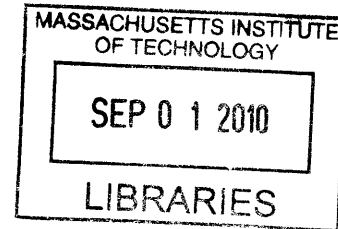**Preliminary Design Capability Enhancement via Development of Rotorcraft Operating Economics Model**

By

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B.S Mechanical and Aerospace Engineering
Cornell University, 2004

Submitted to the MIT Sloan School of Management and the Department of Mechanical
Engineering in Partial Fulfillment of the Requirements for the Degrees of
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**Preliminary Design Capability Enhancement via Development of Rotorcraft Operating Economics Model**

By

Michael P. Giansiracusa

# Abstract

The purpose of this thesis is to develop a means of predicting direct operating cost (DOC) for new commercial rotorcraft early in the design process. This project leverages historical efforts to model operating costs in the aviation industry coupled with a physics-based approach. The physics governing rotorcraft operation are combined with fundamental considerations encountered during rotorcraft design to identify potential design parameters driving operating costs. Sources for obtaining data on these parameters for existing designs are explored. The response data is generated by estimating operating costs for seventy-seven currently available commercial rotorcraft models under a fixed set of operating assumptions. Statistical analysis of this data is combined with the physics and first principles approach to identify key explanatory variables demonstrating a strong relationship to operating cost. Multiple regression techniques are used to develop transfer functions relating rotorcraft design variables to direct operating cost. The analysis shows that the maximum takeoff gross weight of the rotorcraft design is strongly correlated with direct operating costs. Specifically, a simple regression model using the square root of maximum takeoff gross weight as the only explanatory variable can be used to account for over 90 percent of the variation in total direct operating cost (TDOC). After accounting for maximum takeoff gross weight, the analysis suggests that rotorcraft models with two engines have higher TDOC than those with a single engine. A multiple regression model using maximum takeoff gross weight and the number of installed engines in the rotorcraft design is presented and accounts for 97 percent of the variation in TDOC. This model allows designers to quickly estimate TDOC for new rotorcraft early in the design process, before many of the major design parameters have been finalized. In addition to the aggregate or total DOC models, regression models for a few key subcategories of DOC are developed including, fuel related DOC, airframe maintenance related DOC and engine maintenance related DOC. In the case of fuel related and airframe maintenance related DOC, the maximum takeoff gross weight is found to be the single strongest explanatory variable. For the engine maintenance DOC, the engine weight is found to be the single variable most strongly correlated with operating cost. We conclude that an appropriate measure of weight (maximum takeoff gross weight or engine weight) is an important driver for direct operating cost. After accounting for weight, the models are refined by considering additional explanatory variables leading to models of greater accuracy and complexity. The modular nature of the model presented allows operating cost estimates to be improved and refined as additional details of the rotorcraft design become available during the design process.

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# 1 Introduction

During the conceptual or preliminary design phase of any product, there is a need to make trade-offs between design characteristics. The impact of these design decisions must be evaluated on a variety of relevant figures of merit. This internship focuses on operating economics as the figure of merit in the field of rotorcraft design for commercial applications. This internship and thesis study are performed at a major designer and manufacturer of gas turbine engines for helicopter applications. As the supplier of a key aircraft subsystem, an engine manufacturer must have a deep understanding of the design attributes that are valuable to the customer. The underlying motivation for this project is to improve the understanding of one of these critical value attributes, rotorcraft operating costs. To this end, the objective is to develop a model to estimate rotorcraft operating cost early in the helicopter and engine design process.

Within the field of preliminary engine design, engine performance metrics, such as fuel consumption, power output, weight, etc., are widely used to optimize engine design for a given set of rotorcraft requirements. There is a need and opportunity, to improve the ability to perform preliminary design trade-offs using rotorcraft operating economics as the figure of merit.

Mature, widely-accepted, tools exist for estimating operating costs and performing economic trade studies for fixed-wing (airplane) applications. This project sets out to leverage the industry knowledge from fixed-wing operating cost modeling experience and develop an analogous model for rotorcraft applications. The ultimate goal is to improve the quality of rotorcraft operating cost assessment for use in preliminary design.

## 1.1 The Problem – Need for New Design Capability

When designing any product to perform or accomplish a particular mission, it is often necessary to reach a compromise between competing performance metrics. In the simplest case, a single measure of performance must be balanced against the cost required to achieve that performance. In other cases, increasing the performance of a product in one area may adversely affect its performance in other applications, thus requiring a multi-attribute design optimization process. The design of aircraft and the various aircraft systems and subsystems fall into the latter category. Designing such systems involves making trade-offs between multiple performance metrics (outputs) and the consumption of various resources (inputs).

The operation of aircraft consumes resources of various types. Fuel is burned while the engines are operated, the crew consumes time flying the aircraft, maintenance personnel spend time performing maintenance tasks, materials are consumed as parts are replaced at the end of their lives, etc. In order to compare the consumption of one resource with another, all of the resources must be expressed in a common set of units. The natural choice for these units are cost per unit of output, where a unit of output may be flying for a given amount of time (flight hour) or carrying a given amount of cargo a given distance (ton-mile), etc. Throughout this study, we focus on US dollars per flight hour ($/FH) as the chosen unit of measure. There are numerous assumptions involved in converting the physical resources consumed (fuel (gal/hr), maintenance labor (man hours), material, etc) into dollars. The different methods used to perform these conversions in various data sources are a potential source of variation, and hence must be reviewed and managed meticulously.

For this study, we choose a set of reasonable operating assumptions that are widely accepted throughout the industry. Based on these assumptions, we explore the relationships between rotorcraft design and available operating cost data, with the ultimate objective of developing a model to relate

these parameters. The model and associated development provides insights regarding the importance of operating economics to commercial rotorcraft customers. As a major helicopter engine designer and manufacturer, this understanding is imperative to enable design and planning for future applications. Specifically, some industry experts would argue that, "Because an engine generally takes longer to design and develop than an aircraft, the needs that will be associated with future aircraft systems must be anticipated by the engine manufacture well in advance of the commitment to the design a new aircraft" (Kerrebrock). This implies that the engine manufacturer must anticipate the needs of operators sooner than aircraft manufacturers. Regardless of whether one agrees with this statement or not, it is essential that any supplier or developer have a deep understanding of the needs and desires of its customers. The development of this model provides one step towards gaining a better understanding of rotorcraft operating costs, which is a critical attribute to customer value.

## 1.2 Research Methodology

This first step of this project involves obtaining a baseline understanding of the significant elements affecting helicopter usage, costs and important design and operating parameters. The assumptions, notation, methodology and definitions used to develop the model must be consistent with those accepted throughout the rotorcraft industry in order for the results to be useful to other members of the industry. As a result, a thorough understanding of the industry norms and methods for defining and distinguishing relevant subsets of operating costs is imperative.

Next, a thorough review of prior research related to estimating operating costs for rotorcraft and fixed-wing aircraft identifies key results and leverages best practices from existing studies. In parallel, an extensive search of existing sources of rotorcraft operating economic data is conducted and opportunities for gathering such data are identified and prioritized. The usefulness and predictive ability of the model developed herein is only as good as the data upon which it is built. As a result, the integrity and abundance of the response data (operating cost data) is crucial to the success of this project.

Independent from the search for operating cost data, an analysis of the physics and first principles relevant to the design and operation of helicopters is conducted. This physics-based or first principles approach is combined with input from available experts across the industry to identify the key parameters that may be expected to drive operating costs and the functional form of the model. At the outset, the variables identified from the physics-based analysis and first principles are proposed as potential explanatory variables expected to have some statistical relationship to operating costs. After the potential variables or X data have been collected, statistical regression analysis is used to identify significant explanatory variables and determine appropriate transfer functions linking these parameters to operating cost.

In addition to validation techniques consistent with good regression analysis, the results of the model developed are compared to a relevant historical published model and model-specific estimates provided by a helicopter manufacturer.

## 1.3 Thesis Outline

An overview of the organization of this document is provided for reference below:

Chapter 1 describes the basic motivation for this work and provides an overview of the general approach taken during this study.

Next, in Chapter 2, we provide background information related to the aviation industry and the associated operating economics. This section provides a common vocabulary and specifies the conventions for operating economic definitions used throughout this study.

Chapter 3 provides discusses the relevant issues and considerations related to aircraft design and operating economics. These concepts provide the foundation for the construction of the operating economics model.

Chapter 4 describes the key historical work in the field of estimating aircraft operating costs. Existing methodologies are critiqued and leveraged whenever possible to draw inferences and improve the usefulness of the model developed herein.

In Chapter 5, we change gears and describe the sources of data available for the construction of the economic model. This discussion provides important guidance on the limitations of the economic model as well as linking such limitation to potential opportunities for future improvements.

Chapter 6 gives a high-level overview of the physics behind the operation of helicopters and the first principles driving the various economic cost categories. This chapter is focused specifically on those elements that are likely to have a significant impact on operating costs. This chapter provides the physical basis for the construction of the model.

In Chapter 7, we draw on the discussion from preceding chapters to identify key explanatory variables and build a series of simple, robust, regression models to predict operating costs for future designs. The chapter is divided into different sections to cover the various modules of the proposed operating cost model.

In Chapter 8, we validate the models developed in Chapter 7, by comparing the performance of each model in predicting the response of a validation dataset. In addition, we compare the output of the model developed herein with aircraft manufacturer estimates and historical operating cost methods.

In Chapter 9, we summarize the manner in which the models developed in Chapter 7 can be used to provide new modeling and prediction capability during the preliminary design of helicopters and engines. In this section, we also identify future opportunities to extend this analysis and continuously improve the consideration of operating costs early in the design process.

## 2 Background on Aviation Economics

This section provides some background related to the aviation industry and the analytical methods associated with assessing the economics of aircraft operation. This section clearly defines the operating cost categories employed throughout this study and provides the foundation upon which the remaining chapters will build with increasing levels of detail.

### 2.1 *Overview of Commercial Helicopter Market*

The commercial (civil) helicopter market is an important market to the host company. Designers and manufacturers of shaft output gas turbine engines for helicopter operations are key suppliers to helicopter manufacturers. As such, the rotorcraft and engine manufacturers must work closely together to design and build helicopters that meet the demands of their end customer, helicopter operators. These needs and demands vary widely due to the sheer number of operators and variety of missions completed by helicopters. Specifically, as of 2007 over 23,000 helicopters were in commercial operation with over 1000 commercial operators worldwide(HeliCAS: The Ultimate Helicopter Market Information System).
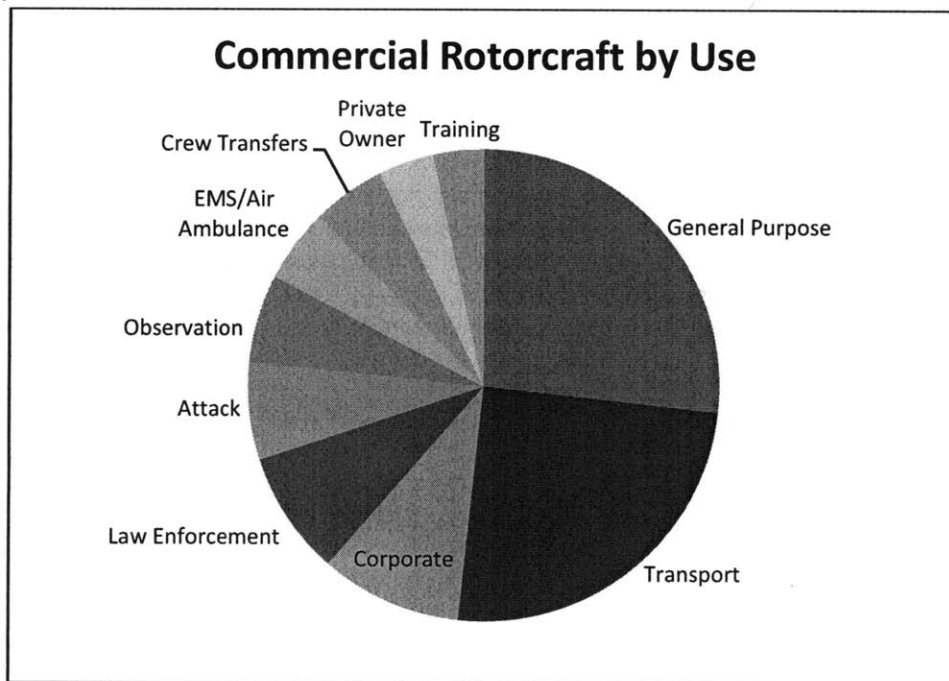


**Figure 1 Commercial Rotorcraft Use by Role or Type**

The most common uses for commercial helicopters are shown in Figure 1. The figure illustrates the wide variety of helicopter uses, which is one of the major complications that distinguish rotorcraft operations from fixed-wing operations. Specifically, most commercial fixed-wing aircraft are used for scheduled passenger transport and hence have very well-defined and characterized flight routes and operating characteristics. In contrast, a single helicopter model may be used to carry cargo, transport passengers, provide search and rescue support, etc. This breadth of helicopter uses complicates the estimation of operating costs due to the additional variation associated with the manner in which the helicopter is used.

The general purpose role shown in Figure 1 alone, includes a wide range of uses including utility applications such as providing maintenance support on power lines, wind turbines, HVAC installation, etc., as well as sight-seeing tours and charter service. The most common use for the larger commercial helicopters is to provide support to offshore oil production in the form of crew transfers as well as search and rescue services. The percentage of aircraft dedicated to crew transport shown in Figure 1 is relatively low. However, although the data is not widely available, on the basis of flying hours, these are very significant operations. Throughout this study, we will frequently use examples from offshore oil operations.

## 2.2 Aircraft Operating Economics

Operating costs refer to any costs that relate to the operation and support of the aircraft in service. There are many variations on the categories of operating costs so care must be taken to ensure that all parties are using consistent definitions. In general, operating costs can be broken down into two major subgroups: Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). In a nutshell, the direct operating costs (DOC) are associated with flying the aircraft and indirect operating costs (IOC) are associated with everything else. It is important to emphasize that direct operating costs (DOC) and indirect operating costs (IOC) do not imply variable costs and fixed costs. Both DOC and IOC have both fixed and variable components.

As mentioned, DOC refers to those costs directly associated with the operation of the aircraft. In evaluating whether a particular cost is a DOC or IOC it is useful to ask oneself if the cost would be incurred if the aircraft were not operating. For example, the cost of fuel required to fly the aircraft is a DOC since if the aircraft stopped flying, in would not consume fuel. The cost for maintaining the aircraft is less clear cut, but it still is a DOC since if one stopped flying the aircraft, the bulk of the maintenance actions would not need to be performed. Note that in reality the maintenance cost would not completely disappear as there would likely be a few maintenance requirements that are based on calendar time regardless of usage. The break down gets slightly less clear when you get into crew costs including salaries for pilots, support personnel, etc. For example, pilots may receive some annual salary independent of the number of hours they fly.

To deal with the existence of some ambiguity associated with the cost categories and avoid any confusion, the definitions used throughout this study are explicitly presented in Section 2.3.

## 2.3 Commercial Rotorcraft Operating Economics

Since the ultimate purpose of this study is to predict the operating costs for new helicopter applications, we must be clear about how we define such costs. It is essential to ensure that these definitions are consistent with those accepted throughout the rotorcraft industry. In addition, when making any estimates, it is often necessary to invoke simplifying assumptions. Any assumptions used in this study should be consistent and realistic with those widely used in the industry.

The need to correctly use industry definitions and assumptions prompted the search for a widely-accepted set of such assumptions. Shortly after beginning a literature search for existing cost accounting methods and practices, it became clear that most helicopter manufacturers strive to prepare their cost estimates in a format consistent with a document produced by the trade organization, Helicopter Association International (HAI). As described in more detail in Section 5.2, HAI is a non-profit, professional trade association dedicated to promoting safe, efficient, economic use of commercial helicopters throughout the rotorcraft industry. Within HAI, there are a number of different committees

dedicated to advancing various aspects of this mission. The Economics Committee is the group tasked with addressing operating cost issues{{91 Helicopter Association International 2009}}.

In response to increasing pressure from industry as well as the growing concerns over the difficulty in quantifying the cost of operating and maintaining a helicopter, HAI and the Aerospace Industries Association of America (AIA) published a "Guide for the Presentation of Helicopter Operating Cost Estimates" in 1981. The purpose of the guide was "to close the gap between manufactures and operators on the subject of operating costs"(Aerospace Industries Association of America. Committee on Helicopter Operating Cost., and Helicopter Association International. ). The first version of the guide, published in 1981, was updated in 1987 and again in 2001. Discussions with members of the HAI Economics Committee involved with the preparation of the guide, suggest that another update may be expected in the early 2010s.

In summary, the AIA and HAI recognized the need for increased consistency in operating cost definitions and assumptions used to estimate costs throughout the rotorcraft industry. They formed a task force to produce a document intended to improve these two areas and provide regular updates. The task force includes helicopter manufacturers, engine manufacturers and helicopter operators, as all three parties are intimately tied via the operating costs. As such, this forum, and the published document they produced provides the ideal common ground upon which to base this study. The definitions and common assumptions recommended in "Guide for the Presentation of Helicopter Operating Cost Estimates, 2001" are adopted as the standards throughout this study. Table 1 shows a summary of the cost categories that make up the total direct operating costs based on the guidelines and definitions from the HAI publication.

The cost breakdown shown in Table 1 provides the basis for discussion throughout this study. When we discuss and present a few examples of data sources in Section 5.1, it will become evident that not all sources are consistent with these definitions. In particular, the greatest amount of deviation from this representation is related to the varying levels of resolution used in presenting costs. As an example, within the category of airframe maintenance costs, some sources will separate airframe maintenance into scheduled and unscheduled, without regard for whether it is line maintenance, overhaul, etc. Other sources will lump all maintenance labor (airframe and engine) together. While dealing with such discrepancies, we will always return to the table in Table 1 as our guiding standard. Every effort will be made to convert the various sources of cost data into categories consistent with the HAI guidelines.

Before proceeding it is worth making a few comments about the cost categories shown in Table 1. First, as described in Section 2.2 on Aircraft Operating Costs, the total cost of operating a helicopter can be divided into Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). While IOCs may be important to the operator, they are not affected by aircraft or engine design decisions, and hence they are not treated here. The HAI guide on the presentation of operating costs focuses on DOCs, as these are the costs that are relevant to all three parties: helicopter manufacturers, engine manufacturers and operators. DOCs are costs directly related to the operation of the aircraft. If the operator were to cease operation of the aircraft, then these costs would not be incurred. Within DOCs there may be variable costs and fixed costs. Variable Direct Operating Costs (VDOC) are defined as, "those costs whose dollar value in a given period varies in proportion to the amount of flight hours accumulated"(Aerospace Industries Association of America. Committee on Helicopter Operating Cost., and Helicopter Association International. ). Appendix A shows a hierarchical diagram of the total operating costs broken down into variable and fixed costs with the addition of the IOCs to illustrate the point that DOC are both variable and fixed.

**Table 1 Rotorcraft Operating Cost Elements**

| Rotorcraft Direct Operating Cost Elements | | |
|---|---|---|
| **Direct Variable Operating Costs (DOC)** | | |
| | | Average Fuel Consumption (gal/FH) |
| | | Fuel Cost ($/FH) |
| | | Cost of Lubricant ($/FH) |
| | Total Fuel and Lubricants Cost ($/FH) | |
| | | Airframe Line Maintenance Labor (MMH/FH) |
| | | Total Airframe Line Maintenance Labor Cost ($/FH) |
| | | Airframe Line Maintenance Parts Replacement Cost ($/FH) |
| | | Reserve for Life Limited Parts Retirement ($/FH) |
| | | Reserve for Overhaul of Major Components ($/FH) |
| | | Unscheduled Airframe Maintenance Labor (MMH/FH) |
| | | Total Unscheduled Airframe Labor Cost ($/FH) |
| | | Total Unscheduled Airframe Parts Cost ($/FH) |
| | Total Airframe Direct Maintenance Cost ($/FH) | |
| | | Reserve for Engine Overhaul ($/FH) |
| | | Engine Line Maintenance Labor (MMH/FH) |
| | | Total Engine Line Maintenance Labor Cost ($/FH) |
| | | Engine Line Maintenance Parts Replacement Cost ($/FH) |
| | Total Engine Direct Maintenance Cost ($/FH) | |
| | Total Direct Maintenance Cost (Airframe and Engine) ($/FH) | |
| **Total Direct Variable Operating Costs ($/FH)** | | |
| | | |
| **Direct Annual Fixed Costs** | | |
| | | Number of Pilots |
| | | Total Pilot Cost ($/yr) |
| | | Total Technician Cost ($/yr) |
| | | Total Support Personnel Cost ($/yr) |
| | Total Crew Cost ($/yr) | |
| | | Hull Insurance, Annual Cost ($/yr) |
| | | Liability Insurance, Annual Cost ($/yr) |
| **Total Direct Fixed Costs ($/yr)** | | |
| **Total Direct Fixed Costs per FH ($/FH)** | | |
| **Total Direct Operating Cost ($/FH)** | | |

The first subset of VDOC shown in Table 1 deals with fuel and lubricant costs. The HAI guide establishes standard flight conditions to be used in estimating the fuel consumption rate, which can then be directly converted to the fuel cost. The cost of lubricant is typically assumed to be a constant percentage of the cost of fuel. The next two subsets of VDOC cover airframe maintenance and engine maintenance. These two categories are discussed in detail in Section 2.4 and Section 6.2. The three major assumptions involved in the estimation of VDOC are the fuel cost per gallon, the lubricant cost as a percentage of fuel cost (typically 3%), and the maintenance labor rates in dollars per maintenance man hour ($/MMH).

Aside from the VDOC, the next subset of DOC shown in Table 1 represents fixed DOCs. The costs are typically expressed on an annual basis, and represent costs that are still directly related to the operation of the helicopter. For example, the cost of paying pilot is an example of this. The pilots are assumed to be paid on an annual basis, and if the operator were to stop flying the aircraft completely it is possible that the operator would no longer employ the pilots. However, as long as some flying operations are continued, the operator must continue to pay pilot salaries regardless of the number of hours flown. More detailed discussions of crew cost as well as the rest of the cost categories are provided in Chapter 6.

As we develop DOC models for the major categories shown in Table 1 it helps to have a sense of the approximate significance of each subset of costs. An example of the relative value of each of the major cost categories is shown in the chart in Figure 2.



**Sample Relative DOC for Commercial Rotorcraft**

Miscellaneous 10%
Fuel and Lubricants 15%
Engine Maintenance 9%
Insurance 14%
Assuming:
500 flight hrs/yr
10 year life
3.00 ($/gal) fuel
75 ($/hr) maintenance labor rate
1 cycle/flight hr
Crew Salary and Benefits 23%
Airframe Maintenance 29%

Source: Conklin & de Decker Associates, Inc. 2009
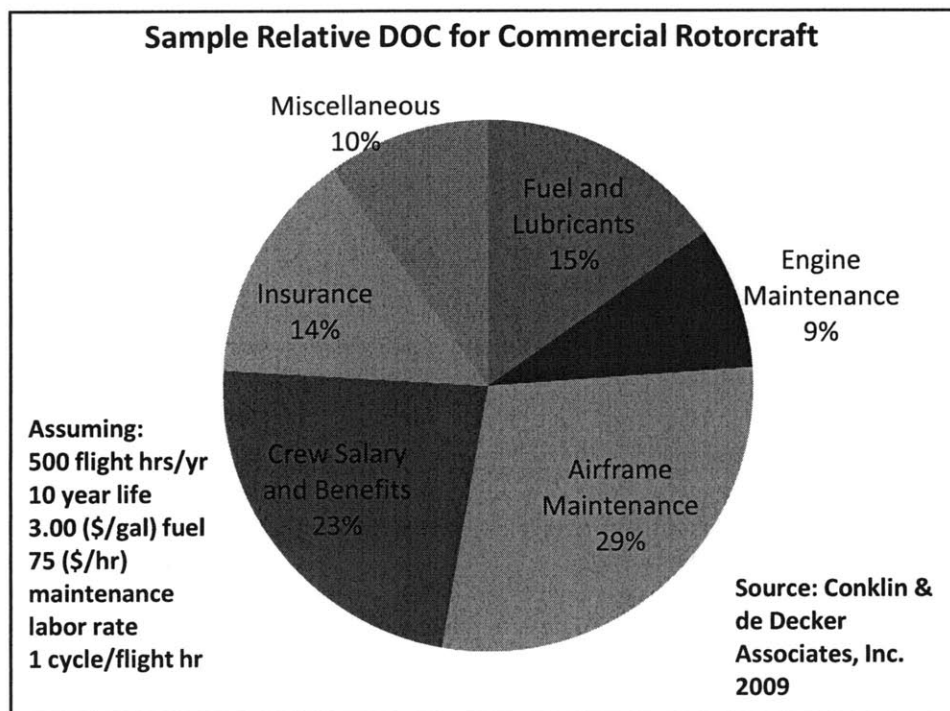
**Figure 2 Sample Breakdown of Commercial Rotorcraft DOC**

The values shown in Figure 2 were generated using life cycle cost data from Conklin & de Decker Associates, Inc., which is described in Section 5.6. For each category of DOC the cost per flight hour is divided by the total DOC per flight hour to generate the percentages. Note that the airframe maintenance related DOC comprises the largest portion of TDOC under the operating assumptions shown in the figure. While each category of DOC will be discussed and developed in subsequent sections of this thesis, the relative significance of these major cost categories sheds some perspective on which costs are most important to commercial helicopter operators.

With a baseline for the definitions and relative significance of each DOC category in mind, we can focus our efforts on those areas that drive the majority of costs. Since maintenance DOC, on both the airframe and the engine, are such as large portion of the total DOC, it is worth saying a few words

related to the way maintenance is managed and handled in the aviation industry in the following section.

## 2.4 Aviation Maintenance Structure

As illustrated in Section 2.3, the operating costs associated with performing maintenance are a substantial portion of the total cost of operating an aircraft. In subsequent chapters, we will also discover that maintenance related DOC can be relatively difficult to predict for new designs. Much of the discussion throughout the remainder of this study deals with maintenance-related DOC. This section provides some background on the maintenance framework commonly used in the aviation industry, which is useful for subsequent discussions.

### 2.4.1 Types of Major Maintenance Programs

There are three categories of maintenance programs that are widely used throughout the aviation industry, known as *Hard Time*, *On Condition*, and *Condition Monitoring* (Hessburg ). As the name implies, *Hard Time* refers to maintenance programs where parts and components must be replaced after a fixed amount of time or cycles on the aircraft. This is the oldest, and perhaps most rudimentary, maintenance process. It is based on the notion that the reliability of a part or component decreases with operating time or exposure. As a result, applying a limit on the amount of time that a part is used is intended to prevent failure. Hard Time maintenance processes are typically applied to parts that have well defined life limits and those whose failure could potentially result in catastrophic consequences. Perhaps the most common example of *Hard Time* limits are applied to aircraft parts subject to metal fatigue as described in Section 3.2.

While the reasons for using *Hard Time* limits are clear, they tend to be extremely expensive. In addition to the cost of material and labor to replace parts at their life limits, the actual process of performing the overhaul or part replacement wears out adjacent parts and provides additional opportunities for maintenance errors. Lastly, *Hard Time* programs may also tend to increase the actual cost of replacement parts due to the lost utility or life in a given component. When the service life of a part is established, the life limit is not the average predicted life for the part. Rather, the limit is chosen to be less than the average life so that the chance of a part failing prior to the life limit is extremely small. The probability of the part failing at any given time is frequently modeled using a Weibull distribution. Weibull distributions are very flexible and hence are widely used to model failure rates across a variety of industries. When a part is replaced at its life limit, it has some residual useful life that is discarded. Improvements in methods of predicting metal fatigue life limits as well as improvements in the characterization of material properties have reduced this waste, but it will inherently continue to be a concern when using such life limits.

In addition to the variation in life for individual parts, the interdependent nature of a complete aircraft system, subsystems, and components lead to additional "wasted" part life due to practical considerations for maintenance scheduling. For example, consider a simplified (very simple) aircraft with only two parts with hard time limits. Part A has a limit of 3000 flight hours, and Part B has a limit of 5000 hours. Scheduling the replacement of these two parts has significant economic consequences. Let's consider three possible scenarios for the practical execution of these hard time maintenance requirements over the first 6000 hours of operation of the aircraft. In the first scenario, we replace Part A at 3000 flight hours and both Part A and Part B at 5000 flight hours. Hence at 6000 hours Part A has 2000 hours of remaining life, and Part B has 4000 hours remaining, and a total of two shop visits or maintenance actions were performed and 1000 hours of residual life on Part A were wasted. In the

second scenario, let's replace Part A at 3000 hours, Part B at 5000 hours, and Part A again at 6000 hours. In this case, at 6000 hours Part A has 3000 hours of residual life, Part B has 4000 hours of life, a total of three shop visits were performed and zero hours of residual life were wasted. In the third scenario, let's replace both Part A and Part B at 3000 hours and 6000 hours. In this case, at 6000 hours Part A has 3000 hours of residual life, part B has 5000 hours, a total of two shop visits were incurred and a total of 4000 hours of residual life on Part B were wasted. It is not possible to determine which of the three scenarios makes the most sense from an economic perspective without more information regarding the part cost, labor cost, opportunity cost per shop visit, etc. The bottom line is that the fact that the hard time limits are not exact multiples of each other leads to inherent waste in the maintenance process. This waste manifests itself either in the form of discarding residual part life (scenarios 1 and 3), or additional shop visits and aircraft downtime (scenario 2).

