBU + TEXPRDU (26)

3C. Cost of Replacement of Condemned Parts

Eqs 27 and 28 calculate the cost of replacement of condemned parts. The term "replacement cost of a part" is synonymous with procurement cost. Eq 27 calculates the cost of replacement of parts condemned during of scheduled maintenance actions.

3c.l. <u>Replacement Cost of Parts Condemned During</u> Scheduled Maintenance Actions (CONDS)

CONDS = TSMA x {[QPESL x (BCONDL + (NRTSL x DCONDL) x ACONDL]

+ [QPESM x (BCONDM + (NRTSM x DCONDM) x ACONDM] + [QPESH x (BCONDH + (NRTSH x DCONDH) x ACONDH]}

(27)

Where the new terms are:

- ACONDL = Average cost of procurement to replace a condemned category L part
- ACONDM = Average cost of procurement to replace a condemned category M part
- ACONDH = Average cost of procurement to replace a condemned category H part

Once a part is removed from the engine for repair, only one of three things can happen to it at the base level. It can: (1) be repaired at base level, (2) condemned at base level, or (3) sent to the depot level. At the depot it can either be repaired or condemned. The following example with hypothetical values is provided:

- QPESL = Average number of category L parts removed for repair during a scheduled maintenance action = 100
- RTSL = Average percent of QPESL that is repaired at base level = 60%
- NRTSL = Average percent of QPESL that is sent to the depot level for repair = 30%
- DCONDL = Average percent of NRTSL that is condemned at depot level = 20%

Out of the 100 parts removed for repair, if 60 percent are repaired at base and 30 percent are sent to depot, then 10 percent must be condemned at base level (1 - RTSL - NRTSL= 1 - 0.6 - 0.3). This 10 percent is the base condemnation rate for category L parts. The base condemnation rate of parts from category L is termed BCONDL. BCONDM and BCONDH represent the same concept for categories M and H. The following relationships apply:

BCONDL = 1 - RTSL - NRTSLBCONDM = 1 - RTSM - NRTSMBCONDH = 1 - RTSH - NRTSH

The total condemnation rate (base and depot) of category L parts can be represented by the term "BCONDL + (NRTSL x DCONDL)."

Using the numbers in this example, this rate would be:

 $BCONDL + (NRTSL \times DCONDL) = 0.1 + (0.3 \times 0.2)$ = 0.1 + 0.06= 0.16

According to this example then, on the average, 16 percent of category L parts that were removed for repair during a scheduled maintenance action, are eventually condemned. Multiplying the total condemnation rate (BCONDL + (NRTSL x DCONDL) by the number of category L parts removed for repair during a scheduled maintenance action, yields the total number of category L parts that are condemned during one scheduled maintenance action. Multiplying this number by the total number of scheduled maintenance actions per year gives the total annual number of condemned parts from category L. And then multiplying this number by the average cost of replacing a condemned category L part, will produce the annual cost of replacing the condemned parts of the category L. Similar formulations would apply to the other two categories. This is the logic behind Eq 27 which calculated the annual procurement cost of replacing condemned parts that were removed due to scheduled maintenance actions.

# 3c.2. <u>Replacement Cost of Parts Condemned During</u> <u>Unscheduled Maintenance Action</u>

Eq 28, which is presented below, calculates the cost of procurement to replace items that were condemned during unscheduled maintenance actions.

CONDU =

[TUMAL x QPEUL x [BCONDL + (NRTSL x DCONDL)] x ACONDL] + [TUMAL x QPESM x [BCONDM + (NRTSM x DCONDM)] x ACONDM] + [TUMAL x QPESH x [BCONDH + (NRTSH x DCONDH)] x ACONDH] + [TUMAM x QPESL x [BCONDL + (NRTSL x DCONDL)] x ACONDL] + [TUMAM x QPEUM x [BCONDM + (NRTSM x DCONDM)] x ACONDM] + [TUMAM x QPESH x [BCONDH + (NRTSH x DCONDM)] x ACONDM] + [TUMAH x QPESH x [BCONDL + (NRTSL x DCONDH)] x ACONDH] + [TUMAH x QPESL x [BCONDL + (NRTSL x DCONDL)] x ACONDH] + [TUMAH x QPESM x [BCONDM + (NRTSM x DCONDM)] x ACONDL] + [TUMAH x QPESM x [BCONDM + (NRTSM x DCONDM)] x ACONDM] + [TUMAH x QPESM x [BCONDM + (NRTSM x DCONDM)] x ACONDM] + [TUMAH x QPESM x [BCONDM + (NRTSM x DCONDM)] x ACONDM]

Where the only new variable is:

## CONDU = the total annual procurement cost of replacing condemned items that were removed from the engine for repair during unscheduled maintenance actions

Eq 28 is rather long because as the reader is familiar by now, unscheduled maintenance actions make it difficult to lump all three categories of the parts together because of the different treatment that the problem category receives in terms of the number of parts removed.

The sum of Eqs 27 and 28 provides the total annual cost of procurement to replace condemned items. This cost, termed TCONST, is the sum of CONDS (Eq 27) and CONDU (Eq 28):

TCONST = CONDS + CONDU(29)

## Total Cost According to Model-A

It was mentioned at the beginning of this chapter that the costs calculated by Model-A fell in the following three categories:

- 1. Costs To Perform Maintenance directly on the Engine
  - 1A. Labor costs associated with maintenance actions (TMALC, Eq 11)
  - 13. Cost of fuel to do engine trims and checks (COSTFU, Eq 12)
- 2. Cost of Repairs

- 2A. Annual repair cost at base level (BRTC, Eq 15)
- 2B. Repair cost at depot level (DRTC, Eq 18)
- 3. Cost of Spares
  - 3A. Cost of expendables associated with maintenance of the engine (EXPM, Eq 21)
  - 3B. Cost of expendables associated with repair actions (TEXPR, Eq. 26)
  - 3C. Cost of replacing condemned parts (TCONST, Eq 29)

The sum of these costs yields the total annual recurring costs associated with the repair and maintenance of a jet engine. Eq 30 then is the final equation of this model and it calculates the total cost (TOTCOST):

TOTCOST = TMALC + COSTFU + BRTC + DRTC + EXPM+ TEXPR + TCONST (30)

# Summary of Chapter III

Chapter III has provided a detailed description of Model-A. The major categories of cost were specified. These categories were then divided into subcategories (for example: base level versus depot level), which were further broken down into lower levels of aggregation. This model uses 51 input variables and 30 equations. Most existing O&S cost models, as was mentioned in Chapter I, are similar to Model-A. They are detailed and require data for a large number of variables. Appendix B is a listing of the computer program that calculates costs according to Model-A.

## IV. Methodology

Chapter III described Model-A which is an accounting type of cost estimating model. Model-A uses 51 input variables and 30 equations. Many existing O&S cost models are significantly larger. As stated earlier, the purpose of this research effort is to develop a CER that is capable of generating nearly the same cost estimates as Model-A.

The methodology employed to do this, involved collecting data which was to be obtained in the form of a range of values that each variable would fall within. This range would then be used as a basis for a simulation exercise that would generate 300 observations. Using the first 250 observations as the data base, multivariate linear regression analysis would be performed to develop a new cost estimating model; Model-S. The remaining 250 observations would be used to test the validity of Model-S.

## Data Problem

This thesis effort ran into problems with the collection of data. The researcher was able to acquire the values, in the form of a range, of only a small minority of variables in Model-A. It was subsequently decided that since the emphasis of the research was on demonstration of a methodology, the research could continue by inputting the range values on a judgement basis. Each variable was
assigned three values: a lower bound, a most likely estimate and an upper bound.

### Simulation

If one were to take, for instance, the most likely values of all 51 independent variables in this model, then that would account for one observation, which will yield a total cost figure if run through Model-A. In order to be able to perform linear regression, several observations are required. This was obtained through the use of simulation. In order to simulate, it was necessary to determine a distribution that would be most appropriate. This distribution was determined to be the triangular distribution. Often, when a minimum, maximum, and a most likely value can be ascertained, a triangular distribution can be used because these values are the only parameters needed to define a triangular distribution (2:134; 21:30).

A SAS (Statistical Analysis System) function called RANTRI, which is a random number function for a triangular distribution can be used to generate any number of observations. This function uses an argument to select an initial seed value, which initializes the random number stream (23:236-238). This method, generates all the numbers from the same stream. Even though the chances of thus inducing any correlation among the variables is slim, a more robust method is to use a different seed for each variable. This was done by using a "call subroutine" within the RANTRI

function. In generating these observations, it was assumed that all variables were independent of each other. In fact the idea of using a more robust method of random number generation was to preserve this independence. By running the simulated sets of data through Model-A, an equal number of total cost (TOTCOST) figures were generated. As a result, a data base was created which would be used to develop a new cost model, Model-S.

### Development of Model-S

Identification: The first step in developing any cost model involves an identification of cost drivers. Cost drivers are those variables which affect cost in a significant way. A change in the value of a cost driver causes a noticeable change in cost. For example, the frequency of maintenance actions is a major determinant of maintenance costs. Frequency of maintenance is often driven by how often parts fail. Mean time between failure (MTBF), therefore would logically be a cost driver when trying to estimate maintenance costs.

Most of the variables in Model-A are very specific. It was felt that while they should be retained as potential candidates for cost drivers, some aggregrate variables needed to be created. One of the objectives of developing a cost estimating relationship (CER) is to facilitate easier estimation of the variables that are specified in the CER. Aggregate variables would be much easier to estimate than

variables that are as specific as most of the 51 original Secondly, if one wanted to affect or variables in Model-A. control costs by certain maintenance polcy decisions, it would be a lot easier; for example, to try to set an aggregate base repair rate than it would be to specify what percent of parts should be sent to depot of those category L parts that were removed for repair during an unscheduled maintenance action. This kind of variable is usually hard to estimate even for systems that are in operation much less for one that is in the beginning stages of acquisition. Descriptions of the new variables are provided here. The listing of the computer program in Appendix B provides the formulas for these variables. The following aggregrate variables were created:

- MCOST = the average cost of doing those maintenance activities that are common to both scheduled and unscheduled maintenance actions
- EXAS = the average cost of expendables associated with a scheduled maintenance action
- EXAU = the average cost of expendables associated with an unscheduled maintenance action
- EXM = the average cost of expendables associated with a maintenance action
- TR = annual number of parts removed for repair
- TRR = average number of parts removed per maintenance action
- TRB = annual number of parts repaired at base
- TRD = annual number of parts repaired at depot

BRT	=	Base repair rate, i.e., what percent of parts removed for repair annually is repaired at base?
DRT	=	depot repair rate, i.e., what percent of parts removed for repair annually is repaired at depot?
BURC	=	average unit repair cost at base
DURC	=	average unit repair cost at depot
URC	3	average unit repair cost
EXPPR	=	average cost of expendables per repair action
СМН	=	Cost per manhour
CONDR	=	Condemnation cost per repair action
MTBF		the aggregate mean time between failure, a figure

categories of cost

Specification: The second step in developing a cost model involves what is known as specification. Specification refers to the nature of the relationship that an independent variable has with the dependent variable. In other words, how does the dependent variable change with a change in the independent variable? For example, the number of scheduled maintenance actions (TSMA) is a function of operational hours (flying hours) and the scheduled maintenance interval (SMI):

$$TSMA = AFH/SMI$$
(1)

where

AFH is the annual number of flying hours. Given that the number of operational hours stay the same, a decrease in

SMI would result in an increase in TSMA. Reducing SMI means that maintenance is performed more often which would result in higher maintenance costs assuming that by doing so, the reduction in failures is not large enough to offset the increase in cost. Everything else being constant, the smaller SMI gets, the larger the maintenance cost. Therefore, one would expect to see a negative or inverse relationship between SMI and cost.

Specification also deals with the issue of whether the relationship between a dependent variable and an independent variable is linear. It was assumed that all relationships are linear unless the statistics showed otherwise.

## Regression Analysis(19)

Model-S was developed using multivariate regression analysis techniques. For a thorough understanding of multivariate regression analysis, one should refer to one of many texts that are avaialable on the subject. A brief discussion of univariate linear regression is included here.

Regression analysis is a statistical tool that utilizes the relation between two or more quantitative variables so that one variable can be predicted from the other or others [31:23].

A basic regression model that is linear and has one independent variable can be expressed as:

 $Y_{i} = B_{0} + B_{1}X_{1} + E_{i}$  (31)

Where

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- $Y_i$  = the value of the dependent variable in the ith trial  $B_o$  and  $B_1$  = parameters or coefficients  $X_i$  = the value of the independent variable in the ith trial
- $E_i = a random error term with mean (expected value) = 0 and variance = <math>\sigma^2$

Since the expected value of the error term is zero, it follows that the expected value or the means of the response (dependent) variable for any given value of X is:

$$E(Y_{i}) = B_{0} + B_{1}X_{i}$$
 (32)

The least squares method of regression analysis, also known as the best fit approach, considers the difference between the observed value of the dependent variable  $(Y_i)$  and its expected value  $(B_0 + B_1 X_i)$  and estimates  $B_0$  and  $B_1$ by coming up with  $b_0$  and  $b_1$  in a way that minimizes the square of the deviations between the observed value of  $Y_i$ and its expected value over n observations. This criterion is denoted by Q in the following expression:

$$Q = \sum_{i=1}^{n} (Y_i - B_o - B_1 X_i)^2$$
(33)

The estimators  $b_0$  and  $b_1$  which minimize Q for any set of data are given by the following equations:

$$\sum Y_i = nb_o + b_1 \sum X_i$$
 (34)

$$\sum x_{i} Y_{i} = b_{o} \sum x_{i} + b_{1} \sum x_{i}^{2}$$
(35)

The equations above are called normal equations and  $b_0$  and  $b_1$  are called point estimators.  $b_0$  and  $b_1$  can be obtained as follows:

$$b_{1} = \sum (x_{i} - \overline{x}) (y_{i} - \overline{y}) / \sum (x_{i} - \overline{x})^{2}$$
(36)

$$b_{0} = \overline{Y} - b_{1}\overline{X}$$
(37)

where  $\overline{X}$  is the mean of the independent variable and  $\overline{Y}$  is the mean of the observed value of the dependent variable. The least square estimators,  $b_0$  and  $b_1$  are are unbiased and have minimum variance among all unbiased linear estimators. Given a set of observations then, the regression equation has the following format:

$$\hat{\mathbf{Y}} = \mathbf{b}_{0} + \mathbf{b}_{1} \mathbf{X}_{1}$$
(38)

where

 $\stackrel{\wedge}{Y}$  is the predicted value of the dependent variable.

Stepwise Multiple Regression: To develop Model-S, a SAS function called "Stepwise" was executed. Stepwise regression uses the least squares best fit criterion to estimate the coefficients of the independent variables in the model. This method adds variables one at a time to the model starting with the most statistically significant variable first. Other variables are systematically added so long as they are significant at a specified level of confidence (85% confidence level in this case). If the inclusion of a new variable to the model results in the reduction of statistical significance of another variable that was already in the model to below 85 percent, then the affected variable is excluded from the model.

The stepwise procedure systematically includes all the ariables that are significant to the level desired and stops when none of the variables outside the model are significant to the level of confidence selected and all the variables inside the model are. Stepwise regression is a good way to get started towards the selection of a model even though it does not gurantee that the best possible model will be selected. The selection of a model often involves numerous iterations of modeling cost as a function of different combinations of variables and then evaluating the properties associated with the various models.

#### Model Evaluation Criteria

Signs of Regression Coefficents: The first things to check in the evalauation process of a model are the signs of the coefficients associated with the independent variables (cost drivers). Are these signs depicting a logical relationship between cost and the cost drivers?

Standardized Regression Coefficients: Regression coefficients are a measure of the change in the mean response per unit change in the independent variable when all other indepenent variables are held constant. However, the magnitude of these coefficients is influenced by the units used to express the independent variables. Therefore, comparing regression coefficients to evaluate the relative "weights" (influence on cost) of the independent variables is akin to comparing apples and oranges. To evaluate the relative weights of the variables in Model-S, standardized regression coefficients were used. Also known as beta coefficients, these statistics facilitate the comparison of regression coefficients. A beta coefficient is unitless; it measures the change in the mean response of the dependent variable (in units of standard deviations of the dependent variable) given a one standard deviation change in the independent variable while all other independent variables are held constant. Standardized regression coefficient of an independent variable is derived by the following formula:

$$Betal = b_1 * (S_1/S_v)$$
(39)

Where

- b1 = the regression coefficient for independent
  variable 1
- S<sub>1</sub> = the standard deviation of variable 1

Sy = the standard deviation of the observed values of the dependent variable Y

The interpretation of regression coefficients, however, standardized or not, gets blurred in the presence of collinearity, i.e., when the independent variables are correlated among themselves.

<u>T-test</u>: A t-test is employed to determine whether an individual independent variable in the model is making a significant contribution to the overall equation. The null hypothesis here is that the regression coefficient of a particular variable is equal to zero. The t-statistic is calculated by dividing the coefficient of the variable by the standard error of the coefficient. If this value exceeds the tabular t-statistic at 80+ percent confidence, then it is reasonable to conclude that the variable is making a significant contribution to the overall equation.

An analysis of variance (ANOVA) (Table I) is presented below to facilitate the understanding of certain model evaluation criteria.

The total sum squares (SST) is the sum of the squared differences between the observed value  $(Y_i)$  and the predicted value when the prediction is based on the regression line (Y). SST and SSE, therefore, are both measures of prediction error. The regression sum of squares (SSR<sub>i</sub>) is the variation in Y explained by the regression line, and is also the difference between SST and SSE. It is a measure

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Analysis of Variance

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares
Regression	$SSR = (\hat{Y}_i - Y)^2$	p-1	MSR = SSR/p-1
Error	$SSE = (Y_i - \hat{Y}_i)^2$	n-p	MSE = SSE/n-p
Total	$SST = (Y_i - Y)^2$	n-1	

where

- $\hat{Y}_{i}$  = predicted value for the ith observation using the regression line
- $\overline{Y}$  = mean of the observed values
- Y<sub>i</sub> = observed of the dependent variable
- p = number of variables in the model including the integers
- n = number of observations in the data set

of the amount of reduction in the predition error obtained when the prediction is based on the regression line is opposed to  $\overline{Y}$ .

<u>F Ratio</u>: Dividing SSR and SSE by their respective degrees of freedom yields the mean square regression (MSR) and the mean square error (MSE), respectively. The F-ratio is calculated as follows:

 $F_{calc} = MSR/MSE$ (40)

The F-ratio can be evaluated to determine the overall statistical significance of the estimating relationship of the model. The null hypothesis here is that every regression coefficient in the model that is associated with an independent variable is equal to zero. The calculated F value is compared to a tabular value of F at a certain confidence level at p-l/n-p degrees of freedom where p is the number of parameters and n is the sample size. If the F-ratio in the ANOVA table ( $F_{calc}$ ) is greater than the tabular F-ratio at 90 percent level of confidence, then it would be reasonable to conclude that the overall relationship depicted by the model is statistically significant.

<u>Coefficient of Determination</u>: This statistic provides information about the strength of the relationship of the dependent variable with the independent variables. In order to calculate this, the total variation (SST) of the observed values from the expected or calculated values is partitioned into the sum-of-squares regression (SSR) and sum-of-squares error (SSE).  $R^2$  is known as the coefficient of determination and basically tells one how much of the total deviation (SST) is explained by the regression line.  $R^2$  can be expressed as follows:

$$R^2 = SSR/SST$$
(41)

The coefficient of determination,  $R^2$  is also known as the goodness of fit measure and all things being equal, a higher  $R^2$  is preferred.