A maintenance process known as *On Condition* maintenance is at the opposite end the maintenance spectrum from *Hard Time* maintenance. In general, *On Condition* maintenance programs do not depend on predicted part or component lives, but rather uses repetitive inspections or tests to detect failure or impending failure. Within this category of maintenance process, there is a wide range of variation in the implementation depending on the magnitude of the importance of the part or component's functionality. A simple example of *On Condition* maintenance that is both applicable to many aircraft as well as a car or bicycle, is the replacement of brake pads. The pads are periodically inspected either visually or by measuring pad thickness, and replacement is completed when the pads reach a minimum accepted thickness or wear limit.

Another example of *On Condition* maintenance may be the inspection of an airframe surface for signs of cracking. If no cracks are detected, then the aircraft can continue operation. However, if cracks are detected, then some maintenance action must be taken to repair or replace the part within a defined period of time (such as the next 100 flight hours). In this hypothetical case, *On Condition* maintenance could be used if the crack growth and propagation characteristics are well understood. The inspection intervals and limits for replacing the part upon detection of a crack depend on the ability to predict crack growth to ensure that action is taken to prevent a failure.

The third major category of maintenance process, called *Condition Monitoring*, applies to parts and systems that show deterioration over time. It can be used in either a predictive manner or as a failure based process (Hessburg ). At one extreme, consider a reading light in the cabin on a helicopter for passenger transport. The light is used until the bulb burns out, and then the light bulb is replaced. Thus, the condition for replacement is when the bulb fails to produce light. In this example, maintenance of this type is possible because the failure of the light does not have major consequences.

In contrast to allowing a part or component to fail before replacement, condition monitoring can be used to predict impending failure or a trend towards failure. Many modern aircraft engines incorporate digital engine controls that can record various engine operating parameters and monitor trends in the performance of the engine. Combining this monitoring or trending of single components with historical or fleet databases, the current condition of the engine can be used to predict the next maintenance action that may be required. Similar monitoring techniques may be used for both the engine and the various rotating helicopter components to trend vibration levels, metallic content in lubrication oil, etc.

## 2.4.2  Development of Maintenance Program for New Designs

The development of a maintenance program for a new helicopter is an integrated part of the helicopter design process.  The manufacture must consider all three types of possible maintenance programs: *Hard Time*, *On Condition*, and *Condition Monitoring*.  After identifying the key parts, components and subsystems that require maintenance treatment, the manufacturer must make quantitative trade-offs between the considerations outlined above to evaluate how to treat each item.  Ultimately, the manufacturer must create a list of recommended scheduled maintenance actions with detailed documentation that is submitted to the appropriate official agency.  These recommendations are reviewed by the official agency and the agency publishes a report of maintenance requirements based on the manufacturer's recommendations.  Once an operator begins operating a particular aircraft, that operator is responsible for substantiating a maintenance program that is acceptable to the official agency.

Through this process, the maintenance recommendations created by the manufacturer may be translated into mandated requirements for operators.  As a result, the process of identifying and defining requirements should not be taken lightly.  The first step of selecting which parts require maintenance treatment can be fairly subjective and rely heavily on local expert opinion and qualitative trade-offs.  The addition of parts and components to a list of items requiring scheduled maintenance is a balancing act.  If the requirements for including an item on the scheduled maintenance list are too conservative, then too many items may end up on the list and operators may be forced to perform maintenance that is not required.  Conversely, if the standard is overly optimistic then some items that truly require periodic maintenance may be excluded from the list.  This makes the *scheduled* maintenance cost elements low, but may lead to unexpected failures and issues which require *unscheduled* maintenance action and incur additional secondary costs of schedule disruption, lower availability, etc.

Some examples of common scheduled maintenance requirements include (Hessburg ):

- Checks to confirm components and subsystems are performing according to some defined performance metric
- Inspections of structural parts, which may by visual or include the use of non-destructive test (NDT) equipment
- Inspection for corrosion
- Lubrication of required components and parts
- Engine maintenance requirements such as replacing filters, lubricating oil, etc.
- Restoration of a part or component to working condition, such as the addition of paint to cover an exposed surface
- Replacement of consumables such as various filters
- Replacement of life limited parts (LLPs)
- Overhaul of various components after hard time requirements are reached

In contrast to *scheduled* maintenance, *unscheduled* maintenance can be simply defined as, "all maintenance performed other than scheduled (Ausrotas, Hsin and Taneja 123)."  Ideally, as a part or system is used in the field, the operator and manufacturer will gain experience regarding the maintenance requirements and take corrective action to convert unscheduled maintenance into scheduled maintenance.  However, many scheduled maintenance actions are structured to check

hardware condition or functionality and repair if necessary. Unscheduled maintenance typically includes the following types of items (Hessburg ):

- Resolution of issues identified by pilot during flight
- Failure of condition monitoring equipment or checks
- Special inspections generated by Airworthiness Directives (ADs)
- Actions required after operating aircraft outside of normal operating envelope (such as exceeding a transmission power limit or engine temperature limit)
- Repair of structural damage to aircraft, which is most commonly caused by contact with equipment on the ground

In addition to the categories of scheduled and unscheduled maintenance, actions can also be divided into *line* maintenance and *base* maintenance according to where the work can be performed. Specifically, line maintenance is performed "on-wing" or in the "shadow of the aircraft," meaning that it can be performed with the component or part installed on the aircraft or with the part or component removed and mounted on some sort support equipment next to the aircraft. In contrast, base maintenance, which is also sometimes called shop maintenance, must be performed in an aircraft hangar or at a specialized service shop. Base maintenance typically covers the more extensive maintenance actions such as the overhaul of major components. For such activities, the aircraft must be removed from operations, or at least the major component must be removed. For example, in the case of an engine overhaul, an engine could be removed from the aircraft and replaced by a spare engine. Thus, the aircraft could operate with a spare engine while the original engine is shipped to a repair facility and overhauled.

### 2.4.3 Economic Impact of Maintenance Program

One may expect that line maintenance would have a lower economic impact on operations than base or shop maintenance. However, since line maintenance is typically performed in a less controlled environment, there may be greater opportunities for errors and secondary damage due to foreign object damage (FOD) or exposure to harsh environmental conditions, such as salt or sand exposure to lubrication systems.

Maintenance processes based on condition monitoring can have immense economic benefits by eliminating the need for inspections or hard time part replacement as well as improving maintenance scheduling, aircraft downtime, and spare parts inventory management, since maintenance actions can be predicted, planned and coordinated. The major enabling technology for increased use of predictive condition monitoring relates to the data collection and analysis processes. Advances in integrated circuitry have enabled more advanced onboard computing power and improved, low-cost sensors of various types. In addition, increased use of "digital" or "glass cockpits" is leading to more widespread use of microprocessors with the ability to perform condition monitoring as well as self-diagnostic tests.

While the maintenance philosophy or program of a given operator can affect the reliability and availability of an aircraft, it is important to highlight the fact that the reliability can never be greater than that which is inherent in the design. That is to say that one cannot "improve reliability by trying to inspect it into a design"(Hessburg ). In fact, frequent inspections and maintenance actions tend to increase wear and the opportunities for maintenance errors which may lead to additional reliability issues. The purpose of maintenance is to "restore safety and reliability levels when deterioration or

damage has occurred"(Hessburg ). Maintenance is closely related to failure, which can be thought of as either "the inability to perform within specified limits or the inability to perform an intended function"(Hessburg ). Failures can affect safety or have economic consequences. Failures that result in safety issues should be avoided at all costs, and designers throughout the aviation industry consider this paramount. Such failures are avoided by protecting crucial functions and systems with redundancy, fault detection, fail-safe designs, fault tolerance, and the use of simplified backup systems.

Any failure that does not affect safety can be considered an economic failure. The economic consequence of such a failure may constitute itself in the form of reduced availability. For example, consider the case where a helicopter has an economic failure during flight while transporting a crew to an offshore oil platform. The fact that it is an economic failure means that there is no safety issue and hence no risk to the passengers and the helicopter can land safely on the platform. However, depending on the failure, it is possible that the helicopter cannot takeoff from the platform until the part or component has been repaired. In this case, there is an economic cost incurred due to the lost availability of the helicopter. The crew may either stuck on the platform, or a second helicopter or ship must be called to provide the transport service. Alternatively, a replacement part, tool, or maintenance personnel may be required to be transported to the platform to repair the aircraft. The economic costs of such failures can escalate very quickly.

Because of the high level of redundancy and continuous increases in complexity to expand capability, there are many systems and parts on modern aircraft that are extraneous to their basic operation. This fact leads to the concept of deferred maintenance as a practical issue that arises throughout the industry. Specifically, every system or installed component is not necessary for operations as long as other remaining operative equipment provides an acceptable level of safety(Hessburg ). This concept led to the establishment of Minimum Equipment Lists (MELs) which specify the equipment on an aircraft that must be operative in order for the aircraft to fly. The MEL's also specify how long a given piece of equipment can be inoperative, or conversely how quickly it must be fixed. A MEL may be specific to a given aircraft model, or may be specific to a given *model and mission*. For example, the minimum equipment required to complete an oil transport mission will likely be different from the minimum equipment required to carry passengers on a sight-seeing trip even for the same helicopter model. The existence of MELs provides operators additional freedom regarding the maintenance actions they choose to complete. We will return to this concept in Section 6.2, since some operators may choose to fly with the bare minimum equipment specified by the MEL, while others will insist that every item is in working order before commencing a flight. These decisions have a considerable impact on operating costs.

In this chapter we provide an overview of the commercial rotorcraft market, some background on aircraft and rotorcraft economics, and a brief description of the maintenance structure commonly used in the aviation industry. We will return to some of the intricacies involved in predicting maintenance costs in Section 6.2 and Chapter 7. However, before we do that, we must review some of the key considerations encountered during the design of aircraft and engines.

# 3 Design Considerations

This chapter provides some background on the relevant issues and considerations that are important for understanding the nuances related to the ultimate objective of this project: to enable the estimation of helicopter operating costs early in the design process. In particular, this chapter starts with some background on the ways aircraft design may differ from the design process for other products. Next, we discuss the preliminary design of helicopters in more detail including a description of the major design decisions encountered during the process. Finally, we discuss considerations related to the design of gas turbine engines for helicopter applications. These design decisions and considerations are highlighted as possible explanatory variables during the construction of the model. These concepts provide the foundation for the construction of the operating economics model.

## 3.1 Aircraft Certification Process

The development of a new aircraft from initial concept through certification can take anywhere from 5 to 10 years(Hessburg ). In the early stages of design, a number of potential aircraft configurations are drafted in a form commonly referred to as "paper" aircraft, meaning that the designs exist only on paper (or more likely in CAD files). As demands from the market, competitive actions, and development of related technologies drive this process, the number of potential aircraft configurations is continuously reduced and further definition is provided. Engine manufacturers may propose one or more potential engine configurations for the proposed aircraft and preliminary engines are selected. The aircraft manufacturer begins identifying and soliciting component manufacturing sources, various vendors, and risk-sharing partners(Hessburg ). Since the certification process for a new aircraft can take up to 5 years, typically the airframe and engine manufacturers will engage with the appropriate official agency, such as the FAA, as early as possible after a final design or configuration has been identified.

Once approved for operation, the certifying authority (e.g. FAA in the US, EASA in Europe) will issue a Type Certificate which entitles the aircraft, engine or component to be operated under given limitations. There are many times when defects or deficiencies in a design may be discovered after some number of years in operation. In order to correct these deficiencies and ensure that the aircraft are safe for operation, specific corrective actions must be taken. The actions required, such as repair, replacement or periodic inspection of a part is officially required through the Airworthiness Directive (AD) system by the FAA(Hessburg ). When estimating the maintenance costs for a new design, it is frequently desirable to set aside some reserve cost to account for the completion of an AD's that may be issued in future years of operation. We will discuss maintenance costs and maintenance cost estimates in great detail in subsequent chapters, but for now, the important point is that Airworthiness Directives (ADs) are the means by which additional limitations or requirements are communicated within the US regulatory structure.

## 3.2 Rotorcraft Design Decisions

To construct a useful operating cost model to be used during the conceptual design phase, the inputs must be chosen carefully to ensure that they will be known and readily available early in the design process. A higher level of aggregation of both costs and design details may be necessary at this level than during the later design stages. As a result, a basic understanding of the process used during the conceptual design of rotorcraft is a prerequisite for building a useful model. In addition, an

understanding of the major design decisions provides a framework for identifying differences in existing rotorcraft models which can be investigated for relationships to operating costs. This section will describe a potential conceptual design process and highlight some of the key decisions and considerations a rotorcraft designer may face during the design of a new helicopter.

### 3.2.1 Preliminary Rotorcraft Design

The preliminary or conceptual design of new helicopters is largely driven by performance requirements. Traditionally, the goal has been to find the optimum helicopter design that meets performance requirements at the lowest possible weight. Helicopter designs must consider the fact that different operators will use the aircraft differently, and even a single operator may use a helicopter for a variety of missions. As a result, this optimization must be done over a diverse mix of missions. During the preliminary design phase, the mission or mission mix must be clearly defined. The designer must have a clear understanding of the important figure of merit, such as the mission effectiveness, in order to accurately consider parameters and make trade-offs that determine the value of the design. One commonly used approach to deal with the complication of designing for a variety of missions is to identify the most demanding mission, and then design the aircraft to meet the performance specifications required to complete that mission. Once the most demanding performance requirements are identified, natural choices for objective functions to optimize the design include:
- Minimize cost
- Minimize size
- Minimize gross weight
- Maximize flight performance (payload, range, endurance)
- Maximize performance per unit cost

In the past, the first possible objective, to minimize cost, was frequently replaced by the objective to minimize weight due to the lack of widely available operating cost data (United States. Army Materiel Command ). Frequently, weight was used as a proxy for cost, and hence designs were optimized to minimize weight. As such, during the first pass in conceptual rotorcraft design, the "best" design may be that which meets all performance requirements at the minimum possible weight. Once a set of requirements are specified, the first rotorcraft design parameters that can be estimated to meet the requirements involve weights (gross weight, empty weight, fuel capacity), and size (rotor area). Researchers at the National Aerospace Laboratory (NLR) in Amsterdam have published work related to the development of an analysis tool to perform this conceptual design step. The work is part of a consortium effort called Value Improvement through a Virtual Aeronautical Collaborative Enterprise (VIVACE), and the rotorcraft conceptual design tool developed is called "SPEcification Analysis of Rotorcraft" (SPEAR)(Boer, Stevens and Sevin ). The methodology employed in SPEAR provides an illustration of the typical conceptual design process for a new rotorcraft application. The process estimates the size and minimum weight of a rotorcraft capable of fulfilling a set of operational requirements. The process begins with the specification of a set of requirements. Examples of the general performance metrics that form these requirements include (Leishman 496):
- Hover capability
- Maximum payload
- Maximum range and endurance
- Maximum speed
- Climb performance in the form of climb rate
- "Hot and High" performance which combines service ceilings at different atmospheric conditions thereby defining the flight envelop

- Maneuverability and agility

The SPEAR tool draws on industry experience and a large database of existing helicopter models to estimate the rotorcraft gross weight, main dimensions, installed power, fuel capacity and mass breakdown for various components, required to meet the set of performance requirements. An example of a potential way to perform this conceptual design process, which is largely consistent with the methodology used in SPEAR is shown in Figure 3.
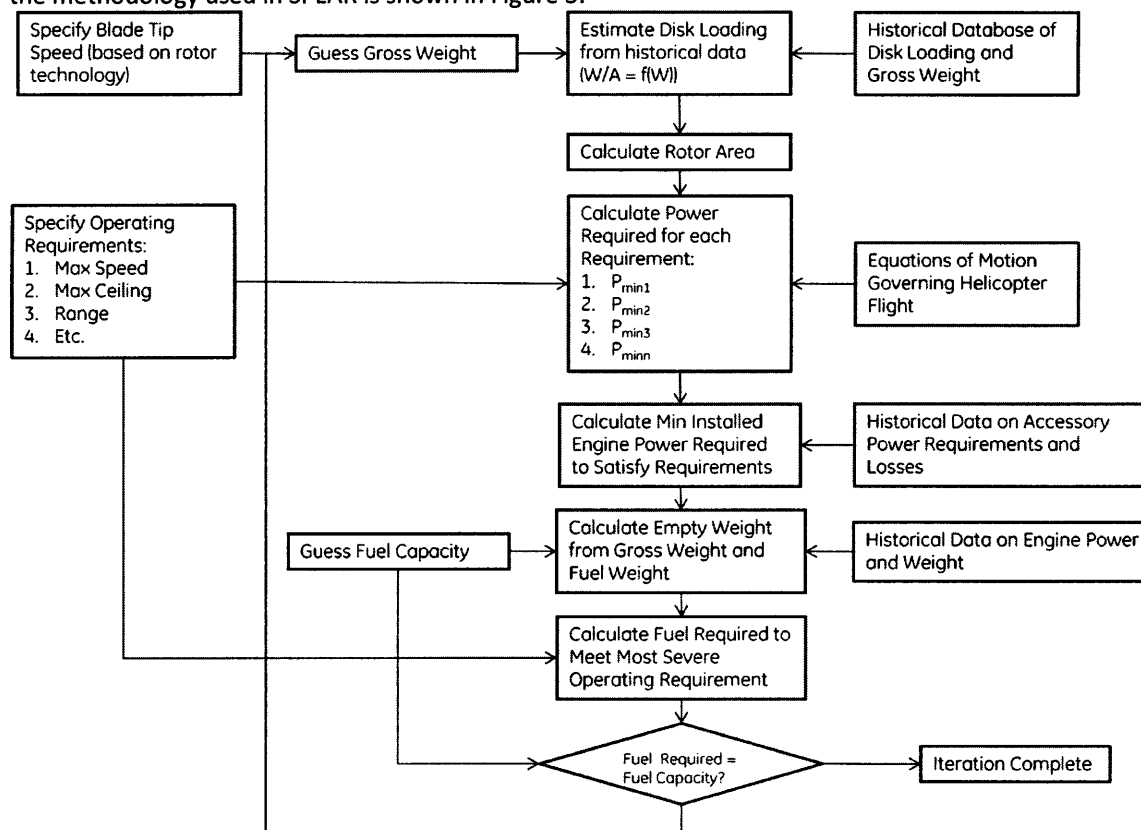


**Figure 3 Possible Helicopter Conceptual Design Process**

The designer must specify the blade tip speed, which is typically determined by the state-of-the-art in rotor technology. The process first determines the main rotor dimensions, which is done by making an initial guess of the gross weight, and then estimating the disk loading from the gross weight based on assumptions and historical data. From the disk loading, the rotor dimensions can be estimated. Next, the rotor power required for each performance requirement is calculated and used to determine the minimum engine power requirement. The engine power required for the most severe performance requirement then determines the minimum acceptable engine power for the design. An initial assumption for the fuel capacity is made and used to calculate the empty weight from the gross weight. Then, the fuel required to complete the most demanding mission requirement is calculated and compared to the assumption. This process is repeated by varying the initial guesses of gross weight, fuel capacity, and disk loading until a solution is reached in which the required fuel is equal to the actual fuel (Boer, Stevens and Sevin ).

This process illustrates a simple way a set of mission or performance requirements can be translated to a general rotorcraft configuration and an accompanying design figure of merit, which in this case is simply the gross weight. The process can be used to estimate the gross weight of the lightest possible rotorcraft design that will meet the given requirements. The process shown in Figure 3 relies heavily on historical data such as the relationship between disk loading and gross weight, accessories power requirements and losses, engine power and weight, and empty weight fraction or fuel fraction. While the process is somewhat crude, it does provide a very quick, high level estimate of the major design parameters in question. The design can be further developed and optimized by considering the various other metrics of a "good design." A discussion of such metrics is provided in (Section 3.2.5).

While the process described in Figure 3 provides a first-level illustration of the simplest rotorcraft conceptual design method, there are many more factors to be considered in specifying the remaining major rotorcraft design parameters. To fully understand the design process, we must address considerations related to these major design decisions and review some of the choices facing rotorcraft designers as well as some of the constraints.

The constraints encountered during the preliminary design of a new helicopter primarily stem from three sources:
1. Civil certification or military specification requirements
2. Customer requirements
3. Physical limitations governing helicopter operation

An example of a constraint stemming from civil certification requirements relates to multi-engine helicopter designs which are certified to operate with one engine inoperative (OEI). In order to meet this requirement, a particular design may be constrained in terms of the transmission rating, load capability, and engine sizing. Customer requirements come in many forms, and may include the ability to operate at high altitude, noise restrictions, maintenance requirements, physical size constraints, landing gear geometry, etc. Physical limitations include issues such as the maximum tip speed due to compressibility effects and vibration constraints.

Throughout the conceptual or preliminary design of a helicopter, the designer must keep these constraints in mind. In particular, the designer has a number of design choices which interact with one another and affect the ability of the overall system design to meet the requirements. A great detailed description of the considerations encountered during helicopter design is provided in the literature by Leishman, Prouty and others. A summary of the considerations is provided here in an attempt to illustrate how they may relate to the operating economics of the design. This discussion highlights a possible method for identifying key design differences in our dataset.

## 3.2.2  Main Rotor Design

The design of the main rotor is the most important element in rotorcraft design{{51 Leishman,J.Gordon 2000}}. An example of the process used to design a main rotor during the conceptual design phase presented by Leishman will be shown here as an example. The design of the main rotor can be broken down into three sub-processes. The first process determines the overall size of the rotor including the selection of the rotor diameter, disk loading, and rotor tip speed. The second process establishes the blade planform, which includes determination of the chord, solidity, blade count, and blade twist.

Finally, the third step, involves the selection of the airfoil sections at various radial positions along the blade(Leishman 496).

The initial sizing to determine the main rotor diameter involves several trade-offs. The hover performance and autorotation considerations favor a large rotor diameter. However, performance during cruise benefit from a smaller rotor due to reduced drag and a smaller and lighter hub. In addition, several physical, non-aerodynamic, considerations favor a smaller diameter including transportation limitations, torque limitations in the transmission and drives, static rotor droop and hence material and stiffness requirements of the blades and clearance between the main rotor and the airframe structure and tail rotor. Typically, a manufacturer will try to find the smallest rotor diameter that will still meet all of the performance requirements(Leishman 496).

Once an initial rotor diameter has been identified, the main rotor rotational speed can be determined by constraints on the rotor tip speed, which is simply the product of rotational speed and the rotor radius. The tip speed is typically constrained on the high side by compressibility effects and noise, and constrained on the low side by limits for autorotation capability and stall on the retreating blade. Recent improvements in blade airfoil design and tip features have mitigated the effects of compressibility concerns thereby enabling slightly higher tip speeds. However, in general, the tip speeds for existing rotorcraft designs are limited to a fairly narrow range.

After the rotor diameter has been determined, the rotor solidity is largely influenced by blade stall limits. All else being equal, higher solidity will result in greater stall margin for the same rotor diameter and tip speed. In turn, the civil certification requirements or military specifications typically specify the required stall margin indirectly, by specifying bank angles and maneuvers that must be demonstrated without stall. In Section 6.1.1, we show that the rotor power required for helicopter flight is directly impacted by the solidity. A lower solidity is desirable to minimize power requirements, while a higher solidity is desirable for stall considerations. Thus, the selection of the appropriate solidity is largely a trade-off between performance, in the form of power requirements and stall margin. Typical values for the rotor solidity are in the range of 0.08 to 0.12(Leishman 496).

Once the rotor solidity is established, the number of blades is typically determined by dynamic considerations rather than aerodynamic concerns(Leishman 496). The number of blades affects both the blade weight and hub weight, and typically fewer blades will result in reduced maintenance costs. A higher blade count generally reduces rotor vibration levels. Most modern helicopters have anywhere from two to seven blades with increasing blade count corresponding to larger (heavier) helicopter models.

While the discussion thus far deals with overall rotor decisions such as rotor diameter, solidity and blade count, the next step in the design process involves focusing on the individual blades. One blade characteristic of interest is the degree of blade twist. Negative twist, which reduces the angle of attack at the tip, can improve hover performance by improving the distribution of lift along the length of the blade. The improvements in hover performance must be balanced with a performance loss in forward flight as the absolute value of the twist is increased. Most existing designs use a negative linear twist of 8 to 15 degrees suggesting that this range is the best compromise between operating performance in the two flight regimes. While the twist incorporated in the design will affect the power required and hence fuel cost, the amount of twist is not expected to have a significant impact on maintenance costs. In addition to blade twist, many modern blade designs incorporate a series of different airfoil shapes along the length of the blade and some type of tip features to improve the aerodynamic performance of

the rotor. The tip features can typically be characterized by three attributes: taper, sweep and anhedral, or any combination of these three. All three, used correctly, can improve the performance of the rotor in hover as well as forward flight, while reducing noise and vibration levels. The use of these characteristics must be balanced with the higher costs of designing and manufacturing the more complex blade shapes.

In addition to the design of the actual blades, there are a few options for the type of main rotor and associated level of performance and cost. Each blade in a rotor system has three degrees of freedom that are of interest. Each blade can rotate about its longitudinal axis thereby changing the angle of attack of the blade airfoil, known as feathering. In addition, at the rotor hub, each blade may be allowed to rotate about the flapping axis allowing the blade tip to move up or down with respect to the plane of the rotor, known as flapping. Each blade can also pivot about an axis parallel to the axis of rotation of the rotor system, allowing the blade tip to lead or lag behind the hub during rotation, known as leading or lagging. There are a few different ways to allow the blades to articulate among these three degrees of motion, which largely account for differences between various rotor designs. There are four basic types of rotor hubs that have been used on various designs, shown in order of increasing technology level(Leishman 496):
- Teetering design
- Articulated design
- Hingeless design
- Bearingless design

In the teetering design, opposing blades are connected together so that as one blade flaps up, the opposing blade must flap down in a teetering motion(Leishman 496). There is a separate feathering bearing on each blade to enable changes in blade pitch(Leishman 496).The teetering design is the simplest design resulting in a lower part count and generally lower maintenance costs. However, the design has a fairly high parasitic drag during forward flight. So, the designer is faced with the classic trade-off between cost and performance.

The fully articulated, or simply "articulated," rotor design is the most widely used configuration at this time. In this design, each blade has a lead/lag and flapping hinge as well as a feathering bearing. The exact configuration of these three joints varies among the manufacturers. In all cases, the configuration is fairly complicated mechanically, resulting in a large number of parts and higher maintenance costs(Leishman 496), yet has shown to be very reliable. In general, the articulated design results in lower drag than the teetering design in forward flight.

Some of the disadvantages of the fully articulated rotor design are overcome by the hingeless design. This design allows the lead/lag and flapping motion to be accomplished by using elastic flexing of a structural member instead of mechanical hinges. The designs still use a bearing to accomplish feathering motion. The resulting design is much simpler than the articulated design, with a lower part count and lower drag. In general, the design of a hingeless rotor is significantly more complicated than an articulated design. This difficulty in correctly designing a hingeless rotor stems from the need to correctly align the axes of the heterogenous materials required to achieve the correct motion without hinges. In particular, the stresses, and stiffness in various directions and planes within the hub structure can become very complicated. Advancements in rotor design processes, material properties modeling, manufacturing tools, and modeling capabilities over the years have been important factors enabling such design.

The most technologically advanced rotor design currently used extends the advantages of the hingeless design to eliminate the need for a mechanical feathering bearing. The resulting design accomplishes all three degrees of freedom simply by elastic deformation of the hub structure. Hence the difficulty in designing this type of rotor is even more complicated than that for the hingeless design described earlier. High strength, directionally heterogeneous composite materials such as Kevlar, carbon fiber, and glass have been vital to enabling the design of bearingless rotors. Such materials must be carefully arranged based on extensive numerical modeling to control stiffness and the coupling of motion in the appropriate directions. After an appropriate design has been completed, the resulting rotor is mechanically the simplest of all four designs resulting in the lowest parts count and theoretically the fewest maintenance requirements and the least drag.

### 3.2.3 Tail Rotor Design

In the standard helicopter configuration consisting of a single main rotor, some type of anti-torque device is required to overcome the reaction torque of the main rotor and provide directional control about the yaw axis. There are three general categories of anti-torque configurations. The most common design consists of a single tail rotor that provides a sideways thrust and functions analogous to a simplified main rotor design. The tail rotor is typically about 1/6 the size of the main rotor. The tail rotor tip speed is frequently about the same as the main rotor tip speed, which implies that the rotational speed of the tail rotor is about six times the main rotor speed. Typically, the tail rotor consumes about 10% of the total rotorcraft power in hover(Leishman 496) and about 3-4% of the total power under forward flight conditions at normal cruise speed(United States. Army Materiel Command ). Conventional tail rotors can be split into the same four categories as the main rotor design: teetering, articulated, hingeless and bearingless designs. In addition, the design can further be categorized as a *pusher* or a *tractor* depending on which side of the vertical fin the rotor is mounted to relative to the direction of thrust generated by the rotor. In a pusher configuration the thrust pushes the vertical fin away from the tail rotor such that the wake of the tail rotor is away from the fin. In contrast, in a tractor design, the thrust pushes the vertical tail toward the tail rotor. The majority of helicopters use a pusher design since this configuration is considered to have a higher overall efficiency(Leishman 496). Most tail rotors have two or four blades, and the size is determined by balancing the desire for a large area to minimize power requirements with the desire for a smaller area to reduce weight and performance in crosswinds or sideways flight.

The second major category of anti-torque configuration consists of a shrouded fan design known as a Fenestron® design. These fan-in-fin designs typically require less power to produce the same amount of thrust and can be smaller and lighter than a conventional tail rotor design. One of the greatest benefits of a ducted fan design is reduced noise when compared to a conventional tail rotor generating the same side force.

The third type of anti-torque device is known as a NOTAR® design, which stands for NO TAil Rotor. The NOTAR® design does not require any external moving parts. Rather, the design generates a sideways force, by controlling small jets of compressed air out the side of the tail boom. The combination of these jets and the main rotor downwash creates a pressure difference along the length of the tail boom resulting in the sideways force. The jets are controlled by varying the pressure of air supplied by a compressor. The main benefit of the NOTAR® design is improved safety since there are no rotating blades which may pose a risk to ground personnel.

While each of these designs has its merits and drawbacks, it is not clear that any one is the "best" for all rotorcraft designs. Different helicopter manufacturers use different configurations for different models, and the configuration chosen may have an important effect on the operating economics. Regardless of the anti-torque device used, most helicopters incorporate a horizontal stabilizer of some type. There are three major types, which can be characterized as a forward mounted stabilizer, an aft mounted low stabilizer and a T-tail design. Some models also feature a stabilator, which is a stabilizer that can rotate to vary its angle of incidence. The use of a stabilitor tends to result in a heavier, more complicated design with higher maintenance costs, but is used on several models to enhance aircraft capability. Aside from the expectation for higher operating costs on designs incorporating a stabilator, it is not immediately clear how choices regarding the three fixed designs (forward mounted, aft mounted low, T-tail) affect operating costs.

### 3.2.4  Other Rotorcraft Design Considerations

The main rotor and transmission system largely determine the operating costs of the model. There are a few issues related to the fuselage design that may also influence operating costs. From the perspective of fuel costs, the fuselage can account for about 30% of total drag during forward flight, and may be an order of magnitude larger than that of a fixed-wing aircraft of the same weight(Leishman 496). As a result, a low drag design can result in significant fuel savings. Helicopter drag is discussed in more detail in Section 6.1.1. The type of landing gear used in the design can also have a major impact on cost. The three major categories of landing gear are skids, fixed wheels and retractable wheels. The choice of landing gear affects drag during flight, weight, maintenance, ground handling, and available cabin volume. In general, retractable wheels result in the lowest drag, followed by skids, and finally fixed wheels.

A rotorcraft preliminary designer must consider all of these design options, while complying with a series of constraints. There are manifold nuances with each of these design decisions that are beyond the scope of this discussion. The purpose here is to illustrate the major design considerations faced during preliminary rotorcraft design, which are summarized below(Leishman 496):
- Types of rotor hub
  - Teetering design
  - Articulated design
  - Hingeless design
  - Bearingless design
- Type of flight control system
  - Mechanical (hydraulic)
  - Fly by wire (FBW)
- Main rotor blades
  - Material
    - Metal
    - Hybrid
    - Full composite
  - Twist
  - Blade Tip
    - Taper
    - Sweep
    - Anhedral

- o   Number of blades
- Fuselage
  - o   Material (% composite)
- Landing gear
  - o   Skids
  - o   Fixed wheels
  - o   Retractable wheels
- Tail rotor
  - o   Conventional
    - ▪   2 blade
    - ▪   4 blade
    - ▪   Pusher
    - ▪   Tracker
  - o   Fenestron® (Fan-in-fin)
  - o   NOTAR®
- Horizontal Stabilizer Design
  - o   Forward mounted
  - o   Aft mounted low
  - o   T-tail
  - o   Stabilator

This list of design considerations provides a means of categorizing different design aspects that may affect operating costs. In Chapter 6 we identify the major design characteristics from this list that we expect to be related to operating costs. Then, in Chapter 7, we proceed to use statistical analysis to identify which of these potential categorical X's are good explanatory variables.


### 3.2.5   Figure of Merit for Rotorcraft Design

In addition to adhering to all the constraints, a helicopter design should be optimized with respect to some figure of merit. As discussed earlier in the chapter, during the conceptual design phase, this figure of merit is often simply the gross weight of the aircraft. Ss the design progresses, it becomes more important for the designer to identify and define a metric that best captures the overall value of a design. The identification and quantification of the appropriate metric is not trivial. We will discuss some possible ways to quantify the various measures of a "good" rotorcraft design.


While the metrics that constitute a "good" helicopter design vary somewhat from the military sector to the civilian market, it is becoming increasingly common to use the same technology and design to satisfy both markets. As a result, the key value characteristics of both must be considered early in the helicopter design phase(Leishman 496). The military emphasis on capability, availability, and survivability must be combined with the emphasis from civilian customers, who are typically influenced by acquisition cost, operating cost, safety, low cabin noise and external noise, passenger comfort, and reliability and maintainability(Leishman 496).


For military applications, the metric of the "goodness" of a design is commonly referred to as the design's *mission-effectiveness*. In this context, "the value of a helicopter design is ultimately measured by its effectiveness in performing the assigned mission"{{47 United States. Army Materiel Command

1974 1976}}. A typical mission-effectiveness equation may be a function of operating factors (mission readiness, survivability, overall performance) and economic factors (cost to design, produce, test, and operate over the life cycle). In general, all four factors (3 operating and 1 economic) have to be traded off in order to obtain the most valuable design. Frequently, the three operating factors can be improved at the expense of the economic factor, by increasing cost{{47 United States. Army Materiel Command 1974 1976}}. As such, it is common to divide the operating factors by cost to express the mission-effectiveness in three factors on a "per unit cost" basis. In this form, the two extreme methods to optimize the design are to fix the effectiveness and then minimize the cost, or fix the cost and then maximize the effectiveness. In reality, the design effort may be some combination of these. In either case, a method of estimating the cost early in the design phase is essential to enable such trade studies.

It is useful to explore the details of a hypothetical mission-effectiveness equation a bit further. Mission readiness can be divided into mission capability and availability. A given design is usually capable of the mission in question or not. For example, if the mission is to transport 15 passengers a distance of 300 miles to an offshore oil platform, then some helicopters have this capability and some do not. In this regard, the mission capability measure is frequently considered a binary variable. The second element of mission readiness, availability, is typically further divided into reliability and maintainability. Reliability is defined as "the probability that an item will perform satisfactorily for a specified period of time"(United States. Army Materiel Command ). The availability (and reliability) of a system is the product of the availabilities (and reliabilities) of each of its major subsystems. Similarly, the availability (and reliability) of each major subsystem is the product of the availability (and reliability) of its components. As a result, the availability (and reliability) of a helicopter is directly related to the complexity of the helicopter as a complete system.

Since complexity is typically driven by performance requirements, the design of a given helicopter cannot merely be simplified for the sake of improving reliability. Improved capability typically leads to increased complexity, which in turn leads to higher cost and reduced availability . However, there are a number of design techniques that can be used to improve reliability(United States. Army Materiel Command ):
- Redundancy (typically at the cost of increased complexity, size, weight, cost and maintenance requirements)
- De-rating (typically at the cost of size, weight, efficiency)
- Diagnostic methods (typically at the cost of increased complexity and cost)
- Conservative design (typically at the cost of size and weight)
- Component development and test (typically at a monetary cost)
- Selection and qualification testing (typically at a monetary cost)

Over time, the complexity of rotorcraft systems have grown, leading to more and more subsystems, each with its own reliability. This trend in isolation, leads to lower reliability and hence lower availability. In order to combat this, increasing emphasis has been placed on improving the maintainability of new designs. It is important that maintainability be incorporated during the early design stages. Improvements introduced after fabrication have only marginally effective results per unit of effort expended. Designing for maintainability means to "incorporate features that reduce the resources (time, manpower, personnel skills, test equipment, tools, technical data, facilities) required to perform maintenance(United States. Army Materiel Command )."

Commercial helicopter operators share concerns with aircraft reliability and maintainability with the military customers. In addition, civil helicopter operators place additional importance on safety, noise

(both internal and external), passenger comfort, and greater emphasis on costs. More and more emphasis has been put on optimizing designs for minimum life cycle costs (LCC). This requires rotorcraft designers to have methods for evaluating design trade-offs involving LCC as the figure of merit. To support increasing customer demand for improved life cycle costs on new helicopter designs, researchers at NLR and consortium members of VIVACE improved the SPEAR tool described in Section 3.2.1 by incorporating a helicopter life cycle model developed by Eurocopter(Boer et al. ). The resulting tool can be used to optimize rotorcraft for minimum LCC rather than weight and perform trade-offs on several rotorcraft design parameters.

The Eurocopter LCC model described by Boer et. al. predicts rotorcraft acquisition cost and direct maintenance cost based on major physical design parameters, including maximum takeoff gross weight, rotor diameter, installed power, fuselage size, etc. It then combines these costs with costs of maintaining and managing spare parts, insurance, pilot salaries and fuel costs (Boer et al. ). An case study example of the use and results of the methodology using a limited subset of available inputs and functionality is described in detail in Boer et. al. The case incorporates ten helicopter design parameters and illustrates the way these can be varied to optimize LCC. In addition to the design parameters handled by the methodology, the case suggests that a conventional tail rotor results in lower mass and cost than a fan-in-fin design. The results suggest that the existence of an engine reduction gearbox has an adverse effect on weight and an even larger adverse effect on cost, and hence to optimize weight and/or LCC, the engine reduction gearbox should be eliminated. In addition, to minimize either weight or LCC, a bearingless main rotor hub and full composite (high complexity) rotor blades should be used. However, the selection of the objective function (weight or LCC) yields different optimal design selection of the flight control system and amount of composite material in the fuselage. The results also show that for the one case examined, using a fly-by-wire flight control versus a mechanical (hydraulic) flight control reduces gross weight by approximately 50 kg (1.4%) but increases LCC by about 2.0% over the life of the aircraft. The acquisition cost of a fly by wire control system is higher than that of a hydraulic flight control, however the fly by wire system requires significantly less maintenance. In this example, the higher acquisition cost more than offsets the reduced maintenance costs leading to a new increase in LCC. In addition, the analysis suggests that to minimize weight a full composite fuselage should be used, while to minimize LCC, the percentage of the composite mass in the fuselage should be about 20%.

The studies described by Boer et. al. provide some insight as to the manner in which different design attributes may affect LCC. In some cases references to specific operating costs were made. The bottom line is that additional case studies using this tool have shown that optimizing a helicopter design for lowest mass or lowest total LCC results in different design choices(Boer et al. ). As a result, choosing the right objective or objectives for the optimization is critically important to the design process.

In this section, we explored some of typical metrics for measuring the value of a given rotorcraft design. The purpose is not to define quantitative measures of design performance. Rather, we highlight the fact that regardless of the details of the metric chosen, a method of estimating costs early in the design phase is essential. In the case of using LCC as the figure of merit, the operating costs are a key subset of the full LCC and hence fit in directly. In the case of military use, the level of reliability and maintainability per unit cost is a direct subset of the full mission-effectiveness equation. Regardless of the figure of merit chosen, an accurate estimate of operating costs early in the design phase is necessary to enable studies making quantitative trade-offs between the various design decisions.

## 3.3  Rotorcraft Engine Design

Gas turbines are largely the engine type of choice for helicopter applications because of their relatively high power output for a given size and weight. As perhaps the most important helicopter subsystem, the engine(s) has a dramatic impact on the helicopter's flight performance, acquisition cost and operating cost. As a result, a basic understanding of some of the engine design variables and considerations encountered during the conceptual or preliminary design of a helicopter engine is necessary to enable a useful operating cost model for the whole helicopter system. Specifically, this section will identify some of the engine design attributes, which we may later use to relate existing designs to operating costs in Chapter 6 and Chapter 7.

While this chapter separates the discussion of aircraft design and engine design into two separate sections, it is important to highlight the fact that the aerodynamics of rotorcraft flight and the thermodynamic operation of the engines are intrinsically coupled. As a result, they should be modeled and optimized as a system(Leishman 496). In addition, many of the propulsion subsystems that were previously considered the responsibility of the helicopter manufacturer have been integrated with the engine design and hence have become the responsibility of the engine manufacturer. This trend has divided responsibility for various components linking the engines to the drive system and increases the need for close coordination between the airframe and engine manufacturer(United States. Army Materiel Command ).

In Section 3.2, we stated that the power required by a helicopter could be calculated early in the design process. More detail on helicopter power requirements is given in Section 6.1.1. In this section, we will consider the power requirement for the engine or engines to be given or known. We will then highlight some of the trade-offs that must be performed in designing the engine. While detailed calculations are beyond the scope of this study, it is worth noting that engine design parameters and characteristics will affect both the power output of the engine as well as the power required by the aircraft. For example, a heavier engine will increase the weight of the whole aircraft and hence require greater power output from the engine(s).

When determining the appropriate engine size for a new helicopter application, it is good practice to anticipate the need for future growth in power output. Specifically, the potential for increases in the gross weight of the aircraft must be considered. Frequently initial weight targets are not met, and as a design process progresses, increases in weight can lead to serious shortfalls in performance, cost and reliability(United States. Army Materiel Command ). In military applications, the Army has typically seen the weight of aircraft increase at rates of about 1% per year for transport helicopters and 2% per year for utility models for each year in production(United States. Army Materiel Command ). These increases are due to weight that is added to correct defects in the original design and/or due to the addition of equipment to increase mission capability. These weight increases could be related to the engine design and performance, or they could be completely independent of engine operation. In either case, it is important to keep potential weight increases in mind early in the engine design phase and also to meticulously manage the aircraft weight throughout the design and development process.

Analogous to an increase in weight, a power or engine performance shortfall can have a serious detrimental impact on the full aircraft design. For example, if the efficiency of the final engine in production is less than predicted, then this may require a larger fuel capacity to accomplish the same range, which then reduces the available payload. Thus, analogous to the careful management of aircraft weight, engine performance and performance predictions must be validated and updated regularly.

The preliminary design of a gas turbine engine begins with the thermodynamic cycle, followed by an approximate aerodynamic flowpath, followed by the detailed mechanical design(Sawyer and Japikse ). The cycle design leads to temperatures and pressures at various cycle points as well as fuel and air flow rates. The design of the approximate flowpath leads to estimates of airflow path lengths and diameters and the number of stages and rotational speeds of the compressor and turbine(Sawyer and Japikse ). Lastly, the detailed mechanical design leads to initial geometries for the individual parts and components throughout the engine.

### 3.3.1 Engine Cycle Design

The first step in the conceptual design of a new engine, focusing on the thermodynamic cycle, is commonly referred to as parametric cycle analysis of the design operating point. This parametric analysis involves the thermodynamic state of the air throughout the engine without any regard to mechanical methods or parts of the engine needed to accomplish the changes in thermodynamic states(Kerrebrock ). Thus the results of this analysis are a series of temperatures and pressures at various stations throughout the engine. There is no guarantee that these states could be achieved with actual engine hardware, and as a result it is common to refer to cycle analysis as a "rubber engine." For example, in parametric cycle analysis, a compressor may be represented by a pressure ratio and efficiency. Notice that this does not in any way provide details regarding the potential mechanical aspects of a hypothetical compressor that may accomplish this pressure ratio and efficiency, such as the number of stages, materials used, architecture (axial, centrifugal, etc). At first pass, the parametric analysis is performed for a single operating point, the so-called design point, which is the set of operating conditions for which the design should be optimized. The design point is based on estimates of the various power requirements of the aircraft and the amount of time that the engine will spend at each operating condition throughout the mission.

This type of analysis is primarily used to relate the desired engine performance parameters such as power and SFC to cycle design choices. The types of inputs that are commonly used in such studies include flight conditions, design limits, component performance and design choices. Most gas turbine engines for aircraft propulsion operate on an open cycle. This restricts the temperature at the start of compression to approximately atmospheric temperature. In addition, the peak temperature after heat addition is typically dictated by some metallurgical limit of the hot section hardware. An example of the parametric cycle analysis for a dual shaft output turbine engine, widely used for helicopter applications, involves the application of the laws of physics to an ideal Brayton thermodynamic cycle. The ideal conditions can be relaxed by including assumptions for various losses throughout the different engine components. Specifically, the cycle of real engines differs from the ideal analysis for several reasons including the following major contributors(Kerrebrock ):
* Non isentropic compression and expansion in the compressor and turbines
* Extraction of compressor discharge air for cooling and aircraft uses
* Incomplete combustion and pressure loss in the burner
* Imperfect diffusion of free stream in flight to engine inlet conditions
* Variation of gas properties throughout cycle and addition of fuel and combustion products

The combined application of physical laws of conservation of energy, isentropic gas relations and assumptions for losses of various processes results in eleven equations that apply to thirteen unknown cycle conditions. Thus, with thirteen unknowns and eleven equations, any two of the unknowns can be varied to solve for the figure of metric of interest. A common way of doing this is to vary the

compressor pressure ratio and the turbine inlet temperature ratio and plot the resulting fuel flow as a function of these two parameters(Sawyer and Japikse ). Thus, for a typical turboshaft engine, with a free power turbine, there are two cycle design choices to be evaluated during the parametric analysis: the compressor pressure ratio and the turbine temperature ratio(Mattingly ).

An important decision during the parametric cycle design phase is whether the engine is being designed for maximum efficiency (minimum SFC) or for maximum specific power. For every combination of temperature ratio and component efficiencies, there is an optimum pressure ratio to achieve maximum efficiency and another pressure ratio to achieve maximum specific power(Wilson and Korakianitis ). The pressure ratio corresponding to maximum efficiency is slightly higher than that for maximum specific power output. Typically, the design point pressure ratio is set to provide a compromise between maximum efficiency versus maximum specific power, as well as a compromise for performance at max power versus partial power operation.

### 3.3.2  Preliminary Flowpath Design

After the parametric cycle analysis is complete, an initial flow path can be generated based on compressor and turbine aerodynamic parameters and Mach numbers. Throughout this process, engine manufacturers draw on experience to evaluate trade-offs related to flowpath design. For example, a smaller flow path will typically decrease the diameter and weight of the engine at the expense of increasing frictional losses due to higher flowthrough Mach number(Sawyer and Japikse ). This trade-off between size and weight versus frictional losses and efficiency must be made based on manufacturer experience and a detailed understanding of the customer requirements. The output from the initial flow path design process is typically an engine cross section describing estimates of approximate flowpath dimensions (lengths and diameters), and the number of stages and rotational speeds of the compressor and turbine.

Among the first decision to make is the type of compressor to be used, either an axial flow, radial flow or a combination. Radial flow or centrifugal compressors can have a much larger pressure rise and enthalphy rise in a single stage. The pressure ratio for a centrifugal compressor stage can be about 5, while that for a single axial stage typically varies between 1.15 and 1.4(Mattingly ). In general, an axial flow compressor tends to be more compact and have a smaller frontal area than a centrifugal flow compressor. Centrifugal compressors will almost always cost less to manufacture than a multistage axial compressor required to accomplish the same pressure ratio and flow rate(Wilson and Korakianitis ). In the class of engine sizes where both can be used, typically axial compressors will have higher efficiencies. In smaller engines, however, a centrifugal compressor may be more efficient due to the tip losses and boundary layer effects in axial compressors. Specifically, as the pressure ratio is increased in an axial flow compressor, the passage size must become smaller and smaller in order to maintain a constant mass flow rate. This leads to the need for relatively small blades in the aft stages of axial compressors. As the blades become smaller, there are greater losses (reduced efficiency) due to the dominance of boundary layers and stronger relative tip losses. Thus, for smaller engines, a centrifugal compressor is typically more efficient(Wilson and Korakianitis ). Many modern turboshaft engines for helicopter applications incorporate a centrifugal compressor, potentially combined with one or more axial compressor stages.

A major step in the process of the mechanical design of the engine components involves matching the compressor stages and turbine stages(Kerrebrock ). There are a few different ways to deal with the

compressor mismatching between stages. The first of the three general approaches involves the use of dual rotors which enable different sections of the compressor to rotate at different speeds. The second major technology, developed by Gerhard Neumann at General Electric, is the use of variable stator blades, which redirect the flow in the radial direction before the following stage of rotating blades. The third option is to use variable compressor bleed at the different stages, specifically the front stages of the compressor. Many modern engines incorporate some combination of all three techniques.

After the initial flowpath design is complete, the engine designer is faced with balancing multiple competing constraints and performance metrics related to detailed design considerations. A brief discussion of the considerations related to each component in the engine is useful for providing means to categorize or describe existing engine designs in the hopes of relating design decisions to operating costs.

### 3.3.3 Turbine Design Considerations

The major operating considerations related to the turbine are the rotation speed, gas flow rate, inlet temperature and pressure, outlet temperature and pressure and required power output(Mattingly ). In a dual spool machine, the primary function of the turbine is to covert enthalpy from the flow path into shaft power to drive the compressor. Approximately 75% of the energy of the flow exiting the combustor is used to drive the compressor(Mattingly ). The energy that is not required to drive the compressor can be used to drive the low pressure turbine and provide shaft power for the aircraft. Thus, maximizing the efficiency of the high pressure turbine is critical to the efficient operation of the whole engine.

Because of the relatively high temperatures encountered in the turbine, the lifespan of a given turbine blade is often limited by its creep life, which is a function of both stress and temperature. The stress in the turbine blades is most strongly driven by centrifugal stresses which are a maximum at the root of the blade. The centrifugal stresses are proportional to the rotational speed squared, and hence provide a physical limit on the rotational speed that can be used. It is desirable to design turbines to rotate as fast as possible since they are commonly fixed to the same shaft as the compressor. The use of higher rotational speeds decreases the loading per stage leading to higher efficiency or reducing the number of required compressor stages(Sawyer and Japikse ). Thus the design of the turbine blades involves a trade-off between the advantages of a high rotational speed with the additional strength required to handle such stresses. As a result, the temperatures encountered in the high pressure turbine tend to pose the greatest challenge for designers. Considerable research effort has focused on the development of materials that have good high temperature capability and advanced techniques for cooling metal components. In the high pressure turbine section, many of the disks and rims are made out of nickel-based alloys, while the blades are made out of a group of materials with very high temperature capability called superalloys. These include both nickel-based superalloys and cobalt-based superalloys(Sims and Hagel ). In addition many modern blades are cast from these materials using a process that aligns the crystal structure in the radial direction, known as directional solidification, or produced from a single crystal. These techniques typically enable an additional 100 to 200 deg F capability over conventional cast blades(Mattingly ). In addition, many engines incorporate thermal barrier coatings (TBC) in the turbine section to reduce the heat transfer from the hot gas path to the metal blades.

Even with advances in blade material to handle higher temperatures, the desire to increase turbine inlet temperature for power/weight and SFC improvements has lead to widespread use of internal blade cooling. Although the exact cooling methods vary from engine to engine, the overall concept involves bleeding high pressure "cool" air from the compressor and routing it through internal passages in the blades and nozzles in the hot section. The air is used to both cool the blade from the inside out and in some cases to provide a "cool" barrier between the blade and the hot exhaust path such as in the use of film cooling.

The shape of the individual turbine blades are typically designed according to the first principles regarding the *shapes of the passages formed between blades*. The engine designer has some flexibility in choosing the number of blades in a given turbine stage. This choice is quantified by the solidity, where a higher solidity reduces the loading on individual blades thereby reducing the possibility of separation and shock losses(Kerrebrock ). However, a higher solidity also increases the total surface area of the blades and hence may increase viscous losses.

### 3.3.4 Compressor Design Considerations

In contrast, compressor blades are typically designed according to the shape *of the actual blades*. These shapes are often tested in rows of similar blades in wind tunnels. As computational tools have become more advanced, there has been a transition to design methods which start from optimum velocity distributions around the blade profile, and then back out the design of the actual blades(Wilson and Korakianitis ). Additional compressor stages can be added to increase the pressure ratio, but this can lead to significant losses when operating off-design as well as difficulties starting.

While the life of turbine blades is often limited by creep life, the compressor blades are exposed to significantly different operating conditions. Specifically, compressor blades are subjected to billions of high cycle fatigue (HCF) cycles due to vibration and aeromechanical interactions encountered during normal engine operation. As a result, the alternating stresses in compressor parts determine the life of the parts. Specifically, parts must be designed so that the stresses that the material can withstand forever are not exceeded. The fatigue properties of the material chosen for the compressor are hence of upmost importance. Aluminum, titanium, stainless steel and nickel-based alloys are common material choices for compressor components. As a general rule of thumb, the HCF capability of titanium is about 10x that of aluminum at room temperature. However, at temperatures above about 480 C, the strength of titanium decreases rapidly and hence nickel-base alloys are typically used for compressor components exposed to higher temperatures. Various coatings are used throughout the compressor to reduce corrosion and provide abradable surfaces for maintaining tip clearances (Wilson and Korakianitis).

### 3.3.5 Combustor Design Considerations

Between the compressor and the turbine is the combustor. The purpose of the combustor is to convert chemical energy in fuel to thermal energy of the flow path gas. A good combustor will convert as much of the chemical energy in the fuel to thermal energy as possible. In addition, a combustor should have the following properties(Mattingly ):
- Complete combustion of fuel
  - Highest possible increase in thermal energy in flow
  - Ideal combustion by-products

- Low pressure loss
- Stable combustion process
- Even temperature distribution
- Compact geometry(short length and small cross section)
- Ability to relight easily
- Operation over wide rate of temperatures, pressures and flow rates

The chemical reaction of fuel in a combustor can be modeled using the laws governing chemical kinetics such as the Arrhenius equation. In general, the reaction rate depends on both pressure and temperature. In most operating regimes in gas turbine engine combustors, the rate of combustion will be limited by the rate at which fuel can be vaporized and mixed with air rather than the kinetics. The desire to meet the operating qualities listed above, combined with chemical and physical limitations, such as the lean and rich flammability limits and spontaneous ignition temperatures, dictate the overall size of the combustor. The cross-sectional area of the combustor is largely determined by the desire to contain the flame front within the combustor. This is accomplished by sizing the cross-sectional area based on the mass flow rate with the known flame speed to ensure that the flame front is not blown out of the combustor, nor propagate too far upstream.

While all combustors are designed to best accomplish these desirable characteristics, there are three primary types of combustion chambers in use: can designs, annular designs, and cannular designs. A can design consists of multiple cylindrical burners all positioned in a burner case. This type of design is modular and was more commonly used in older jet engines(Mattingly ). The cannular design consists of multiple cylindrical burners arranged in a common annulus. The most commonly used combustor design in current aircraft engines is the annular design. This design contains a single burner with an annular cross section and tends to have better uniformity, shorter length and reduced surface area.

The temperature of the gas path exiting the combustion chamber has important implications for the design and operation of mechanical components downstream, namely the turbine rotors and stators. In addition to the average temperature of the gas leaving the combustor, the variation of temperature across the exit plane is extremely important. There are two parameters commonly used to quantify and describe this temperature variation. A parameter called the *pattern* factor is used to quantify the variation in temperature circumferentially. This variation is primarily of concern for the stationary airfoils and components in the hot section such as the nozzles. The radial variation is temperature is commonly quantified by the *profile* factor and has implications for both stationary and rotating downstream hardware. A highly non-uniform temperature distribution will typically result in shorter life for the turbine section, or require heavier, more expensive turbine hardware to achieve the same part life.

### 3.3.6 Other Rotorcraft Engine Design Considerations

A fairly sophisticated control system is required to keep the operation of the engine within various operating limits while providing the best performance possible. The control system may control variables such as the fuel flow rate, variable stator vane position, and bleed valve settings (Kerrebrock ). In order to accomplish this, the control system may require inputs such as temperatures, pressures and speeds throughout the engine. In the past, most engine controls used a series of levers, cams and flowing fuel or air to implement the required logic in hydromechanical control units (HMU's) (Kerrebrock). While HMU's have proven to be very robust and effective at providing engine control,

they lack some of the flexibility that is now available in electronic engine controls. Advances in integrated circuits have permitted more complex control logic leading to improved performance and reliability and are widely used on modern engines(Kerrebrock )

Control system of an engine is intended to perform three primary functions(Wilson and Korakianitis ):
1. Protect the engine (and aircraft) hardware by adhering to various limits
2. Reduce pilot workload to fly and operate aircraft
3. Operate at conditions or along transient points between conditions to optimize fuel consumption, engine durability, or some other parameter

Typical physical limits on the engine may include maximum rotational speeds, maximum temperatures, maximum fuel flow, maximum torque or power output. The limits are also a function of aircraft parameters such as transmission torque or power limits, and certain torque or power limits while the aircraft is on the ground.

Throughout the preliminary design of new engines, most major engine manufacturers have extensive, internally developed preliminary design tools which draw on a combination of theory and experience. These tools help guide the design of components for input values of pressure ratio, turbine inlet temperature, and airflow. For example, during the design of a compressor, such a program may output the number of stages, rotational speed, blade shapes and spacing, and estimates of compressor weight and efficiency(United States. Army Materiel Command ). While the exact details of such tools and relationships are not publically available, the purpose of this discussion is simply to provide the requisite background and foundation for use in developing the economic modeling content of this study. To that end, the major design considerations faced during preliminary turboshaft engine design, are summarized below:

- Parametric cycle analysis
  - Compressor pressure ratio
  - Turbine inlet temperature
- Compressor
  - Axial
  - Centrifugal
  - Axi-Centrifugal
  - Number of stages
  - Material
  - Matching technique (variable geometry, bleed, multi-spool)
- Type of combustor
  - Annular
  - Can
  - Cannular
- Turbine
  - Axial
  - Centrifugal
  - Number of stages
  - Material
  - Cooling
  - Blade count (solidity)
- Flowpath geometry
  - Trade-off of size versus losses

- Control system
  - Hydromechanical
  - EECU
  - FADEC
- Starter type
  - Air-powered
  - hydraulic
  - Electric (starter/generator)

In subsequent chapters we will refer to this list of design considerations to help us categorize and describe existing engine designs. In Section 6.1, we will show that the engine cycle design parameters are directly related to fuel consumption based on the physics of engine operation. In Chapter 7, statistical analysis is used to identify the design attributes from the list above that show some relation to operating costs.