Collinearity: The problem of collinearity occurs when an independent variable is nearly a linear combination of other independent variables in the model. The observations for the original 51 input variables in Model-A were independent because of the method used to generate the data. It was not expected that there would be any collinearity among them. A person's pairwise correlation index was obtained to confirm this. However, since new variables were created which were aggregation of the original variables, it was reasonable to expect that some collinearity might be introduced. Collinearity problems can cause unstable estimates and normally do inflate the variances of the variables involved. Therefore, collinearity diagnostics were used to determine the extent to which collinearity was affecting the model and to identify which variables were involved in collinear relationsh\_ps.

The TOL and COLLINOINT options in the SAS regression procedure provide collinearity diagnostics. TOL stands for tolerance value. When subtracted from one, tolerence yields a muliple  $R^2$  statistic. This statistic is a measure of how correlated a particular independent variable in the model is with other independent variables in the model. As

a criterion, tolerance values below 0.3 are signs of multicollinearity.

The collinoint option computes condition numbers. If all condition numbers equal one, there is no collinearity in the model. Increasing condition numbers indicate the degree of collinearity in the model. A condition number greater than 5 was considered to be high.

The condition number also computes the variance proportion of each regression coefficient. The sum of the variance proportions in each column equals 1. The presence of no more than one large variance proportion in any row indicates that there are no collinear relationships in the model. This will result in a low condition number. If on the other hand, there are more than one high variance proportion numbers in any row, there may be a problem with collinearity if this situation is accompanied by a high condition number in the same row. The following example (Table II) will help illustrate these concepts:

The condition number in row 6 is 5.43549. The variance proportion statistics (VAR PROP) in row 6 shows that variables 3 and 4 have high proportions associated with them. Similarly in row 7, variables 1 and 2 have high VAR PROP values and a condition number of 6.20098. These statistics indicate that variables  $X_1$  and  $X_2$  are correlated and so are variables  $X_3$  and  $X_4$ . The condition number associated with these rows is high enough to warrant that

Tab	le	II
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	<b></b> , <b>-</b> - <b>-</b> ,	ROW 1 2 3 4			CONDITI NUMBER 1 1.06117 1.17564 1.51004	ON	
		5 6 7			2.17646 5.43549 6.20098		
R	VAR	VAR	VAR	VAR	VAR	VAR	VAR
O	PROP	PROP	PROP	PROP	PROP	PROP	PROP
W	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>	X <sub>6</sub>	X <sub>7</sub>
1	0.0085	0.0057	0.0173	0.0170	0.0233	0.0153	0.0198
2	0.0194	0.0211	0.0109	0.0116	0.0034	0.0001	0.0026
3	0.0005	0.0038	0.0068	0.0070	0.1073	0.1477	0.0494
4	0.0000	0.0033	0.0001	0.0001	0.0025	0.1571	0.6295
5	0.0081	0.0014	0.0007	0.0023	0.5179	0.5528	0.1552
6	0.0098	0.0065	0.9479	0.9527	0.0000	0.0000	0.0049
7	0.9535	0.9583	0.0161	0.0094	0.3466	0.1271	0.1388

## Collinearity Diagnostics

collinearity may be unduly influencing the model. Rows 1, 2, 3 and 4 do not have any high VAR PROP associated with them and the condition numbers in these rows are also low. Row 5 shows variables 5 and 6 involved in a moderate collinear relationship with variaance proportion numbers of 0.5179 and 0.5528. The condition number in row 5 is a moderate 2.17646 and it indicates that the collinearity between variables 5 and 6 is moderate at best.

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Outliers: Outliers are extreme observations. An extreme observation may be an outlier either with respect to the regression line or with respect to the independent variables or both. Studentized residual (SRESID) is a statistic that identifies outliers with respect to the regression line. Its value is obtained by taking the residual (the difference between the observed value and the predicted value) and dividing it by appropriate standard error of the residuals. Studentized residuals follow a t-distribution and an observation with a studentized residual that falls outside the 90 percent confidence level of the t-statistic (n-p degrees of freedom) is an outlier with respect to the regression line.

Outliers with respect to independent variables are identified by a statistic called leverage value. Leverage value measures how far an observation is from a hypothetical observation which has the same characteris as the average values of the independent variables. A leverage value greater than 2p/n, where p is the number of parameters and n the sample size, indicates an outlier with respect to the independent variables.

An outlier is considered influential if by its presence, it is pulling the fitted regression line towards itself. This happens because the least quares best fit method tries to minimize the sum of squared deviations. SRESID and leverage value help identify outliers and are

also used to form a statistic called Cook's D. Whether an outlier is influential (pulling the regression line) or not is determined by checking Cook's D statistic ( $D_i$ ). A Cook's D value higher than an F-ratio (p-1/n-p degrees of freedom) at 50 percent level of confidence indicates that the outlier is influential. The manner in which the data for this research was generated would normally create some outlying observations. Outlier statistics were used to identify observations that were influential outliers.

# Measures of Predictive Ability of Model-S

The size of the standard error of the estimate is directly related to the overall ability of the model to predict. The square root of MSE (presented in the ANOVA table) is the standard error of the estimate.

The standard error divided by the mean of the dependent variable results in the coefficient of variation (C.V.) statistic. C.V. is the measure of the relative magnitude of the standard error. The predictive ability of Model-S was evaluated by analyzing the magnitude of the difference between the observed value and the predicted value. This difference is called the residual. Residuals were expressed as a percentage of the observed value. The predictive ability of Model-S was also evaluated by the width of its prediction intervals at 95 percent level of confidence. The prediction intervals indicate that the next observation will fall between the upper and lower bounds of the prediction

interval within a probaility equal to the level of confidence. The width of the prediction interval depends on the size of the standard error, the ability of the model to estimate the true population coefficents and the level of confidence. The lower the standard error and the better the ability of the model to estimate the population coefficients, the smaller the bound will be. These factors held constant, the higher the level of confidence, the wider the interval and vice-versa. The predictive ability of Model-S was evaluated by examining the magnitude of the bound and the bound expressed as a percentage of the predicted value.

# Validation of Model-S

Models normally predict better the observations in the data set than they do observations not in the data set. This is so because the criterion used to develop a model is to maximize its predictive capability. One approach of validating a model is to withhold part of the data and not use it in the development of the model. These omitted observations can then be used to test the predictive ability of the model. During this research effort, 300 observations were generated out of which 250 were used to develop Model-S and the the last 50 observations were used to evaluate how the TOTCOST figures generated by Model-S compared to ones generated by Model-A.

# Other Diagnostics

Because of the nature of the simulation used to generate the data, it was not necessary to test the assumptions that the error terms are normally distributed; that their distributions have the same variance (homoscedasticity) and that the error terms are independent of each other (no auto-correlation).

# V. Analysis Of Results

# Chapter Overview

This chapter contains the results of the data analysis. It presents Model-S, and analyzes its statistical properties.

# Model-S

TOTCOST	= -1,371,743 + 1,318,707 * NMA D 314,105 * TSM	A
	+ 572,799.3 * BRT + 907,253.4 * DRT	
	+ 14,550.22 * SQEXPPR - 83,640,101 * RECITTR	
	+ 20.95721 * MTBF	

## Where

NMA	=	Annual number of maintenance actions (scheduled & unscheduled)
TSMA	H	Annual number of scheduled maintenance actions
BRT	Ħ	Base repair rate (a percent value)
DRT	=	Depot repair rate (a percent value)
SQEXPPR	Ħ	Square root of the average cost of expendables per repair action
RECITRR	=	the reciprocal of TRR which stands for the average number of parts removed per maintenance action
MTBF	=	aggregate mean time between failure

The estimates of the coefficients and their levels of significance are presented in Table III. Also presented in this table are the standardized regression coefficients.

### Table III

Parameter Estimates

Variable	Parameter Estimate	Standardized Estimate	T for HO: Parameter=0	PROB >  T
INTERCEP	-1371743		-7.818	0.0001
NMA	1318707	0.5487198	16.107	0.0001
TSMAD	-314105	-0.0691199	-2.048	0.0417
BRT	572799.3	0.1019253	3.306	0.0011
DRT	907253.4	0.1281324	4.175	0.0001
SQEXPPR	14550.22	0.9303619	56.025	0.0001
RECITRR	-83640101	-0.44647	-31.744	0.0001
MTBF	20.95721	0.02730877	2.118	0.0352

#### Discussion

All variables in this model are significant to a high degree of confidence. Even the least significant variable, TSMA is significant at 95+ percent confidence (1 - 0.0417). Five of the independent variables are significant to the 99+ percent level of confidence.

The variable SQEXPPR (square root of cost of expendables per repair action) appears to be the most influential cost driver with the largest standardized regression coefficient of 0.9303619. This indicates that a one standard change in SQEXPPR results in a 0.9303619 standard deviation change in TOTCOST. The variable EXPPR had always remained very significant in the Model-S development process; however when the residuals were plotted against this variable, it appeared that cost increased at a decreasing rate as EXPPR increased. The square root, natural log and reciprocal transformations were tried in an attempt to model this non-linear relationship. In this case, the square root transformation seemed to produce the best results.

Another variable that needed to be transformed was the variable TRR (average number of parts removed for repair per maintenance action). The plot of TRR against the residuals showed a similar pattern to the EXPPR plot; cost seemed to be increasing at a decreasing rate as TRR increased. In this case, however, a reciprocal transformation produced the best results.

The reciprocal of TRR (RECITRR) comes in the selected model with a high rate of significance (99.99%) and its standardized regression coefficient compares favorably with the other cost drivers in the model. TRR is positively correlated with cost; more parts removed during a maintenance means more repairs, more replacements and more condemnations. Therefore as TRR goes up, so does cost.

However, as TRR goes up, its reciprocal (1/TRR) goes down. RECITRR therefore has a negative regression coefficient.

EXPPR is followed by NMA (annual number of maintenance actions) with the second largest standardized regression coefficient (0.5487198). However, this variable is highly correlated with the variable TSMA (annual number of scheduled maintenance actions). Because of this collinearity, the standardized coefficient is hard to interpret. However, NMA comes in the model at the 99.9+ percent level of significance.

NMA equals the sum of TSMA and TUMA (annual number of unscheduled maintenance actions). Therefore these three variables (TSMA, TUMA and NMA) are correlated by definition. In the selected model, TSMA has a negative regression coefficient value of -314,105. Logic dictates that cost should increase as TSMA increases; the larger the number of maintenance activities, the larger the cost. In other words TSMA should be positively correlated with cost. One could suspect that the seemingly nonsensical regression coefficient of TSMA might be because of presence of collinearity. Often the presence of strong correlation can play havoc with the regression coefficents; however, in this case there is a logical reason for the negative coefficient of TSMA in this model. The way Model-A is structured, it requires the removal of a larger number of parts during an unscheduled maintenance action than it does during a

scheduled maintenance action. As such, an unscheduled maintenance action is typically costlier than a scheduled maintenance action. A model that has NMA as an independent variable but does not have TSMA or TUMA as one of its variables, can not distinguish whether a change in NMA is because of TSMA or TUMA. If NMA increases by one, it may be because TSMA increased by one or because TUMA increased by one. With respect to Model-S then, if one were to hold all the other variables constant with the exception of TSMA and NMA, the equation would look like this:

TOTCOST = 1,318,707 \* NMA - 314,105 \* TSMA

If TSMA goes up by one, so does NMA. The change in TSMA  $(\Delta TSMA)$  is 1 and the change in NMA  $(\Delta NMA)$  is also one. The change in the dependent variable  $(\Delta TOTCOST)$  would be:

 $\Delta TOTCOST = (1,318,707 * \Delta NMA) - (314,105 * \Delta TSMA)$   $\Delta TOTCOST = (1,318,707 * 1) - (314,105 * 0)$   $\Delta TOTCOST = 1,318,707 - 314,105$  $\Delta TOTCOST = 1,004,602$ 

It can be seen that if TSMA goes up by 1, TOTCOST increases by \$1,004,602. If however, NMA were to go up by 1 because the number of unscheduled maintenance actions went up by one, then delta NMA (the change in NMA) would be 1 but delta TSMA would be zero because there is no increase in the

number of scheduled maintenace actions, only in the unscheduled ones. The change in TOTCOST would now be:

 $\Delta TOTCOST = (1, 318, 707 * \Delta NMA) - (314, 105 * \Delta TSMA)$ 

 $\Delta \text{TOTCOST} = (1,318,707 * 1) - (314,105 * 0)$ 

 $\Delta TOTCOST = 1,318,707$ 

One can see that when TUMA goes up by one, the increase in total cost is \$1,318,707 while the increase in total cost with a similar increase in TSMA was \$1,004,602. The difference between these two figures is \$314,105 which happens to be the coefficient of TSMA. Thus, the regression coefficient of TSMA in the Model-S reflects the cost difference between a scheduled and a unscheduled maintenance action. In the presence of NMA in the model, the regression coefficient of TSMA has to be negative to adjust for this cost difference.

Base repair rate (BRT) and depot repair rate (DRT) are also selected as cost drivers. Base repair rate is the ratio of annual number of parts repaired at base divided by annual number of parts removed for repair. DRT similarly is the ratio of annual number of parts repaired at depot divided by the total number of parts removed for repair. This pair of variables can also be expressed as a function of each other. BRT, DRT and the total condemnation rate must sum to 1. This is so because any removed part will

either be repaired at base or at depot or will be condemned; there are no other possibilities. Generally, the more repairs that are performed at base level, the less the number of parts that will be sent to the depot for repair. There is an inverse relationship between BRT and DRT. As long as the condemnation rate stays fairly small, these two variables are highly correlated. As a result, it is difficult to change one while holding the other constant. Not being able to do this makes it difficult to interpret the regression coefficients.

The variable MTBF (aggregate mean time between failure) comes in the model at 96+ percent level of significance. Interestingly enough, it has a positive regression coefficient. On the surface again, this does not seem logical. As mean time between failure increases, failures go down. This should result in fewer unscheduled maintenance actions and therefore maintenance related costs should go down. Logically, then MTBF should come in the model with a negative coefficient. There are a few reasons why sometimes a variable that is negatively correlated with the dependent variable, shows up in the model with a positive regression coefficient and vice-versa. These reasons are:

1. <u>Anomaly in the data</u>: If the data is clustered together, one bad observation away from the cluster is





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enough to change the direction of the regression line and produce unexpected signs in coefficients. This is not true of the data set used in this thesis because simulation under the triangular distribution would not produce clusters of data.

2. <u>Statistical Fluke</u>: When there are a few observations in the data set and the correlation between the dependent variable and the independent variable is a weak one (close to zero), the coefficient is liable to show up positive or negative due to the random variability in the sample. In this database, there are a large number of observations; so this reason can be discarded as well.

3. <u>Characteristic of the Data</u>: It is possible for a variable to have a statistical relationship to cost that is opposite to the logical relationship. This may happen when a variable in the model is capturing the effects of variables not in the model. In the following example, the variable V2 is negatively correlated with cost:

Cost = 60 + 11 V1 - 6 V2 (42)

Table IV provides some values for Vl and V2 and the resulting cost figures:

The data in Table IV shows that as V2 increases, so does cost. However Eq 42 showed that V2 was negatively related to cost. Because the data set in this research effort has numerous variables, and several three or four way

Tab	le	IV
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Example Data Set

OBS	V1	V2 (	Cost
1	7	2	125
2	10	3	152
3	16	4	212

correlationships may exist, it is possible that the positive coefficient of MTBF ocurrs because of such a phenomenon.

#### Model Statistics

The significance of the F-ratio, the magnitude of the coefficient of determination, and the small standard error of the estimate all indicate that from a statistical perspective, this is an outstanding model.

Table V shows that the model has an  $R^2$  of 0.9686 which signifies that 96+ percent of the variation in the observed values of TOTCOST can be explained by this model. The F-ratio is by definition at least as significant as the least significant variable in the model, which in this case was over 95 percent. The F-ratio for the model is very large (1066.744) and is significant to the 99.999+ percent.

Tab	le	V
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#### Analysis of Variance

DEP VARI	ABLE:	TOTCOST			
SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL ERROR C TOTAL	7 242 249	2.33347E+13 756238323734 2.40909E+13	3.33352E+12 3124951751	1066.744	0.0001
ROOT M DEP ME	IS E AN	55901.27 895426.5	R-SQUARE C.V.	0.9686 6.242976	

The model has a small standard error of the estimate (6.24% of the mean of TOTCOST) and therefore prediction intervals of about 12 percent about the predicted value can be made with 95 percent confidence, when estimating at the middle of the data.

#### Collinearity

Tables VI and VII present the collinearity diagnostics: The tolerance values for the variables NMA, TSMA, BRT, and DRT are underlined because they are low and indicate collinearity. The tolerance value for DRT is 0.1377179, which means that when regressed against the other variables in the model, DRT is correlated at 86+ percent (1-0.1377179). The other three variables have lower tolerence numbers and

#### Table VI

### Collinearity Diagnostics

NMA     0.1117691       TSMA     0.1138464       BRT     0.1364286       DRT     0.1377179       SQEXPPR     0.4703847       RECITRR     0.6557183       MTBF     0.7805896	

are correlated to higher degrees. Next, Table VII shows the nature of these correlationships.

The condition number in row 6 is 5.43549. The variance proportion statistics (VAR PROP) in row 6 shows that variables BRT and DRT have high variance proportion values (.9479 and .9527) associated with them. Similarly in row 7, variables NMA and TSMA have high VAR PROP values (.9535 and .9583) and a condition number of 6.20098. These statistics indicate that variables NMA and TSMA are correlated and so are variables BRT and DRT. The conditions number associated with rows 6 and 7 are high enough to warrant that collinearity may be unduly influencing the model. Rows 1,2, 3 and 4 do not have any high VAR PROP associated with them and the condition numbers in these rows are small. Row 5 shows variables SQEXPPR and RECITTR involved in a moderate collinear relationship with variaance proportion numbers of

# Table VII

	·	DOM					
		RUW			NUMBER		
		1			1		
		2		1.06117			
		3		1.17564			
		4		1.51004			
		5			2.17646	ı	
		6			5.43549	)	
		7			6.20098	1	
				·····			
R	VAR						
0	PROP						
W	x <sub>1</sub>	x <sub>2</sub>	x <sub>3</sub>	X <sub>4</sub>	x <sub>5</sub>	x <sub>6</sub>	x <sub>7</sub>
<u> </u>			-		···· · · · ·		· · · · · · · · · · · · · · · · · · ·
1	0.0085	0.0057	0.0173	0.0170	0.0233	0.0153	0.0198
2	0.0194	0.0211	0.0109	0.0116	0.0034	0.0001	0.0026
3	0.0005	0.0038	0.0068	0.0070	0.1073	0.1477	0.0494
4	0.0000	0.0033	0.0001	0.0001	0.0025	0.1571	0.6295
5	0.0081	0.0014	0.0007	0.0023	0.5179	0.5528	0.1552
6	0.0098	0.0065	0.9479	0.9527	0.0000	0.0000	0.0049
7	0.9535	0.9583	0.0161	0.0094	0.3466	0.1271	0.1388

Collinearity Diagnostics Variance Proportions

0.5179 and 0.5528. The condition number in row 5 is moderate at 2.17646 and it indicates that the collinearity between variables SQEXPPR and RECITTR is moderate at best. Last, the variance proportion number for SQEXPPR in row 7 is 0.3466 which indicates that it may be involved in a weak 3 way correlationship with NMA and TSMA. The collinearity between NMA and TSMA and between BRT and DRT was expected because both pairs of variables are correlated by definiton. Collinearity is not a problem if the relationship between the involved variables is maintained outside the model also. This is true for both sets of variables. As has been explained earlier, both sets of variables are functionally related and therefore these relationships will always be maintained.