# 4 Literature Review of Rotorcraft Economic Models

An important step in this project involves researching existing methods and models for predicting operating costs. An extensive literature search confirms that a widely accepted method for predicting rotorcraft operating costs for new designs is not available. Methods for predicting operating costs and life cycle costs for existing rotorcraft models are available. The most widely used source of this data discovered is available from Conklin & de Decker Associates as described in Section 5.6(Conklin & de Decker Associates, Inc. ). This source was used as the source of response data for the creation of the model developed herein. The main conclusion of this section is that the most recent published method for predicting operating costs was developed and published by Lockheed Martin and New York Airways in 1967(Stoessel and Gallagher 1-17). Despite the limited availability of operating cost models, a brief review of the historical work helps guide the development of the model developed in this work. In addition, reviewing available case studies provides data and insights relevant to the application of first principles as discussed in sections of Chapter 6.

## 4.1 Existing Aircraft Operating Cost Models

The first universally accepted method for estimating the direct operating cost of aircraft was published by the Air Transport Association of America (ATA) in 1944. This methodology and empirical equations were refined several times to take advantage of additional field experience and account for changes in technology, such as the use of turboprop and turbojet engines(Air Transport Association of America ). The newest methodology published under this title forms the benchmark for most models used to estimate or predict direct operating costs for fixed-wing applications in practice. The intent of the ATA method is to provide a standard way of comparing alternative options. It was not intended to predict how much it would cost to run an airline(Van Bodegraven ).

The model published by ATA does not include any cost elements that are unique to rotorcraft operation or contain any rotorcraft field experience. As a result, Robert Stoessel of Lockheed Martin started with the ATA model, and presented a set of revised formulas, accounting for helicopter experience at an AIAA conference in 1967(Stoessel and Gallagher 1-17). The modifications to the formulas were based on rotorcraft operating experience with New York Airways (NYA), which offered scheduled passenger service on helicopters in the greater New York City area as described in Section 4.2.

The largest difference between the cost structure for fixed-wing aircraft and rotorcraft is related to maintenance costs. The 1967 ATA method for fixed-wing aircraft relates maintenance costs as a function of flight hours and flight cycles. For rotorcraft, some recommend the use of rotor hours in place of flight hours, since when the rotor if fully engaged, most systems are operational. Specifically, Stoessel et. al. felt that maintenance costs should be modeled as a function of rotor hours, flight cycles, and engine shutdowns(Stoessel and Gallagher 1-17). The data available at that time showed significant variation in the ratio of rotor hours to flight hours, ranging from 1.08 to 1.78(Stoessel and Gallagher 1-17). If flight hours were used in place of rotor hours as the dependent variable, the additional variation in this ratio could disguise the true relationship between the hardware use and consequent maintenance requirements.

Approximately one year after Stoessel et. al. published their model, the Aerospace Industries Association of America (AIA), published a modified version of the Lockheed-NYA methodology that split airframe maintenance cost into maintenance costs related to the dynamic system of the rotorcraft(Ausrotas, Hsin and Taneja 123). The dynamic system includes the main rotor, tail rotor, transmission, etc., representing a significant portion of the total airframe maintenance. It is thought

that the intent of the AIA methodology was to use the 1967 ATA method to predict most of the operating costs and then add the AIA prediction for maintenance associated with the dynamic system that is unique to rotorcraft. Although a report by researchers at MIT Flight Transportation Laboratory (FTL) referenced this AIA model, the details of this method were not found. The study performed at MIT FTL in 1974 developed maintenance cost formulas using regression techniques to fit operating data from two helicopter operators offering scheduled passenger service, New York Airways and SFO Helicopter. The models were used to estimate maintenance related direct operating costs only. They compared the estimates using their models to those using the Lockheed-NYA model and AIA model(Ausrotas, Hsin and Taneja 123). More details on this study will be discussed in Section 4.2.

For fixed-wing applications the 1967 ATA model has been the foundation for many studies that aimed to update and improve the model. All of these efforts have focused on fixed-wing applications, and most are based on data available for scheduled passenger service. The 1967 ATA methodology has been further refined and modified by helicopter manufacturers for internal use. For example, Boeing has conducted fairly significant data collection, analysis, and DOC model developments since the early 1970s. Each year since 1971, Boeing revises their model for internal use but no public version has been released(Van Bodegraven ).

Our review of existing operating cost models identified the model by Stoessel et. al., which we will refer to as the Lockheed-NYA model as the best benchmark or baseline model. While we have an understanding of the functional form and approach used for models related to fixed-wing operations, the Lockheed-NYA model shows the greatest resemblance to the model we seek to develop as part of this effort.

## 4.2 Case Studies

The most extensive attempt to relate maintenance costs with helicopter operations involved data generated by New York Airways (NYA) in the late 1960s and early 1970s. NYA operated Sikorsky S-61L helicopters to provide passenger transport service in the greater New York City area. They kept detailed logs of maintenance costs separated by sub-category: airframe, engine, and dynamic system. In addition to being heavily involved in the development of the 1967 Lockheed-NYA operating cost model described earlier, the NYA data set has been analyzed by numerous researchers including those at the MIT Flight Transportation Laboratory (FTL) as described in Ausrostas et. al.

In the analysis published by MIT FTL (Ausrotas, Hsin and Taneja 123), the authors present a detailed regression analysis using both total monthly maintenance costs and maintenance cost per flight hour as the response variables. Within each subcategory (airframe, engine, dynamic system), the authors developed models to predict the cost of labor, materials (parts), and outside service. They concluded that it is not possible to derive highly satisfactory statistical models for the maintenance subsystems based on the available data. They proposed that a possible cause for this lack of correlation may be leading or lagging data since maintenance "damage" is accrued and then paid for as a lump sum. The authors attempted to deal with this accrual issue by looking at quarterly costs as the response rather than monthly costs in the hope of "smoothing" any large payments. Again, the results were not satisfactory from a statistical standpoint(Ausrotas, Hsin and Taneja 123).

The authors hypothesized that the scheduled maintenance cost should be inversely proportional to the time between overhaul (TBO) as described by Equation 37 in Section 6.2. Their analysis of the NYA data did not support this expected relationship, and they concluded that the unscheduled maintenance costs

experienced by NYA completely dominated the total maintenance costs and are sufficient to mask the expected relationship in scheduled maintenance costs(Ausrotas, Hsin and Taneja 123).

In addition to NYA, another commercial helicopter operator, called SFO Helicopter, provided scheduled passenger service during the same timeframe. SFO Helicopter provided service to feed the San Francisco airport from Oakland Airport, Emeryville and Marin City in the late 1960s and early 1970s. Researchers at MIT FTL compiled and analyzed quarterly maintenance cost data from SFO Helicopter operations between 1968 and 1974. They used regression analysis to relate maintenance costs to operating characteristics.

The authors found a strong correlation between quarterly costs and flight hours as expected. However, no statistically significant correlation was found between productivity measures, such as the available seat miles per hour (asm/hr) and maintenance costs using the quarterly data(Ausrotas, Hsin and Taneja 123). Available seat miles (asm) is a widely-used measure of passenger carrying capacity. If an aircraft has ten seats and flies ten miles, then this trip would represent 100 seat miles of capacity. After analyzing quarterly data, the researchers at MIT FTL looked at yearly data and found a satisfactory relationship between direct maintenance costs, the fleet size, and the utilization, in revenue hours/day. Thus, they developed a model with maintenance DOC as the response and with two explanatory variables: fleet size and utilization (rev hr/day). Note that the explanatory variables included here are purely operational and not a function of aircraft design. Only a single helicopter design was included in the dataset analyzed by MIT FTL. The fact that fleet size is a statistically significant variable supports the notion that there are economies of scale involved in providing maintenance support to the fleet.

While interesting to review, these case studies are different from the intent of this study in a couple of important ways. First, the case studies only deal with maintenance costs rather than the total direct operating costs. Second, both the NYA and SFO Helicopter data analyzed by MIT FTL researchers only include a single helicopter model. As a result, the researchers attempted to relate *operating* variables to maintenance costs, while holding the *design* variables fixed. In contrast, the objective of this study is to relate rotorcraft *design* parameters to operating costs while holding *operating* parameters constant. As a result, the response data used to develop the models in Chapter 7 include a variety of rotorcraft models (and hence design parameters) under fixed operating conditions. While these case studies are not directly comparable to the model developed herein, they provide a reference for the methodology employed.

## 4.3 Critique of Existing Operating Economics Models

No economic model can be expected to exactly predict the costs for operating a particular airline or operator. The variability in missions, operating environments, maintenance methodologies, etc., leads to variation in operating expenses between operators, even when the same aircraft are used. However, the basic purpose of these economic models is to determine comparisons between operating expenses rather than absolute levels(Stoessel and Gallagher 1-17). The fact that various models emerged over the years illustrates the need for such capability at the industry level. The various models and methods brought awareness and attention to the need to adopt a consistent set of assumptions and cost definitions throughout the industry.

Most of the operating cost models reviewed during this study suffers from one of two limitations when being considered for use in this study. First, most of the models are based on data from fixed-wing applications only. Second, many of the models are intended to be used for existing designs, rather than in the preliminary or conceptual design phase.

The published models that were developed for fixed-wing applications do not apply to rotorcraft directly because of the significant differences in the both the design and the use of fixed-wing aircraft versus rotorcraft as described in Section 2.1. The fact that many models are restricted to fixed-wing operation is natural since the air transportation market is largely dominated by fixed-wing aircraft.

The second limitation of many of the models reviewed is related to the stage of the aircraft design. The "best" economic model must be selected based on the available data, the current stage of the design process, and the level of new technology. Stoessel et. al. splits the life of an aircraft into four distinct phases: Initial Concept, Configuration Definition and Initial Specification, Detail Design, and Operational Status(Stoessel and Gallagher 1-17). By the time a design reaches the Configuration Definition phase, it is probably best to refine the cost estimates by benchmarking existing models with similar design characteristics and then applying estimated "deltas" or factors. These factors, commonly referred to as "complexity factors" or "growth factors" in the literature, are used to adjust the cost data for existing aircraft to account for unique aspects of the new design under consideration including improved technology, materials, accessibility, etc. By the time a design reaches the Detailed Design phase, it is likely that estimates for the proposed subassemblies and even individual components will be known and should be used to conduct relevant design trade studies. Lastly, when an aircraft is in the Operational phase, thorough collection, compilation, and analysis of demonstrated costs can be used to provide the best estimate of future costs.

The focus of this thesis is to develop a model for use in the early stages of the product life cycle, in what Stoessel et. al. calls the Initial Concept phase. We will return to this notion when we select potential explanatory variables in Section 7.2. Many of the models reviewed, including the 1967 ATA method, require inputs such as the number of maintenance man hours required per flight hour. This type of data is not known early in the design phase.

We feel the Lockheed-NYA model is the best benchmark for this project due to its applicability to rotorcraft models as well as being based on explanatory variables available early in the life of a design.. This model can be used to estimate operating costs based on aircraft gross weight, airframe weight, engine weight, max speed, engine cost and aircraft cost. We will use this model to predict operating costs for a sample of modern aircraft and compare the results to those generated using our model in Section 8.2.

Overall, the biggest critique of existing models is that a modern, simple, statistically relevant, published operating cost model does not exist. Other processes and methods currently available for estimating costs, particularly maintenance costs, are not useful early in the design phase because they require detailed knowledge of the aircraft and part design. We expect that the individual helicopter manufacturers each have their own proprietary methods for predicting operating costs. However, these methods are not published for widespread use.

This chapter has shown that, while somewhat limited, the case studies performed in the past, particularly the Lockheed-NYA model, provide a valuable point of comparison for validating the models developed herein. In addition, the insights gained from researching the various studies in this field led to the consideration of many variables and functional forms to be used during the construction of the model in Chapter 7.

# 5 Data Sources and Data Integrity

Any project involving the construction of a prediction model is intrinsically linked to the quality and quantity of available relevant data. In this chapter, we will provide an overview of the main sources of data considered for this project. As we will describe, the response (operating cost) data is significantly more limited than the available potential explanatory variable data. We will discuss the limitations of available response data. Some of these limitations tie directly to the opportunities for further work discussed in Section 9.5. The source of the response data used to build the economic model is described in more detail in this section as well as the inherent limitations of this data which have implications for the applicability of the final model.

## 5.1 Overview of Data Sources

To provide a model that would be available to a broad spectrum of readers, every effort was made to obtain sufficient data from publically available sources. This is particularly important for the intended use of the model to predict operating costs early in the design phase. The explanatory variables included in the model (aircraft and engine design parameters) must be readily available for the model to be useful. If the model requires inputs that are difficult to know or to estimate, then the usefulness of the model will be limited. While this preference towards publically available data sources largely influenced the research process, numerous non-public sources were considered as well.

Many aircraft and engine design parameters are publically available in documentation published by the manufacturers as well as many research firms including Jane's Information Group, Aviation Week, and Flight International. Thus, the explanatory variables, or "X" data, are widely available for existing designs. For future designs, the required inputs need to be specified by the aircraft manufacturer or estimated based on expert opinion and past design experience as described in Section 3.2.

Sources of the response data, or "Y" data, were significantly more limited and required the majority of resources of the research effort. Several sources of operating cost data were considered for the purpose of addressing this problem, including the following:

Publically available sources:
- Public estimates from helicopter manufacturers
- Operator responses to anonymous surveys from trade groups such as Helicopter Association International
- Financial statements from operators
- Financial statements from government agencies using rotorcraft
- Third-party collections, databases, and publications:
  - Aviation Week Intelligence Network (AWIN)
  - Jane's Information Group
  - Flight International – HeliCAS Database
  - OAG Aviation Solutions – AeroStrategy Civil Helicopter Maintenance, Repair & Overhaul Forecast
  - Conklin de Decker & Associates, Inc.

Proprietary sources from:
- Helicopter manufacturers
  - Cost databases
  - Cost models
- Helicopter operators

- o Cost databases
- o Financial and operational performance metrics
- Maintenance, repair and overhaul (MRO) shops
  - o Financial and operational performance metrics

A full description of each potential source is not necessary for the development of this study. However, a brief description of sources or considerations related to the collection of data is given in the subsequent sections of this chapter. The most attention is given to cases where issues influence either the creation of the model, the applicability of the model, or opportunities identified for future study and research.

## 5.2  Trade Organization Involvement

Helicopter Association International (HAI) is the major rotorcraft industry trade organization. Specifically, HAI is a non-profit, professional trade association with over 1,400 member organizations from over 70 nations. It was founded in 1948 with the primary mission to, "...advance the international helicopter community by providing programs that enhance safety, encourage professionalism and economic viability while promoting the unique contributions vertical flight offers society"(Helicopter Association International ). Within HAI there are a number of different committees dedicated to advancing various aspects of this mission. The Economics Committee is the group tasked with addressing operating cost issues. As described in Section 2.3, the Economics Committee publishes guidelines regarding the presentation of operating cost estimates. The Economics Committee is comprised of representatives from helicopter manufacturers, engine manufacturers, operators, and independent industry research and consulting firms. As a result, the HAI Economics Committee provides a key common interest which we leveraged in attempts to engage aircraft manufacturers and operators in this project.

In addition to providing a starting point for reaching out to industry experts, the HAI has conducted several surveys of rotorcraft operators over the past several years. The publication, titled "HAI Survey of Operating Performance" was first conducted in 1991, and its most recent publication in 2006 was the twelfth edition. The intent of the survey is to, "provide feedback on meaningful financial, operating, and Direct Operating Cost (DOC) information about the helicopter industry to its members and other interested parties compiled directly from the civil helicopter industry"(Helicopter Association International ). All editions of the survey are publically available from HAI, and the most recent years are available on the HAI website. These surveys provide a great overview of the issues and operating considerations facing current helicopter operators. However, the survey data was not a sufficient source for response data for the purpose of this project for primarily two reasons. First, there is no way to link the exact composition of an operator's fleet, such as the number of each model of helicopter, to the response on the survey. Second, many of the financial measures or costs reported in the survey are relative rather than absolute dollar figures. While not sufficient for the purpose of this project, interested readers are encouraged to review the survey publications available from HAI.

## 5.3  Helicopter Manufacturer Estimates

When a helicopter operator is interested in purchasing a new aircraft, there will likely be several different models from different manufacturers that would fit the required need. Typically, the

helicopter manufacturers will provide technical information on their models as well as some estimates of direct operating costs for prospective customers. These estimates were considered as a potential source for the response data.

The initial helicopter market analysis indicates that there are five helicopter manufacturers responsible for over 80% of the turbine powered helicopters in active commercial operation(HeliCAS: The Ultimate Helicopter Market Information System). The top five helicopter manufacturers which are the focus of this aspect of the data collection include:

- Agusta
- Bell Helicopters
- Eurocopter
- MD Helicopters
- Sikorsky

Some of these manufactures publish direct operating cost estimates that are publically available either on the company website or by request. The estimates are of varying levels of detail and most manufacturers provide estimates on only a limited number of models. In addition, the assumptions used to generate the estimates vary. Some manufactures clearly state the underlying assumptions, while others fail to do so. In either case, some assumptions must be made and analysis is required before comparisons between models are possible. The maintenance cost numbers estimated by manufacturers are normally quoted as "mature" costs, which is an effort to account for the fact that maintenance costs typically start out low, increase rapidly in the early years of the aircraft being fielded, level off for the majority of the aircraft life, and then increase again due to aging(Van Bodegraven ).

Because of the differing assumptions used by the different manufacturers, as well as the limited quantity of models available, these estimates were not sufficient as a sole source for response data for this project. It is likely that some correlations and conclusions could be identified from this data, but many would argue that each manufacturer biases their estimates in favor of their product.

In addition to using the publically available manufacturer estimates, efforts were made to engage the helicopter manufacturers in this project. We leveraged the mission of HAI and the common interests of those manufactures involved in the HAI Economics Committee to reach out for support in the form of requests to provide additional data. While overall these efforts had only a marginal success, we gained some good insights regarding the process typically used to generate operating cost estimates. We also confirmed that at least one manufacturerhas done some significant life cycle cost modeling to be used during conceptual design as described in Section 3.2 and Boer et. al.

## 5.4 Required Reporting by Operators

In our search for operating cost data, we considered all reporting that operators are required to complete for various government agencies. These requirements span the full spectrum from requirements to maintain airworthiness certificates to financial filings with the Securities and Exchange Commission (SEC) for publically traded companies as well as analogous requirements for US-based non-profit organizations. While this effort yielded limited success, in this section we will provide a brief discussion of the potential sources.

### 5.4.1 Department of Transportation Form 41 Data

For the most part, all air carriers providing scheduled passenger transport in the United States are required to file certain data with the United States' Department of Transportation (DOT). The DOT is administered by the Secretary of Transportation and has the duty of "regulation of air commerce." In order to provide air service in the US, operators require two certifications, one economic and one operating. The DOT is the issuing body for the economic authority, while the FAA issues the operating certificate(Hessburg ).

Certain data reported by carriers on DOT Form 41 is publically available via the Bureau of Transportation Statistics (BTS), and is widely used for performing technical analysis on operating and cost data for fixed-wing applications. The data includes relevant measured performance metrics including revenue, fuel cost, maintenance cost, labor cost, etc. In short, the data includes all the parameters of interest for this study as well as a wealth of additional information. The catch is that due to the reporting requirements and the common uses of helicopters, all of the available data is for fixed-wing (airplane) operators that provide scheduled passenger service.

Scheduled passenger service is not a typical use for helicopter applications, and in fact, there is only one known operator providing such service in the US at the end of 2008. As a result, scheduled passenger service by rotorcraft represents a negligible percentage of the total flight hours flown by commercial operators. In addition, the single operator providing scheduled passenger service, US Helicopter, uses only a single model of helicopter, and only a limited subset of the data is available from BTS. Thus while Form 41 reporting is the primary source of the data used to generate operating cost models for fixed-wing aircraft, it is not a feasible source of data for rotorcraft operations at this time.

### 5.4.2 Financial Filings with the SEC

Many of the large commercial helicopter operators are publically traded companies. As a result, they have to satisfy certain financial reporting requirements. One of our strategies for collecting operating cost data involves deriving and compiling operator data from these publically available financial statements.

We used statistics on the installed fleet of helicopters described earlier to target the operators that manage and operate the largest fleets and account for the largest total flight hours. We then researched this list to identify the companies that are publically traded, and their associated country of registration. We then retrieved the available financial statements for relevant operators. While initially promising, we eliminated this as a potential source of data due to a few limitations. First, it turns out that many operators are subsidiaries of larger companies. As a result, their financial statements aggregate the financial data from the commercial helicopter operations with data from the rest of the company. There is not enough publically available data to extract the revenues and expenses associated with helicopter operations. Second, even for the few stand alone commercial operators, the financial statements are too aggregate to provide useful information. For example, many do not report the number of flying hours per year or per aircraft, and many have operations with fixed-wing aircraft interspersed with rotorcraft operations.

While the financial statements of publically traded commercial operators provide some aggregate information, they were not a sufficient source of operating cost data for this project. It is possible that additional research and analysis could be performed to combine other bits and pieces of data with the

financial statements. However, for the purpose of this project, the benefits of such efforts were not considered sufficient to justify the effort required.

## 5.5 Operator Engagement

In addition to reaching out to aircraft manufacturers to support this project, efforts were made to engage helicopter operators. The process of doing so revealed two common themes. First, most operators (particularly the large ones) are not willing to share any data related to their operations or their costs. This is a highly competitive market and hence the operators' costs and structure are highly sensitive. Second, even those operators who were willing to share some limited cost data, did not have a good handle on the actual costs incurred in the various subsets.

In response to the first challenge encountered, we targeted smaller operators to see if they may be less protective of their cost data. After interviewing one US-based helicopter operator providing Emergency Medical Service (EMS), it became apparent that most small operators actually contract with the handful of larger operators to provide service. There is huge variation in the possible arrangements of this type. The large operator could provide a complete service including the helicopter, pilots, maintenance support, logistics, etc., or any individual element. In most cases, the contracts between the large and small operators preclude the small operators from revealing any pricing or cost data. Thus, soliciting data from operators was ruled out as a potential source of data to build an economic model.

## 5.6 Third-party Reports and Database Products

Numerous research papers and database products created by different industry consulting and research firms were considered as sources for potential response data. The source that was best suited to this project is a data product created by Conklin & de Decker Associates which provides life cycle cost (LCC) estimates for various commercial rotorcraft models currently in use(Conklin & de Decker Associates, Inc.). The dataset provided includes seventy-seven different models which met the criteria of interest for this study.

The product relies on data obtained and compiled from aircraft manufacturer estimates, relationships with operators and third-party MRO companies, as well as industry research and analysis. The LCC program by Conklin & de Decker Associates allows the user to specify a set of input criteria including the rotorcraft model of interest, the number of flight hours per year, the total number of years of the program, etc. The tool then simulates the various costs or expenses that the operator is expected to incur over the life of the program, which can be summarized on a per hour basis. The underlying data output of this product was used to arrive at the response data for the model developed herein. A sample of a full output report from the program is available from the Conklin & de Decker website(Conklin & de Decker Associates, Inc.).

# 6 Physics-based Considerations for Economic Model

When building any type of model, an understanding of the physical laws relevant to the relationships between variables of interest is extremely valuable. The appropriate use of the governing physics helps highlight important variables and can provide insight regarding the functional form for the transfer functions. Significant emphasis is placed on developing an understanding of the physics and first principles prior to creating scatter plots and inferring relationships from the data. We review the physics of helicopter flight and engine operation by applying the laws of physics to appropriately simplified approximations. Thus, what we call "physics-based" relationships are derived directly from the laws of physics: conservation of mass, energy, and momentum. Next we apply "first principles" to provide additional insights related to functional relationships we expect to see in the data.

## 6.1 First Principles Approach for Cost of Fuel Consumption

The cost associated with the consumption of fuel is perhaps the most suitable operating cost category to be treated using a physics-based approach. The flight of any aircraft requires the consumption of energy. The laws of physics can be applied to determine the energy consumption or power that must be transferred from the helicopter rotor system to the air. After calculating the power requirements of the rotor system, the physics governing the operation of gas turbine engines can be applied to calculate the efficiency of converting chemical energy in the fuel into mechanical energy in the rotor. Thus, the physics governing helicopter flight and gas turbine operation provide significant insights regarding the factors that affect fuel consumption and the associated operating cost based on the laws of physics.

### 6.1.1 Considerations Based on Physics of Helicopter Flight

The purpose of this section is highlight key considerations from helicopter operation as they relate to the associated economics. A full description and analysis of the dynamics of rotorcraft design and operations is outside the scope of this project. The interested reader is referred to J. Gordon Leishman's text, titled Principles of Helicopter Aerodynamics for a thorough discussion of this topic. Throughout this section, efforts were made to use nomenclature and terminology consistent with this reference. The physics-based approach is most directly applicable to the fuel consumption of the helicopter and the associated cost. As such, the focus of this section is to describe the fundamentals of helicopter design considerations as they affect the power required and hence fuel consumption.

The heart of any helicopter design is the rotor system. The rotor of a helicopter must provide three essential functions(Leishman 496):

1. Generate vertical force (lift) to oppose aircraft weight
2. Generate horizontal force to overcome drag for forward flight
3. Generate forces and moments to control the position, direction and attitude of the aircraft

The fact that the rotor system must simultaneously accomplish all three of these tasks makes them somewhat more complex than fixed-wing airplanes. On fixed-wing aircraft, typically the three functions listed above (vertical force, horizontal force, moments to control attitude, etc) are separate. In general, the wing on an airplane generates vertical force to overcome gravity, the engine provides a horizontal force to overcome drag, and the various control surfaces (elevator, rudder, ailerons, etc.) provide the forces and moments to control flight. As mentioned, the rotor system on a helicopter must accomplish all three of these functions. The aerodynamics and blade dynamics involved in designing rotor systems to provide these three functions in a manner that can be controlled by a pilot are quite complex.

At an elementary level, the rotor, consisting of some number of airfoil-shaped blades, can produce a force that is a function of the angle of attack and dynamic pressure of each blade. Based on the aerodynamics of a simple airfoil, the total force (lift) generated by each blade is proportional to the relative velocity between the air and the blade squared. Hence, the total force produced by the rotor is proportional to the blade tip speed *squared* and the power transferred through the rotor is proportional to the tip speed *cubed*. Hence we expect the tip speed of the blades to be correlated with the power required by the rotor via this cubic relationship.

When a helicopter is hovering, the force generated by the rotor system is primarily used to overcome the weight of the aircraft (force of gravity acting on the mass). When the helicopter is in forward flight, the net force of the rotor is "upward and forward" such that a portion of the force is used to overcome gravity and a portion of the force is used to provide horizontal force to overcome the drag of the aircraft moving in forward flight. The change in direction of the net force from the rotor is accomplished by tilting the plane of the rotor forward, while increasing the absolute force generated by the rotor so that the vertical component is sufficient to overcome the weight. In forward flight, even with the rotor rotating at a constant speed, the relative velocity between the blades and the free stream varies at the blade completes a revolution. For example, consider the case when the blade is perpendicular to the direction of flight on either side of the aircraft. In one case the relative velocity is the rotational velocity *plus* the flight speed of the helicopter. When the blade reaches the same position on the other side of the aircraft, the relative velocity is the rotational velocity *minus* the flight speed of the helicopter. This means that the dynamic pressure varies significantly as a function of the blade's rotational position relative to the direction of flight. To produce a constant rotor, thrust as each blade completes a full revolution, its angle of attack must be continuously varied.

While the complexity of continuously varying the pitch of each blade throughout its rotation has been conquered by clever mechanical design, the nature of this operation sets some physical limitations for traditional rotor systems. During flight, when the blade is moving in the direction opposite to the flight speed (called the retreating blade), it has a very low relative velocity. As a result, a rather high angle of attack is required to maintain the lifting force. If the angle of attack is increased too far, the blade will stall thereby reducing the overall force generated by the rotor system. Conversely, on the opposite side of the helicopter, when the blade is moving in the same direction as flight (called the advancing blade), only a low angle of attack is required due to fairly high relative velocities and dynamic pressures. In fact, as the flight speed increases, the advancing blade can approach a regime in which the tips approach the speed of sound leading to significant increases in drag (wave drag) and ultimately transonic operation with the formation of shock waves(Leishman 496). These dynamics result in a substantial increase in the power required to propel the helicopter and can lead to significant vibration, stress, and noise issues.

This fundamental nature of the operation of a helicopter rotor system limits the maximum flight speed of the aircraft due to both the conditions encountered by the retreating blade due to stall and the advancing blade due to transonic conditions and the formation of shock waves. While advances in aerodynamic research, modeling and blade design have increased the speeds achievable by helicopters, these considerations are likely to continue to limit designs in the future.

Despite the complexity involved in fully characterizing the aerodynamics of rotorcraft flight, simplified methods exist for estimating the power required by a helicopter. This power required can then be directly related to the fuel consumption and associated cost which will be an important element in the economic model. As a starting point, it is possible to use an approach known as *momentum theory* to

derive a first-order prediction of rotor thrust and power from three fundamental laws of physics: conservation of mass, conservation of momentum, and conservation of energy(Leishman 496). It is useful to begin this method for the case of a helicopter in hover under the assumption of one dimensional, quasi-steady, incompressible, inviscid flow. By applying conservation of mass and momentum to an appropriately defined control volume surrounding the rotor and its wake area, a relationship describing the rotor thrust, T is given by:

$$T = \dot{m}v_\infty$$

**Equation 1**

$$where \; T = rotor \; thrust$$
$$\dot{m} = mass \; flow \; rate \; through \; control \; volume$$
$$v_\infty = slipstream \; velocity \; far \; downstream \; from \; the \; rotor$$

The principle of conservation of energy states that the work done on the rotor is equal to the energy gain of the fluid per unit time. The power consumed by the rotor (work per unit time) is equal to the thrust of the rotor multiplied by the induced velocity at the plane of the rotor. Thus, application of the conservation of energy leads to:

$$Tv_i = \frac{1}{2}\dot{m}v_\infty^2$$

**Equation 2**

$$where \; v_i = induced \; velocity \; at \; the \; plane \; of \; the \; rotor$$

Combining Equation 1 and Equation 2, leads to an expression for the induced velocity at the plane of the rotor :

$$v_i = \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{1}{2\rho}\left(\frac{T}{A}\right)}$$

**Equation 3**

$$where \; A = rotor \; disk \; area$$

The ratio of rotor thrust to rotor area (T/A), appears in many relationships describing helicopter performance and is called the *disk loading*. The power required from the rotor to hover is the rate of work done on the fluid per unit time per unit thrust, is given by:

$$P_{ideal} = Tv_i = T\sqrt{\frac{T}{2\rho A}} = T\sqrt{\frac{1}{2\rho}\left(\frac{T}{A}\right)} = \frac{T^{3/2}}{\sqrt{2\rho A}}$$

**Equation 4**

The ideal power required is a function of the density of air. A lower air density, due to higher temperature, altitude or lower atmospheric pressure leads to higher power requirements. Thus, the "hot and high" capability of a helicopter is an important performance metric, since these conditions represent the scenario requiring the greatest power. The ideal power is proportional to the cube of the induced velocity, which can be seen from rewriting Equation 4 to give:

$$P_{ideal} = Tv_i = (\dot{m}v_\infty)v_i = (\rho Av_i)(v_\infty)v_i = (\rho Av_i)(2v_i)v_i = \left(2\rho Av_i^3\right)$$

**Equation 5**

This relationship leads to the fundamental design feature of all helicopters, which requires that the disk area of the rotor be fairly large in order to have a large mass flow through the rotor while minimizing the induced velocity(Leishman 496).

Applying Bernoulli's principle to a streamline above and below the plane of the rotor disk, it is possible to show that the under the assumptions of steady, one-dimensional, inviscid flow, the jump in pressure across the disk is uniform and equal to the disk loading, T/A. This fact, combined with the demonstrated occurrence of this ratio in the application of momentum theory above, highlights the importance of the disk loading as a critical parameter in helicopter design. For a single rotor helicopter, which is the focus of this analysis, and the majority of the designs in operation, the rotor thrust required in hover is simply equal to the weight of the helicopter. As a result, it is common to substitute the weight of the helicopter, W, for the rotor thrust, T, and write the disk loading as W/A.

An "efficient" rotor will consume as little power as possible to generate a given amount of thrust. This "hovering efficiency" is commonly considered as the ratio of the thrust generated divided the ideal power, T/P. Again, it is common to substitute the weight of the helicopter for the thrust and write the *power loading* as W/P. Recalling that the ideal power required to hover is given by $P=Tv_i$ from Equation 4, it is worth noting that the ideal power loading is inversely proportional to the induced velocity, $v_i$. Dividing Equation 4 by T, results in a simple relationship between the power loading and disk loading for a helicopter in hover under the simplifying assumptions of the assumptions of one-dimensional, quasi-steady, incompressible, inviscid flow:

$$\left(\frac{P}{T}\right)_{ideal} = \left(\frac{T}{P}\right)_{ideal}^{-1} = v_i = \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{1}{2\rho}\left(\frac{T}{A}\right)}$$

**Equation 6**

The power loading (T/P) decreases quickly with increasing disk loading, so rotors with a low disk loading will require a high ideal power loading and tend to be more efficient(Leishman 496).

The discussion up to this point is based on the approach presented by Leishman et al., demonstrating how the application of momentum theory can be used to develop a first-order relationship describing the ideal rotor power required to a helicopter to hover. This analysis treats the rotor area as a uniform disk and invokes the assumptions of one-dimensional, quasi-steady, incompressible, inviscid flow. Three fundamental laws of physics, conservation of mass, conservation of momentum, and conservation of energy are used to ultimately generate Equation 6. From earlier comments, we know that in reality, the rotor system is not a solid disk, but rather made up of some number of rotating airfoils. These rotating airfoils create downwash, tip vortices, and wakes resulting in swirl and three-dimensional flow. In addition, we know that air at standard atmospheric conditions is a compressible and viscid fluid. Hence, it appears that all of the assumptions we used to generate the expression in Equation 6 do not hold for normal helicopter operation. Nonetheless, Equation 6 tells us that we expect power loading, T/P, and disk loading, T/A, to be crucial, first-order, design parameters affecting the power required, and hence fuel consumption required for a given helicopter.

In an effort to improve the ideal momentum theory analysis, Leishman et al. present a minor modification to the ideal result to account for several effects including nonuniform flow, tip losses, wake swirl, and a finite number of blades (Leishman 496). Specifically, the authors present an induced power correction factor, $\kappa$, which can be combined with Equation 4 and Equation 6 to write:

$$P_{induced} = \kappa P_{ideal} = \frac{\kappa T^{3/2}}{\sqrt{2\rho A}}$$

**Equation 7**

$$\left(\frac{P}{T}\right)_{induced} = \left(\frac{T}{P}\right)_{induced}^{-1} = \kappa \sqrt{\frac{1}{2\rho}\left(\frac{T}{A}\right)}$$

**Equation 8**

The induced power correction factor, $\kappa$, is an empirical coefficient derived from testing or estimated from advanced blade element methods. A typical value is about 1.15(Leishman 496).

In addition to the induced power, the rotor must overcome the profile drag on the individual rotor blades. The power required to accomplish this is referred to as profile power. The total profile drag for a rotor design can be calculated using an elemental blade analysis and integrating the drag on each section of the airfoil. This drag will be a function of the drag coefficient for each blade, which is a function of Reynolds number, Mach number, and the blade chord. Since these three parameters will vary along the length of the blade, the drag coefficient itself will be a function of the radial position along the blade. A reasonable simplifying assumption often made in practice is to assume that the profile drag coefficient is constant along the length of the blade and independent of Reynolds number and Mach number(Leishman 496). This leads to an expression for the profile drag given by:

$$P_{profile} = \frac{1}{8}\sigma C_{d0}\left(\rho A V_{tip}^3\right)$$

**Equation 9**

$$where\ \sigma = \frac{N_b cR}{A} = \frac{Total\ Blade\ Area}{Disk\ Area}\ is\ called\ the\ rotor\ solidity$$

$N_b$ = number of blades

c = chord of blade (assumed constant)

$C_{d0}$ = profile drag coefficient (typical value ~0.01)

The rotor solidity represents the fraction of the disk area that is "filled" with blades, with typical values in range 0.07-0.12(Leishman 496). The prediction for the actual power required from the rotor during hover can be found after relaxing the earlier assumptions by adding the induced power (based on modified momentum theory) to the profile power (accounting for the drag on the rotor blades), leading to:

$$P_{actual} = P_{induced} + P_{profile} = \kappa P_{ideal} + P_{profile} = \frac{\kappa T^{3/2}}{\sqrt{2\rho A}} + \frac{1}{8}\sigma C_{d0}(\rho A V_{tip}^3)$$

**Equation 10**

Based on this relationship, we expect rotor solidity and the profile drag coefficient to have first order effects on the profile power, and hence second order effects on the total power required. In addition to the use of the power loading, T/P, as a proxy for the "efficiency" of the rotor system, a dimensionless figure of merit has become widely accepted throughout the industry. First introduced by in the 1940s, the figure of merit follows a "typical efficiency" form of ideal/actual, as:

$$Figure\ of\ Merit\ (FM) = \frac{ideal\ power\ required\ to\ hover}{actual\ power\ required\ to\ hover} = \frac{P_{ideal}}{P_{actual}} = \frac{P_{ideal}}{P_{induced} + P_{profile}}$$

$$FM = \frac{P_{ideal}}{P_{actual}} = \frac{P_{ideal}}{P_{induced} + P_{profile}} = \frac{\dfrac{T^{3/2}}{\sqrt{2\rho A}}}{\dfrac{\kappa T^{3/2}}{\sqrt{2\rho A}} + \dfrac{1}{8}\sigma C_{d0}(\rho A V_{tip}^3)}$$

**Equation 11**

With this definition the figure of merit for any real rotor must always be less than one. Under the ideal assumptions used to reach Equation 6, the induced power correction factor, $\kappa$, is equal to unity and the profile drag coefficient for the blades, $C_{d0}$, is equal to zero. Substituting these values into Equation 11 results in a figure of merit equal to unity as we would expect. The figure of merit can be used to evaluate the efficiency with which a hovering rotor is generating thrust for a given power. With current technology, a figure of merit between 0.7 and 0.8 is considered good hovering performance for a helicopter rotor(Leishman 496).

Note however, that at low operating thrust (low disk loading), the numerator in Equation 11 is fairly small and the profile drag term in the denominator dominates, resulting in a low figure of merit. As the thrust increases, the profile drag becomes less significant and, in the limit, the figure of merit asymptotically approaches a value of $1/\kappa$. For this reason, it is only meaningful to compare rotors at the same disk loading, T/A. The importance of disk loading, T/A, on the figure of merit can be seen by dividing the numerator and denominator in Equation 11 by T, giving:

$$FM = \frac{P_{ideal}}{P_{actual}} = \frac{\left(\dfrac{1}{T}\right)\dfrac{T^{3/2}}{\sqrt{2\rho A}}}{\left(\dfrac{1}{T}\right)\dfrac{\kappa T^{3/2}}{\sqrt{2\rho A}} + \left(\dfrac{1}{T}\right)\dfrac{1}{8}\sigma C_{d0}(\rho A V_{tip}^3)} = \frac{\sqrt{\dfrac{1}{2\rho}\left(\dfrac{T}{A}\right)}}{\kappa\sqrt{\dfrac{1}{2\rho}\left(\dfrac{T}{A}\right)} + \dfrac{1}{8}\sigma C_{d0}\left(\dfrac{A}{T}\right)(\rho V_{tip}^3)}$$

$$FM = \frac{P_{ideal}}{P_{actual}} = \frac{\left(\frac{1}{A}\right)\frac{T^{3/2}}{\sqrt{2\rho A}}}{\left(\frac{1}{A}\right)\frac{\kappa T^{3/2}}{\sqrt{2\rho A}} + \left(\frac{1}{A}\right)\frac{1}{8}\sigma C_{d0}\left(\rho A V_{tip}^3\right)} = \frac{\left(\frac{T}{A}\right)^{3/2}\sqrt{\frac{1}{2\rho}}}{\kappa\left(\frac{T}{A}\right)^{3/2}\sqrt{\frac{1}{2\rho}} + \frac{1}{8}\sigma C_{d0}\left(\rho V_{tip}^3\right)}$$

**Equation 12**

By considering the case of a helicopter in hover, we illustrate the manner in which physical principles can be applied to develop approximate equations governing motion. In addition to identifying four potentially important design variables, we also identified two quantitative metrics to evaluate "rotor efficiency," the power loading, T/P, and the figure of merit, FM. Note that these efficiency metrics reflect the efficiency of the rotor system, rather than the whole helicopter, and are related to the *hovering* performance of the rotor system.

Helicopters clearly do more than simply hover. In addition to hovering, they may climb and descend vertically (in the direction of the axis of rotation of the rotor). They may also fly horizontally, or any combination of these maneuvers. While the mathematics gets significantly more complicated, momentum theory can be applied in an analogous manner to approximate the power requirements of a helicopter in various flight conditions.

For a rotor in vertical (axial) climb or descent, this simplified momentum analysis can be used to relate the power required for climb to the power required to hover presented in Equation 10. Letting $P_c$ represent the power required to climb, and $P_h$ the power required to hover from Equation 10, we can write:

$$\frac{P_c}{P_h} = \frac{V_C}{v_h} + \frac{v_i}{v_h}$$

**Equation 13**

The terms on the right hand side of Equation 13 represent the work to change the potential energy of the rotor and the work done on the air. The ratio of the power required to climb divided by the power required to hover is given by:

$$\frac{P_c}{P_h} = \frac{V_C}{2v_h} + \sqrt{\left(\frac{V_C}{2v_h}\right)^2 + 1}$$

**Equation 14**

Substituting the expressions for $P_h$ and $v_h$ from Equation 10 and Equation 3 respectively, gives:

$$P_c = \left[\frac{\kappa T^{3/2}}{\sqrt{2\rho A}} + \frac{1}{8}\sigma C_{d0}\left(\rho A V_{tip}^3\right)\right]\left[\frac{V_C}{2\left(\sqrt{\frac{T}{2\rho A}}\right)} + \sqrt{\left(\frac{V_C}{2\left(\sqrt{\frac{T}{2\rho A}}\right)}\right)^2 + 1}\right]$$

**Equation 15**

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As expected, the power required for vertical climb is greater than the power required to hover. Similarly, the power required during vertical (axial) descent is less than the power required to hover. When the rate of climb, $V_c$, goes to zero the helicopter is in hover and Equation 15 reduces to the power required to hover, Equation 10. It is interesting to note that as the descent speed increases, there is a point at which the power required goes to zero. At this point, the rotor system is extracting energy from the airstream. An adept pilot can use this characteristic to trade potential energy (altitude) for rotational kinetic energy in the rotor system in a maneuver called an autorotation. An autorotation provides a means for a pilot to safely land a helicopter that has lost power to the rotor system due to engine or transmission failure. As the aircraft approaches the ground, the pilot can trade some of the kinetic energy in the rotating rotor system to do work on the air and generate lift to reduce the rate of descent and mitigate the damage upon impact with the ground. While the aerodynamics involved in performing an autorotation are outside the scope of this analysis, the autorotation capability of a helicopter is a very real (potentially lifesaving) design requirement.

While a similar analysis can be performed to estimate the power required during forward flight, the mathematics become significantly more complex and numerical methods are required in some regimes of flight. Nonetheless, it is valuable to look at an expression estimating the total power requirements for a rotor system in forward flight to identify the significant variables that will affect performance. Leishman et al., presents an expression for the total power required in the following form(Leishman 496):

$$P_{rotor} = P_{induced} + P_{profile} + P_{parasite} + P_{climb}$$

**Equation 16**

Where $P_{induced}$ is the power exerted to generate lift via the induced velocity at the rotor plane introduced earlier, which can be written as:

$$P_{induced} = \kappa T v_i$$

**Equation 17**

When the rotor is in hover, the induced velocity is given by Equation 3, repeated here:

$$v_h = \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{1}{2\rho}\left(\frac{T}{A}\right)}$$

If forward velocity is fairly high, such as at cruise speed, then the induced velocity can be approximated by (Glauert's formula):

$$v_i = \frac{T}{2\rho A V_\infty}$$

Combining Equation 17 and Glauert's formula gives:

$$P_{induced} = \frac{\kappa T^2}{2\rho A V_\infty}$$

**Equation 18**

$P_{profile}$ is the power required to overcome the profile drag or the rotating airfoil shaped blades presented in Equation 9 and modified here to account for the non-uniform flow field and radial component of velocity encountered during forward flight:

$$P_{profile} = \frac{1}{8}\sigma C_{d0}\left(\rho A V_{tip}^3\right)(1 + K\mu^2)$$

**Equation 19**

Where a numerical value of K = 4.6-4.7 is considered reasonable for forward flight(Leishman 496), and $\mu$ is the tip speed ratio or advance speed ratio.

$$\mu = \frac{V_\infty cos\alpha}{\Omega R} = \frac{Velocity\ of\ rotor\ parallel\ to\ rotor\ plane\ relative\ to\ free\ stream}{Tip\ speed\ of\ rotor\ blade\ in\ hover\ in\ still\ air}$$

Where $\alpha$ represents the angle between the free stream and the plane of the rotor.
$P_{parasite}$ represents the power required to overcome the drag of the aircraft as it moves relative to the free stream. This parasite drag is typically represented in the form:

$$P_{parasite} = \frac{1}{2}\left(\frac{f}{A}\right)(\mu^3)(\rho A V_{tip}^3)$$

**Equation 20**

Where f is the equivalent wetted are or equivalent flat-plate area, and accounts for the drag force ($D_f$) on the hub, fuselage, landing gear, etc.

$$f = \left(\frac{D_f}{\frac{1}{2}\rho V_\infty^2}\right)$$

$P_{climb}$ is equal to the power required to increase the potential energy of the rotor, which is simply equal to the time rate of change of the potential energy of the rotor and can be written as:

$$P_{climb} = TV_c = WV_c$$

**Equation 21**

While the formulas presented here are useful for identifying the key parameters affecting the rotor power requirements, it is helpful to plot the various elements to see how the relative importance of the power needs changes as a function of flight speed. Figure 4 shows an example of a characteristic plot of rotor power versus flight speed for a large commercial helicopter. The speed ranges from zero at hover to the maximum speed of the helicopter as limited by the rotor dynamics described earlier.
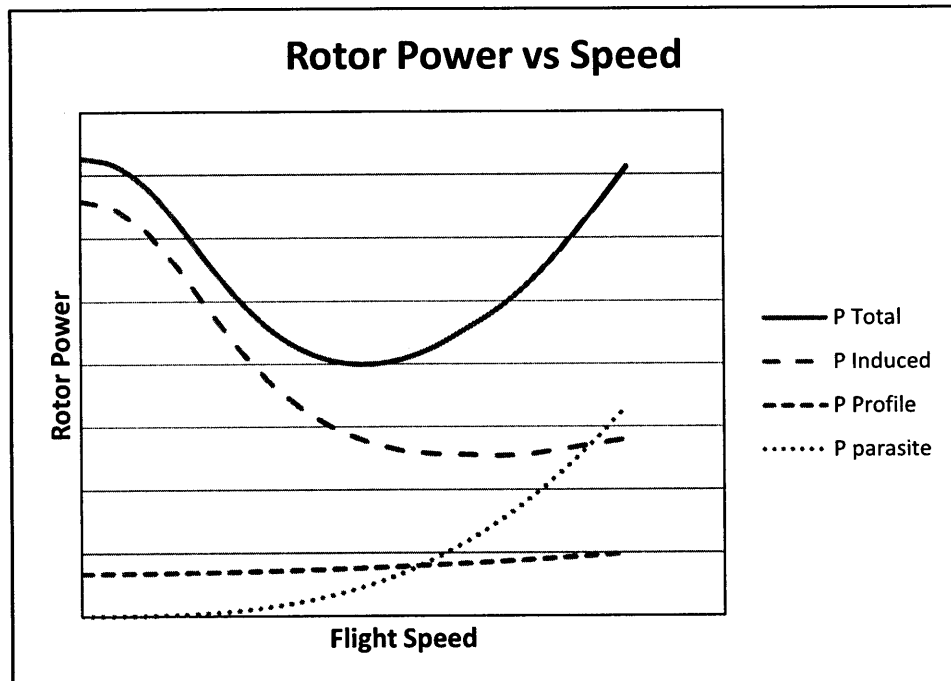
**Figure 4 Main Rotor Power Required versus Flight Speed – Horizontal Forward Flight**

In this example, the maximum total rotor power required during hover is greater than that required throughout the range of flight speeds shown. This is not true for all helicopters, but the characteristic shape of the total power requirements is typical. In addition, we see that the induced power drops quickly as flight speed increases from hover. Conversely, the power required to overcome parasite drag is zero at hover and then increases dramatically with the cube of the flight speed. The plot also illustrates the importance of specifying a flight speed when quoting the power requirement or fuel consumption of a particular helicopter design.

Most conventional helicopter designs incorporate the use of a tail rotor in addition to the main rotor. The tail rotor is used as a counter-torque device to overcome and control the torque generated by the main rotor. Similar to the main rotor, the tail rotor requires some amount of power to perform this function and thus must be considered when evaluating the total power requirements of the aircraft. The required tail rotor thrust can be calculated from a force balance and must be sufficient to overcome the reaction force on the fuselage from the main rotor. As a result, the required thrust is a function of the main rotor power, the distance between the axis of the main rotor and the tail rotor, and the angular velocity of the main rotor. In addition, most conventional designs incorporate a vertical fin which can be used to generate an aerodynamic sideways force during forward flight. This helps reduce the power requirements of the tail rotor during forward flight.

For modern helicopter geometries, the power required by the tail rotor is typically 5-10% of the main rotor power(Leishman 496). For the purpose of this study, we note that distance between the axis of the main rotor and the tail rotor has a first order effect on the tail rotor power required and hence has a second order effect on the total power required.

From this discussion of the rotor aerodynamics of a helicopter, we identify a few key rotor design parameters that we expect to have a significant effect on the energy conversion performance of the rotor. The ability of a rotor system to convert power into thrust has a direct relationship to the fuel consumption and associated operating costs. Specifically, the operating cost associated with fuel consumption is simply the product of the fuel unit cost and the fuel flow rate:

$$DOC_{fuel}\left(\frac{\$}{FH}\right) = Fuel\ Flow\ \left(\frac{gal}{hr}\right) * Fuel\ Unit\ Cost\ \left(\frac{\$}{gal}\right)$$

**Equation 22**

We can then relate the fuel flow rate to the rotor power required by noting that

$$Fuel\ Flow\ \left(\frac{gal}{hr}\right) = C * Fuel\ Conversion\ Efficiency * Total\ Power\ Required$$

**Equation 23**

Where C is a constant, which physically represents the energy density of the fuel in the units of choice. The total power required can then be broken into three subsets given by:

$$Total\ Power\ = Main\ Rotor\ Power + Tail\ Rotor\ Power + Accessories\ and\ Losses$$

**Equation 24**

While a detailed treatment of the accessories and losses is outside the scope of this discussion, this accounts for things such as electric power generation for aircraft systems, supplying compressed air for environmental control systems, losses in bearings, gear meshes, and other frictional interfaces, etc.

Equation 22, Equation 23, and Equation 24 show how the direct operating cost associated with fuel consumption is directly related to the main rotor power required. As a result, the discussion of main rotor power requirements in this section helps us identify the key variables that may affect fuel-related operating costs. Specifically, by applying momentum theory to analyze a rotor in hover under ideal conditions, we identified the power loading, T/P, and the disk loading, T/A, as important first-order design parameters. By considering the modified momentum theory presented by Leishman et al. we were able to account for many of the non-ideal conditions associated with the induced power by lumping these "losses" into an empirically derived induced power correction factor, κ. While this treatment does not highlight any second order design parameters associated with the induced power correction factor, we have revealed the functional form we should expect. By considering the simplified calculation of profile drag, we identified the rotor solidity, σ, and the profile drag coefficient for the blades as having first-order effects on the profile power, and hence second order effects on the actual power. After extended the discussion to forward flight, we see that the equivalent wetted area can be used to account for the parasite drag force on the aircraft. In forward flight, the profile drag on the blades increases by an additional term given in Equation 20 to account for the flight speed of the helicopter. Lastly, we see that the power required to climb or descend is simply proportional to the weight of the aircraft and the rate of climb or descent.

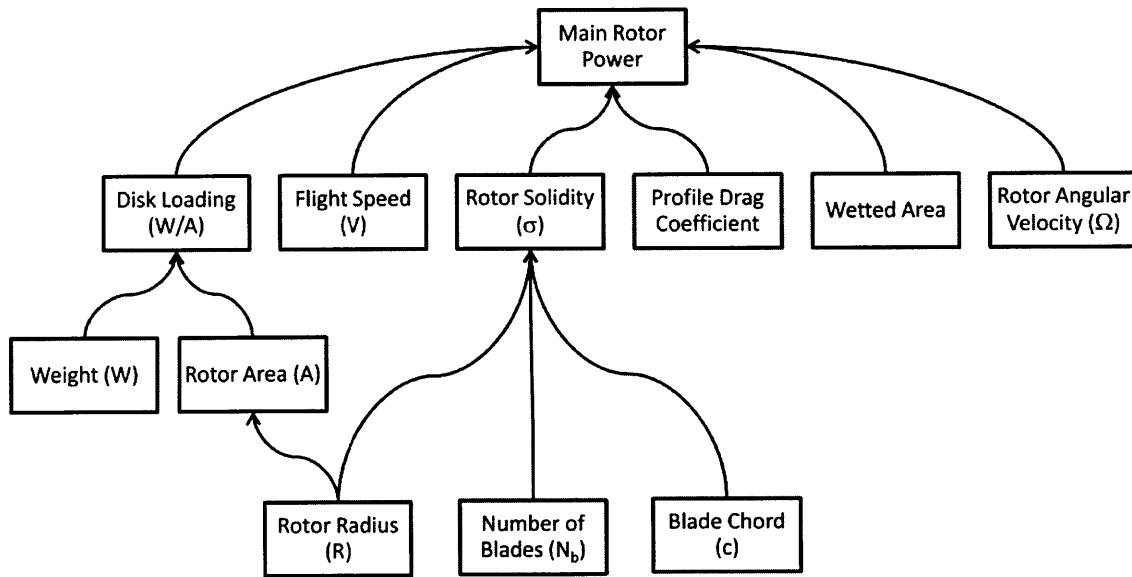A simplified summary of the variables affecting the main rotor power is presented in Figure 5.

**Figure 5 Variables Affecting Main Rotor Power**

Since the main rotor power can be linked directly to the fuel-related DOC, we would expect that the variables presented in Figure 5 may have an impact on the operating cost associated with fuel. While the intent of this analysis is not to provide a mathematical proof of the equations of motion governing rotorcraft flight, it provides some useful insights as to which helicopter design parameters we expect may be significant explanatory variables in our model. These insights will help guide the analysis of field data from existing helicopter designs. Specifically, we highlight the physical parameters shown in Table 2 for potential consideration.

**Table 2 Summary of Rotorcraft Parameters Related to Physics of Flight**

| Physical Parameter | Symbol (units) | Common Grouping (units) |
|---|---|---|
| Weight | W (lbs) | W/A (lb/ft2), W/P (lb/shp) |
| Rotor Radius | R (ft) | D=2R (ft), A=$\pi R^2$ (ft2), Rotor solidity $\sigma = \frac{N_b cR}{A}$ |
| Rotor Angular Rotation Speed | $\Omega$ (radians/s) | |
| Number of Blades | $N_b$ (blades/rotor) | Rotor solidity $\sigma = \frac{N_b cR}{A}$ |
| Average Chord of Blade | c (ft) | Rotor solidity $\sigma = \frac{N_b cR}{A}$ |
| Blade Tip Speed in Hover | $V_{tip}$ (ft/sec) | $V_{tip} = \Omega R$ (ft/sec) |
| Distance between Main Rotor Axis and Tail Rotor | $d_{tr}$ (ft) | Tail Rotor Power (shp) |
| Blade Profile Drag Coefficient | $C_{do}$ (unitless) | |
| Rotor Solidity | $\sigma$ (unitless) | |
| Equivalent Wetted Area | f (unitless) | |
| Blade Advance Speed Ratio | $\mu$ (unitless) | |

The relationships between these helicopter design parameters can be fairly complex. Some variables can be directly calculated from others, such as the rotor area, solidity, etc, while others are indirectly related such as the number of blades and the weight. In any case, the parameters are certainly not independent of one another and in many cases may be an exact linear combination of other variables. This is something we must be cognizant of when using regression, since multicollinearity may be prevalent.

## 6.1.2 Considerations Based on Physics of Engine Operation

One or more gas turbine engines provide the power required by the rotor system. Typically, the engines provide power via an output shaft which connects to a transmission, which in turn provides shaft power to the main rotor and tail rotor. In addition to providing power to the rotors, the engines must also provide power for several accessories such as an electric generator, fuel pump, lubrication oil pump, etc. They must also provide sufficient power to overcome any friction or losses in the transmission system, including both the main transmission and any related drives or gearboxes to power the tail rotor. While in Section 3.3, we discuss some of the decisions and considerations facing an engine designer, the purpose of this section is to present a simple description of the physical laws governing the operation of gas turbine engines. The emphasis in this section is related to the principle purpose of the engine to convert chemical energy in a fuel to mechanical shaft power. Maintenance related considerations are treated in Section 3.3 and Section 6.2.

The purpose of the engine in a helicopter is to provide the power needed for flight with the minimum consumption of resources. The resources in this case could be considered fuel, payload (weight), space (volume), material (parts), labor (for maintenance). With this in mind, three of the most important metrics for an engine are fuel conversion efficiency, weight and size (volume). The fuel conversion efficiency is typically expressed in the form of specific fuel consumption defined as the flow rate of fuel (by weight) consumed to produce a unit of power output. The engine weight is considered both in absolute terms, and as a power to weight ratio. Similarly, the volume is considered both in its raw form as well as the specific power, which is the power output per flow rate of air (by weight) through the engine.