#### Outliers

Tables VIII and IX present outlier statistics:

#### Table VIII

Outliers With Respect To The Independent Variables (X)

OBS	LEVER	NMA	TSMA	BRT	DRT	SQEXPPR	RECITRR	MTBF
14	.065	-1.14	-1.07	-1.7	1.44	1.72	2.94	-0.39
49	.068	-0.33	0.00	.47	-0.51	1.85	3.05	-1.57
76	.069	-4.85	2.85	-2.01	2.23	-0.44	-0.35	-1.8
97	.090	2.30	0.92	-1.94	1.39	1.11	0.05	0.19
106	.070	1.00	1.25	-1.16	-0.04	1.16	1.70	1.12
159	.063	-1.92	-2.05	-0.38	-0.62	0.45	1.47	0.38
188	.064	-0.18	-0.45	0.96	-0.88	2.41	3.17	0.45
238	.061	2.68	3.05	-0.03	0.25	-0.96	0.35	0.18
245	.062	0.08	-0.66	-1.36	0.76	3.47	1.76	-0.87

In Table VIII, column 1 is the ith observation; column 2 has the leverage values and columns 3 thru 7 represent the seven variables of the model. Table VIII shows nine observations

where the leverage value either exceeded the criterion threshold of 0.064 or was close to it. These observations were analyzed in terms of the values of the seven variables in the model for those nine observations. Table VIII contains these values in terms of how many standard deviations they were away from their mean for those particular observations. Negative values indicate that the values were below their mean. All values that were two or more standard deviations away have been underlined in Table VIII. One can see that with the exception of observation 106, each observation had at least one variable that was an extreme value with respect to its mean, thus causing that observation to be an outlier with respect to the independent variables. Observation 106 has a leverage value of .070 (column 2) which does exceed the criterion value of .064 (2p/n). This observation has six out of seven variables that are between one and two standard deviations away from their means so that even though no one particular variable is an extreme by itself, the combination of six moderately high values makes this observation an outlier.

Outliers With Respect to the Regression Line: There were 25 observations that had a higher studentized residual than than the t-statistic at the 90 percent level of confidence. At this level of confidence, one would expect approximately 10 percent of the observations to fall out of

bounds. Twenty-five happens to be exactly 10 percent of 250, the number of observations used to develop the model.

Influential Outliers: Cook's-D statistics indicated that there were no influential outliers. This is logical because, with 250 observations, it would be difficult for any one observation to exert any individual influence the regression line. The Cook's-D criterion was 0.907 and the largest Cook's-D value obtained was 0.110. Table IX lists seven observations that had the highest Cook's-D:

#### Table IX

VALUE OBS	0.907 COOK'S-D	1.645 SRESID	0.064 LEVERAGE
133	0.110667	3.73700	.0596
10	0.108516	4.14060	.0481
238	0.105077	-3.57950	.0615
156	0.072863	3.57570	.0436
115	0.064065	2.82730	.0602
76	0.0519845	-2.35090	.0699
64	0.0517324	3.43060	.0339
	VALUE OBS 133 10 238 156 115 76 64	VALUE OBS         0.907 COOK'S-D           133         0.110667           10         0.108516           238         0.105077           156         0.072863           115         0.064065           76         0.0519845           64         0.0517324	VALUE         0.907         1.645           OBS         COOK'S-D         SRESID           133         0.110667         3.73700           10         0.108516         4.14060           238         0.105077         -3.57950           156         0.072863         3.57570           115         0.064065         2.82730           76         0.0519845         -2.35090           64         0.0517324         3.43060

Highest Cook's-D Values

Table IX presented the seven highest Cook's-D values and the associated SRESID and LEVERAGE value. None of the Cook's-D value comes close to the criterion value of 0.907;
however, in each of these cases SRESID is significantly above its criterion of 1.645. Observation 76 is an outlier both with respect to the regression line and the independent variables with a leverage value of 0.069. It is the only observation in this group which exceeded its leverage value criterion of 0.064. Appendix D of this thesis contains a complete listing of outlier statistics.

# Predictive Ability of Model-S

The predictive ability of Model-S was evaluated by analyzing both the magnitude of the difference between the observed value and the predicted value (point estimates) and the width of the 95 percent prediction interval for each observation.

#### Point Estimates:

Ninety percent of the predicted cost values by Model-S were within 10 percent or less of the TOTCOST value generated by Model-A. The estimating error ranged from a low of \$1,969 (less than two/tenth of a percent of actual cost) to a high of \$134,993 (35 percent of actual cost). Table X presents some selected observations.

In Table X, column 1 is the ith observation, column 2 is the TOTCOST figure generated by Model-A, column 3 is the predicted figure by Model-S (YHAT), column 4 is the difference between the two (TOTCOST-YHAT), and column 5 is this difference expressed as a percent of TOTCOST ((RESID/TOTCOST) x 100).

Table	X
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Observat	ions of	: Predicti	ive Cost
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OBS	TOTCOST	YHAT	RESID	RESIDPC
5	1,263,076	1,268,530	-5454	-0.432
12	581,691	584,646	-2955	-0.508
31	803,755	798,061	5694	0.708
67	1,112,055	1,114,024	-1969	-0.177
137	973,661	976,777	-3116	-0.320
143	724,020	727,089	-3070	-0.424
74	462,264	345,073	117,190	25.35
78	463,403	327,006	136,396	29.43
58	427,889	307,868	120.020	28.049
115	456,871	303,656	153,215	33.536
208	382,217	248,224	134,993	35.226

To be able to estimate 90 percent of the observations to within 10 percent of the actual, speaks well for Model-S' predictive ability.

A pattern was noted with the observations where Model-S had large estimating errors. Wherever the estimation error (RESID) is large, the associated TOTCOST value is relatively small. Furthermore, in each of these instances Model-S has not only missed the mark, it has consistently underestimated. The mean value of TOTCOST is \$895,426. Out of

the 250 observations, there are eight observations where the estimating error is 20 percent or greater. In seven of these TOTCOST has been in the 400,000 - 500,000 range and each of these seven times, the estimation has been lower yet.

The fact that almost everytime Model-S has underestimated when estimating errors have been 20 percent or above and also that in most these instances TOTCOST has been below \$500,000, led the researcher to speculate that the distribution of TOTCOST might not be normal. In fact, if the distribution of TOTCOST were to be right skewed, these results would make sense because the low values of TOTCOST would not occur in the far left tail as they would in a normal distribution. Model-S which assumes that error terms are normally distributed would place an equivalent number of values in each tail of a symmetrical distribution except that in the left tail of the distribution, it would miss the low values of TOTCOST because they are skewed to the right. Indeed, under such a scenario the regression based model would consistently under-estimate the low values of TOTCOST.

A measure of skewness test was run which generated a skewness statistic of 0.977. A normal distribution generates a skewness statistic of close to zero. Left skewed distributions generate negative values and right skewed distributions generate positive values. The test to see how skewed a distribution is requires comparing the

skewness statistic to its standard deviation calculated by the expression " $\sqrt{(6/n)}$ ." With n equal to 250, this number is equal to 0.155. The skewness statistic of 0.977 is, therefore, six standard deviations away from zero which means that the distribution of TOTCOST is extremely skewed to the right.

Appendix E is a complete listing of Table X.

## Prediction Intervals

Table XI presents data which is in the form of prediction intervals constructed at 95 percent confidence level around the predicted value:

#### Table XI

Observations of Predictive Intervals

OBS	YHAT	L95	<u>U</u> 95	BOUND	BOUNDPC
5	1,268,530	1,156,853	1,380,207	111,677	8.80
12	584,646	473,486	695,805	111,159	19.01
10	1,792,748	1,680,009	1,905,487	112,739	6.28
67	1,114,024	1,002,447	1,225,601	111,577	10.01
115	303,656	190,270	417,041	113,385	37.34
58	307,868	196,040	419.696	111,828	36.32
78	327,006	215,459	438,553	111,547	34.11

In Table X, column 1 is the ith observation; column 2 is the predicted cost by Model-S (YHAT); columns 3 and 4 are the lower and upper bounds respectively (L95 and U95). Column 5 represents the bound; it is the differnce between U95 and YHAT which is the same difference between YHAT and L95. Finally, column 6 in table 9 is a term called BOUNDPC which is the bound expressed as a percent of YHAT ((Bound/YHAT) x 100). BOUNDPC (column 6) ranged from a low of approximately six percent to a high of 41 percent. It was observed that even though BOUNDPC fluctuates, the bound itself remains between 111,000 to 113,000. The size of the bound is a function of the standard error of the model and its ability to have regression coefficients that are close to the poulation coefficients. A large data base typically allows the model to better estmate the population. It is because of this strength of the model that is keeping the bound very stable. A complete listing of the prediction intervals is provided in Appendix F.

#### Validation of Model-S

Of the three hundred observations that were generated, 50 were withheld from being used to develop Model-S. Because models generally predict observations in the data set better than they do observations not in the data set, this data was used to evaluate the validity of Model-S, i.e., its predictive accuracy. YHATS, point estimates of

Model-S were compared with TOTCOST. Table XII presents the results:

## Table XII

OBS	TOTCOST	YHAT	DIFF	PERDIFF
251	6957966	58914	36882	5.30
252	1060244	1085562	-25318	-2.38
253	1044413	1044454	-41	-0.004
257	838258	948801	110543	-13.18
266	339264	153774	185489	54.67
269	601497	584518	16979	2.82
283	456575	334403	122172	26.75
284	629188	615957	13232	2.10
285	1130761	1135019	-4258	-0.37

Predictive Accuracy

In Table XII, column 1 is the ith observation; column 2 is the TOTCOST figure generated by Model-A; column 3 is the YHAT estimate of Model-S; column 4 is the difference of the two and column five is this difference expressed as a percent of TOTCOST ((DIFF/TOTCOST) x 100).

Out of the 50 observations, 43 observations were within 10 percent or less of TOTCOST; furthemore 31 of these observations were within 5 percent or less. Of the seven observations that were over 10 percent away, three were between 10 percent and 20 percent; another three were between 20 percent and 30 percent and observation number 266 was unique because it differed by 54 percent. This observation happens to be the lowest TOTCOST value and in keeping with the logic of its skewed distribution, this error is understandable. With this one exception, Model-S seems to have performed quite accurately. Appendix F provides a complete listing of Table XII.

# VI. Conclusions

Because the data for this research effort was artificially generated, the results of Model-S are not valid for cost-estimating purposes. However, the purpose of demonstrating methodology was served. The research questions posed in Chapter I have been answered by this thesis.

Model-A has 51 variables. In terms of identifying cost drivers, it was felt that an aggregation of some of those 51 variables was necessary. Variables such as "annual number of maintenance actions (NMA)" and "base repair rate (BRT)" are two of twenty such variables that are aggregations of the original 51 and were tested for their influence on cost. It would have been entirely possible to consider only the original 51 variables for selection in the model and perhaps still come up with a Cost Estimating Relationship (CER) that would have been extremely difficult, given that one is trying to cost a new weapon system, to estimate these variables because they are extremely specific.

The selection of variables like NMA, TSMA (annual repair rate) in Model-S also affords one the opportunity to control these costs to some extent. Base repair rate (BRT) and depot repair rate are, to an extent, policy driven. The

number of scheduled maintenance actions is entirely dependent on flying hours and the scheduled maintenance interval. Both these variables can be influenced by policy decisions.

In Model-S the variables TSMA and MTBF (aggregate mean time between failure) came in with signs that were opposite of what would be logically expected. Often during multivariate regression analysis, combinations of variables can prevent pictures that on the surface seem illogical. The negative coefficient of TSMA in Model-S is a good case in point. These scenarios need to be analyzed further and not discarded immediately because there is a chance that the behavior indeed does make sense. As it turned out, in every instance the variable TSMA added strength and explanatory power to the model. It was not too long before it was discovered why the negative coefficient of TSMA made all the sense in the world, given that NMA was present in the model. The negative sign of TSMA in Model-S which also had NMA as a variable was to reflect the cost difference between a scheduled maintenance and an unscheduled maintenance action. It was not as easy to determine why MTBF came in the model with a positive sign. The characteristic of the data sometime causes such phenomenon. Since in each case, MTBF added a good deal of significance to the overall CER and came in individually significant also, the decision was made to keep it in the model.

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The functional relationship of cost with the dependent variable needs to be determined statistically. Though it may be apparent that cost should go up or down with the increase or decrease in a particular variable, does it go up or go down with a decreasing rate? In Model-S the variables EXPPR and TRR needed to be transformed because their relationship with cost was not linear.

The variables EXPPR (average coat of expendables) and TRR (average number of parts removed per maintenance action) appeared to be related to cost in a nonlinear manner. Cost increased at a decreasing speed as either one of these variables increased. These variables were transformed into the square root (SQEXPPR) and the reciprocal (RECITRR). Both transformed variables were selected for inclusion in Model-S. EPRPR is the most individually significant variable in the model. The variable SQEXPPR (square root of the average cost of expendables per repair action) was the most significant cost driver in the model with the highest standardized regression coefficient.

Statistically, Model-S is an outstanding model. It has very high explanatory power; it can explain 96 percent of the variation in observed cost. All variables are significant at least to the 95 percent level. The overall model is significant to the 99.999 percent level of confidence.

The inclusion of NMA, TSMA, BRT, and DRT caused the presence of collinearity in the model. However, since NMA and TSMA are functionally related just as BRT and DRT are, collinearity was not considered to be a problem.

Out of 250 observations, there were none observations that were outliers with respect to the independent variables. In eight of these cases, at least one variable had an extreme value that fell more than two standard deviations away from its mean. There were 25 observations that were outliers with respect to the regression line meant that 10 percent of the observations fell out of the bounds t-statistic at 90 percent level of confidence. This was perfectly normal.

Model-S was estimated within ten percent or less for actual values for 90 percent of the observations. It predictive ability was also tested with observations that were withheld from being used in its development. This is one way to validate a model. The results were equally good. Where estimating errors were large, Model-S consistently underestimated observations that turned out to be relatively low values as well. This was because, as it was discovered, the cost figures generated by Model-A (TOTCOST) were not normally distributed. Instead this distribution was right skewed.

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#### Suggestion for Future Research

In this research effort, data was generated through simulation with the assumption that the independent variables were not correlated among themselves. As a result, during simulation, the variables were essentially free to take on any value within their respective bounds. Real world data, of course, would not be independent. Therefore, the methodology of generating observations in this manner would create some unrealistic combination of variables. For example, if variables A and B both can range from 1 to 10 but they are correlated so that if A has a value of 9 then B could only be a number above 5, then a value of 9 for A and 3 for B is an unrealistic combination. The simulation procedure used in this effort could create such combinations because of the assumption of independence. With more realistic data, the simulation process would have to take the dependencies in consideration and impose limits other than the just the rang of a given variable. When a large number of variables are involved, multiple correlations can make such simulation a real challenge. A study would be done that repeats the methodology of this research with this particular modification.

## Appendix A: Glossary of Input Variables for Model-A

- ACONDH = Average cost of procurement to replace a condemned item from category H.
- 2. ACONDL = Average cost of procurement to replace a condemned item from category L.
- 3. ACONDM = Average cost of procurement to replace a condemneditem from category M.
- 4. AFH = Annual flying hours per engine.

- 5. BURCH = The average base level cost of repair of a part from category H.
- 6. BURCL = The average base level cost of repair of a part from category L.
- BURCM = The average base level cost of repair of a part from category M.
- 8. CMH = average cost per manhour for personnel directly involved in maintenance/repair activity of jet engines.
- 9. DCONDH = Of those parts of category H that are sent to the depot for repair, DCONDL is a percent that on the average, is condemned at the depot level.
- 10. DCONDL = Of those parts of category L that are sent to the depot for repair, DCONDL is a percent that on the average, is condemned at the depot level.
- 11. DCONDM = Of those parts of category M that are sent to the depot for repair, DCONDL is a percent that on the average, is condemned at the depot level.
- 12. DURCH = The average depot level cost of repair of a part from category H.
- 13. DURCL = The average depot level cost of repair of a part from category L.
- 14. DURCM = The average depot level cost of repair of a part from category M.

- 15. EXPRBH = the average cost of expendables associated with a base level repair action on category H parts.
- 16. EXPRBL = the average cost of expendables associated with a base level repair action on category L parts.
- 17. EXPRBM = the average cost of expendables associated with a base level repair action on category M parts.
- 18. EXPRDH = the average cost of expendables associated with a depot level repair action on category H parts.
- 19. EXPRDL = the average cost of expendables associated with a depot level repair action on category L parts.
- 20. EXPRDM = the average cost of expendables associated with a depot level repair action on category M parts.
- 21. EXPSH = the average cost of expendables associated with category H parts with each scheduled maintenance action.
- 22. EXPSL = the average cost of expendables associated with category L parts with each scheduled maintenance action.
- 23. EXPSM = the average cost of expendables associated with category M parts with each scheduled maintenance action.
- 24. EXPUH = the average cost of expendables associated with category H with each unscheduled maintenance action caused by a problem with category H part(s).
- 25. EXPUL = the average cost of expendables associated with category L with each unscheduled maintenance action caused by a problem with category L part(s).
- 26. EXPUM = the average cost of expendables associated with category M with each unscheduled maintenance action caused by a problem with category M part(s).

- 27. FUEL = Cost of fuel per gallon.
- 28. FUELTC = average number of gallons of fuel required to test the engine after repair.
- 29. FUELTP = average number of gallons of fuel required to trim the engine while removed.
- 30. MHIE = Average number of manhours needed to install an engine; this includes the time required to transport the engine back.
- 31. MHRE = Average number of manhours needed to remove an engine; this includes the time required to transport the engine to the repair facility.
- 32. MHSMA = Average number of manhours needed to perform "on hands" maintenance for a scheduled maintenance action. This refers to the time consumed doing actual maintenance related chores such as removing and replacing parts, etc.
- 33. MHTB = Average number of manhours needed to do test bed run.
- 34. MHTE = Average number of manhours needed to trim an engine.
- 35. MHUMA = Average number of manhours needed to perform "on hands" maintenance for an unscheduled maintenance action. This refers to the time consumed doing actual maintenance related chores such as removing and replacing parts, etc.
- 36. MTBFH = Given that there is no preventative maintenance, the amount of time the engine will operate before it needs to be removed for repair because of a problem with category H part(s).
- 37. MTBFL = Given that there is no preventative maintenance, the amount of time the engine will operate before it needs to be removed for repair because of a problem with category L part(s).

38. MTBFM = Given that there is no preventative maintenance, the amount of time the engine will operate before it needs to be removed for repair because of a problem with category M part(s).

- 39. NRTSH = is the average percent of the parts removed from category H for repair, that is sent to the depot level.
- 40. NRTSL = is the average percent of the parts removed from category L for repair, that is sent to the depot level.
- 41. NRTSM = is the average percent of the parts removed from category M for repair, that is sent to the depot level.
- 42. QPESH = average number of parts, coded for repair, removed from the category H during a scheduled maintenance action.
- 43. QPESL = average number of parts, coded for repair, removed from category L during a scheduled maintenance action.
- 44. QPESM = average number of parts, coded for repair, removed from category M during ascheduled maintenance action.
- 45. QPEUH = Given that the engine was removed for repair because of a problem with category H part(s) (causing unsheduled maintenance), QPEUH is the average number of parts, coded for repair, that are removed from category H?
- 46. QPEUL = Given that the engine was removed for repair because of a problem with category L part(s) (causing unsheduled maintenance), QPEUL is the average number of parts, coded for repair, that are removed from category L.
- 47. QPEUM = Given that the engine was removed for repair because of a problem with category M part(s) (causing unsheduled maintenance), QPEUM is the average number of parts, coded for repair, that are removed from category M?
- 48. RTSH = is the average percent of the parts, removed from the category H for repair, that is repaired at base level (as opposed to being sent to depot or being condemned).
- 49. RTSL = is the average percent of the parts, removed from the category L for repair, that is repaired at base level (as opposed to being sent to depot or being condemned).