The ideal operation of gas turbine engines can be described by the Brayton Cycle, which consists of four major steps:
1. Adiabatic, reversible (isentropic) compression of working fluid (2-3)
2. Constant pressure heat transfer (increasing energy of working fluid) (3-4)
3. Adiabatic, reversible (isentropic) expansion of working fluid (4-8)
4. Constant pressure heat transfer (reducing energy of working fluid) (8-2)

Under the assumptions of an ideal Brayton Cycle where the working fluid has a constant coefficient of specific heat, the ideal thermal efficiency can be written as:

$$\eta_{th,i} = \frac{W_{net}}{Q_{in}} = \frac{W_{turbine} - W_{compressor}}{Q_{in}}$$

**Equation 25**

The First Law of Thermodynamics can be used to calculate the work of the turbine and compressor as well as the heat addition, leading to:

$$\eta_{th,i} = \frac{W_{net}}{Q_{in}} = \frac{W_{turbine} - W_{compressor}}{Q_{in}} = \frac{C_p(\Delta T_{turbine} - \Delta T_{compressor})}{C_p \Delta T_{combustor}} = \frac{C_p[(T_8 - T_4) - (T_3 - T_2)]}{C_p(T_4 - T_3)}$$

**Equation 26**

The absolute value of the work done by the turbine and the compressor can be calculated from the First Law of Thermodynamics as:

$$W_{turbine,ideal} = C_p(\Delta T_{turbine}) = C_p[T_8 - T_4]$$

**Equation 27**

$$W_{compressor,ideal} = C_p(\Delta T_{compressor}) = C_p[T_3 - T_2]$$

**Equation 28**

Invoking the assumption of constant specific heat, Cp, and using the isentropic relation for temperature and pressure, the ideal thermal efficiency can be written as:

$$\eta_{th,i} = \frac{W_{net}}{Q_{in}} = \frac{[(T_8 - T_4) - (T_3 - T_2)]}{(T_4 - T_3)} = 1 - \frac{1}{\left(\frac{P_3}{P_2}\right)^{\gamma - \frac{1}{\gamma}}} = 1 - \frac{1}{(PR)^{\gamma - \frac{1}{\gamma}}} = f(PR)$$

**Equation 29**

Letting PR denote the compressor pressure ratio ($P_3/P_2$), we see that for the ideal Brayton Cycle, the overall thermal efficiency is a function of only the compressor pressure ratio.

As illustrated above, in the ideal Brayton Cycle, the turbine and compressor work are a function of the temperature change of the working fluid over the respective cycle points. In reality, the compression and expansion processes are not truly isentropic. This can be accounted for by considering the isentropic efficiency of each component:

$$\eta_{turbine} = \frac{W_{t,actual}}{W_{t,ideal}} = \frac{C_p(T_8 - T_4)_{actual}}{C_p(T_8 - T_4)_{ideal}}$$

**Equation 30**

$$\eta_{compressor} = \frac{W_{c,ideal}}{W_{c,actual}} = \frac{C_p(T_3 - T_2)_{ideal}}{C_p(T_3 - T_2)_{actual}}$$

**Equation 31**

Note that in both cases, the efficiency for the turbine and compressor will always be less than one. The actual work extracted by the turbine will be less than the ideal work, and the actual work done by the compressor on the working fluid will always be greater than the ideal work required by the compressor. By substituting the isentropic relations for pressure and temperature, the component efficiencies can be rewritten as:

$$\eta_{turbine} = \frac{W_{t,actual}}{W_{t,ideal}} = \frac{(T_8 - T_4)_{actual}}{(T_8 - T_4)_{ideal}} = \frac{1 - \left(\frac{T_8}{T_4}\right)}{1 - \left(\frac{P_8}{P_4}\right)^{\frac{\gamma-1}{\gamma}}}$$

**Equation 32**

$$\eta_{compressor} = \frac{W_{c,ideal}}{W_{c,actual}} = \frac{C_p(T_3 - T_2)_{ideal}}{C_p(T_3 - T_2)_{actual}} = \frac{\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{T_3}{T_2}\right) - 1}$$

**Equation 33**

Thus, we see that the component efficiencies of the turbine and compressor under nonisentropic operation are a function of both the pressure ratio and the temperature ratio across the component. If we know the isentropic efficiencies of the turbine and compressor, then we can calculate the overall efficiency of the engine under the more realistic condition ofnonisentropic compression and expansion as:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{turbine,actual} - W_{compressor,actual}}{Q_{in}} = \frac{\eta_t W_{t,ideal} - \left(\frac{1}{\eta_c}\right) W_{c,ideal}}{Q_{in}} = f\left(\frac{P_3}{P_2}, \frac{T_4}{T_2}, \eta_t, \eta_c\right)$$

**Equation 34**

So far, we have not mentioned how the working fluid in the Brayton cycle goes from state 3 at the exit of the compressor to state 4 at the entrance of the turbine. This change of thermal energy states is accomplished by the transfer of chemical energy in the fuel to thermal energy in the fluid via the combustion process. Under ideal conditions, 100% of the chemical energy is converted to thermal energy, and there is no change in pressure throughout the process. In real engines, the combustion process is not ideal. The deviations from the ideal scenario can be accounted for by accounting for a combustor efficiency which represents the fraction of chemical energy in the fuel that is converted to thermal energy, and a combustor pressure loss.

Based on the above analysis, a few engine operating parameters can be identified as being likely to impact the operating cost associated with fuel consumption. Note that each of the parameters above represents an operational characteristic of the engine cycle rather than an engine hardware design characteristic. This means that if two engines each have the same fuel conversion efficiency (or SFC) and the same weight, then they would have equivalent fuel consumption and associated operating cost. Whether these performance metrics are achieved with a fantastic compressor and a mediocre turbine or vice-versa makes no difference. Similarly, one engine could operate with a very high compressor pressure ratio and relatively low combustor discharge temperature and have an equivalent efficiency (SFC) to a different engine with a lower pressure ratio but higher combustor temperature.

In Section 6.1.1 we illustrated how to determine the power required by a helicopter. With this in mind, an engine with the best fuel conversion efficiency (lowest SFC) will have the lowest fuel consumption and associated operating cost. Note however, that the weight of the engine affects the weight of the entire aircraft and hence the power required by the rotors. The weight of the engine is added to the

weight of the airframe when calculating the total aircraft weight. In addition to this direct impact, the weight of the engine will also affect the weight of the airframe structure required to support the engine as well as the weight of the transmission, rotor system, landing gear, etc. required as a result of an increase in the overall aircraft weight with a heavier engine. The bottom line is that while the physics-based considerations suggest that engine weight is an important variable, the analysis is likely to underestimate the importance of engine weight since it does not account for the second order effects of increased airframe weight.

Lastly, the size of the engine does not surface based on the discussion of the physics of engine operation presented here. However, by applying first principles, we can reason that a larger engine envelop will require a larger airframe and support structure and hence additional airframe weight. In addition, a larger engine volume may cause an increase in the equivalent wetted area of the aircraft and an associated increase in parasite drag and power. A widely-used metric for the "volumetric efficiency" of a gas turbine engine is the specific power, which is defined as the output power per unit mass flow of air:

$$Specific\ Work = \frac{Net\ Power\ Output}{Mass\ flow\ of\ Air} = \frac{P_{net}}{\dot{M}_{air}}$$

**Equation 35**

For an ideal Brayton cycle, it is possible to show that the specific work is a function of cycle conditions only:

$$Specific\ Work = \frac{P_{net}}{\dot{M}_{air}} = f\left(\frac{P_3}{P_2}, \frac{T_4}{T_2}\right)_{ideal}$$

**Equation 36**

Thus under ideal conditions, we expect that the fuel consumption performance of the engine will be a function of only cycle conditions. This means that to the first order, the fuel conversion efficiency term in Equation 23 is only a function of compressor pressure ratio and turbine inlet temperature. While this is simple to state in principle, we have not said anything about the engine components or architecture. We note that a number of considerations arise when designing the actual engine hardware to achieve the cycle conditions of interest, as discussed in Section 3.3. In addition, the weight of the engine will be important parameter because of its impact on the weight of the complete aircraft. In addition, the volume of the engine envelop may also be important via its impact on the size and weight of the helicopter. Based on this discussion of the fundamental relationships affecting engine operation, we identify a few key operating parameters that we expect to be closely related to fuel consumption as shown in Table 3.

**Table 3 Summary of Engine Parameters Related to Physics of Engine Operation**

| Physical Parameter | Symbol | Common Grouping |
|---|---|---|
| Compressor Discharge Pressure | $P_3$ | P3/P2 |
| Combustor Discharge Temperature | $T_4$ | T4/T2 |
| Engine Weight | $W_{eng}$ | Power/Weight |
| Engine Volume | $V_{eng}$ | Specific Power |
| Engine Airflow | $M_{eng}$ | Specific Power (SHP/$M_{eng}$) |

### 6.1.3 Estimation of Operating Cost Associated with Fuel ConsumptionConsiderations

The discussion of the physics of helicopter flight and gas turbine engine operation provide some direct insights regarding the operating cost associated with fuel consumption. At the highest level, the fuel cost is simply the required fuel multiplied by the cost per unit of providing that fuel to the aircraft. Note that the cost of providing fuel to the aircraft, often referred to as the cost of fuel "in the wing" can be significantly higher than the cost to purchase fuel on the world market or even at a local pump. For example, refueling a helicopter consumes resources in addition to the fuel itself. The helicopter must taxi to an appropriate refueling location (consuming time and fuel to do so), the pilots must wait for the aircraft to be refueled, and the aircraft must be removed from revenue-generating service during that time. All of these represent opportunities costs and must be added to the price of fuel at the pump. In addition, depending on the operating environment, there may be considerable costs associated with getting fuel to an appropriate pump. As an example, consider a helicopter operator providing offshore oil support by transferring crews to oil platforms. If the helicopter has to refuel at the oil platform, then fuel must be transported to the oil platform via ship or some other means, again requiring additional time and resources to provide fuel to the helicopter. An example from the military arena occurs where the cost of getting fuel to the appropriate location in a battle environment can be orders of magnitude higher than the unit cost on the world market.

Because of the huge range of possible cost per unit of fuel provided, the fuel costs can span a large range of the proportion of total costs. Because of the difficulty in modeling fuel costs, and since this model will be tailored towards comparisons, the cost per unit of fuel will be an assumed input. With this assumption in mind, the operating cost associated with fuel consumption is the product of the assumed cost per unit of fuel and the required fuel flow rate to the engine. In turn, the required fuel flow rate is a function of the power required by the helicopter and the overall fuel conversion efficiency of the engine.

## 6.2 First Principles Approach for Maintenance Cost

Maintenance cost tends to be the operating cost element that is the most difficult to predict{{42 Ausrotas,Raymond A. 1974}}. In general, helicopters have significantly higher maintenance costs relative to total operating costs when compared to fixed-wing aircraft. Many suggest that this difference can be largely attributed to the fact that helicopters are typically used for short-haul missions when compared to fixed-wing missions(Ausrotas, Hsin and Taneja 123). Another factor contributing to the relatively high maintenance costs are the additional moving components involved in the transmission, propulsion and drive system. Rather than depend on speculation and opinion, the purpose of this section is to investigate the first principles that drive maintenance cost. These principles will then help guide the development and construction of the maintenance related operating cost model.

Historically, maintenance costs have been forecast by grouping shop visits into various categories, and then using an average cost per shop visit multiplied by a forecast shop visit rate to get an estimated cost. The visit rates could be measured in flying hours, flying cycles, or some combination of the two. If the utilization and operating patterns of a particular airline were known as inputs, the maintenance costs could be estimated per unit of time (quarter, year, etc){{70 DAY, M. J. 1979}}. This process however, does not lend itself well to predicting costs for new designs, due to the heavy reliance on historical shop cost and shop visit rate data.

An alternative approach is to start from the bottom up, meaning to start with the lives of individual components and parts and build up to the whole system level. This process has been used by major engine manufacturer, Rolls-Royce, since the early 1970s(DAY and STAHR 45-52). Using this method, a material cost per flight hour (or cycle) can be calculated by simply dividing the price of the part by the expected life. If the part prices are taken as a given, then the material cost estimate is as accurate as the part life estimate(DAY and STAHR 45-52). Methods for estimating part lives have continued to improve through advances in modeling, component test, data analysis, and statistical and simulation tools enabled by computational advancements. These tools can be used in combination to develop Weibull distributions describing the life of each engine part in question. Again, this process does not lend itself well to predicting costs for new designs because it requires detailed life estimates for individual parts, which are not available early in the design phase.

As discussed in Chapter 3, during the preliminary aircraft design process, the requirements for maintenance must be considered. While efforts should be made to reduce the amount of maintenance required, it is necessary to perform some amount of maintenance to keep aircraft in airworthy condition. A scheduled maintenance plan should be developed as early in the design process as possible. A key part of this process is the identification of key parts, components, and subsystems that have sufficient maintenance requirements to warrant treatment in a maintenance plan. This process draws largely from detailed part life calculations and past experience at the manufacturer.

One of the major drivers for a scheduled maintenance plan is the existence of parts on the aircraft that have limited lives, known as life limited parts (LLPs). Many of the parts, components and subsystems throughout a helicopter are exposed to forces caused by vibration generated from the rotor or other rotating components. The alternating stresses experienced by such components lead to fatigue, which typically limits the life of the part by its material fatigue life. The fatigue life is the number of alternating stress cycles that the part can withstand prior to failure, at a given stress level. Thus, the magnitude of the alternating stress must be measured or calculated based on structural and dynamic analysis of the helicopter. The part life for the given stress levels, the fatigue life, can be calculated from material properties as the number of cycles the part can withstand. Since the frequency of the alternating stress is typically known or can be measured, the fatigue life can be converted from units of cycles to units of hours. The fatigue life of the various components lead directly to the life limited part (LLP) limits. Closely related to fatigue life is the endurance limit, which is the maximum value of alternating stress to which a material can be subjected for an infinite number of cycles without failure(United States. Army Materiel Command ). Designing parts and components to operate at stresses lower than their endurance limit reduces the number of life limited parts on the aircraft and in theory leads to lower maintenance requirements. This is not always feasible given the other constraints and metrics involved in optimizing the engine performance.

When a given part or component is designed with a finite life, the part's exposure time to the assumed failure must be limited. The exposure time is a major driver in determining part life (reliability). By decreasing the number of alternating stress cycles to which the part is exposed (the exposure time), the probability of failure is reduced. In the case of parts with well defined fatigue lives, part life limits are used to limit the exposure of the part and hence the name *life limited part*. As such a part is used in operation, its life is "consumed" until it is removed and either overhauled, or discarded. For most parts that are given life limits, it is difficult (or impossible) to detect an impending failure and a failure of the part in operation could jeopardize safety.

In contrast, if the failure mode is such that a particular inspection could detect a failure or impending failure, then periodic inspections can be imposed to ensure the safe operation of the part or component while avoiding a major redesign. It is important to note that these inspections are established to confirm if a certain failure has occurred or not, and hence represent a failure-finding task only. They do not provide any maintenance function(Hessburg ). This is inherently different from the life limited part replacement requirements in which a particular part must be replaced after so many cycles, hours, or calendar days. Such activities constitute a maintenance action and are handled differently from inspection requirements. It is clearly desirable to minimize, or completely eliminate the need for any required inspections. Such inspections adversely affect maintenance programs and aircraft availability. Operators and maintenance experts frequently consider such inspections to be the result of poor design(Hessburg ).

Regardless of the technical drivers for the maintenance plan, adhering to the required plan consumes a variety or resources including labor, material (parts) and requires space, such as maintenance hanger, tooling, and trained technicians. The cost of performing maintenance is dependent on both the frequency with which maintenance must be performed and the total resources consumed (cost) per maintenance event. As such, maintenance costs could be high due to frequent yet inexpensive maintenance events or infrequent maintenance events which require significant resources for each event. Based on this characteristic, Ausrotas et. al., at the MIT Flight Transportation Laboratory proposed an expected correlation between the cost to perform scheduled maintenance and the time between maintenance events in the form:

$$\text{Direct Scheduled Maintenance Cost} = k_1 + k_2/\text{TBO}$$

**Equation 37**

Where $k_1$ is a fixed cost, such as a periodic maintenance check or inspection, $k_2$ captures the cost per maintenance action, and TBO represents the Time Between Overhaul, which is a term widely used in the industry (Ausrotas, Hsin and Taneja 123). Thus, the ratio in the second term captures the balance between frequency of maintenance, TBO, and the cost per maintenance action, $k_2$. A high cost per maintenance action combined with a high TBO (low frequency) or a low cost per maintenance action combined with a low TBO (high frequency) may result in the same direct scheduled maintenance cost. The authors point out that this type of relationship is expected for *scheduled* maintenance, which highlights the importance to distinguish between two categories of maintenance costs.

Scheduled maintenance is based on estimates of the lives of the parts or systems and generated by engineering estimates provided by the manufacturer. As discussed in Section 2.4, the scheduled maintenance actions may be recommended by the manufacturer or may be required by a government regulatory agency such as the FAA. The maintenance action could consume only labor, such as a required inspection or labor and materials such as the replacement of a part with limited life, as described above. The time between overhaul (TBO) is specified by the manufacturer and may be in the form of calendar time, such as annual inspections, operating time in hours, operating cycles, or some combination. In any case, scheduled maintenance is something that the helicopter operator can predict, plan for, and schedule.

Historically, the split between scheduled maintenance and unscheduled maintenance has been approximately fifty-fifty. Although unscheduled maintenance is by definition difficult to predict or plan for, it is reasonable to expect that the total direct maintenance (scheduled and unscheduled) should follow a relationship of the form presented by Ausrotas et. al. in Equation 37 above. While the total

maintenance required to keep a helicopter in operation is frequently separated into maintenance on the airframe, avionics, and engine, the functional form of this relationship is expected to hold for each of these subsets individually as well as for the sum (i.e. for the complete aircraft).

The constant in the second term, $k_2$, will be affected by the cost of materials and the cost of labor to perform the particular maintenance event. It may be reasonable to assume that the cost of material may be proportional to the initial cost to purchase the part or system.

Note that the TBO represents the maximum time between overhaul, and to accommodate other operating logistics throughout the fleet, an operator may choose to perform maintenance actions sooner than the TBO. Along these lines, the maintenance philosophy of a particular operator can have a significant effect on the maintenance cost. In general, the amount of resources spent on maintenance actions will directly impact the reliability of the operator's fleet. Specifically, an operator could spend more on maintenance in order to achieve higher reliability in the hope that the higher reliability will allow the operator to be able to generate greater revenue. This means that two different operators with identical fleets, performing identical missions, may still have greatly different maintenance costs due to differing maintenance philosophies stemming from differences in the value they place on reliability.

In addition to the variation associated with operators choice in when to perform overhauls or replace parts prior to their certified TBO, the fact that many components each have different life limits as discussed in Section 2.4.1 also presents a modeling challenge. As a result, the value of TBO used in the above equation can be difficult to define or calculate. An example of the life limits for LLPs and the TBO for a modern production helicopter (MD500E) is shown in Appendix C.

Regarding the maintenance philosophy, there is a trend towards outsourcing more and more of the required maintenance actions to third-party maintenance providers via contractual arrangements. Such arrangements reduce the capital expenditures for an operator while enabling them to maintain their fleet. The type, variety, and potential complexity of such contracts are vast. Operators could pay for maintenance items to be completed as they are required, or they could pay a fixed "per hour" price for the contractor to provide varying levels of service coverage. Such contracts can be made between the operator and the aircraft manufacturer, engine manufacturer, a third-party provider, or some combination of the three. While the structure and details of such contracts are too complex to model for the whole industry, many experts feel that the use of such contracts increases the maintenance related DOC incurred by many operators, because of the "risk premium" paid for *per hour* contracts. These contracts enable operators to predict their future cash flow required to cover maintenance costs and also reduce the volatility or variation in maintenance related expenses from period to period. Both of these benefits are valuable to operators and hence the contractors are able to capture that value by charging some premium for the services.

In addition to the cost directly associated with the consumption of resources to perform maintenance, most maintenance requirements have substantial secondary effects. For example, if you can reduce line maintenance required by one dollar per flight hour, this will likely reduce the total operating cost of the helicopter by more than one dollar per flight hour(Asher ). The "primary" effect of reducing the maintenance cost per hour is an equal reduction in total operating cost per hour. However, the important characteristic to observe is the *secondary* effect, caused by increased utilization. A reduction in the amount of time required to perform maintenance means that the aircraft will be available to perform revenue-generating missions for a larger percentage of time. At typical levels of utilization, this

"secondary" effect is very significant. For example, a study that analyzed data based on a military operation in Algeria using H-21 helicopters, showed that the ratio between this primary and secondary effect was about 2.5(Asher ). In this example, this means that each dollar per hour of maintenance results in an additional (secondary) cost of 2.5 dollars per flight hour due to the lower utilization(Asher ). Thus, a one dollar per hour reduction in maintenance cost could lead to a 3.5 dollar per hour reduction in total operating cost(Asher ). While the exact details of this data and analysis may not relate directly to commercial helicopter operation, the example illustrates the important point. Specifically, commercial operators may incur significant opportunity costs due to lost revenue while aircraft are out of service for maintenance.

Another example of the secondary effects associated with maintenance actions involves the interaction between design parameters and maintenance limits. We have already discussed the fact that frequently parts are replaced before they reach their life limit due to interactions with other components and constraints related to when it is "convenient" to perform such maintenance for a particular operator. As a result, there will inevitably be some residual part life that is "wasted" due to mismatching between component lives as described in Section 2.4.1. There is an additional related nuance that arises due to the dependencies between parts arising from higher system level interactions. This concept is best illustrated with a hypothetical example related to engine maintenance. Let us assume that a design engineer is working on a project to propose an increase in the life limit for a compressor component. Assume that a thorough (and accurate) analysis has been completed, and the increase in part life is justified from a safety and structural perspective. Will implementing the project to increase the life of the component decrease the operating cost for the aircraft? Not necessarily. For example, implementing this life extension may have an adverse effect on the efficiency of the compressor. As a result, the engine would require more fuel to produce the same amount of power, thereby increasing the DOC related to fuel consumption. In addition, this may increase the temperatures experienced by the turbine, thereby reducing the life of the turbine components. Thus, in this example, an increase in compressor life to reduce the maintenance cost associated with the compressor, may result in an increase in maintenance cost associated with the turbine, and an increase in fuel consumption leading to an overall increase in operating costs(DAY and STAHR 45-52). Clearly the details of the design and operation need to be closely evaluated to determine the net effect of such a change. However, this example illustrates the type of system-level interactions that must be considered.

Since the focus of this study is to relate operating costs to design parameters, we will focus on relating the parameters summarized in Section 3.2 to maintenance costs when we construct the model in Chapter 7. In doing so, it is useful to consider some general trends in rotorcraft performance that have reduced maintenance costs over the last thirty years. These factors help provide some guidance when trying to identify explanations for differences in maintenance cost for existing models and are summarized below(Ausrotas, Hsin and Taneja 123):
- No lubrication requirements in main and tail rotors
    - Main rotor incorporating elastomeric bearings
    - Tail rotor using graphite composite beam with sufficient flexibility to allow pitch changes without joints
    - Hingeless and ultimately bearingless rotor system
- Modular main transmission leading to lighter design
- Transmission and rotor design to separate thrust load (MD Helicopters)
- Tail gear box that is grease packed and sealed for life
- Intermediate gear box that is grease packed and sealed for life

- Tail rotor drive system couplings that require no lubrications
- (Nickel) coated blade leading edges to reduce abrasion
- (Titanium) coated blade leading edges to reduce corrosion
- Vibration absorbers to reduce vibration transmitted throughout airframe
  - Bifilar (Sikorsky)
  - Main rotor suspension system (Bell)
- Increased use of titanium and composites

During construction of the economic model in Chapter 7, we relate some of the rotorcraft design attributes discussed in Section 3.2, to the improvements in designs that have reduced maintenance requirements listed above. To this end, we conducted a thorough review of the design attributes discussed in Section 3.2 and identified those with the strongest links to maintenance costs based on first principles. The major drivers identified are shown in Figure 6 with the various attributes in order of increasing technology level.
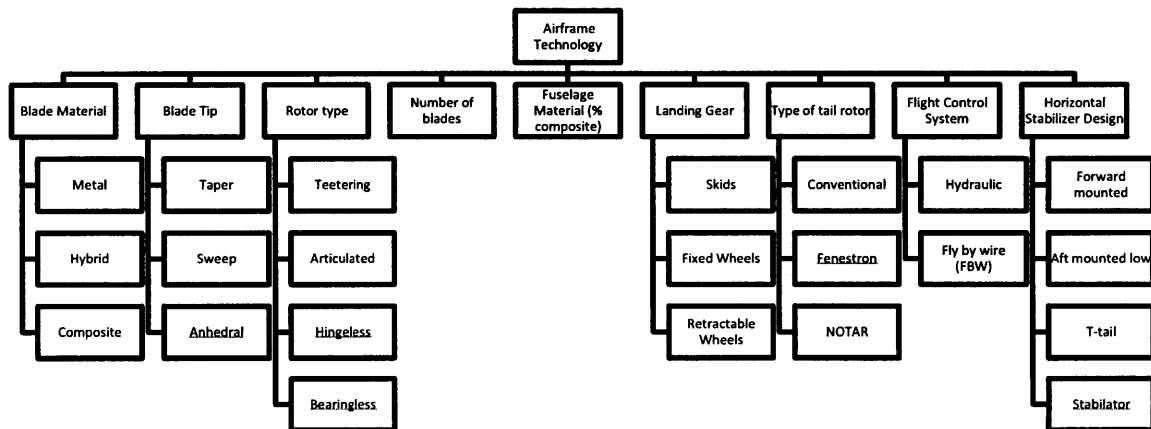


**Figure 6 Rotorcraft Design Attributes Potentially Affecting Maintenance DOC**

For example, the four main rotor types as described in Section 3.2 may have a significant effect on maintenance cost. Specifically, we would expect the bearingless design, which is the most technologically advanced, to have fewer maintenance requirements than the articulated design because the bearingless design eliminates the need for two hinges and a feathering bearing. Similarly, in the case of landing gear, we expect retractable wheels to require maintenance of the associated mechanism that would not be present in the case of a rotorcraft with skids. Thus, we will keep these attributes in mind when we construct the model in Chapter 7.

While the previous discussion focuses on design parameters associated with the aircraft only (excluding the engine), we can apply the same reasoning and approach to link engine design attributes with the maintenance related considerations discussed in this section. Specifically, Figure 7 shows a diagram of the engine design decisions that may have an impact on maintenance DOC. The design attributes in this figure are identified and explained in Section 3.3.
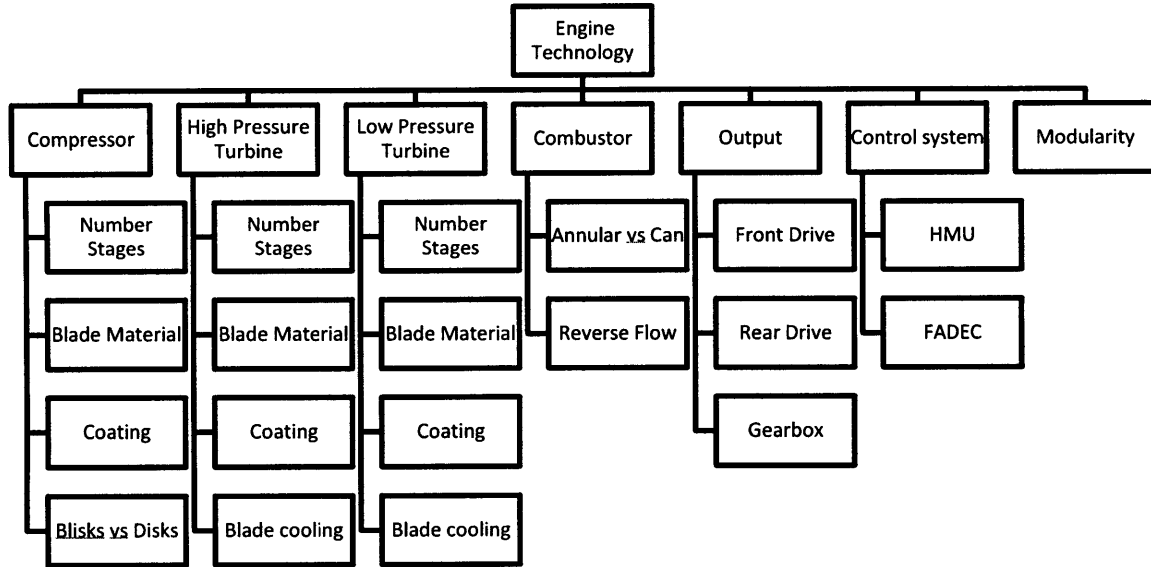


**Figure 7 Engine Design Attributes Potentially Affecting Maintenance DOC**

Some of the engine design considerations shown in Figure 7 have a more direct impact on maintenance DOC than others. For example, under the subset of types of output, it is not clear whether a front drive shaft versus a rear drive would impact engine maintenance costs. However, it seems likely that the inclusion of an engine reduction gearbox would affect maintenance costs due to the additional mechanical components and gear mesh involved. The potential influence of many of these attributes is not as clear as those depicted in Figure 6 for rotorcraft design. In addition, the data describing some of these engine design parameters for existing engines is not always widely available. We will return to this fact in Section 7.2, when we discuss the criteria for including potential explanatory variables in the model. Nonetheless, this discussion identifies those parameters that may have some influence based on first principles.