- 50. RTSM = is the average percent of the parts, removed from the category M for repair, that is repaired at base level (as opposed to being sent to depot or being condemned).
- 51. SMI = Scheduled maintenance interval.

Appendix B: SAS Computer Program for Running Model-A

```
OPTIONS LINESIZE = 80;
 LIBNAME RAJ '[RVERMA]';
 DATA null ;
 SEED1 = 66065:
                                               SEED4=63573;
                                                              SEED5=73796;
                SEED2=31060:
                               SEED3=85269;
                                               SEED9=88685;
                                                              SEED10=99594;
                SEED7=11805;
                               SEED8=83452;
 SEED6=98520;
 SEED11=65481; SEED12=80124; SEED13=74350; SEED14=69916; SEED15=09893;
 SEED16=91499; SEED17=80336; SEED18=44104; SEED19=12550; SEED20=63606;
 SEED21=61196; SEED22=15474; SEED23=94557; SEED24=42481; SEED25=23523;
 SEED26=04493; SEED27=00549; SEED28=35963; SEED29=59808; SEED30=46058;
 SEED31=32179; SEED32=69234; SEED33=19565; SEED34=45155; SEED35=94864;
 SEED36=98086; SEED37=33135; SEED38=80951; SEED39=79752; SEED40=18633;
 SEED41=74029; SEED42=54178; SEED43=11664; SEED44=48324; SEED45=69074;
 SEED46=32533; SEED47=04805; SEED48=68953; SEED49=02529; SEED50=99970;
 SEED51 = 74717;
 L1 = 200;
                           H1 = 350;
              M1 = 250;
 L2 = 500;
              M2 = 750;
                           H2 = 1000;
 L3 = 1000;
              M3 = 2000;
                           H3 = 5000;
 L4 = 5000;
              M4 = 7000;
                           H4 = 10000;
 L5 = 500;
              M5 = 750;
                           H5 = 1000;
 L6 = 25;
              M6 = 50;
                           H6 = 100;
              M7 = 25;
                           H7 = 50;
 L7 = 5;
              M8 = 5:
                           H8 = 10;
 L8 = 1;
 L9 = 35;
              M9 = 65:
                           H9 = 125;
 L10 = 10;
              M10 = 30;
                           H10 = 75;
 L11 = 1;
              M11 = 10;
                           H11 = 25;
 L12= .5;
                           H12= .8;
              M12 = .65;
              M13 = .5;
                           H13 = .75;
. L13 = .25;
              M14 = .25;
                           H14 = .4;
 L14 = 0;
                           H15= .5;
              M15 = .65;
 L15= .8;
 L16= .75;
                            H16 = .9;
              M16 = .85;
              M17= .85;
 L17 = .75;
                            H17 = 1;
 L18 = .1;
              M18 = .2;
                            H18 = .3;
 L19 = .05;
              M19 = .15;
                            H19= .25;
              M20 = .10;
                            H20 = .15;
 L20 = .05;
              M21 = 100;
                            H21 = 175;
 L21 = 60;
              M22 = 300;
                            H22 = 500;
 L22 = 150;
 L23 = 700;
              M23 = 1000;
                           H23 = 1500:
 L24 = 150;
              M24 = 350;
                            H24 = 700;
 L25 = 750;
              M25 = 1250;
                           H25 = 1700;
 L26 = 1500;
              M26 = 2000;
                           H26 = 3000;
 L27 = 10;
              M27 = 12;
                            H27 = 15;
 L28 = 10;
              M28 = 12;
                            H28 = 15;
 L29 = 5;
              M29 = 6;
                            H29 = 7.5;
 L30 = 4;
              M30 = 6;
                            H30 = 10;
              M31 = 750;
                            H31 = 1000;
 L31 = 500;
 L32 = 800;
              M32 = 1200;
                            H32 = 1500;
 L33 = 1000;
              M33 = 1500;
                            H33 = 2500;
 L34 = 2500;
              M34 = 5000;
                           H34 = 10000;
```

L35 = 7500	);	M35= 10000; H35= 15000;
L36 = 1500	);	M36 = 2500; H36 = 4000;
L37 = 3000	);	M37 = 6000; H37 = 12000;
L38 = 8000	);	M38 = 12000; H38 = 17500;
L39 = 50;	-	M39= 75; H39= 125;
L40= 125;		M40 = 250; H40 = 500;
L41 = 375	;	M41 = 500; H41 = 750;
L42 = 100		M42 = 150; H42 = 250;
L43= 250;		M43 = 500; H43 = 1000;
L44= 750;		M44 = 1000; H44 = 1500;
L45= 250;		M45 = 500; H45 = 1000;
L46 = 1500	Ĵ;	M46 = 10000; H46 = 20000;
L47 = 2500	) <b>0;</b>	M47 = 35000; H47 = 50000;
L48= 175;	;	M48= 200; H48= 300;
L49= 125;		M49 = 150; H49 = 200;
L50= .60;		M50 = .75; $H50 = 1.00;$
L51 = 12;	•	M51 = 16; $H51 = 25;$
DO I =	= 1	TO 300:
		CALL RANTRI (SEED1.(M1-L1)/(H1-L1).X1);
AFH =	=	(H1-L1)*X1+L1;
REP +1;		
		CALL RANTRI (SEED2,(M2-L2)/(H2-L2),X2);
MTBFL =	=	(H2-L2)*X2+L2;
		CALL RANTRI (SEED3, (M3-L3)/(H3-L3), X3);
MTBFM =	2	(H3-L3)*X3+L3;
		CALL RANTRI (SEED4, $(M4-L4)/(H4-L4), X4$ );
MTBFH =		(H4-L4)*X4+L4;
		CALL RANTRI (SEED5, (M5-L5)/(H5-L5), X5);
SMI =	2	(H5-L5)*X5+L5;
		CALL RANTRI (SEED6, (M6-L6)/(H6-L6), X6);
QPESL =	2	(H6-L6)*X6+L6;
		CALL RANTRI (SEED7,(M7-L7)/(H7-L7),X7);
QPESM =	2	(H7-L7)*X7+L7;
		CALL RANTRI (SEED8,(M8-L8)/(H8-L8),X8);
QPESH =	3	(H8-L8)*X8+L8;
		CALL RANTRI (SEED9,(M9-L9)/(H9-L9),X9);
QPEUL =	=	(H9-L9)*X9+L9;
		CALL RANTRI (SEED10,(M10-L10)/(H10-L10),X10);
QPEUM =	=	(H10-L10)*X10+L10;
		CALL RANTRI (SEED11,(M11-L11)/(H11-L11),X11);
QPEUH =	2	(H11-L11)*X11+L11;
		CALL RANTRI (SEED12,(M12-L12)/(H12-L12),X12);
RTSL =	=	(H12-L12)*X12+L12;
		CALL RANTRI (SEED13,(M13-L13)/(H13-L13),X13);
RTSM =	3	(H13-L13)*X13+L13;
		CALL RANTRI (SEED14,(M14-L14)/(H14-L14),X14);
RTSH =	*	(H14-L14)*X14+L14;
		CALL RANTRI (SEED15,(M15-L15)/(H15-L15),X15);
KL =	-	(H15-L15)*X15+L15;
		CALL RANTRI (SEED16,(M16-L16)/(H16-L16),X16);
KM =	-	(H16-L16)*X16+L16;
		CALL RANTRI (SEED17,(M17-L17)/(H17-L17),X17);
KH =	=	(H17-L17)*X17+L17;

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		CALL RANTRI (SEED18.(M18-L18)/(H18-L18).X18):
DCONDL	-	(H18-L18)*X18+L18:
		CALL RANTRI (SEED19.( $M19-L19$ )/( $H19-L19$ ).X19):
DCONDM	-	(H19-L19)*X19+L19:
		CALL RANTRI (SEED20, (M20-L20)/(H20-L20), X20);
DCONDH	-	(H20-L20)*X20+L20;
		CALL RANTRI (SEED21, (M21-L21)/(H21-L21), X21);
BURCL	*	(H21-L21)*X21+L21;
		CALL RANTRI (SEED22, (M22-L22)/(H22-L22), X22);
BURCM	=	(H22-L22)*X22+L22;
		CALL RANTRI (SEED23,(M23-L23)/(H23-L23),X23);
BURCH	3	(H23-L23)*X23+L23;
		CALL RANTRI (SEED24,(M24-L24)/(H24-L24),X24);
DURCL	2	(H24-L24)*X24+L24;
		CALL RANTRI (SEED25,(M25-L25)/(H25-L25),X25);
DURCM	=	(H25-L25)*X25+L25;
		CALL RANTRI (SEED26, (M26-L26)/(H26-L26), X26);
DURCH	=	(H26-L26) * X26 + L26;
		CALL RANTRI (SEED27, (M27-L27)/(H27-L27), X27);
MHRE	-	(H27-L27)*X27+L27;
		CALL RANTRI (SEED28, (M28-L28)/(H28-L28), X28);
MHIE	3	(H28-L28)*X28+L28;
		CALL RANTRI (SEED29, $(M29-L29)/(H29-L29), X29);$
MHTE	-	(H29 - L29) * X29 + L29;
MITT		CALL RANTRI (SEED30, $(M30-L30)/(H30-L30), X30);$
en 1 b	3	$(H_{3}) - L_{3}) + X_{3} + L_{3}$
MUCMA	-	CALL KANIKI (SEEDSI, $(MSI - LSI)/(HSI - LSI), XSI);$
MISMA	-	(DJI-LJI)~AJI+LJI; (AII DANTDI (CEED3) (M3)_I3)/(U3)_I3) V3).
MHIIMA	з	$(H32 - I32) \times Y32 + I32$
		CALL RANTRI (SEED33 (M33-L33)/(H33-L33) X33)
EXPSL	×	(H33-L33)*X33+L33:
		CALL RANTRI (SEED34. $(M34 - L34)/(H34 - L34). X34)$ :
EXPSM	-	(H34-L34)*X34+L34:
		CALL RANTRI (SEED35, (M35-L35)/(H35-L35), X35);
EXPSH	=	(H35-L35)*X35+L35;
		CALL RANTRI (SEED36, (M36-L36)/(H36-L36), X36);
EXPUL	-	(H36-L36)*X36+L36;
		CALL RANTRI (SEED37,(M37-L37)/(H37-L37),X37);
EXPUM	-	(H37-L37)*X37+L37;
		CALL RANTRI (SEED38,(M38-L38)/(H38-L38),X38);
EXPUH	-	(H38-L38)*X38+L38;
_		CALL RANTRI (SEED39, (M39-L39)/(H39-L39), X39);
EXPRBL	*	(K39-L39)*X39+L39;
<b></b>		CALL RANTRI (SEED40, (M40-L40)/(H40-L40), X40);
EXPREM	-	$(H4U-L4U) \times X4U+L4U;$
EVDDD	-	UALL KANTKI (SEED I, $(M41-L41)/(H41-L41), X41);$
LYKOH	-	(141-141)*X41+141; CALL DANTEL (CEREA) (M/) 1/0//(4/) 1/0/ 4/0/
זתפפעק	<b>,</b>	UALL RANIKI (SEEU42, $(M42-L42)/(H42-L42), X42);$ ( $U(2) = I(2) + V(2) = I(2).$
	-	(144744)"8447444; CALL DANTDI (SERDA3 (9634143)//0634143) 963).
EXPROM	-	(H43-I.43)*X43+I.43
on ton		CALL RANTRI (SFFD44 (M44-144)//444-144) V44).
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EXPRDH (H44 - L44) \* X44 + L44;CALL RANTRI (SEED45, (M45-L45)/(H45-L45), X45); ACONDL (H45-L45)\*X45+L45: CALL RANTRI (SEED46, (M46-L46)/(H46-L46), X46); (H46-L46)\*X46+L46: ACONDM = CALL RANTRI (SEED47, (M47-L47)/(H47-L47), X47); ACONDH (H47-L47)\*X47+L47; = CALL RANTRI (SEED48, (M48-L48)/(H48-L48), X48); FUELTP (H48-L48)\*X48+L48; CALL RANTRI (SEED49, (M49-L49)/(H49-L49), X49); FUELTC (H49 - L49) \* X49 + L49;CALL RANTRI (SEED50, (M50-L50)/(H50-L50), X50); FUEL (H50-L50)\*X50+L50;CALL RANTRI (SEED51, (M51-L51)/(H51-L51), X51); CMH  $(H51 - L51) \times X51 + L51;$ PL 1 - EXP (-SMI/MTBFL);PM 1 - EXP (-SMI/MTBFM);1 - EXP (-SMI/MTBFH);PH  $KL \star (1-RTSL);$ NRTSL  $KM \star (1-RTSM);$ NRTSM KH \* (1-RTSH); NRTSH (MTBFL+MTBFM+MTBFH)/3; MTBF TSMA AFH/SMI; TUMAL PL \* TSMA; TU MAM PM \* TSMA; -TUMAH PH \* TSMA; = TU MA = TUMAL + TUMAM + TUMAH; NMA TUMA + TSMA; = BRTCS TSMA \*((QPESL\*RTSL\*BURCL)+ (QPESM\*RTSM\*BURCM) + (QPESH\*RTSH\*BURCH)); BRTCU TUMAL \*((QPEUL\*RTSL\*BURCL) + (QPESM\*RTSM\*BURCM) + (QPESH\*RTSH\*BURCH)) + TUMAM\*((QPESL\*RTSL\*BURCL) + (QPEUM\*RTSM\*BURCM) + (QPESH\*RTSH\*BURCH)) + TUMAH\*((QPESL\*RTSL\*BURCL) + (QPESM\*RTSM\*BURCM) + (QPEUH\*RTSH\*BURCH)); BRTC BRTCS + BRTCU; TSMA \*((QPESL\*NRTSL\*(1-DCONDL)\*DURCL) DRTCS + (QPESM\*NRTSM\*(1-DCONDM)\*DURCM) + (QPESH\*NRTSH\*(1-DCONDH)\*DURCH)); DRTCU TUMAL \*((OPEUL\*NRTSL\*(1-DCONDL)\*DURCL) + (QPESM\*NRTSM\*(1-DCONDM)\*DURCM) + (QPESH\*NRTSH\*(1-DCONDH)\*DURCH)) + TUMAM \* ((QPESL\*NRTSL\*(1-DCONDL)\*DURCL)

		<pre>+ (QPESH*NRTSH*(1=DCONDH)*DURCH) + (QPESH*NRTSH*(1=DCONDH)*DURCH)) + TUMAH*((QPESL*NRTSL*(1=DCONDL)*DURCL) + (QPESM*NRTSM*(1=DCONDM)*DURCM) + (QPEUH*NRTSH*(1=DCONDH)*DURCH));</pre>
DRTC	72	DRTCS + DRTCU;
MHMA	2	MHRE + MHIE + MHTE + MHTB;
MCOST	-	(TSMA + TUMA)*MHMA*CMH;
TMALC	2	(MHMA * (TSMA + TUMA) + (TSMA*MHSMA) + (TUMA*MHUMA))*CMH;
EXPMS	2	TSMA *(EXPSL+EXPSM+EXPSH);
EXPMU	=	(TUMAL *(EXPUL+EXPSM+EXPSH))+ (TUMAM * (EXPSL+EXPUM+EXPSH)) + (TUMAH * (EXPSL+EXPSM+EXPUH));
EXPM	=	EXPMS + EXPMU;
EXAS	2	EXPSL + EXPSM + EXPSH;
EXAU	-	EXPUL + EXPUM + EXPUH;
EXM	=	EXPM/(TSMA+TUMA);
TOTL	3	QPESL * ( TSMA +TUMAM+TUMAH)+ (QPEUL*TUMAL);
TOTM	Ŧ	QPESM * ( TSMA +TUMAL+TUMAH)+ (QPEUM*TUMAM);
Toth	=	QPESH * ( TSMA +TUMAL+TUMAM)+ (QPEUH*TUMAH);
TR TRR	2	TOTL + TOTM + TOTH; TR/(TSMA+TUMA);
TOTLRB TOTLRD	=	TOTL * RTSL; TOTL * NRTSL*(1-DCONDL);
TOTMRB TOTMRD	3 2	TOTM * RTSM; TOTM * NRTSM*(1-DCONDM);
TOTHRB TOTHRD	2	TOTH * RTSH; TOTH * NRTSH*(1-DCONDH);
TRB TRD		TOTLRB + TOTMRB + TOTHRB; TOT'RD + TOTMRD + TOTHRD;
BRT	3	TRB/TR;
DKI	<b>a</b>	100/10,
DURC	3	DRTC/TRD;

DCONDW +DUDCW

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TEXPRBS	-	TSMA * ((QPESL*RTSL*EXPRBL)+(QPESM*RTSM*EXPRBM) + (QPESH*RTSH*EXPRBH));
TEXPRDS	3	TSMA * ((QPESL*NRTSL*(1-DCONDL)*EXPRDL) + (QPESM*NRTSM*(1-DCONDM)*EXPRDM) + (QPESH*NRTSH*(1-DCONDH)*EXPRDH));
TEXPRBU	-	<pre>TUMAL *((QPEUL*RTSL*EXPRBL) + (QPESM*RTSM*EXPRBM) +(QPESH*RTSH*EXPRBH)) + TUMAM *((QPESL*RTSL*EXPRBL) + (QPEUM*RTSM*EXPRBM)+(QPESH*RTSH*EXPRBH)) + TUMAH*((QPESL*RTSL*EXPRBL)+(QPESM*RTSM*EXPRBM) + (QPEUH*RTSH*EXPRBH));</pre>
<b>TEXP RDU</b>	2	<pre>TUMAL *((QPEUL*NRTSL*(1-DCONDL)*EXPRDL) + (QPESM*NRTSM*(1-DCONDM)*EXPRDM) + (QPESH*NRTSH*(1-DCONDH)*EXPRDH)) + TUMAM * ((QPESL*NRTSL*(1-DCONDL)*EXPRDL) + (QPEUM*NRTSM*(1-DCONDM)*EXPRDM) + (QPESH*NRTSH*(1-DCONDH)*EXPRDH)) + TUMAH*((QPESL*NRTSL*(1-DCONDL)*EXPRDL) + (QPESM*NRTSM*(1-DCONDM)*EXPRDM) + (EXPUH*NRTSH*(1-DCONDH)*EXPRDH));</pre>
TEXPR	=	TEXPRBS + TEXPRDS+ TEXPRBU + TEXPRDU;
EXPRB	=	EXPRBL + EXPRBM + EXPRBH;
EXPRD	=	EXPRDL + EXPRDM + EXPRDH;
EXPR	=	TEXPR/(TSMA+TUMA);
EXPPR	=	TEXPR/(TRB+TRD);
CONDS	3	<pre>(TSMA*QPESL*((1-RTSL-NRTSL)+(NRTSL*DCONDL))*ACONDL) + (TSMA*QPESM*((1-RTSM-NRTSM)+(NRTSM*DCONDM))*ACONDM) + (TSMA*QPESH*((1-RTSH-NRTSH)+(NRTSH*DCONDH))*ACONDH);</pre>
CONDU	2	<pre>(TUMAL*QPEUL*((1-RTSL-NRTSL)+(NRTSL*DCONDL))*ACONDL) + (TUMAL*QPESM*((1-RTSM-NRTSM)+(NRTSM*DCONDM))*ACONDM) + (TUMAL*QPESH*((1-RTSH-NRTSH)+(NRTSH*DCONDH))*ACONDH) + (TUMAM*QPESL*((1-RTSL-NRTSL)+(NRTSL*DCONDL))*ACONDL) + (TUMAM*QPEUM*((1-RTSM-NRTSM)+(NRTSM*DCONDM))*ACONDM) + (TUMAM*QPESH*((1-RTSH-NRTSH)+(NRTSH*DCONDH))*ACONDH) + (TUMAH*QPESL*((1-RTSL-NRTSL)+(NRTSL*DCONDL))*ACONDH) + (TUMAH*QPESM*((1-RTSM-NRTSM)+(NRTSM*DCONDL))*ACONDL) + (TUMAH*QPESM*((1-RTSM-NRTSM)+(NRTSM*DCONDM))*ACONDM) + (TUMAH*QPEUH*((1-RTSH-NRTSH)+(NRTSH*DCONDH))*ACONDM)</pre>
TCONST	=	CONDU + CONDS;
COSTFU	=	(TSMA+TUMA) * (FUELTP + FUELTC) * FUEL;

TMCS (MCOST/TSMA) + (EXAS + MHSMA \*CMH); TMCU (MCOST/TUMA) + (EXAU + MHUMA \*CMH); TMCM ((TMCS \* TSMA)+ (TMCU \*TUMA))/ (TSMA + TUMA); BURC + EXPRB; TURCB TURCD DURC + EXPRD; URC ((TURCB \* TRB)+ ( TURCD \* TRD )) / (TRB + TRD); TCONST /(TRB+TRD); CONDR BRTC + DRTC + TMALC + EXPM + TEXPR + TCONST + COSTFU; TOTCOST =FILE RESULTS2:

PUT REP AFH MTBFL MTBFM MTBFH SMI QPESL QPESM QPESH QPEUL QPEUM QPEUH RTSL RTSM RTSH NRTSL NRTSM NRTSH DCONDL DCONDM DCONDH BURCL BURCM BURCH DURCL DURCM DURCH MHRE MHIE MHTE MHTB MHSMA MHUMA EXPSL EXPSM EXPSH EXPUL EXPUM EXPUH EXPRBL EXPRBM EXPRBH EXPRDL EXPRDM EXPRDH ACONDL ACONDM ACONDH FUELTP FUELTC FUEL CMH MCOST TUMA TSMA MTBF NMA EXAS EXAU EXM EXPRB EXPRD EXPR TCONST TOTL TOTM TOTH TOTLRB TOTLRD TOTMRB TOTMRD TOTHRB TOTHRD TR TRR TRB TRD BRT DRT BURC DURC TMCS TMCU TMCM TURCB TURCD URC CONDR EXPPR TOTCOST; END;

Appendix C: Thesis Database

R MTBF	29 3117.17	80 3869.49	12 3773.38	90 3854.22	95 4100.37	16 3842.33	49 3444.34	16 4233.21	77 3574.04	18 3602.26	18 4115.42	67 4930.48	51 3476.24	89 3392.47	81 4046.34	76 3759.98	50 2938.57	09 3596.80	43 3522.08	17 3876.30	90 3556.17	24 3853.27	69 3408.20	50 3366.76	82 3421.10	22 3287.54	21 3104.67	79 3411.30	94 2933.08	53 3790.81	55 4141.37
RECITR	0.00948	0.00959	0.01049.	0.01051	0.01107	0.01211	0.00806	0.01201	0.01094	0.01038	0.01087	0.008616	0.01346	0.010478	0.00919	0.01110.0	0.01583	0.00873	0.00739	0.00967	0.008635	0.01055	0.01065	0.00836	0.00773	0.01024	0.00913	0.00970	0.01186	0.01154	0.01220
SQEXPPR	119.491	117.907	107.861	113.555	107.086	115.938	80.872	132.193	97.067	115.072	117.426	80.595	105.022	143.174	100.450	84.765	143.732	76.189	101.543	80.388	105.393	112.437	89.735	60.382	89.660	71.715	92.453	102.859	128,948	138.392	97.438
DRT	0.304156	0.312568	0.327943	0.320053	0.325553	0.233533	0.302437	0.277584	0.349839	0.290293	0.355250	0.319716	0.347365	0.331478	0.298879	0.221522	0.288013	0.331044	0.330536	0.333601	0.324916	0.342786	0.318342	0.224225	0.326349	0.295566	0.399550	0.327350	0.351675	0.298410	0.239729
BRT	0.594962	0.577556	0.580678	0.584887	0.581703	0.662813	0.587165	0.621105	0.554478	0.574463	0.491859	0.563338	0.523590	0.498730	0.615704	0.699896	0,606239	0.552143	0.564955	0.556375	0.556269	0.549307	0.568520	0.714707	0.515807	0.586200	0.500496	0.561803	0.506421	0.586484	0.653615
TSMA	0.320690	0.351693	0.407247	0.247374	0.336647	0.300235	0.444318	0.428392	0.287846	0.457885	0.358117	0.268320	0.430144	0.306127	0.353538	0.316499	0.361953	0.336297	0.289412	0.279037	0.254877	0.377482	0.362666	0.392000	0.342318	0.336845	0.331415	0.425191	0.291625	0.268525	0.438212
NMA	0.70098	0.80248	0.81875	0.50780	0.65666	0.61937	0.96263	0.82692	0.67413	0.93791	0.77113	0.52267	0.90356	0.69629	0.68317	0.72676	0.73008	0.69408	0.66570	0.62584	0.60119	0.83312	0.81020	0.80186	0.71267	0.70204	0.71749	0.85344	0.79552	0.62373	0.84232
TOTCOST	1065803	1153114	963130	643108	733366	685749	828532	1196395	653273	1202105	962874	451400	749723	1222568	829674	508900	962011	525486	930419	485187	840659	1042134	640311	427409	756221	427889	751988	941455	1115257	1019931	693131
OBS	33	3 <b>4</b>	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63

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MTBF	2885.66	3041.70	3614.54	3873.42	4007.21	3523.73	3023.98	3094.87	3489.97	4096.61	3510.32	2845.64	3251.55	4261.95	3340.76	4093.11	3934.12	3259.74	4689.45	3775.86	4381.16	2942.97	3531.15	3805.80	3173.43	3309.70	3835.14	3282.43	3232.79	3267.32	3074.98	3900.74
RECITRR	0.0114135	0.0095716	0.0118108	0.0089283	0.0116363	0.0083657	0.0094027	0.0107717	0.0114902	0.0104397	0.0120061	0.0100332	0.0132413	0.0097329	0.0134469	0.0115848	0.0087445	0.0118035	0.0100738	0.0116199	0.0098181	0.0085128	0.0129605	0.0099482	0.0079823	0.0112148	0.0117767	0.0131503	0.0111756	0.0110094	0.0096929	0.0118036
SQEXPPR	98.396	105.009	126.146	116.667	77.775	83.494	96.340	111.726	127.378	82.086	132.879	98.102	121.410	71.156	117.209	100.903	99.038	133.374	82.625	130.045	75.760	108.257	106.979	93.702	94.727	92.637	101.806	121.174	128.616	111.634	114.102	94.205
DRT	0.295236	0.305306	0.344682	0.381837	0.280799	0.320307	0.305538	0.251533	0.336589	0.288062	0.258640	0.406365	0.332823	0.304595	0.341899	0.345533	0.345323	0.245767	0.268813	0.378324	0.315293	0.307050	0.324660	0.336568	0.259101	0.302107	0.355425	0.308786	0.354130	0.341980	0.363228	0.285369
BRT	0.584817	0.614666	0.568693	0.480908	0.600660	0.523430	0.604517	0.638732	0.588554	0.620700	0.654351	0.469091	0.563834	0.576990	0.559152	0.553089	0.550861	0.639660	0.648698	0.520175	0.581606	0.583219	0.506781	0.526282	0.652861	0.606962	0.507608	0.555945	0.512798	0.572676	0.515799	0.630115
TSMA	0.301857	0.354428	0.393617	0.467191	0.458782	0.293805	0.377101	0.285217	0.288004	0.277260	0.427085	0.556190	0.401062	0.363349	0.420377	0.313298	0.340478	0.481941	0.293652	0.270792	0.438212	0.517632	0.423728	0.310353	0.338628	0.353005	0.289400	0.374781	0.254753	0.386855	0.479911	0.354025
NMA	0.66151	0.77571	0.79442	0.97853	0.83023	0.64627	0.80685	0.70881	0.65915	0.59148	0.90058	1.14364	0.82858	0.67902	0.92262	0.66215	0.72445	0.98437	0.52780	0.71359	0.80810	1.16687	0.90720	0.71544	0.78545	0.72009	0.55807	0.81796	0.56137	0.87630	1.07291	0.70662
TOPCOST	606429	937526	1112055	1538917	485410	626968	839606	811522	975977	462264	1316265	1120173	937718	463403	963425	628033	886951	1416011	412961	1065953	580798	1643417	772441	683074	904585	597433	487968	909327	799853	1049482	1524899	624423
OBS	65	66	67	68	69	70	11	72	73	74	75	76	77	78	61	80	81	82	83	84	85	86	87	88	89	06	16	92	93	94	95	96

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2939.58 3336.96 3712.70 3925.40 4032.94 3172.17 3475.18 3168.16 3252.15 3756.19 3909.45 4044.30 3926.99 3740.45 3930.68 4423.95 3375.68 4291.38 3402.56 3234.46 3550.39 3276.36 3657.62 3268.74 4084.81 3319.03 3864.91 4344.76 3867.32 3752.02 2697.81 2998.41 MTBF 0.0107018 0.0102230 0.0129210 0.0117035 0.0084684 0.0112119 0.0102902 0.0105868 0.0090898 0.0107722 0.0096081 0.0135385 0.0101038 0.0075907 0.0079312 0.0103885 0.0092513 0.0118396 0.0103271 0.0112303 0.0128119 0.0116305 0.0106512 0.0121785 0.0121107 0.0116309 0.0112482 0.0084918 0.0108808 0.0118120 0.0089158 0.0110576 RECITRR SQEXPPR 119.448 130.749 109.283 39.964 05.299 117.174 129.628 89.076 32.319 95.224 92.244 .03.450 84.426 .18.810 115.418 75.965 138.636 77.863 29.467 13.720 74.613 114.249 23.608 31.503 80.614 .13.836 07.006 86.261 .09.832 .15.391 05.214 23.322 0.370460 0.272420 0.268120 0.292096 0.288758 0.325005 0.373296 0.331426 0.297405 0.253509 0.382419 0.273976 0.238779 0.283235 0.284444 0.383002 0.267354 0.276024 0.356493 0.328772 0.339255 0.302937 0.362857 0.315308 0.295918 0.322243 0.249112 0.380607 0.247207 0.308477 0.305221 0.290521 DRT 0.644833 0.550685 0.674640 0.516260 0.588230 0.616003 0.576520 0.685685 0.622140 0.500755 0.611288 532920 0.539340 0.522456 0.614009 0.513814 0.646416 0.675943 0.516563 0.651316 0.614527 0.625271 0.621897 0.560640 0.576264 0.502100 585059 0.473761 0.638457 0.503791 0.551151 0.589091 BR'T . . 0.425410 0.408116 0.417494 0.325767 0.386269 0.300559 0.372858 0.366976 0.447326 0.291385 0.290075 0.484266 0.375412 0.435673 0.425574 0.357003 0.493143 0.281103 0.446022 0.413414 0.365758 0.263795 0.245387 0.271726 0.499962 0.346362 0.351450 0.351595 0.441712 0.344127 0.375931 0.287491 TSMA 0.80100 0.68630 0.98978 0.99029 0.90173 0.82550 0.70264 0.83194 0.79638 0.90303 0.64634 0.84342 0.79685 1.04035 0.72122 0.83609 0.90242 0.89796 0.79157 0.79067 0.59378 0.63508 0.57922 0.83385 72385 1.07627 0.66094 0.81247 0.66006 0.66261 1.10402 0.74661 NMA . . 725350 655832 002269 584518 446264 1622290 232530 757389 804699 302786 1073156 737468 1127843 1327374 918402 113275 927779 1061306 552322 TOTCOST 973802 696107 783103 268291 1058972 456871 511577 627087 877021 409692 705307 586203 044155 OBS 00 .05 106 108 109 110 112 113 L14 115 116 113 19 20 122 123 124 125 128 02 07 111 117 21 126 127 97 98 03 04 66 01

MTBF	3614.94	3288.57	4024.43	3698.63	3755.58	3622.75	3522.84	2934.24	3188.38	3795.71	3182.88	3588.11	3065.56	3525.86	3310.35	3391.44	4056.86	4588.85	4285.40	3965.85	3642.58	3894.61	2802.43	3959.27	3452.33	3199.92	3087.51	3635.48	3426.52	3141.73	3733.98	3146.87
RECITRR	0.0104166	0.0082350	0.0078810	0.0098620	0.0095471	0.0100135	0.0099522	0.0154474	0.0100186	0.0084613	0.0155632	0.0137130	0.0085501	0.0095582	0.0099658	0.0102085	0.0118135	0.0091044	0.0124655	0.0102448	0.0094140	0.0117121	0.0122573	0.0093120	0.0092160	0.0144719	0.0114386	0.0091253	0.0104823	0.0090527	0.0131226	0.0093631
SQEXPPR	122.977	88.040	100.109	119.542	149.760	114.114	94.533	142.565	112.331	101.219	154.740	128.764	99.486	110.167	95.853	79.464	90.834	83.061	104.530	91.667	93.738	111.975	115.522	113.685	96.832	156.661	109.803	139.281	94.829	107.797	116.978	105.212
DRT	0.244195	0.320095	0.386713	0.380200	0.307047	0.308884	0.350752	0.311190	0.351544	0.243272	0.338645	0.224164	0.350719	0.280621	0.295499	0.341455	0.309829	0.373360	0.342991	0.236825	0.355514	0.355106	0.281294	0.306494	0.305294	0.322254	0.279802	0.393938	0.394145	0.318682	0.283596	0.275908
BRT	0.686039	0.539840	0.481334	0.510296	0.570265	0.587424	0.559568	0.607911	0.554818	0.670404	0.532140	0.707594	0.496295	0.610777	0.610918	0.525142	0.570758	0.497791	0.535109	0.658081	0.555461	0.528189	0.630278	0.584230	0.571524	0.549162	0.630422	0.485246	0.500552	0.518910	0.559332	0,603321
TSMA	0.272443	0.282596	0.331586	0.374080	0.343654	0.255773	0.310659	0.323403	0.356374	0.312811	0.379730	0.442361	0.400843	0.269383	0.394604	0.438992	0.333806	0.320264	0.349238	0.385005	0.474580	0.275934	0.322481	0.352431	0.396578	0.387587	0.338635	0.367014	0.324787	0.446958	0.222350	0.337736
NMA	0.70395	0.66518	0.69279	0.79909	0.88896	0.57019	0.66696	0.81014	0.72831	0.68176	0.79189	0.91742	0.89561	0.65933	0.73878	0.86233	0.66412	0.59151	0.74336	0.75100	0.95409	0.64933	0.77815	0.84339	0.78432	0.88460	0.70195	0.85044	0.66618	0.88990	0.52545	0.75377
TOTCOST	1047426	680927	934781	1149313	1959612	755249	656471	1086276	973661	892552	1163319	1126487	1095935	853554	724020	579889	500594	524701	680132	675123	957798	686052	867940	1178637	871328	1425892	777504	1804807	640220	1116454	533459	889119
OBS	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160

CALL CONTRACT STREET

TOTCOST		NMA	TSMA	BRT	DRT	SQEXPPR	RECITRR	MTBF
958957 0.78414 0.4	0.78414 0.4	0.4	04905	0.568855	0.322786	104.180	0.0088655	3817.77
911349 0.82332 0.36	0.82332 0.36	0.36	32884	0.498204	0.379641	110.600	0.0116604	3377.91
1272278 0.80121 0.41	0.80121 0.41	0.41	5593	0.573450	0.331530	112.636	0.0080767	3601.94
1041979 0.98874 0.457	0.98874 0.457	0.45	1991	0.531550	0.349966	93.767	0.0093060	3917.15
648496 0.72115 0.343	0.72115 0.343	0.343	1225	0.698368	0.214126	98.206	0.0110858	3553.97
1117458 0.74512 0.367	0.74512 0.36	0.36	1224	0.499194	0.358691	110.730	0.0082831	4060.33
761945 0.86431 0.450	0.86431 0.450	0.45(	)545	0.656499	0.245077	95.573	0.0107811	3224.26
535927 0.68377 0.313	0.68377 0.313	0.313	3506	0.548868	0.342425	76.749	0.0089033	3032.50
763671 0.73519 0.347	0.73519 0.347	0.347	1647	0.560290	0.345331	114.661	0.0133545	3433.76
1443072 1.11733 0.552	1.11733 0.552	0.552	610	0.571626	0.294359	110.957	0.0094143	3648.89
1145432 0.85616 0.388	0.85616 0.388	0.388	495	0.564962	0.327371	146.545	0.0157843	4075.55
790800 0.66498 0.273	0.66498 0.273	0.273	857	0.626236	0.246782	114.319	0.0108904	3109.74
733221 0.82587 0.412	0.82587 0.412	0.412	036	0.535556	0.334193	91.592	0.0100118	3741.59
1040746 0.86132 0.410	0.86132 0.410	0.410	303	0.721161	0.211994	106.219	0.0096141	3787.06
727745 0.67666 0.288	0.67666 0.288	0.288	018	0.648484	0.258237	106.516	0.0115057	2877.78
949909 0.90571 0.415	0.90571 0.415	0.415	238	0.565558	0.307036	106.327	0.0110801	3195.72
753599 0.67536 0.345	0.67536 0.345	0.345	696	0.517864	0.363160	101.347	0.0098825	3231.21
493493 0.52043 0.234	0.52043 0.234	0.234	274	0.567805	0.339241	107.856	0.0128430	3450.24
1199337 0.74039 0.308	0.74039 0.308	0.308	306	0.559950	0.330017	125.947	0.0096557	3771.95
687226 0.63294 0.299	0.63294 0.299	0.299	299	0.468325	0.431327	96.521	0.0095247	3724.56
588767 0.71935 0.317	0.71935 0.317	0.317	174	0.640775	0.279225	85.844	0.0102239	3643.51
1229115 0.63762 0.289	0.63762 0.289	0.289	332	0.587693	0.295851	132.349	0.0088525	3299.91
1003184 0.85434 0.404	0.85434 0.404	0.404	891	0.548594	0.324069	115.941	0.0115321	3522.94
1059270 1.01252 0.554	1.01252 0.554	0.554	1786	0.559313	0.312907	104.133	0.0109122	4006.02
735302 0.63081 0.271	0.63081 0.271	0.271	792	0.581188	0.306255	119.219	0.0117182	4068.62
843536 0.66171 0.317	0.66171 0.317	0.317	505	0.548274	0.344532	113.208	0.0103344	3763.14
1475576 0.75005 0.346	0.75005 0.346	0.346	495	0.568862	0.353938	144.785	0.0104806	3721.40
1087521 0.74979 0.331	0.74979 0.331	0.331	586	0.633586	0.271760	155.781	0.0162619	3761.41
736v54 0.65396 0.28	0.65396 0.28	0.28	3604	0.598710	0.264093	104.954	0.0092405	3906.22
1043808 0.81565 0.38	0.81565 0.38	0.38	5618	0.567652	0.341955	118.022	0.0109859	3150.07
993144 0.71833 0.290	0.71833 0.290	0.29(	0846	0.603465	0.280571	138.092	0.0135334	2954.17
1108875 0.89108 0.371	0.89108 0.371	0.371	.820	0.541618	0.354200	120.058	0.0115407	3265.02