Aside from the design parameters, it is still helpful to keep some of the operational drivers for maintenance related DOC in mind as we proceed. A summary of the *non-design* variables influencing maintenance costs are is given below(Hessburg ):

- Flight operations
  - Ambient environmental conditions
  - Sand, water, extreme heat, etc.
- Fleet characteristics (not including aircraft design)
  - Aircraft age
  - Fleet size and composition (degree of commonality)
- Maintenance practices
  - Third-party versus in-house
  - Power by the hour contracts

- o Philosophy regarding Minimum Equipment List (MEL) policy
- o Incorporation of service bulletins
- Accounting practices
  - o Tax rates, depreciation, insurance, spares, labor
  - o Warranty pursuits
  - o Cost allocation and overhead

In this section, we identified some of the key drivers affecting rotorcraft maintenance costs. While this subset of DOC typically are the most difficult to predict and have the greatest uncertainty, a strong foundation on the key drivers will help us make informed choices while constructing the model.


## 6.3 First Principles Approach for Crew Cost

The crew costs consist of the costs of employing pilots, technicians and support personnel. These costs are usually estimated on a fixed annual basis, since it is commonly assumed that they will be employed by the operator. They are considered fixed since they do not vary in direct proportion to the number of flying hours. However, they are still direct since if the operator decided to stop flying entirely, these costs would not be incurred. It is important to highlight the fact that this category covers costs that are directly associated with the operation of the aircraft. They do not include salaries paid to management personnel, scheduling, facility housekeeping, etc., which are indirect costs and are typically lumped into a "General and Administrative" category under indirect costs.

Beginning with the pilots, it is conceivable that the salary paid to pilots would be proportional to their experience (cumulative flight hours) and some metric indicative of the "complexity" of the aircraft in which they logged each hour of experience. While these are both descriptors related to the pilot, we need to relate the pilot cost to the helicopter design under consideration. Specifically, we would expect that on average, a more complex helicopter design would require a more experienced and skilled pilot, who could command a higher salary. So as a first pass, we propose relating the salary paid per pilot to some metric of complexity of the helicopter. This complexity measure could be some combination of aircraft weight, aircraft acquisition cost, or aircraft age. In general, we expect to see increasing pilot salary with increasing weight, cost and decreasing age. The expected trends in pilot salaries with these variables may be offset by the fact that more complex aircraft tend to require more pilots than simpler aircraft. In the case of rotorcraft, this typically means that simpler aircraft require only one pilot, while more complex aircraft require two. As such, it may turn out that all pilots are paid about the same annual salary, since they have the assistance of another pilot for more complex aircraft.

The use of one or two pilots clearly has a direct impact on the total pilot costs for operating an aircraft since the two cases will likely differ by nearly a factor of two. As a result, we expect the direct annual fixed costs for pilots to be directly proportional to the number of pilots, which in turn is influenced by the size and complexity of the aircraft. In addition, we may look for trends in the individual salary per pilot with these same two variables, which would compound the increasing crew cost with aircraft size and complexity. The simple equation to calculate crew cost once these factors are known is given by:

$$Crew\ Cost\ (\$/FH) = \frac{N_p S}{U}$$

**Equation 38**

Where $N_p$ = the number of pilots/aircraft
S = Pilot Salary ($/yr)

The crew costs for technicians and support personnel are more difficult to estimate from first principles, but again we may expect them to increase with increasing aircraft weight and complexity. In addition, they may be affected by the total size of the operator's fleet or the total number of flying hours, since we may expect some economies of scale in which technicians and support personnel could work on multiple aircraft. In addition, if the flight operations are geographically spread over large areas, then we may expect more support personnel than if the operations were concentrated in a single location.

While the application of first principles allows us to highlight a few expected relationships between crew costs and aircraft design parameters, it is worth highlighting a few additional challenges associated with estimating these costs. First, these are fixed annual costs, and hence to be comparable to the variable costs, they must be averaged over the total flying hours of the operator. As a result, we expect that they may be highly sensitive to the utilization or number of hours flown per year. Both the utilization per aircraft and the operator's fleet size (or the total flying hours for the operator) may be important due to the economies of scale mentioned above. In addition, the number of flying hours performed by a given pilot is subject to certain limitations related to the total number of hours the pilot can log per year, month, week, 24-hour period, etc. Thus, the number of pilots required per aircraft will be a function of both the total utilization and the scheduling pattern or operating characteristics. For example, an aircraft used 2 hours per day for 250 days of the year for a total of 500 hrs per year may only require one set of pilots. However, operating that same aircraft 500 hours per year providing 24-hr fire-fighting or search and rescue support may require two or more sets of pilots. Thus, we see that the crew cost per hour may be a function of the fixed cost, utilization, fleet size, while the fixed cost itself is a function of utilization, fleet size, operating characteristics, etc. These variables are shown in the diagram given in Figure 8.
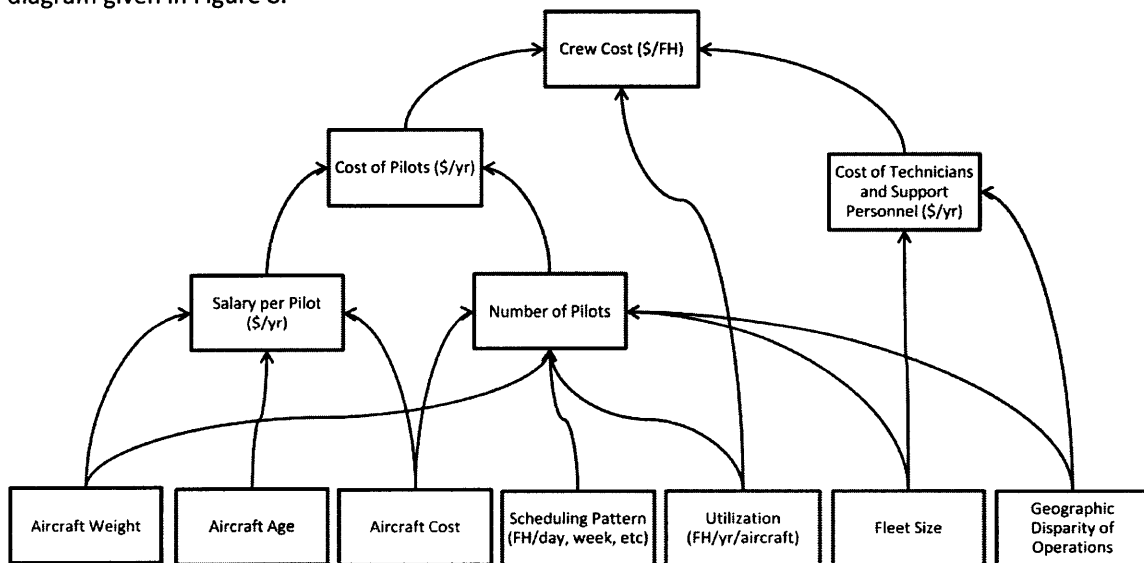


**Figure 8 Potential Factors Affecting Crew Cost**

Note that of all the potential variables included in Figure 8, only one is a direct design attribute of the aircraft. The remaining factors stem from the operating characteristics of the particular rotorcraft operator. In addition to the aircraft weight, the number of pilots may be considered an indirect design parameter, since the number of pilots required per aircraft is a function of the aircraft design and

capability as well as the operators' procedures. For example, a particular helicopter model may require two pilots to be operated safely in accordance with the appropriate regulatory agency. In this regard, the number of pilots required per aircraft is a design variable. However, a given operator may have its own operating procedures that are more stringent than the regulations. As an example, a helicopter may be certified for single pilot operation, but a given operator may require two pilots in operation to improve safety by reducing pilot workload, and providing a "backup" pilot for redundancy.

This discussion shows that we may expect crew costs to be dominated by operating conditions which vary from helicopter operator to operator. Nonetheless, we expect that the weight of the aircraft and the number of pilots required per aircraft may be significant design decisions affecting operating cost.

## 6.4 First Principles Approach for Insurance Cost

The cost of insurance related to helicopter operation can be split into liability insurance and hull insurance. Liability insurance is likely to be a constant annual cost and hence not dependent on any of the aircraft design parameters. Hull insurance can be calculated directly from the insurance rate and the acquisition cost of the aircraft. The insurance rate varies from about one percent up to ten percent depending on the helicopter model. The insurance rate is based on the accident rate for a given model and the cost per claim. In general, we may expect smaller, less complex helicopters to have a higher insurance rate, so we will look for this trend in the data. For comparative purposes, it may be useful to assume a fixed insurance rate. Once the insurance rate is established, the hull insurance cost is directly proportional to the insurance rate and the acquisition cost.

## 6.5 Conclusions from Physics and First Principle Considerations

By reviewing the physics of helicopter flight and engine operation, we identified several factors that we expect will influence the fuel consumption and associated cost for new helicopter designs as summarized in Figure 5, Table 2 and Table 3. Next, by applying first principles and critically reviewing the costs associated with maintenance actions, we identified a few factors that are likely to be strong drivers. The key potential drivers for airframe maintenance DOC and engine maintenance DOC are summarized in Figure 6 and Figure 7 respectively. In Figure 8 we summarize some of the key variables likely to be related to DOC associated with crew costs. This discussion, combined with the discussion from Chapter 3, provides some critical insights and considerations guiding the exploration of collected data and the structural foundation for building the economic model in subsequent sections.

# 7 Construction of Economic Model

In the previous chapter, we identified a number of key design parameters that may be expected to influence helicopter operating costs. Previous economic modeling work, such that published by Stoessel et. al. and Ausrotas et. al., described in Chapter 4, show that the number of flying hours is a key *operating parameter* affecting DOC for a given period (month, quarter, year, etc.). The focus of this thesis is on relating rotorcraft *design parameters* to operating costs. As a result, in an attempt to remove the influence of the number of flying hours on operating costs, the response for the modeling work developed here is in units of cost per flight hour ($/FH).

The purpose of this chapter is to draw on the discussion up to this point to construct a meaningful, robust model to predict operating costs. We strive for a simple model that is able to predict operating costs for new rotorcraft early in the design phase. To that end, we will begin by constructing the simplest possible model to predict total direct operating costs (TDOC) which requires only one explanatory variable, the maximum takeoff gross weight (MTOGW). Using this model as a baseline, we will then create sub-models for the first three of the five major subsets of direct operating costs as shown in Figure 9.

| $Y = f(X)$ | $Y$ = Direct Operating Cost (DOC) ($/FH) |
|---|---|
| $Y_1 = f_1(X_1,X_2,...,X_N)$ | $Y_1$ = Fuel Related DOC ($/FH) |
| $Y_2 = f_2(X_1,X_2,...,X_N)$ | $Y_2$ = Aircraft Maintenance Related DOC ($/FH) |
| $Y_3 = f_3(X_1,X_2,...,X_N)$ | $Y_3$ = Engine Maintenance Related DOC ($/FH) |
| $Y_4 = f_4(X_1,X_2,...,X_N)$ | $Y_4$ = Crew Related DOC ($/FH) |
| $Y_5 = f_5(X_1,X_2,...,X_N)$ | $Y_5$ = Insurance Related DOC ($/FH) |

**Figure 9 Description of Five Sub Models**

For each sub-model, we will start with a bivariate model that provides the greatest prediction power with only a single explanatory variable. Then, we will gradually add complexity to the model by adding explanatory variables whose consideration are warranted based on the selection criteria discussed in Section 7.2.

## 7.1 Exploration of Data and Expected Relationships from Physics and First Principles

In order to build our operating cost model we used the Conklin & de Decker Associates database for the response data. The Conklin database includes 77 different rotorcraft models of interest for this study. Operating cost estimates for the 77 models of interest were generated based on the following assumptions:

- 500 flight hours per year
- 10 year life
- $75/man hour for labor
- $3.00/gal fuel

- 1 flight cycle/flight hour
- 1 engine cycle/flight hour

These assumptions are reasonable and consistent with the guidelines discussed in Section 2.3. The purpose here is to identify relationships between design variables and operating cost under constant assumptions. We begin by exploring the relationship between maximum takeoff gross weight (MTOGW) and total direct operating costs as shown in the scatter plot in Figure 10.
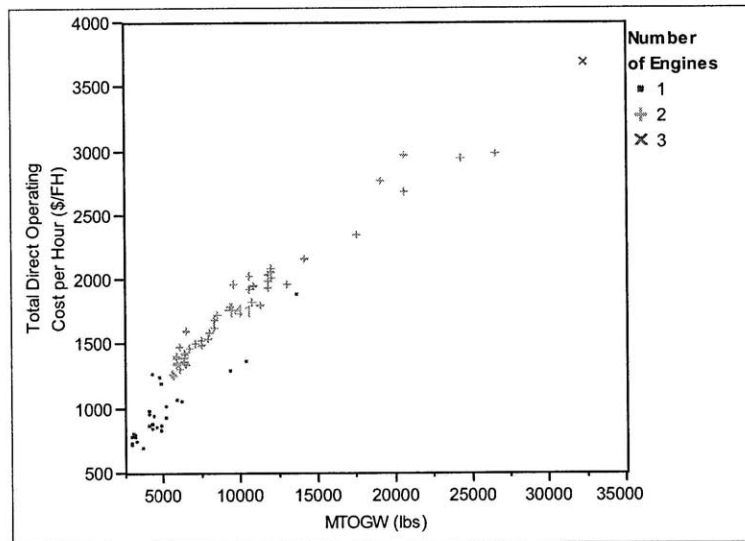


**Figure 10 Scatter Plot of Total DOC versus Gross Weight**

The three different colors and marker types illustrate the aircraft with one, two and three engines. As one would expect, there is a general trend of increasing engine count with increasing gross weight. While all of the data points indicate a strong trend with MTOGW, the data suggests that we may need to treat the aircraft in subgroups according to the number of engines. We note that there is only one model that includes three engines, and hence this represents a potential outlier at a high weight and high operating cost.

The relationship between operating cost and the number of engines can also be seen in a scatter plot of the two as shown in Figure 11.
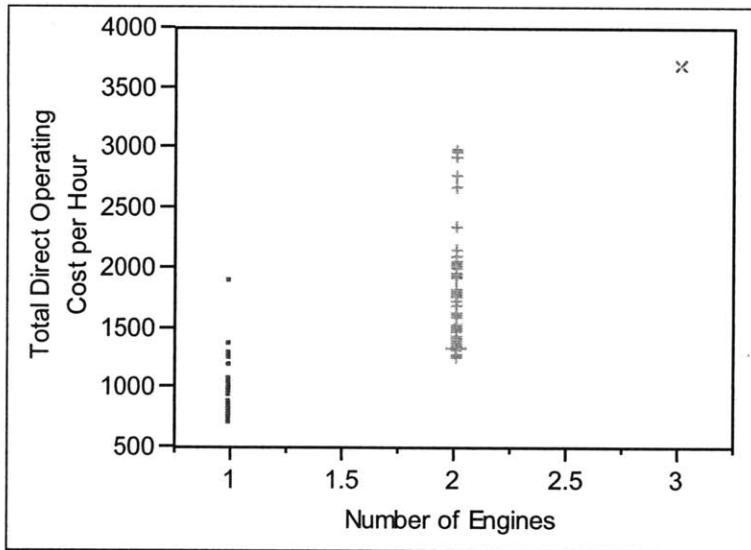
**Figure 11 Scatter Plot of Total DOC versus Number of Engines**

Comparing the TDOC for the helicopter models with a single engine (red squares) to those with two engines (green +) in Figure 11 shows that designs with two engines have higher TDOC than those with a single engine. This is consistent with the vertical displacement between designs with one versus two engines shown in Figure 11. We must use caution in drawing any conclusions regarding three-engine aircraft since we only have a single data point. There is also considerable variation within a given group.

In addition to engine weight and the number of engines, our exploration of bivariate relationships between total direct operating costs and the various potential explanatory variables included in this data set identified a general relationship between operating costs and aircraft acquisition cost as may be expected. A scatter plot showing this relationship is shown in Figure 12.
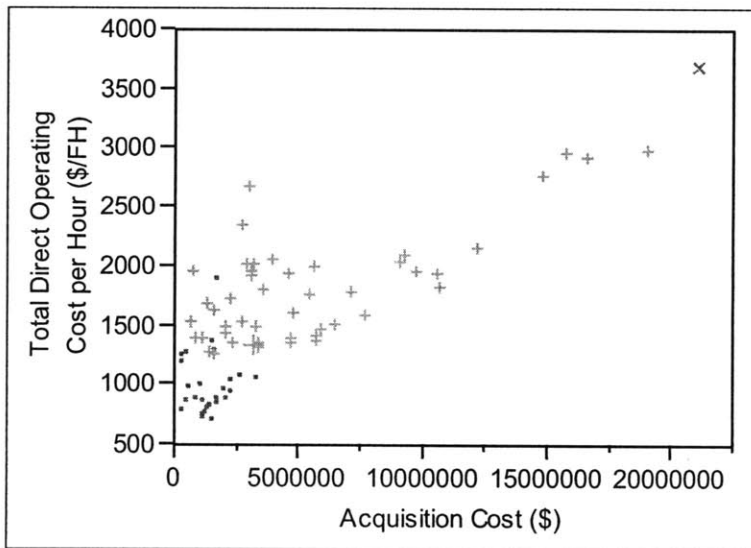


**Figure 12 Scatter Plot of Total DOC versus Aircraft Acquisition Cost**

While there is considerable scatter in this plot, there appears to be a general trend of increasing operating cost with increasing initial cost. Since the weight, number of engines and acquisition cost are inter-related we must examine more complex relationships to see if each is important.

In this section, we presented a few examples of the types of scatter plots used to explore the data set for bivariate relationships. We use such plots as a way to gain a high-level feel for the data and potential underlying correlations between variables. During this data exploration, we also create scatter plots to investigate possible relationships between the explanatory variables. This process is extremely important to check for multicollinearity before constructing a full regression model. In the case of rotorcraft design parameters, we identified and confirmed the existences of some strong correlations among potential explanatory variables. The overview of the rotorcraft conceptual design process discussed in Section 3.2 and the overview of that process shown in Figure 3, explained how such relationships between parameters are in fact used to develop new designs. For example, in the process shown in Figure 3, a designer may estimate the rotorcraft disk loading (W/A) from the relationship between disk loading and gross weight. Thus, the use of such relationships during the design of rotorcraft highlights the importance of such relationship between explanatory variables. As we develop our model we need to choose explanatory variables carefully to avoid issues of multicollinearity. Alternatively, we may be willing to tolerate multicollinearity in our model as long as we are aware of the implications of doing so, and the resulting limitations on the interpretation of the model results and coefficients.

## 7.2 Identification and Selection of Explanatory Variables for Consideration

There are many possible explanatory variables highlighted in Chapter 6 and throughout the rest of this study. Typically, some measures of the "goodness of fit" of a regression model can always be improved by adding more explanatory variables. However, the purpose of this model is to predict future operating costs, and hence the danger of overfitting the data is very important. As a result, we developed a criterion for evaluating whether a potential variable should be considered for inclusion in the model. Specifically, in addition to proving to be statistically significant at an appropriate level, any variable to be included in the model must be:

1. Logically (fundamentally) related to operating costs
2. Accurately known or measured
3. Readily available for existing designs
4. Established early in design process

Before any statistical analysis is performed, the potential explanatory variables are measured against these four criteria. Determining whether each potential variable meets these four criteria requires considerable input from relevant experts in the industry. To this end, the three primary sources to evaluate each variable in this manner were:

- Input from experts at aircraft manufacturers, engine manufacturers, operators, and industry research and consulting firms
- Previous studies and model development work and the associated discussion (see Chapter 4)
- Analysis and discussion of physics and first principles (see Chapter 6)

These three main sources were combined to determine an overall metric for each of the potential variables considered. Quality Function Deployment (QFD) was used to quantify how well each potential variable meets the four requirements for consideration listed above. The resulting QFD containing the most relevant variables is shown in Table 4 and a related Pareto plot of the "score" for each variable is shown in Figure 13.

**Table 4 QFD of Potential Explanatory Variables**

## Explanatory Variable Name

| Requirement | Importance | Max Takeoff Gross Weight (W0) | Disk Loading (W/A) | Rotor Type | Landing Gear Type | Power Loading (W/P) | Rotor Area (A) | Tail Rotor Type | Number of Engines | Installed Power (P) | Number of Blades | Solidity | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Logically (fundamentally) related to DOC | 9 | H | H | H | H | H | H | M | M | M | M | M | 648 |
| Accurately known | 6 | H | H | H | H | M | M | H | M | M | M | M | 396 |
| Readily available for existing designs | 6 | H | H | H | H | H | H | H | H | H | H | H | 648 |
| Established early in design process | 3 | H | H | L | L | H | M | L | H | M | M | M | 156 |
| | | | | | | | | | | | | | |
| Total | | 216 | 216 | 192 | 192 | 180 | 162 | 138 | 126 | 108 | 108 | 108 | |
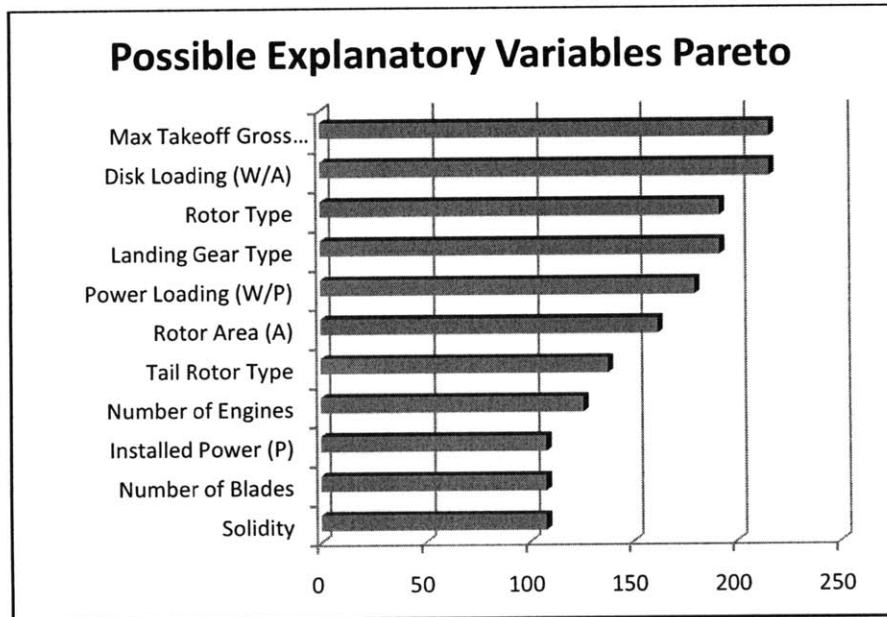


**Figure 13 Pareto of Possible Explanatory Variables**

This discussion identified the Maximum Takeoff Gross Weight as a key explanatory variable. This is fortunate, since gross weight was also the variable most strongly correlated with operating cost as identified during the data exploration in Section 7.1. With this discussion of the criteria for including explanatory variables completed in Chapter 6, combined with the quantification of such merits in this section, we are now ready to begin constructing our economic model and sub models. We begin with a simple bivariate model and add complexity as appropriate.

## 7.3 Construction of Overall DOC Model

For the final construction each of the multiple regression sub-models, we randomly excluded about 20% of the data (15 models) to be used for the test data set. In addition to exploring the relationships between variables as in the scatter plots in Section 7.1, we considered various transformations of both the explanatory and response variables. Figure 14 shows a plot of Total DOC versus Gross Weight with ordinary least squares regression fits under three data transformations: the linear case (no transform), taking the square root of the explanatory variable (weight), and taking the log of the explanatory variable (weight).
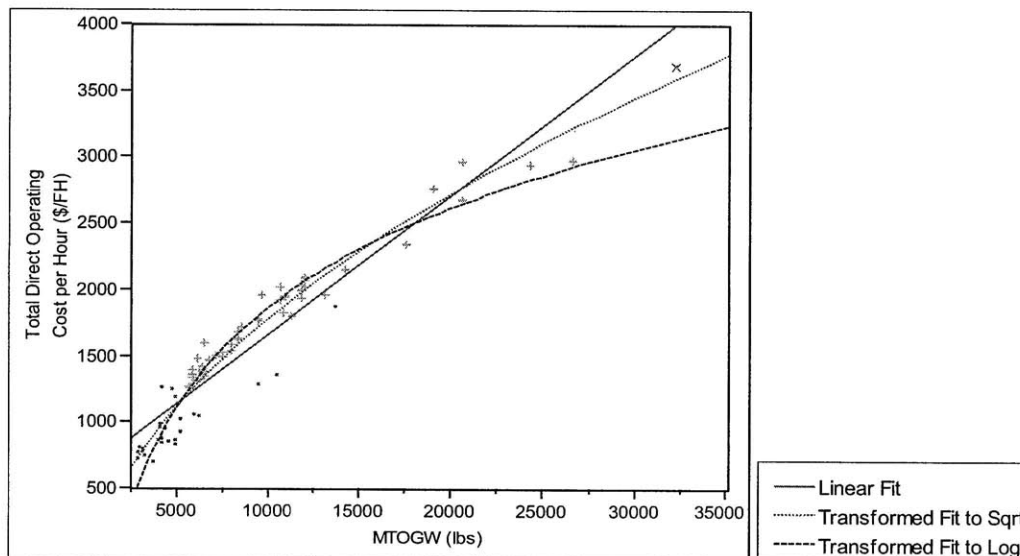


**Figure 14 TDOC versus Gross Weight**

Graphically Figure 14 suggests that transforming the explanatory variable by taking the square root of the gross weight seems to best fit the data. This observation is confirmed by the reviewing the measures of goodness of fit from the regression output. There are a handful of previous studies as well as expert opinion that suggest that the relationship between TDOC and gross weight would not quite be linear.

Thus the simplest, single regression model to predict Total DOC as a function of the square root of gross weight is shown in Figure 15.
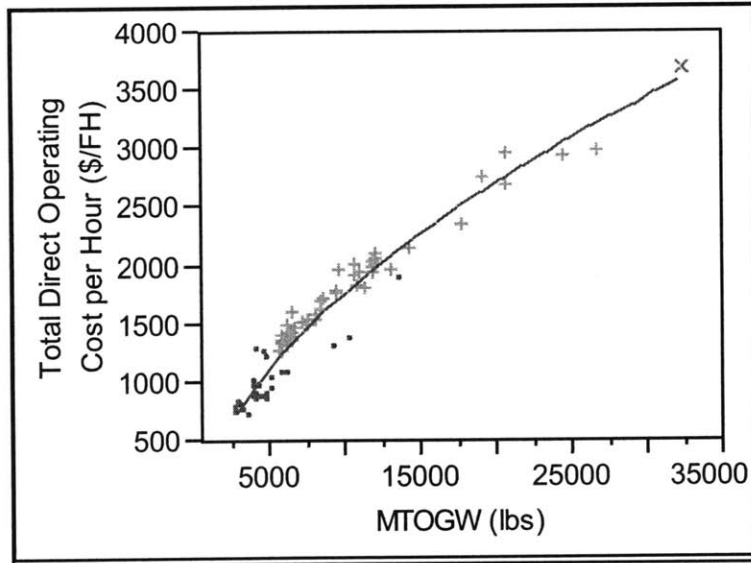
**Figure 15 Regression Model 1 for TDOC vs Gross Weight**

The model yields an R-square value of 0.931, and RMSE of 166.56, and a PRESS RMSE of 169.03. Note that the PRESS RMSE provides a measure of how well the model is expected to perform at predicting *new* observations and is described in Section 8.1. The full regression output for TDOC Model 1 is presented in Appendix D. Overall, we discover that a simple rotorcraft design variable, gross takeoff weight, can be used as a fairly good predictor of total direct operating costs. The existence of a strong relationship between TDOC and gross weight, combined the physical importance of gross weight described in Chapter 6, and the fact that it is among the first variables known in the design process make it an ideal candidate as an explanatory variable.

Using this simple model as a baseline, there are a number of ways we can attempt to develop improved models. The word "improved" can mean one of three things: Better overall fit to the dataset, finer resolution regarding detailed operating cost categories, or increased robustness. In the subsequent sections of this chapter, we will develop key sub-models in a process similar to that used here. To finish the discussion of predicting TDOC, it is important to see if any of the other potential explanatory variables discussed in Section 7.2 may be used to create a multiple regression model with improved measures of fit. In order to evaluate such variables, we created numerous scatter plots of the residuals from the model above versus the potential explanatory variables. We completed this for all the variables shown in Figure 13, as well as most of the remaining parameters that are readily available. We discovered that the number of engines is the only other variable that suggested a relationship with the residuals. As described in Chapter 6, it seems logical that a helicopter with two engines would cost more to operate than a helicopter with one engine, assuming that all else is equal.

In addition to the scatter plots of residuals versus number of engines indicating a trend, the use of the different markers and colors to represent the number of engines in each model graphically seems to suggest that there may be separate populations segmented by the number of engines. As a result, we will now explicitly add the number of engines to the multiple regression model. Specifically, a dummy variable with binary values of 1 or 0 representing a design with one engine versus more than one engine respectively is used. Note that the assignment of 1 or 0 to each group does not matter. However, to avoid confusion, we assigned models with one engine to have a dummy variable equal to 1, and those

with more than one engine to have a value equal to zero. Since we may expect the helicopters with one engine to have lower operating cost than those with multiple engines, we expect the coefficient associated with the linear term of the dummy variable to be negative.