R MTBF	17 3622.17	11 3227.33	33 4649.05	53 3887.97	32 2948.61	98 3982.28	58 3729.85	52 3954.94	59 3529.71	53 3354.01	21 3216.64	79 3331.53	21 3939.55	77 3187.32	57 4231.09	55 3490.46	23 3410.87	72 4019.55	21 3560.72	17 3239.19	00 3201.64	78 3423.15	58 3959.36	35 4061.21	58 3457.74	72 2991.98	23 3482.32	90 3355.42	35 4067.81	74 3657.66	06 2901.82	12 4448.43
RECITRI	0.01107	0.009151	0.009239	0.008796	0.010165	0.010100	0.009725	0.009655	0.00997	0.009966	0.009292	0.00988	0.012542	0.011077	0.008536	0.009026	0.010862	0.012267	0.009713	0.010811	0.01074(	0.011457	0.009756	0.008648	0.009946	0.010927	0.009102	0.010619	0.010378	0.011517	0.009710	0.01118]
SQEXPPR	112.085	78.009	97.106	84.503	85.470	101.232	90.362	112.265	118.235	103.602	105.303	98.619	130.213	137.640	87.557	71.336	151.769	119.143	110.896	90.956	118.706	117.349	78.361	76.383	101.774	145.335	113.231	89.619	101.539	89.112	106.756	95.556
DRT	0.294744	0.281233	0.276232	0.230132	0.234505	0.333823	0.280165	0.272485	0.296365	0.284960	0.279481	0.280568	0.287925	0.309739	0.218417	0.251310	0.407580	0.318516	0.306891	0.262108	0.256878	0.246959	0.377479	0.318766	0.330072	0.294156	0.392238	0.350495	0.275374	0.268745	0.315543	0.279425
BRT	0.585394	0.614519	0.629256	0.652439	0.700918	0.553242	0.627668	0.587454	0.620366	0.608669	0.630755	0.605197	0.621696	0.536322	0.693549	0.664566	0.452124	0.560892	0.596628	0.654670	0.622215	0.641482	0.483076	0.543252	0.584611	0.588188	0.498564	0.554467	0.637251	0.645479	0.598882	0.646304
TSMA	0.300068	0.396830	0.292559	0.272857	0.286067	0.415946	0.458749	0.318406	0.361093	0.312682	0.296388	0.425864	0.457737	0.442776	0.361445	0.268098	0.341238	0.433033	0.394860	0.348200	0.366423	0.347258	0.45228	0.327681	0.388927	0.365917	0.321269	0.384726	0.246450	0.478037	0.376921	0.374707
NMA	0.61030	0.86297	0.59577	0.57342	0.67699	0.79477	0.86788	0.71542	0.81936	0.67091	0.73055	0.83139	0.98248	0.99393	0.70322	0.56069	0.85582	0.83189	0.85562	0.76368	0.82474	0.77709	0.82230	0.61010	0.82064	0.95280	0.70969	0.73430	0.49723	0.94520	0.82010	0.79449
TOTCOST	712963	656943	637637	476478	547909	854974	821327	933106	1191868	731853	919723	873597	1328879	1584614	678944	383217	1748774	968225	1133833	659538	1065879	937423	611546	4656 <b>u</b> 1	956514	1780092	1073221	602553	512784	716417	986708	686660
OBS	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224

4127.24 2857.75 4055.70 4058.84 3656.79 2939.30 3687.84 3653.16 3186.55 3806.02 4166.98 3221.52 4334.08 3193.05 3392.14 4288.40 3740.95 3520.09 3402.79 3568.51 2843.47 3359.36 3418.63 3341.07 3616.01 3572.21 MTBF 0.0090958 0.0116396 0.0087969 0.0100623 0.0111485 0.0114618 0.0081380 0.0143275 0.0096708 0.0092548 0.0105899 0.0101190 0.0120892 0.0112705 0.0090543 0.0112426 0.0140729 0.0100165 0.0136772 0.0093399 0.0110954 0.0118551 0.0093204 0.0092793 0.0078753 0.0083741 RECITRR SQEXPPR 87.735 91.515 49.258 176.238 97.748 91.807 86.978 97.350 14.738 79.222 126.005 91.023 92.882 00.966 77.157 94.053 44.847 93.156 76.696 112.626 85.492 .06.747 106.997 105.342 06.921 73.161 0.242980 0.345310 0.285533 0.263263 0.322389 0.230983 0.260169 0.349736 0.404100 0.260765 0.321054 0.322981 0.299371 0.302443 0.356834 0.321432 0.343334 0.296127 0.326110 0.345926 0.339324 0.281204 0.351103 0.264421 0.330811 0.28758 DRT 0.569437 0.542585 0.455799 0.662038 0.528410 0.600280 0.546188 0.500622 564248 0.505560 0.629958 0.549496 577317 0.617464 0.532779 0.609128 0.522144 0.663155 0.570397 0.648196 0.635126 0.641211 0.605631 0.577337 0.586362 0.579193 BR'T 0 0 0.293398 0.312220 0.341388 0.499558 0.251820 0.282638 0.321906 0.340064 0.412514 0.579672 0.281329 U.296505 0.332160 0.317834 0.247169 0.467447 0.518086 0.297919 0.342524 0.363877 0.372192 0.390147 0.377262 0.426577 0.349331 0.402027 TSMA 0.73120 0.77345 0.72240 0.93670 0.75785 0.72135 0.85204 0.63517 0.71950 0.66059 0.72686 0.72686 0.81091 1.11953 0.73888 0.63899 0.75178 0.78409 0.55891 0.90925 1.14898 0.71647 0.60361 0.79411 0.74901 0.63141 NMA 724633 747959 612958 185499 610154 758735 617980 845282 518413 951201 565357 589803 562473 640519 447030 848263 601762 591101 1256893 918802 893291 TUTCOST 826581 703177 452791 092851 64444OBS 235 238 239 240 244 245 225 226 227 228 229 230 231 232 233 234 236 237 241 242 243 246 247 243 249 250

Service Services

Appendix D: Outlier Statistics

OBS	SRESID	LEVERAGE	COOKD
1	0.4066	0.0263583	0.000559
2	0.4509	0.0196528	0.000509
3	0.2234	0.0253819	0.000162
4	-1.0065	0.0235220	0.003050
5	-0.0990	0.0285435	0.000036
6	-1.0297	0.0311139	0.004256
7	0.8695	0.0175330	0.001687
8	-0.7192	0.0370938	0.002491
9	0.5376	0.0185283	0.000682
10	4.1406	0.0481957	0.108516
11	-0.8646	0.0259164	0.002486
12	-0.0534	0.0190310	0.000007
13	-1.2677	0.0253137	0.005217
14	-0.2180	0.0650025	0.000413
15	-0.7140	0.0377093	0.002497
16	-0.4488	0.0179192	0.000459
17	0.2652	0.0203317	0.000182
18	-0.6269	0.0207945	0.001043
19	-1.6586	0.0394756	0.014132
20	0.4977	0.0229407	0.000727
21	0.5274	0.0245153	0.000874
22	0.0967	0.0229639	0.000027
23	-0.7885	0.0419548	0.003404
24	-0.8045	0.0153443	0.001261
25	-0.4438	0.0586176	0.001533
26	-0.6567	0.0254714	0.001409
27	0.4863	0.0179223	0.000539
28	-0.2984	0.0095292	0.000107
29	-0.3133	0.0258831	0.000326
30	-0.2256	0.0252186	0.000165
31	0.1034	0,0302105	0.000042
32	-0.5062	0.0347455	0.001153
33	-0.2468	0.0220713	0.000172
34	-0.5626	0.0156901	0.000631
35	-0.3251	0.0143301	0.000192
36	-1 0106	0 0282331	0.003709
37	-0 0185	0 0204147	0.000001
38	-0 1984	0 0287819	0.000146
39	-2 0809	0.0289044	0.000140
40	-2.0009	0 0460344	0 00017
<u>4</u> 0 <u>4</u> 1	0.0527	0.0400344	0.000017
42	0.3001	0.0201414	0.000435
42	_1 0700	0.0203140	0.000047
43	-1.0780	0.0506035	0.004341
	0.7641	0.0397035	0.000774
40	-0.4303	0.033/026	0.000884

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OBS	SRESID	LEVERAGE	COOKD
46	-1.6926	0.0548954	0.020802
47	0.1936	0.0245590	0.000118
48	0.6712	0.0437417	0.002576
49	0.8945	0.0688106	0.007392
50	0.3117	0.0182989	0.000226
51	-0.7449	0.0254774	0.001813
52	1.0151	0.0273464	0.003621
53	0.0145	0.0198763	0.000001
54	-0.4675	0.0131072	0.000363
55	-0.7705	0.0183729	0.001389
56	0.0471	0.0522360	0.0000153
57	-0.4544	0.0398151	0.0010703
58	2.1814	0.0313287	0.0192383
59	-0.2552	0.0399712	0.0003390
60	-0.9657	0.0134440	0.0015884
61	-0.4502	0.0496585	0.0013236
62	-1.4603	0.0252518	0.0069057
63	0.2945	0.0326762	0.0003662
64	3.4306	0.0339696	0.0517324
65	1.0960	0.0318075	0.0049330
66	-0.4067	0.0217066	0.0004589
67	-0.0357	0.0266990	0.0000044
68	2.4587	0.0476841	0.0378361
69	1.1884	0.0353251	0.0064644
70	1.0835	0.0401988	0.0061466
71	-0.6569	0.0192928	0.0010612
72	-0.8250	0.0272186	0.0023805
73	-0.7081	0.0284831	0.0018378
74	2.1252	0.0269303	0.0156244
75	0.4046	0.0283774	0.0005976
76	-2.3509	0.0699810	0.0519845
77	-0.1684	0.0210493	0.0000762
78	2.4725	0.0261470	0.0205166
79	-0.5566	0.0293695	0.0011719
80	0.1758	0.0220434	0.0000871
81	-0.1914	0.0160808	0.0000748
82	0.5489	0.0454316	0.0017926
83	1.9726	0.0486210	0.0248585
84	-1.0781	0.0453754	0.0069063
85	0.9694	0.0310464	0.0037635
86	1.8697	0.0563799	0.0261071
87	-0.9280	0.0546175	0.0062198
88	-0.1638	0.0255610	0.0000879
89	-0.7127	0.0281463	0.0018390
90	0.5313	0.0166096	0.0005961
91	0.4508	0.0321873	0.0008447
92	-0.1893	0.0222124	0.0001018
93	-1.9676	0.0340210	0.0170431
94	-0.4173	0.0211606	0.0004706
95	1.7054	0.0360030	0.0135770

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OBS	SRESID	LEVERAGE	COOKD
96	1.6337	0.0179173	0.0060870
97	0.6235	0.0906045	0.0048409
98	-0.1272	0.0275005	0.0000572
99	-2.2039	0.0513332	0.0328536
100	-0.2917	0.0176669	0.0001913
101	-0.4786	0.0211367	0.0006182
102	-0.3800	0.0195365	0.0003597
103	0.2728	0.0426143	0.0004141
104	-0.2153	0.0317610	0.0001901
105	-0.6088	0.0274945	0.0013098
106	-0.6637	0.0700753	0.0041488
107	-0.7073	0.0289753	0.0018659
108	-0.3995	0.0229653	0.0004690
109	0.7330	0.0350195	0.0024371
110	0.3448	0.0266771	0.0004072
111	-0.1659	0.0477012	0.000172
112	-1.3864	0.0465037	0.011718
113	0.7933	0.0130109	0.001037
114	0.5185	0.0261851	0.000903
115	2.8273	0.0602520	0.064065
116	1.6285	0.0367704	0.012655
117	0.4573	0.0364454	0.000989
118	-1.1184	0.0284994	0.004586
119	0.1574	0.0273980	0.000087
120	1.8426	0.0422918	0.018740
121	-0.8662	0.0103680	0.000983
122	1.6670	0.0439598	0.015972
123	-0.2949	0.0286706	0.000321
124	0.6083	0.0372927	0.001792
125	- 0.4675	0.0402756	0.001146
126	-0.0804	0.0250624	0.000021
127	2.1915	0.0284998	0.017611
128	0.1112	0.0217781	0.000034
129	-0.5828	0.0402401	0.001780
130	0.0633	0.0332972	0.000017
131	-0.2045	0.0340351	0.000184
132	-0.8040	0.0211002	0.001742
133	3.7370	0.0596176	0.110667
134	-1.0840	0.0168907	0.002523
135	-0.1696	0.0192208	0.000070
136	0.3125	0.0634540	0.000827
137	-0.0565	0.0262557	0.000011
138	0.2570	0.0253414	0.000215
139	-0.3405	0.0559408	0.000859
140	0.3104	0.0500413	0.000635
141	0.2444	0.0362652	0.000281
142	-0.7469	0.0172283	0.001223
143	-0.0557	0.0293548	0.000012
144	-0.5745	0.0272452	0.001155
145	1.3519	0.0209485	0.004833

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OBS	SRESID	LEVERAGE	COOKD
146	0.9146	0.0466051	0.005111
147	-0.0823	0.0331354	0.000029
148	0.4634	0.0210462	0.000577
149	-1.3284	0.0303222	0.006897
150	-1.2284	0.0251642	0.004869
151	-0.2873	0.0321474	0.000343
152	-0.4010	0.0290872	0.000602
153	0.3344	0.0159954	0.000227
154	0.1795	0.0386625	0.000162
155	0.1692	0.0218350	0.000080
156	3.5757	0.0436030	0.072863
157	0.2967	0.0306758	0.000348
158	-0.1549	0.0527239	0.000167
159	0.4014	0.0639452	0.001376
160	-0.6612	0.0173051	0.000962
161	-0.8900	0.0225009	0.002279
162	-0.3056	0.0180374	0.000214
163	0.9159	0.0491707	0.005422
164	-0.6609	0.0327376	0.001848
165	0.1196	0.0250271	0.000046
166	0.1301	0.0355229	0.0000780
167	-0.3532	0.0332057	0.0005356
168	0.7975	0.0346337	0.0028525
169	0.3176	0.0249927	0.0003233
170	0.3113	0.0500314	0.0006381
171	-0.1462	0.0617777	0.0001760
172	-0.5206	0.0338212	0.0011861
173	-0.6906	0.0129047	0.0007794
174	-0.3766	0.0398775	0.0007364
175	0.8017	0.0314495	0.0026084
176	-0.5789	0.0153295	0.0006522
177	0.0264	0.0287226	0.000026
178	0.9502	0.0392314	0.0046087
179	-0.5890	0.0199482	0.0008828
180	-0.4971	0.0506504	0.0016479
181	0.3782	0.0243220	0.0004458
182	-0.1569	0 0433925	0.0001395
183	-0.5216	0.0093619	0.0003214
184	-0.3792	0 0547632	0.0010412
185	-1 6283	0 0225046	0 0076306
186	-0.8268	0 0130783	0 0011325
187	0 2220	0 0543484	0.0003541
188	-0.3725	0.0646397	0 0011987
189	-1 5297	0 0318459	0.0096219
190	-0.6993	0 0194580	0.0012131
101	-0 5550	0 0344935	0 0012750
192	-1 0742	0 0250697	0 00137099
193	-0 1679	0.0167468	0 0000,000
194	-0.1070	0.02/0175	0 0008841
105	-0.5272	0.02401/3	0.0010141
トンフ	-0.002/	0.0403034	0.0012100

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OBS	SRESID	LEVERAGE	COOKD
196	0.3632	0.0351923	0.0006015
197	0.8755	0.0515056	0.0052034
198	-0.3840	0.0173596	0.0003257
199	-0.0093	0.0233671	0.000003
200	-0.5640	0.0287789	0.0011782
201	0.2231	0.0159062	0.0001006
202	-0.6156	0.0110680	0.0005302
203	-0.2908	0.0217790	0.0002353
204	0.0691	0.0204364	0.0000125
205	0.0601	0.0354888	0.0000166
206	0.9782	0.0405221	0.0050520
207	-0.1309	0.0380643	0.0000848
208	2,4587	0.0353801	0.0277163
209	1.8184	0.0486758	0.0211488
210	-0.4176	0.0253225	0.0005662
211	0.0945	0.0100270	0.0000113
212	0.6107	0.0212822	0.0010137
213	-0.3673	0.0190098	0.0003269
214	-0.3404	0.0167427	0.0002466
215	0.2686	0.0407109	0.0003827
216	1.1309	0.0317964	0.0052506
217	0.2264	0.0140397	0.0000912
218	2.6191	0.0445692	0.0400000
219	0.1698	0.0262270	0.0000971
220	0.0925	0.0274930	0.0000302
221	-0.0584	0.0295906	0.000013
222	-0.5733	0.0268968	0.001136
223	-0.6498	0.0240062	0.001298
224	-0.7989	0.0422529	0.003519
225	-0.0144	0.0234109	0.000001
226	0.1617	0.0263141	0.000088
227	-0.5401	0.0130822	0.000483
228	1.5967	0.0421363	0.014019
229	-0.2892	0.0244358	0.000262
230	-0.1680	0.0157706	0.000057
231	0.0516	0.0310932	0.000011
232	-0.1495	0.0222890	0.000064
233	0.5946	0.0377994	0.001736
234	0.1411	0.0438283	0.000114
235	0.8248	0.0262305	0.002291
236	-0.5731	0.0177650	0.000743
237	0.3577	0.0490957	0.000826
238	-3.5795	0.0615695	0.105077
239	-0.3706	0.0361590	0.000644
240	1.0370	0.0578594	0.008255
241	-0.5337	0.0230097	0.000839
242	-1.5705	0.0314314	0.010005
243	0.0094	0.0279318	0.00000
244	-0.7232	0.0268017	0.001801
245	-0.1999	0.0627358	0.000334

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OBS	SRESID	LEVERAGE	COOKD
246	1.1645	0.0407702	0.007205
247	-0.4889	0.0300589	0.000926
248	-1.3482	0.0578601	0.013954
249	0.1016	0.0449061	0.000061
250	-0.5331	0.0233710	0.000850

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## Appendix E: Point Estimate Data

Column 1 - observation number (1-250)

- Column 2 TOTCOST figure generated by Model-A
- Column 3 point estimate of TOTCOST called COSTHAT generated by Model-S

Column 4 - the difference of the two (column 2 - column 3)

Column 5 - the difference expressed as a percent of TOTCOST

1	2	3	4	5
OBS	TOTCOST	YHAT	RESID	RESIDPC
1	711350	688922	22428	3.153
2	1019614	994659	24955	2.447
3	638735	626406	12329	1.930
4	629978	685577	-55599	-8.826
5	1263076	1268530	-5454	-0.432
6	886556	943215	-56658	-6.391
7	1397821	1349642	48179	3.447
8	767661	807112	-39450	-5.139
9	768213	738443	29770	3.875
10	2018565	1792748	225817	11.187
11	983400	1031103	-47703	-4.851
12	581691	584646	-2955	-0.508
13	841063	911028	-69964	-8.319
14	784773	796559	-11786	-1.502
15	767055	306206	-39151	-5.104
16	650921	675784	-24863	-3.820
17	697351	682680	14671	2.104
13	594371	729047	-34675	-4.994
19	702501	793368	-90867	-12.935
20	1030152	1002651	27501	2.670
21	846346	817229	29117	3.440
22	521133	515787	5346	1.026
23	1024593	1067739	-43146	-4.211
24	980503	1025130	-44627	-4.551
25	852709	876778	-24069	-2.823
26	963372	999614	-36242	-3.762
27	1228062	1201124	26938	2.194
28	627442	644045	-16603	-2.646
29	1003328	1020615	-17287	-1.723
30	1064978	1077427	-12449	-1.169
31	903755	798061	5694	0.708

1	2	3	4	5
OBS	TOTCOST	YHAT	RESID	RESIDPC
32	588800	616600	-27801	-4.722
33	1065803	1079446	-13643	-1.280
34	1153114	1184315	-31201	-2.706
35	963130	981173	-18043	-1.873
36	643108	698801	-55692	-8.660
37	733366	734388	-1022	-0.139
38	685749	696680	-10931	-1.594
39	828532	943166	-114634	-13.836
40	1196395	1199272	-2877	-0.240
41	653273	633409	19864	3.041
42	1202105	1195173	932	0.577
13	962874	1022214	-59340	-6.163
44	451400	401272	50128	11.105
45	749723	774465	-24742	-3.300
46	1222568	1314555	-91987	-7.524
40	829674	818983	10691	1,289
48	508900	472207	36693	7.210
40	962611	914355	48255	5.013
50	525486	508221	17265	3,285
51	930419	971528	-41109	-4.418
52	485187	429225	55962	11.534
53	840659	839856	803	0.096
54	1042134	1068098	-25964	-2.491
55	640311	682984	-42674	-6.665
56	427409	424845	-2564	0,600
57	756221	781112	-24891	-3.292
58	427889	307868	120020	28.049
59	751988-	765967	-13979	-1.859
60	941455	995073	-53618	-5.695
61	1115257	1139789	-24532	-2.200
62	1019931	1100527	-80596	-7.902
63	693131	676939	16192	2.336
64	1812890	1624398	188492	10.397
65	606429	546143	60287	9.941
56	937526	960015	-22489	-2.399
67	1112055	1114024	-1969	-0.177
68	1538917	1404791	134126	8.716
69	485410	420162	65249	13.442
70	626968	567627	59341	9.465
71	839606	875972	-36367	-4.331
72	811522	857008	-45486	-5.605
73	975977	1014995	-39018	-3.998
74	462264	345073	117190	25.351
75	1316265	1293971	22294	1.694
76	1120173	1246911	-126739	-11.314
77	937718	947033	-9314	-0.993
78	463403	327006	136396	29.434
79	963425	994080	-30656	-3.182

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1	2	3	4	5
OBS	TOTCOST	YHAT	RESID	RESIDPC
80	628033	618313	-9719	1.548
81	886951	897563	-10612	-1.196
82	1416011	1386031	29980	2.117
83	412961	305402	107559	26.046
84	1065953	1124839	-58886	-5.524
85	580798	527457	53341	9.184
86	1643417	1541890	101527	6.178
87	772441	822883	-50442	-6.530
88	683074	692110	-9037	-1.323
89	904585	943863	-39278	-4.342
90	597433	567978	29455	4.930
91	487968	463178	24790	5.080
92	909327	919791	-10464	-1.151
93	799853	907955	-108103	-13.515
94	1049482	1072562	-23080	-2.199
95	1524899	1431299	93600	6.138
96	624423	533916	90506	14.494
97	1622290	1589054	33236	2.049
98	1232530	1239544	-7014	-0.569
99	757389	877387	-119998	-15.844
100	973802	989966	-16164	-1.660
101	804699	831168	-26469	-3.289
102	696107	717142	-21036	-3.022
103	1302786	1287864	14922	1.145
104	725350	737194	-11844	-1.633
105	783103	816664	-33562	-4.286
106	1073156	1108932	-35776	-3.334
107	737468	776429	-38960	-5.283
108	655832	677909	-22077	-3.366
109	1268291	1228041	40250	3.174
110	1127843	1108830	19013	1.686
111	1327374	1336422	-9048	-0.682
112	1002269	1077947	-75678	-7.551
113	584518	540461	44058	7.537
114	1058972	1030372	28600	2.701
115	456871	303656	153215	33.536
116	1511577	1422229	89348	5.911
117	627087	601993	25094	4.002
118	918402	980022	-61620	-6.710
119	1113275	1104599	8676	0.779
120	446264	345464	100800	22.587
121	927779	975948	-48170	-5.192
122	877021	968137	-91116	-10.389
123	1061306	1077552	-16246	-1.531
124	552322	518956	33365	6.041
125	1409692	1384091	25601	1.816
126	705307	709744	-4437	-0.629
127	1586203	1465456	120747	7.612

1	2	3	4	5
OBS	TOTCOST	YHAT	RESID	RESIDPC
128	1044155	1038005	6150	0.589
129	1047426	1079343	-31917	-3.047
130	680927	677450	3477	0.511
131	934781	946015	-11233	-1.202
132	1149313	1193780	-44467	-3.869
133	1959612	1757033	202579	10.338
134	755249	815330	-60081	-7.955
135	656471	665860	-9388	-1.430
136	1086276	1069368	16908	1.557
137	973661	976777	-3116	-0.320
138	892552	878369	14183	1.589
139	1163319	1181813	-18494	-1.590
140	1126487	1109574	16913	1.501
141	1095935	1082523	13412	1.224
142	853554	894948	-41394	-4.850
143	724020	727089	-3070	-0.424
144	579889	611563	-31674	-5.462
145	500594	425817	74777	14.938
146	524701	474781	49920	9.514
147	680132	684654	-4523	-0.665
148	675123	649491	25632	3.797
149	957798	1030920	-73122	-7.634
150	686052	753852	-67800	-9.883
151	867940	883743	-15803	-1.821
152	1178637	1200726	-22089	-1.874
153	871328	852784	18544	2.128
154	1425892	1416056	9836	0.690
155	777504	768150	9354	1.203
156	1804807	1609328	195479	10.831
157	640220	623893	16327	2.550
158	1116454	1124879	-8425	-0.755
159	533459	511750	21709	4.069
160	889119	925762	-36642	-4.121
161	958957	1008148	-49191	-5.130
162	911349	928276	-16927	-1.857
163	1272278	1222353	49925	3.924
164	1041979	1078312	-36333	-3.487
165	648496	641897	6599	1.018
166	1117458	1110314	7144	0.639
167	761945	781359	-19414	-2.548
168	535927	492122	43805	8.174
169	763671	746139	17533	2.296
170	1443072	1426109	16963	1.176
171	1145432	1153350	-7918	-0.691
172	790800	819408	-28608	-3.618
173	733221	771578	-38357	-5.231
174	1040746	1061375	-20629	-1.982
175	727745	693612	44103	6 060

1	2	3	4	5
OBS	TOTCOST	YHAT	RESID	RESIDPC
176	949909	982023	-32114	-3.381
177	753599	752142	1457	0.193
178	493493	441427	52066	10.551
179	1199337	1231935	-32598	-2.718
180	687226	714300	-27075	-3.940
181	588767	567882	20885	3.547
182	1229115	1237691	-8576	-0.698
183	1003184	1032206	-29022	-2.893
184	1059270	1079878	-20608	-1.945
185	735302	825298	-89996	-12.239
186	843536	889454	-45918	-5.444
187	1475576	1463507	12069	0.818
188	1087521	1107661	-20140	-1.852
189	736054	820196	-84142	-11.432
190	1043808	1082518	-38710	-3.709
191	993144	1023628	-30484	-3.069
192	1108875	1168166	-59291	-5.347
193	712963	722263	-9301	-1.305
194	656943	686046	-29103	-4.430
195	637637	670637	-33000	-5.175
196	476478	456534	19944	4.186
197	547909	500242	47667	8.700
198	854974	876255	-21281	-2.489
199	821327	821838	-511	-0.062
200	933106	964177	-31071	-3.330
201	1191868	1179495	12373	1.038
202	731853	766077	-34224	-4.676
203	919723	935800	-16078	1.748
204	873597	869772	3825	0.438
205	1328879	1325581	3298	0.248
206	1584614	1531048	53566	3.380
207	678944	586121	-7177	-1.057
208	383217	248224	134993	35.226
209	1748774	1649626	99148	5.670
21)	968225	991270	-23045	-2.380
211	1133833	1128576	5257	0.464
212	659538	625765	33773	5.121
213	1065879	1086218	-20339	-1.908
214	937423	956289	-18866	-2.013
215	611546	596841	14705	2.405
216	465601	403392	62208	13.361
217	956514	943950	12564	1.314
218	1780092	1636979	143113	8.040
219	1073221	1063854	9367	0.873
220	602553	59/454	5099	0.846
221	512/84	516001	-3217	-0.627
222	/1641/	/48034	-3161/	-4.413
223	986708	1022593	-35885	-3.63/

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1	2	3	4	5
OBS	TOTCOST	YHAT	RESID	RESIDPC
224	686660	730363	-43703	-6.365
225	644441	645237	-796	-0.124
226	610154	601232	8921	1.462
227	826581	856574	-29993	-3.629
228	601762	514406	87356	14.517
229	758735	774704	-15969	-2.105
230	617980	627297	-9317	-1.508
231	591101	588259	2841	0.481
232	703177	711440	-8263	-1.175
233	1256893	1224290	32603	2.594
234	845282	837571	7711	0.912
235	518413	472912	45501	8.777
236	951201	982952	-31751	-3.338
237	565357	545858	19500	3.449
238	724638	918476	-193838	-26.750
239	747959	768299	-20340	-2.719
240	612958	556689	56268	9.180
241	589803	619295	-29492	-5.000
242	1185499	1271899	-86400	-7.288
243	562473	561953	520	0.092
244	918802	958685	-39883	-4.341
245	1640519	1651337	-10818	-0.659
246	452791	389034	63758	14.081
247	893291	920206	-26915	-3.013
248	1092851	1166005	-73154	-6.694
249	1447030	1441480	5550	0.384
250	848263	877712	-29450	-3.472

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OBS	YHAT	L95	U95	BOUND	BOUNDPC
1	688922	577363	800480	111558	15.6826
2	994659	883466	1105853	111193	10.9054
3	626406	514901	737911	111505	17.4572
4	685577	574173	796981	111404	17.6838
5	1268530	1156853	1380207	111677	8.8417
6	943215	831398	1055031	111817	12.6125
7	1349642	1238564	1460720	111078	7.9465
8	807112	694971	919252	112140	14.6080
9	738443	627311	849575	111132	14.4663
10	1792748	1680009	1905487	112739	5.5851
11	1031103	919568	1142637	111534	11.3417
12	584646	473486	695805	111159	19.1097
13	911028	799526	1022529	111502	13.2572
14	796559	682920	910199	113639	14.4805
15	806206	694032	918379	112174	14.6239
16	675784	564685	786882	111099	17.0679
17	682680	571450	793911	111230	15.9504
18	729047	617791	840303	111256	16.0225
19	793368	681099	905637	112269	15.9813
20	1002651	891279	1114024	111372	10.8113
21	817229	705771	928687	111458	13.1693
22	515787	404414	627161	111374	21.3715
23	1067739	955336	1180142	112403	10.9705
24	1025130	914171	1136088	110958	11.3165
25	876778	763480	990076	113298	13.2868
26	999614	888104	1111124	111510	11.5750
27	1201124	1090025	1312223	111099	9.0467
28	644045	533405	754685	110640	17.6335
29	1020615	909083	1132148	111533	11.1163
30	1077427	965931	1188924	111496	10.4694
31	798061	686293	909828	111768	13.9057
32	616600	504587	728614	112013	19.0240
33	1079446	968120	1190771	111325	10.4452
34	1184315	1073338	1295292	110977	9.6241
35	981173	870271	1092076	110903	11.5148
36	698801	587140	810461	111660	17.3626
37	734388	623153	845623	111235	15.1677
38	696680	584990	808370	111690	16.2873
39	943166	831470	1054863	111697	13.4813
40	1199272	1086650	1311895	112623	9.4135
41	633409	521863	744956	111547	17.0750
42	1195173	1083778	1306568	111395	9.2666
43	1022214	910441	1133988	111773	11.6083
44	401272	287922	514623	113351	25.1109
45	774465	662508	886422	111957	14.9331
46	1314555	1201456	1427654	113099	9.2509
47	818983	707522	930443	111461	13.4343
48	472207	359708	584706	112499	22.1063
49	914355	800513	1028197	113842	11.8264
50	508221	397102	619341	111120	21 1461

Second Report Notices

OBS	YHAT	L95	U95	BOUND	BOUNDPC
51	971528	860017	1083038	111510	11.9850
52	429225	317613	540837	111612	23.0039
53	839856	728651	951062	111206	13.2284
54	1068098	957263	1178934	110836	10.6355
55	682984	571861	794108	111124	17.3546
56	424845	311889	537801	112956	26.4281
57	781112	668825	893399	112287	14.8485
58	307868	196040	419696	111828	26.1349
59	765967	653671	878263	112296	14.9332
60	995073	884218	1105927	110854	11.7748
61	1139789	1026971	1252606	112818	10.1158
62	1100527	989029	1212026	111498	10.9319
63	676939	565037	788840	111901	16.1443
64	1624398	1512427	1736369	111971	6.1764
65	546143	434289	657997	111854	18.4447
66	960015	848710	1071321	111305	11.8722
67	1114024	1002447	1225601	111577	10.0334
68	1404791	1292079	1517502	112711	7.3241
69	420162	308117	532206	112045	23.0825
70	567627	455319	679935	112308	17.9129
71	875972	764799	987146	111174	13.2412
72	857008	745403	968613	111605	13.7526
73	1014995	903322	1126669	111674	11.4423
74	345073	233484	456663	111589	24.1398
75	1293971	1182303	1405639	111668	8.4837
76	1246911	1133006	1360815	113904	13.1685
77	947033	835763	1058302	111269	11.8660
78	327006	215459	438553	111547	24.0713
79	994080	882358	1105802	111722	11.5963
80	618313	506990	729637	111324	17.7258
81	897563	786565	1008561	110998	12.5146
82	1386031	1273441	1498621	112590	7.9512
83	305402	192640	418164	112762	27.3057
84	1124839	1012252	1237426	112587	10.5621
85	527457	415644	639270	111813	19.2516
86	1541890	1428712	1655068	113178	6.8868
87	822883	709800	935967	113084	14.6398
88	692110	580595	803625	111515	16.3255
89	943863	832207	1055518	111655	12.3433
90	567978	456951	679005	111027	18.5841
91	463178	351303	575052	111875	22.9267
92	919791	808458	1031124	111333	12.2434
93	907955	795981	1019929	111974	13.9993
94	1072562	961286	1183837	111276	10.6029
95	1431299	1319218	1543380	112081	7.3501
96	533916	422818	645015	111099	17.7922
97	1589054	1474057	1704051	114997	7.0886
98	1239544	1127924	1351164	111620	9.0562
99	877387	764479	990294	112908	14.9075
100	989966	979991	1101051	111005	11 4074

OBS	YHAT	L95	U95	BOUND	BOUNDPC
101	831168	719894	942442	111274	13.8281
102	717142	605955	828329	111187	15.9727
103	1287864	1175426	1400303	112438	8.6306
104	737194	625342	849045	111852	15.4204
105	816664	705044	928284	111620	14.2536
106	1108932	995023	1222842	113909	10.6144
107	776429	664728	888129	111701	15.1465
108	677909	566535	789283	111374	16.9821
109	1228041	1116013	1340069	112028	8.8330
110	1108830	997254	1220405	111576	9.8928
111	1336422	1223710	1449135	112712	8.4914
112	1077947	965299	1190595	112648	11.2393
113	540461	429630	651291	110831	18.9610
114	1030372	918823	1141921	111549	10.5337
115	303656	190270	417041	113385	24.8178
116	1422229	1310106	1534351	112123	7.4176
117	601993	489888	714098	112105	17.8771
118	980022	868348	1091697	111675	12.1597
119	1104599	992985	1216214	111615	10.0258
120	345464	233043	457885	112421	25.1916
121	975948	865262	1086634	110686	11.9302
122	968137	855626	1080648	112511	12.8288
123	1077552	965868	1189236	111684	10.5233
124	518956	406805	631108	112151	20.3054
125	1384091	1271778	1496403	112312	7,9671
126	709744	598256	821232	111488	15.8070
127	1465456	1353782	1577131	111675	7.0404
128	1038005	926696	1149314	111309	10.6602
129	1079343	967033	1191653	112310	10.7225
130	677450	565515	789385	111935	16.4386
131	946015	834040	1057989	111975	11.9787
132	1193780	1082507	1305052	111272	9.6816
133	1757033	1643682	1870385	113351	5.7844
134	815330	704287	926373	111043	14.7028
135	665360	554690	777029	111170	16.9344
136	1069368	955811	1182924	113556	10.4537
137	976777	865224	1088329	111553	11.4571
138	878369	766866	989872	111503	12.4926
139	1131813	1068659	1294968	113155	9.7269
140	1109574	996736	1222412	112838	10.0168
141	1082523	970428	1194619	112095	10.2283
142	894948	783887	1006009	111061	13.0116
143	727089	615368	838811	111721	15.4307
144	611563	499957	723170	111607	19.2462
145	425817	314553	537081	111264	22.2264
146	474781	362127	587434	112653	21.4700
147	684654	572728	796580	111926	16.4565
148	649491	538222	760760	111269	16.4813
149	1030920	919147	1142694	111774	11.6698
150	752952	642259	965215	111402	16 2515

OBS	YHAT	L95	U95	BOUND	BOUNDPC
151	883743	771871	995616	111873	12.8894
152	1200726	1089019	1312432	111707	9.4776
153	852784	741790	963778	110994	12.7385
154	1416056	1303831	1528281	112225	7.8705
155	768150	656838	879462	111312	14.3166
156	1609328	1496837	1721820	112492	6.2329
157	623893	512100	735685	111793	17.4616
158	1124879	1011897	1237862	112982	10.1197
159	511750	398167	625333	113583	21.2918
160	925762	814696	1036827	111065	12.4916
161	1008148	896799	1119496	111349	11.6114
162	928276	817171	1039381	111105	12.1913
163	1222353	1109562	1335145	112791	8.8653
164	1078312	966408	1190217	111905	10.7396
165	641897	530411	753383	111486	17.1915
166	1110314	998259	1222370	112055	10.0277
167	781359	669429	893289	111930	14.6900
163	492122	330115	604129	112007	20.8997
169	746139	634655	857623	111484	14.5984
170	1426109	1313271	1538946	112838	7.8193
171	1153350	1039883	1266817	113467	9.9060
172	819408	707445	931371	111963	14.1582
173	771578	660753	382403	110825	15.1148
174	1061375	949085	1173666	112291	10.7894
175	683642	571808	795477	111835	15.3673
176	982023	871066	1092980	110957	11.6808
177	752142	640455	863829	111687	14.8204
178	441427	329171	553682	112256	22.7472
179	1231935	1120725	1343144	111209	9.2726
180	714300	601429	827171	112871	16.4241
181	567882	456434	679329	111448	18.9290
182	1237691	1125211	1350171	112480	9.1513
183	1032206	921576	1142837	110631	11.0280
184	1079878	966786	1192969	113092	10.6764
185	825298	713950	936647	111349	15.1433
136	889454	778620	1000288	110834	13.1393
137	1463507	1350438	1576577	113069	7.3627
138	1107661	994041	1221281	113620	10.4476
189	820196	708340	932052	111856	15.1967
190	1082518	971336	1193701	111183	10.6516
191	1023628	911629	1135627	111999	11.2772
192	1168166	1056678	1279654	111488	10.0542
193	722263	611229	833298	111035	15.5737
194	686046	574571	797520	111475	10.9687
195	670637	558312	782961	112325	1/.6158
196	456534	344497	568571	112037	23.5137
197	500242	387325	613159	112917	20.608/
198	876255	/65187	98/324	111068	12.9908
199	821838	/10442	933233	111396	13.5629
200	964177	852487	10/2800	111690	11.969/

AUTO CONDECTOR

OBS	YHAT	L95	U95	BOUND	BOUNDPC
201	1179495	1068506	1290484	110989	9.3122
202	766077	655353	876802	110724	15,1293
203	935800	824491	1047109	111309	12.1025
204	869772	758536	981008	111236	12,7331
205	1325581	1213528	1437635	112053	8.4322
206	1531048	1418723	1643374	112325	7.0885
207	686121	573928	798314	112193	16.5246
208	248224	136177	360272	112048	29.2387
209	1649626	1536862	1762391	112765	6.4482
210	991270	879768	1102772	111502	11,5161
211	1128576	1017908	1239243	110667	9.7605
212	625765	514483	737048	111282	16.8727
213	1086218	975060	1197376	111158	10,4288
214	956289	845254	1067324	111035	11.8447
215	596841	484505	709176	112336	18.3691
216	403392	291539	515246	111854	24.0235
217	943950	833063	1054836	110887	11.5928
218	1636979	1524435	1749523	112544	6.3224
219	1063854	952302	1175405	111551	10.3941
220	597454	485834	709074	111620	18,5245
221	516001	404267	627735	111734	21.7897
222	748034	636446	859622	111588	15.5758
223	1022593	911163	1134024	111430	11.2932
224	730363	617944	842782	112419	16.3718
225	645237	533839	756636	111398	17.2860
226	601232	489676	712788	111556	18,2833
227	856574	745739	967408	110835	13,4088
228	514406	401994	626819	112413	18.6806
229	774704	663250	886158	111454	14.6894
230	627297	516315	738278	110981	17.9588
231	588259	476444	700075	111815	18,9165
232	711440	600103	822777	111337	15.8334
233	1224290	1112112	1336469	112178	8,9251
234	837571	725068	950075	112504	13.3096
235	472912	361361	584463	111551	21.5179
236	982952	871862	1094043	111090	11.6790
237	545858	433070	658645	112787	19.9497
238	918476	805020	1031932	113456	15.6569
239	768299	656209	880389	112090	14.9861
240	556689	443432	669947	113257	18.4772
241	619295	507919	730671	111376	18.8836
242	1271899	1160066	1383733	111834	9.4335
243	561953	450309	673597	111644	19.8488
244	958685	847102	1070267	111582	12.1443
245	1651337	1537819	1764856	113518	6.9196
246	389034	276695	501373	112339	24.8103
247	920206	808447	1031966	111759	12.5110
248	1166005	1052747	1279262	113257	10.3635
249	1441480	1328919	1554042	112562	7.7788
250	877712	766317	989108	111396	13.1322

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Appendix F: 95 Percent Prediction Intervals

OBS	YHAT	LOWER	UPPER	BOUND	BOUNDPC
1	688922	577363	800480	111558	16.1932
2	994659	883466	1105853	111193	11.1790
3	626406	514901	737911	111505	17.8008
4	685577	574173	796981	111404	16.2497
5	1268530	1156853	1380207	111677	8.8037
6	943215	831398	1055031	111817	11.8548
.7	1349642	1238564	1460720	111078	8.2302
8	807112	694971	919252	112140	13.8940
9	738443	627311	849575	111132	15.0495
10	1792748	1680009	1905487	112739	6.2886
11	1031103	919568	1142637	111534	10.8170
12	584646	473486	695805	111159	19.0131
13	911028	799526	1022529	111502	12.2391
14	796559	682920	910199	113639	14.2662
15	806206	694032	918379	112174	13.9138
16	675784	564685	786882	111099	16.4400
17	682680	571450	793911	111230	16.2932
18	729047	617791	840303	111256	15.2604
19	793368	681099	905637	112269	14.1509
20	1002651	891279	1114024	111372	11.1078
21	817229	705771	928687	111458	13.6385
22	515787	404414	627161	111374	21.5930
23	1067739	955336	1180142	112403	10.5272
24	1025130	914171	1136088	110958	10.8238
25	876778	763480	990076	113298	12.9221
26	999614	888104	1111124	111510	11.1553
27	1201124	1090025	1312223	111099	9.2496
28	644045	533405	754685	110640	17.1789
29	1020615	909083	1132148	111533	10.9280
30	1077427	965931	1188924	111496	10.3484
31	798061	686293	909828	111768	14.0049
32	616600	504587	728614	112013	18.1663
33	1079446	968120	1190771	111325	10.3132
34	1184315	1073338	1295292	110977	9.3706
35	981173	870271	1092076	110903	11.3031
36	698801	587140	810461	111660	15.9788
37	734388	623153	845623	111235	15.1466
38	696680	584990	808370	111690	16.0317
39	943166	831470	1054863	111697	11.8427
40	1199272	1086650	1311895	112623	9.3900
41	633409	521863	744956	111547	17.6105
42	1195173	1083778	1306568	111395	9.3204
43	1022214	910441	1133988	111773	10.9344
44	401272	287922	514623	113351	28.2478
45	774465	662508	886422	111957	14.4560

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OBS	YHAT	LOWER	UPPER	BOUND	BOUNDPC
46	1314555	1201456	1427654	113099	8.6036
47	818983	707522	930443	111461	13.6096
48	472207	359708	584706	112499	23.8241
49	914355	800513	1028197	113842	12.4505
50	508221	397102	619341	111120	21.8644
51	971528	860017	1083038	111510	11.4778
52	429225	317613	540837	111612	26.0032
53	839856	728651	951062	111206	13.2410
54	1068098	957263	1178934	110836	10.3769
55	682984	571861	794108	111124	16.2703
56	424845	311889	537801	112956	26.5876
57	781112	668825	893399	112287	14.3753
58	307868	196040	419696	111828	36.3234
59	765967	653671	878263	112296	14.6607
60	995073	884218	1105927	110854	11.1403
61	1139789	1026971	1252606	112818	9.8981
62	1100527	989029	1212026	111498	10.1313
63	676939	565037	788840	111901	16.5305
64	1624398	1512427	1736369	111971	6.8931
65	546143	434289	657997	111854	20,4807
66	960015	848710	1071321	111305	11,5941
67	1114024	1002447	1225601	111577	10,0157
68	1404791	1292079	1517502	112711	8.0234
69	420162	308117	532206	112045	26.6670
70	567627	455319	679935	112308	19.7855
71	875972	764799	987146	111174	12.6915
72	857008	745403	968613	111605	13.0226
73	1014995	903322	1126669	111674	11.0024
74	345073	233484	456663	111589	32.3379
75	1293971	1182303	1405639	111668	8.6299
76	1246911	1133006	1360815	113904	9.1349
77	947033	835763	1058302	111269	11.7493
78	327006	215459	438553	111547	34.1115
79	994080	882358	1105802	111722	11.2387
80	618313	506990	729637	111324	18,0044
81	897563	786565	1008561	110998	12.3666
82	1386031	1273441	1498621	112590	8.1232
83	305402	192640	418164	112762	36.9224
84	1124839	1012252	1237426	112587	10.0092
85	527457	415644	639270	111813	21.1985
86	1541890	1428712	1655068	113178	7.3402
87	822883	709800	935967	113084	13.7424
88	692110	580595	803625	111515	16.1123
89	943863	832207	1055518	111655	11.8296
90	567978	456951	679005	111027	19.5478
91	463178	351303	575052	111875	24.1537
92	919791	808458	1031124	111333	12.1041
93	907955	795981	1019929	111974	12.3325
94	1072562	961286	1183837	111276	10.3747
95	1/21200	1210210	1543380	112081	7 9307

OBS	YHAT	LOWER	UPPER	BOUND	BOUNDPC
96	533916	422818	645015	111099	20.8083
97	1589054	1474057	1704051	114997	7.2368
98	1239544	1127924	1351164	111620	9,0050
99	877387	764479	990294	112908	12,8686
100	989966	878881	1101051	111085	11.2211
101	831168	719894	942442	111274	13.3877
102	717142	605955	828329	111187	15.5042
103	1287864	1175426	1400303	112438	8,7306
104	737194	625342	849045	111852	15,1726
105	816664	705044	928284	111620	13.6678
106	1108932	995023	1222842	113909	10.2720
107	776429	664728	888129	111701	14.3864
108	677909	566535	789283	111374	16.4290
109	1228041	1116013	1340069	112028	9.1225
110	1108830	997254	1220405	111576	10.0625
111	1336422	1223710	1449135	112712	8.4339
112	1077947	965299	1190595	112648	10.4502
113	540461	429630	651291	110831	20.5067
114	1030372	918823	1141921	111549	10.8261
115	303656	190270	417041	113385	37.3401
116	1422229	1310106	1534351	112123	7.8836
117	601993	489888	714098	112105	18.6224
118	980022	868348	1091697	111675	11.3951
119	1104599	992985	1216214	111615	10.1046
120	345464	233043	457885	112421	32.5420
121	975948	865262	1086634	110686	11.3414
122	968137	855626	1080648	112511	11.6214
123	1077552	965868	1189236	111684	10.3646
124	518956	406805	631108	112151	21.6109
125	1384091	1271778	1496403	112312	8.1145
126	709744	598256	821232	111488	15,7082
127	1465456	1353782	1577131	111675	7.6205
128	1038005	926696	1149314	111309	10.7234
129	1079343	967033	1191653	112310	10.4054
130	677450	565515	789385	111935	16.5230
131	946015	834040	1057989	111975	11.8365
132	1193730	1082507	1305052	111272	9.3210
133	1757033	1643682	1870385	113351	6.4513
134	815330	704287	926373	111043	13.6193
135	665860	554690	777029	111170	16.6957
136	1069368	955811	1182924	113556	10.6190
137	976777	865224	1088329	111553	11.4205
138	878369	766866	989872	111503	12.6943
139	1181813	1068659	1294968	113155	9.5747
140	1109574	996736	1222412	112838	10.1695
141	1082523	970428	1194619	112095	10.3550
142	894948	783887	1006009	111061	12.4098
143	727089	615368	838811	111721	15.3655
144	611563	499957	723170	111607	18.2494
145	425817	314553	537081	111264	26.1295

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KKANGAANADA

**NOTATION** 

OBS	YHAT	LOWER	UPPER	BOUND	BOUNDPC
146	474781	362127	587434	112653	23.7274
147	684654	572728	796580	111926	16.3478
148	649491	538222	760760	111269	17.1318
149	1030920	919147	1142694	111774	10.8421
150	753852	642358	865345	111493	14.7898
151	883743	771871	995616	111873	12.6589
152	1200726	1089019	1312432	111707	9.3033
153	852784	741790	963778	110994	13.0155
154	1416056	1303831	1528281	112225	7.9252
155	768150	656838	879462	111312	14.4910
156	1609328	1496837	1721820	112492	6.9900
157	623893	512100	735685	111793	17.9186
158	1124879	1011897	1237862	112982	10.0439
159	511750	398167	625333	113583	22.1950
160	925762	814696	1036827	111065	11.9972
161	1008148	896799	1119496	111349	11.0449
162	928276	817171	1039381	111105	11.9690
163	1222353	1109562	1335145	112791	9.2274
164	1078312	966408	1190217	111905	10.3777
165	641897	530411	753383	111486	17.3682
166	1110314	998259	1222370	112055	10.0922
167	781359	669429	893289	111930	14.3250
168	492122	380115	604129	112007	22.7600
169	746139	634655	857623	111484	14.9415
170	1426109	1313271	1538946	112838	7.9123
171	1153350	1039883	1266817	113467	9.8380
172	819408	707445	931371	111963	13.6639
173	771578	660753	882403	110825	14.3634
174	1061375	949085	1173666	112291	10.5797
175	683642	571808	795477	111835	16.3587
176	982023	871066	1092980	110957	11.2989
177	752142	640455	863829	111687	14.8492
178	441427	329171	553682	112256	25,4302
179	1231935	1120725	1343144	111209	9.0272
180	714300	601429	827171	112871	15.8016
181	567882	456434	679329	111448	19.6252
182	1237691	1125211	1350171	112480	9.0879
183	1032206	921576	1142837	110631	10.7179
184	1079878	966786	1192969	113092	10.4726
185	825298	713950	936647	111349	13.4919
186	889454	778620	1000288	110834	12.4609
187	1463507	1350438	1576577	113069	7.7259
188	1107661	994041	1221281	113620	10.2576
189	820196	708340	932052	111856	13.6377
190	1082518	971336	1193701	111183	10.2707
191	1023628	911629	1135627	111999	10.9414
192	1168166	1056678	1279654	111488	9.5439
193	722263	611229	833298	111035	15.3732
194	686046	574571	<b>79752</b> 0	111475	16.2489
195	670637	558312	782961	112325	16 7489

OBS	YHAT	LOWER	UPPER	BOUND	BOUNDPC
196	456534	344497	568571	112037	24.5409
197	500242	387325	613159	112917	22.5724
198	876255	765187	987324	111068	12.6753
199	821838	710442	933233	111396	13.5545
200	964177	852487	1075866	111690	11.5840
201	1179495	1068506	1290484	110989	9.4099
202	766077	655353	876802	110724	14.4534
203	935800	824491	1047109	111309	11.8946
204	869772	758536	981008	111236	12.7891
205	1325581	1213528	1437635	112053	8.4532
206	1531048	1418723	1643374	112325	7.3365
207	686121	. 573928	798314	112193	16.3517
208	248224	136177	360272	112048	45.1397
209	1649626	1536862	1762391	112765	6.8358
210	991270	879768	1102772	111502	11.2484
211	1128576	1017908	1239243	110667	9.8059
212	625765	514483	737048	111282	17.7834
213	1086218	975060	1197376	111158	10.2335
214	956289	845254	1067324	111035	11.6110
215	596841	484505	709176	112336	18.8217
216	403392	291539	515246	111854	27.7282
217	943950	833063	1054836	110887	11.7471
218	1636979	1524435	1749523	112544	6.8751
219	1063854	952302	1175405	111551	10.4856
220	597454	485834	709074	111620	18.6826
221	516001	404267	627735	111734	21.6538
222	748034	636446	859622	111588	14.9175
223	1022593	911163	1134024	111430	10.8968
224	730363	617944	842782	112419	15.3922
225	645237	533839	756636	111398	17.2647
226	601232	489676	712788	111556	18.5546
227	856574	745739	967408	110835	12.9393
228	514406	401994	626819	112413	21.8529
229	774704	663250	886158	111454	14.3866
230	627297	516315	738278	110981	17.6920
231	588259	476444	700075	111815	19.0078
232	711440	600103	822777	111337	15.6495
233	1224290	1112112	1336469	112178	9.1627
234	837571	725068	950075	112504	13.4321
235	472912	361361	584463	111551	23.5882
236	982952	871862	1094043	111090	11.3017
237	545858	433070	658645	112787	20.6624
238	918476	805020	1031932	113456	12.3526
239	768299	656209	880389	112090	14.5893
240	556689	443432	669947	113257	20.3448
241	619295	507919	730671	111376	17.9844
242	1271899	1160066	1383733	111834	8.7927
243	561953	450309	673597	111644	19.8671
244	958685	847102	1070267	111582	11.6391
245	1651337	1537819	1764856	113518	6.8743

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OBS	YHAT	LOWER	UPPER	BOUND	BOUNDPC
246	389034	276695	501373	112339	28.8764
247	920206	808447	1031966	111759	12.1450
248	1166005	1052747	1279262	113257	9.7133
249	1441480	1328919	1554042	112562	7.8088
250	877712	766317	989108	111396	12.6916

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## Appendix G: Model-S Validation Data

X X X X X X X X

Column 1 - observation number (251-300); Column 2 - TOTCOST figure generated by Model-A; column 3 - point estimate of TOTCOST called COSTHAT generated by Model-S; Column 4 - the difference of the two (column 2 - column 3); column 5 - the difference expressed as a percent of TOTCOST;

1	2	3	4	5
OBS	TOTCOST	COSTHAT	DIFF	PERDIFF
251	695796	658914	36882	0.05301
252	1060244	1085562	-25318	-0.02388
253	1044413	1044454	-41	-0.00004
254	744470	797767	-53297	-0.07159
255	1230937	1259899	-28962	-0.02353
256	802437	843661	-41224	-0.05137
257	838258	948801	110543	-0.13187
258	1084530	1086562	-2032	-0.00187
259	512303	547499	-35196	-0.06870
260	631300	608668	22632	0.03585
261	1130608	1172114	-41506	-0.03671
262	1465433	1421846	43587	0.02974
263	1197534	1247163	-49629	-0.04144
264	1037298	1031407	5891	0.00563
265	554400	530746	23654	0.04267

1	2	3	4	5
OBS	TOTCOST	COSTHAT	DIFF	PERDIFF
266	339264	153774	185489	0.54674
267	472527	414314	58212	0.12319
268	1367699	1309195	58504	0,04278
269	601497	584518	16979	0.02823
270	714295	695048	19247	.0.02695
271	597962	615868	-17906	-0.02994
272	1094512	1164346	-69834	-0.06380
273	923530	896961	26570	0.02877
274	888978	950216	-61238	-0.06889
275	1106653	1111347	-4694	-0.00424
276	551507	522970	28536	0.05174
277	550713	539170	11544	0.02096
278	982094	1054406	-72312	-0.07363
279	1200391	1237092	-36701	-0.03057
280	978053	989565	-11512	-0.01177
281	527517	527183	334	0.00063
282	601191	573661	27530	0.04579
283	456575	334403	122172	0.26758
284	629188	615957	13232	0.02103
285	1130761	1135019	-4258	-0.00377
286	986194	1053595	-67402	-0.06835
287	481462	341183	140280	0.29136
288	1562784	1469976	92808	0.05939
289	1208535	1187327	21208	0.01755

1	2	3	4	5
OBS	TOTCOST	COSTHAT	DIFF	PERDIFF
290	449687	365296	84391	0.18767
291	682577	640799	41778	0.06121
292	1175174	1203270	-28096	-0.02391
293	462763	336240	126524	0.27341
294	552021	497535	. 54486	0.09870
295	923818	900184	23634	0.02558
296	995474	1033998	-38524	-0.03870
297	1096033	1103370	-7337	-0.00669
298	1118050	1150632	-32582	-0.02914
299	654990	669520	-14529	-0.02218
300	956316	982817	-26501	-0.02771

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### Abstract

. This thesis demonstrated a methodology of developing a Cost Estimating Relationship (CER) that is capable of generating nearly the same cost estimates as an accounting type of cost model. A cost model was first developed that estimated annual recurring maintenance and repair associated costs of a jet engine. This model used 51 input variables and 30 equations and represented an accounting approach to cost estimating with input requirements at low levels of detail. Using techniques of multiple linear regression, a CER was developed that used only seven aggregated variables to estimate the same cost at an acceptable level of accuracy.

The emphasis in this thesis is on the demonstration of a methodology that can be used to develop CERs. Both the accounting type cost model and the CER in this thesis are exclusively for the validation of a methodology and were developed using an artificially generated data base. As such they are not valid for any cost estimation purposes.

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