The way we used a dummy variable is analogous to developing two separate models, one for those aircraft containing one engine and another for those with more than one. We allowed both the intercept and the slope of the relationship to be different between the two models. This is because we expect models with more engines to have higher operating costs both due to the additional engine (different intercept) as well as due to the associated increase in complexity in the airframe and drive system such as additional inputs and gearing in the transmission. The addition of the linear dummy variable term to the model allows the intercept to be different for the two groups, and the addition of the interaction term, which is the product of the dummy variable and the gross weight, allows the slope to be different. A plot of the resulting model is shown below in Figure 16 and the details of the model are presented in Appendix E.
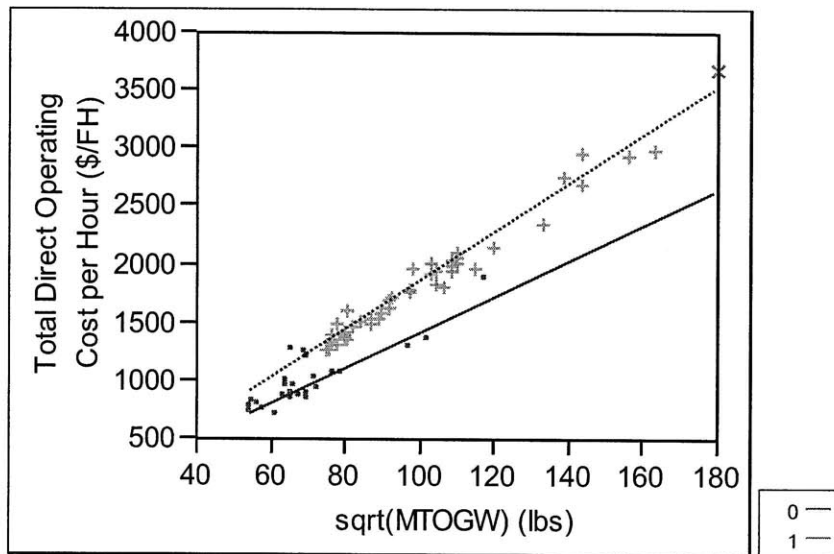


**Figure 16 TDOC Regression Model 2**

Note that here the blue line (upper) represents the aircraft having more than one engine and the red line (lower) represents models having a single engine. Also note that the horizontal axis is the square root of the MTOGW. The R-square value for this model is 0.974, the RMSE is 104.55, and the PRESS RMSE is 114.45. The overall F-statistic as well as the p-values associated with the parameter estimates suggest that it is a significant improvement over the model that does not account for the number of engines in a given aircraft. The full output shown in Appendix E including the prediction equations confirms that the coefficient associated with the linear term of the dummy variable is negative when the variable equals 1 as expected. The plots of actual by predicted and residuals by predicted suggest that there does not appear to be any relationship in the residuals. It is also important to note that the number of engines to be used for a new helicopter design typically must be determined early in the design phase since this decision affects many other factors including the transmission design and structural elements of the airframe. As a result, this parameter is usually readily available early in the design process, and may be easier to obtain than the acquisition cost discussed earlier.

After constructing this model (TDOC Model 2) we again created plots of the residuals versus additional explanatory variables. These scatter plots suggest that there are not any additional explanatory variables that could be included to improve the predictive ability of the model.

## 7.4 Construction of Fuel Related DOC Model

The relationship between fuel and lubricant DOC and the various rotorcraft design parameters are similar to those for the Total DOC model. Typically fuel and lubricant costs are lumped together. Since the lubricant is simply calculated as 3% of the fuel cost, we will develop this sub-model specifically for fuel related DOC only (excluding lubricant). Constructing the model this way makes it quicker to calculate fuel flow rates (by dividing by the fuel cost) which can be compared to advanced rotorcraft aerodynamic models and engine thermodynamic models. In practice, it is likely that the rotor power required and hence fuel flow required may be calculated using proprietary models to generate more accurate estimates of fuel flow over specific aircraft missions. The modular nature of this model makes it easy to replace any given sub-model with an input value. For example, the fuel flow required in gallons per hour could be input directly rather than relying on the fuel related DOC sub-model. Nonetheless, the model is included here for completeness, and to provide a quick estimate of operating cost breakdown during the early design process.

Similar to the case with TDOC, the gross aircraft weight shows the strongest relationship with fuel related DOC. Figure 17 below shows a plot of the simple regression model incorporating this one explanatory variable and the full regression output is shown in Appendix F.
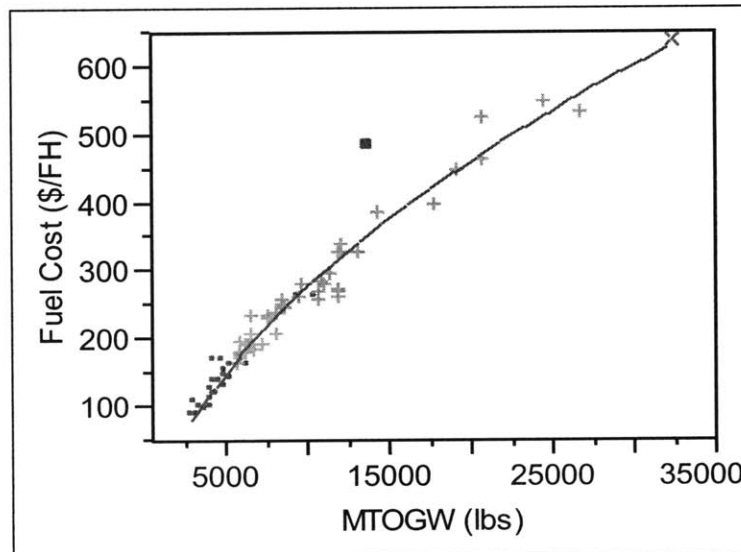


**Figure 17 Fuel Related DOC Regression Model 1**

Again, the different markers indicate the number of engines in each model. One particular model is highlighted in a red square as an outlier from the rest. Upon investigating the details of this data point, this represents a commercial version of a military helicopter. This particular version has a single engine which is relatively large (oversized) to meet the military requirements for hot and high operation and allow the aircraft to carry significant external loads. In addition to the relatively large engine size, the

engine itself has higher than average SFC. Lastly, the aircraft was last produced almost thirty years ago. All three of these factors (with the oversized nature of the engine being the most significant) combined results in a fuel consumption that is significantly higher than expected. Because the underlying cause for the high fuel consumption was identified, we felt that it would be best to exclude this data point from the sample for the purpose of this model. It is worth noting that while the point is an outlier, it does not actually have very high leverage. Thus the exclusion (or inclusion) of the model does not significantly affect the coefficients of the model. In any case, in order to avoid skewing the measures for the goodness of fit, this helicopter model was removed from the dataset. The resulting R-square, RMSE, and PRESS RMSE are 0.977, 18.27 and 18.80 respectively.

After accounting for the variation in fuel cost with gross weight, none of the remaining explanatory variables provided addition descriptive power. Specifically, scatter plots of the residuals versus each of the explanatory variables did not indicate any significant trends. In addition, there are not any significant interaction terms when using stepwise multiple regression techniques. Based on the scatter plots, if any inferences can be drawn, there may be a slight increase in fuel cost with increasing number of blades. Thus, the simplest model relating fuel cost to the square root of gross weight is the best model for predicting fuel cost.

## 7.5 Construction of Airframe Maintenance Related DOC Model

In order to compile the dataset for the airframe maintenance DOC, we removed the engine related maintenance costs from the total maintenance costs in the dataset. We began the construction of the airframe maintenance sub-model exploring the dataset creating various scatter plots. Again the gross takeoff weight has the strongest correlation with the airframe maintenance cost. The relationship between airframe maintenance DOC and gross weight is shown in Figure 18.
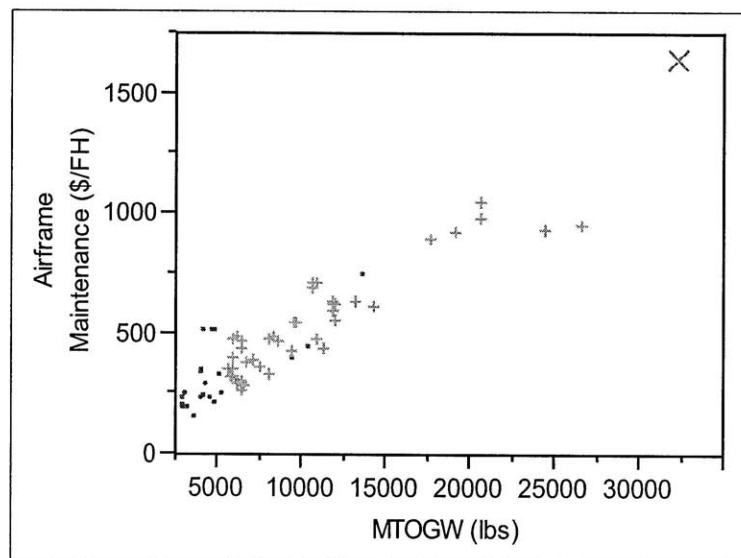


**Figure 18 Scatter Plot of Airframe Maintenance DOC versus Gross Weight**

Again the different markers indicate the different number of engines. We note that the single helicopter model in the dataset containing three engines is an outlier, and has significantly higher airframe maintenance costs than the models with only two engines. Keep in mind that the response

variable in this case, the airframe maintenance cost, does not include the engine maintenance. As a result, the higher airframe maintenance for the model with three engines is unrelated to the fact that there is 50% more engine maintenance required. We believe that the relatively higher maintenance costs for the model with three engines is a result of the additional complexity of the structure and drive system required to accommodate the third engine. For example, the main transmission has three input drives rather than the two input drives used for twin-engine models.

As the power output for new engines under development continues to increase, it is expected that the use of two engines, each generating more power, would be advantageous over the use of three engines as in this model. As a result, three reasons lead us to exclude this data point as an outlier during the construction of our model. First, we only have one observation with this configuration. Second, we do not expect that this configuration will be common in the future. Third, the point is both an outlier and has high leverage, and thus we expect that inclusion of the point would adversely affect the performance of the model in predicting future observations.

In the following construction of the model, the same 15 observations described in Section 7.3 are excluded from the training data and set aside to be used during model validation. The best model for predicting airframe maintenance DOC involves transforming the weight by taking the square root. A regression plot of the resulting model is shown in Figure 19, and the full regression output is presented in Appendix H.
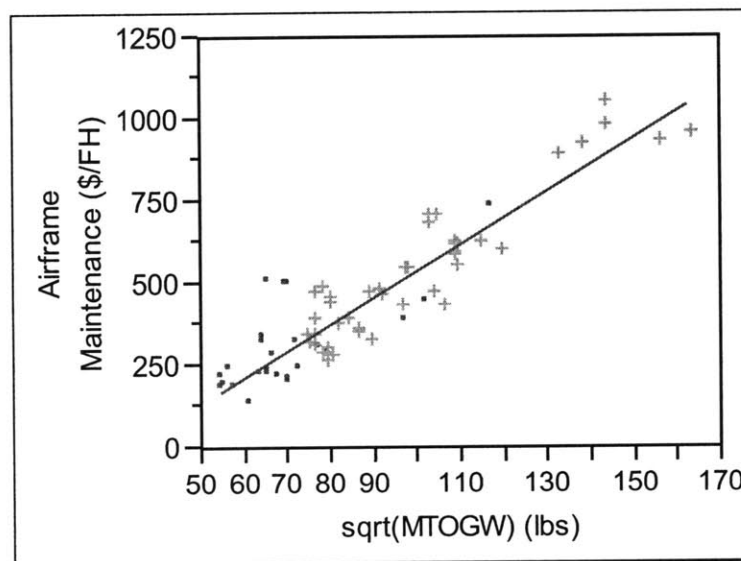


**Figure 19 Airframe Maintenance DOC Regression Model 1**

The resulting model has an R-Square value of 0.834, an RMSE of 87.742 and a PRESS RMSE of 89.568, and hence represents a reasonably good fit for a model with only a single explanatory variable. Scatter plots of the residuals versus the remaining available potential explanatory variables were explored to consider adding to the model. A few of the attribute design variables discussed in Section 7.5 suggest that they may be important parameters affecting airframe maintenance DOC. Scatter plots of these variables are shown in Appendix I. The scatter plots suggest that the following variables may require further consideration:

- Landing gear type
- Rotor hub type
- Blade material
- Tail rotor type

As discussed in Section 3.2 and Section 7.5, there are three major types of landing gear: skids, fixed wheels, and retractable wheels, given in order of increasing maintenance requirements based on first principles. In our dataset, there are three helicopter models that feature the fixed wheels as the type of landing gear. However, two of these models are minor variations of one another, and hence there are really only two major models with fixed wheels. These models are among the oldest in the dataset and there is a huge (almost three standard errors) difference in maintenance related DOC between them as shown on the scatter plot in Appendix I. Because the sample of data with fixed gear is not representative of the rest of the helicopter population, this type has been excluded from the model. Based on first principles, we would expect the maintenance related DOC of a model incorporating fixed wheels to be higher than that for a comparable model with skids, but lower than that for retractable wheels. For future aircraft designsincorporating fixed wheels, the maintenance related DOC estimate can be bound using the values for a model with skids and a model with retractable gear.

After removing the fixed wheels as a landing gear type, a pair of box plots comparing the residuals from Airframe Maintenance DOC Model 1 for the two types is shown in Figure 20.
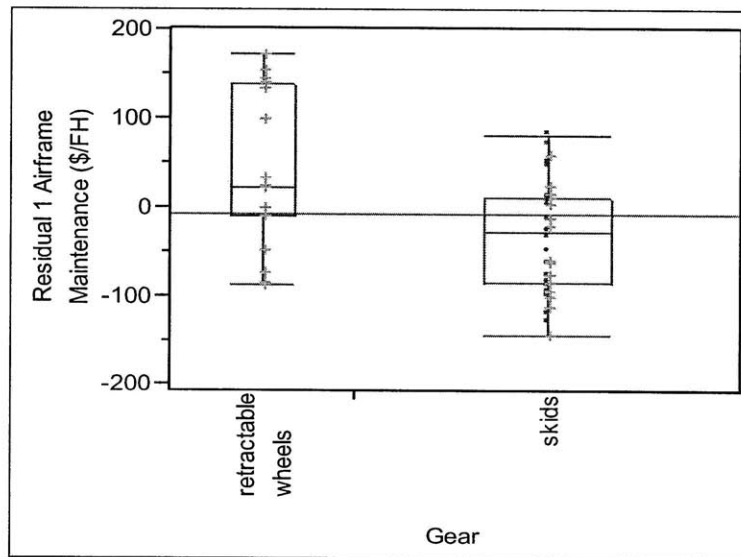


**Figure 20 Box Plots of Residuals for Airframe Maint. DOC Model 1 vs Landing Gear**

A one-way ANOVA comparing the two samples confirms that there is a statistically significant difference in the residual maintenance cost depending on the type of landing gear chosen. On average, the maintenance DOC for models with retractable wheels is about 70 ($/FH) higher than those incorporating skids at comparable gross weight. The full ANOVA output from this analysis is shown in Appendix J.

In addition to the importance of the type of landing gear, the data supports the trend related to the impact of the rotor hub technology chosen. The four rotor types described in Section 3.2 and Section

7.5 are shown in the box plot in Figure 21 and can be categorized in order of increasing maintenance requirements based on first principles as: bearingless, hingeless, teetering, articulated.
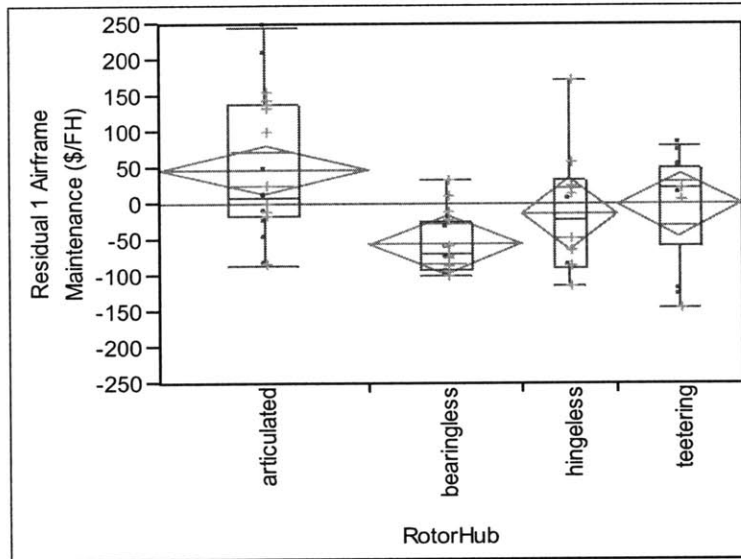


**Figure 21 Box Plots of Residuals for Airframe Maint. DOC Model 1 vs Rotor Hub**

A full one-way ANOVA supports the hypothesis that the type of rotor hub has a significant impact on airframe maintenance DOC. Based on the fit for Airframe Maintenance DOC Model 1, which is a function of only gross weight, the teetering design results in average response, the articulated hub adds an average of about 48 ($/FH) and the hingeless and rotorless designs lead to a reduction of about 13 ($/FH) and 57 ($/FH) from the teetering design respectively. A full ANOVA output is given in Appendix K.

The last attribute design element that shows a statistically significant relationship to airframe maintenance DOC is the material of the main rotor blades. This type of data is not as widely available as the other attribute data, and as a result, only about half of the models are included. Box plots illustrating the impact of this variable along with the full one-way ANOVA output is shown in Appendix L. Based on this limited dataset, the hybrid and metal blades are roughly equivalent, and the use of composite blades reduces airframe maintenance DOC by about 60 ($/FH) for the same gross weight.

Based on the analysis of the residuals from Airframe Maintenance DOC Model 1, we have good insight for constructing a refined model to take advantage of the explanatory power of the type of landing gear and type of rotor hub used for a given design. We will not include the blade material as an explanatory variable because of the limited data available. Thus, our Airframe Maintenance DOC Model 2 is a function of gross weight, landing gear type, and rotor hub type. A plot of the actual versus predicted values for this model is given in Figure 22.
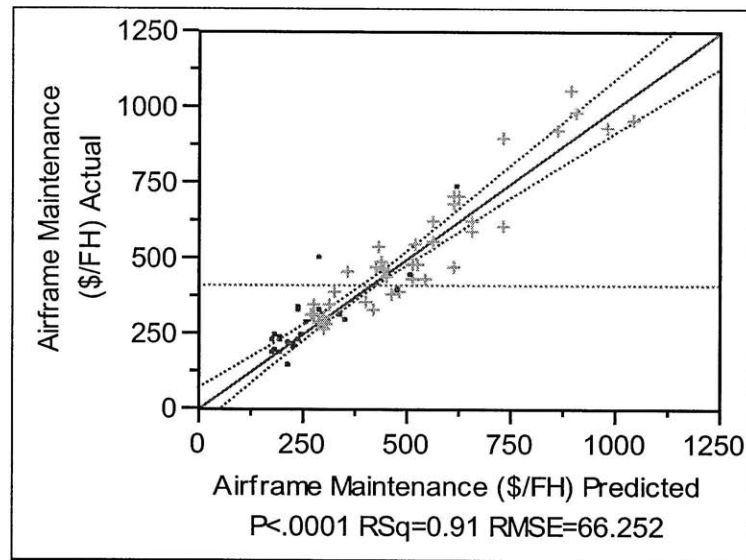
**Figure 22 Airframe Maintenance DOC Regression Model 2**

By taking advantage of the explanatory variables describing the type of landing gear and the type of rotor hub, Airframe Maintenance DOC Model 2 provides a significant improvement over the previous model, which was only a function of gross weight. The full details of Airframe Maintenance DOC Model 2 are shown in Appendix M. The attribute data describing the landing gear type was incorporated by using a dummy variable equal to 1 for models with retractable wheels, and zero otherwise (models with skids). Three dummy variables were used to capture the rotor hub type, one for teetering, hingeless and bearingless. A helicopter model with an articulated hub is depicted by setting all three of these variables to zero. Since the articulated hub corresponds to the highest maintenance DOC, the coefficients for the three dummy variables above are all negative. All of the one-way interactions between these variables were tested and removed one by one as we conclude that there were not any significant interactions. Note that for the rotor hub type, from a statistical perspective, only the coefficient associated with the bearlingless design is significant at any reasonable level. However, the author supports the school of thought that if the attribute (rotor hub type) is statistically significant, as shown earlier, than all levels of the attribute should be included in the model.

In this section, we apply the insights from previous chapters to construct two regression models to predict the airframe maintenance DOC. Specifically, Airframe Maintenance DOC Model 1is a simple regression model using only gross weights as the explanatory variable. We then analyzed the residuals from that model and discussed ways to modify the basic model to account for a few key attribute design parameters such as the type of landing gear, rotor hub, and blade material. This method allows a future user to use just gross weight to predict a baseline DOC, and then refine and improve that prediction as additional information becomes available as the rotorcraft design progresses. Finally, we present a second multiple-regression model that is a function of gross weight, landing gear type and rotor hub type. This model, denoted Airframe Maintenance DOC Model 2, can be used directly once all three design parameters are known. The results from this analysis of the data are consistent with the expectations based on input from industry experts as well as from the literature and first principles.

## 7.6 Construction of Engine Maintenance Related DOC Model

In some ways, the engine can be considered a system whose maintenance costs are largely independent of the helicopter in which the engine is installed. The engine maintenance costs are not entirely independent of the rotorcraft model installation however, for two general reasons. Specifically, the labor required to perform engine maintenance while installed on the aircraft may differ depending on the accessibility of the engine in a particular aircraft. The second major reason that engine maintenance may be dependent on the aircraft installation is a result of the fact that engines may be operated at different power conditions depending on the aircraft installation. For example, the maximum power output may be limited to adhere to an aircraft limit such as the transmission limit. As an example, an engine that is certified to 1000 shp, may be limited to 800 shp when installed in a particular helicopter. Usually, when this situation arises, the engine manufacturer creates a new "minor" model designation for the reduced engine, but this is not always the case. For the engine maintenance DOC model there are only 53 observations (engine models) in the training set (compared to 61 aircraft models) due to cases where the same engine model is used in more than one helicopter model and a few missing values in available data.

While exploring the engine maintenance related DOC data, it immediately became clear that there is considerably more scatter in the data than in the case of the previous two (aircraft-level) models. The variable that shows the greatest correlation with maintenance cost is the engine weight. A few selected scatter plots are shown in Appendix N. It is worth noting that various transformations of the response and explanatory variables were explored. In addition, plots of the maintenance cost per unit power output ($/FH/SHP) and per unit engine weight ($/FH/lb) were also explored. A simple regression model based on engine weight is shown in Figure 23 and the full regression output is shown in Appendix O.
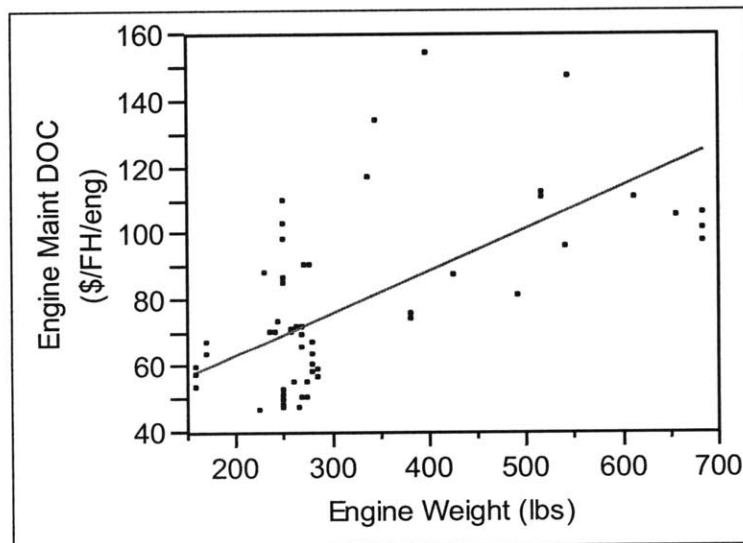


**Figure 23 Engine Maintenance DOC Regression Model 1**

The plot in Figure 23 and the output shown in Appendix O illustrate the additional uncertainty in the engine maintenance DOC prediction. The R-square value for this model is only 0.368, the RMSE 21.44 and the PRESS RMSE 21.91. While not nearly as satisfying from a statistical standpoint, this model is the best that could be constructed with a single explanatory variable and the available data.

Interestingly, after accounting for engine weight, the power output of the engine is not a statistically significant variable affecting maintenance cost. Specifically, plots of the residuals versus engine power do not show any significant relationship. There is a slight trend of increasing engine maintenance DOC with increasing SFC (worse efficiency), which suggests that more efficient designs may have slightly lower maintenance DOC. This may be more a result of the fact that newer engines tend to be both more efficient and have lower maintenance costs. However, in any case, the relationship between efficiency and engine maintenance DOC is not statistically significant after accounting for engine weight. This, combined with the fact that SFC is not typically known early in the design phase, led us to exclude it from the model.

The number of stages in both the low pressure turbine (LPT) and high pressure turbine (HPT) of the engines in the dataset suggested a relationship with the residuals from Engine Maintenance DOC Model 1, suggesting that these parameters may be important explanatory variables for predicting engine maintenance related DOC. All of the engines in this dataset use either one or two stages in both the HPT and LPT, with the exception of one. The single outlier employs a single spool, and hence does not have clearly defined separation between the "high" and "low" pressure sections of the turbine. As a result, this engine was excluded from the dataset while investigating the importance of these two variables. To account for the number of LPT and HPT stages in the design, we split the engines into those incorporating a single LPT or HPT and those with two stages. The corresponding dummy variable names *OneStageLPT?* and *OneStageHPT?* equal one when there is a single stage and zero otherwise (i.e. two stages). Box plots showing the relationship between these attribute parameters and the residuals from Engine Maintenance DOC Model 1are shown in Figure 24 and Figure 25 for the LPT and HPT respectively. A full ANOVA analysis is shown in Appendix P for the number of LPT stages and Appendix Q for the number of HPT stages.
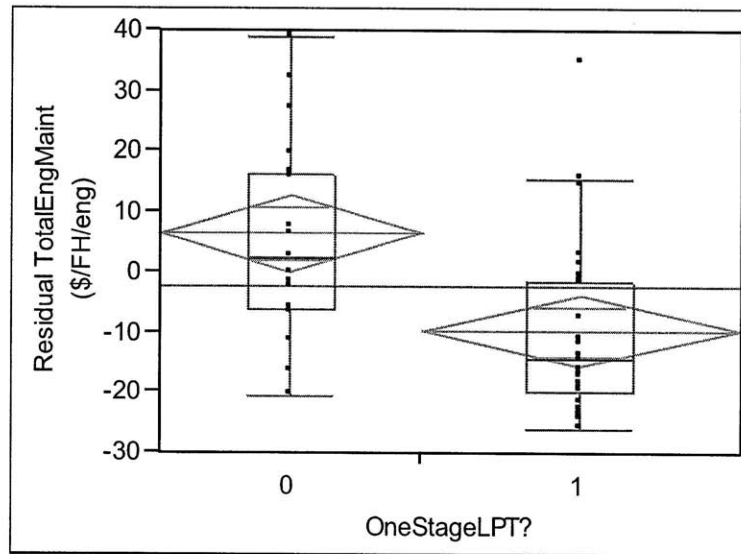


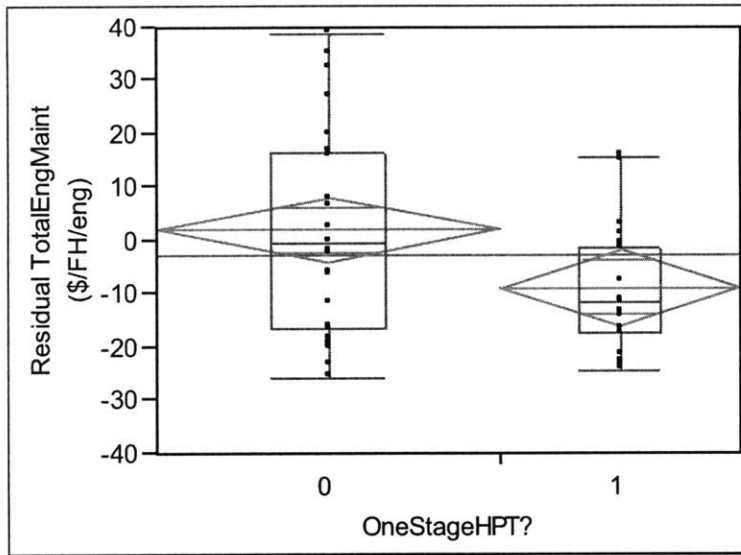**Figure 24 Box Plots of Residuals for Engine Maint. DOC Model 1 vs OneStageLPT?**

**Figure 25 Box Plots of Residuals for Engine Maint. DOC Model 1 vs OneStageHPT?**

As shown in the detailed output in Appendix P, after accounting for engine weight, designs with a two stage LPT tend to have higher engine maintenance related DOC by about 16 ($/FH/engine). Engines with two HPT stages tend to have higher engine maintenance related DOC by about 11 ($/FH/engine).

These two engine design attributes are added to the engine weight as explanatory variables and used to create a second model, which we will denote Engine Maintenance DOC Model 2. Both the main effects for the two variables as well as their interaction with engine weight proved to be statistically significant for this dataset. A plot of the actual versus predicted engine maintenance related DOC values is shown in Figure 26 and a full regression analysis output is shown in Appendix R.
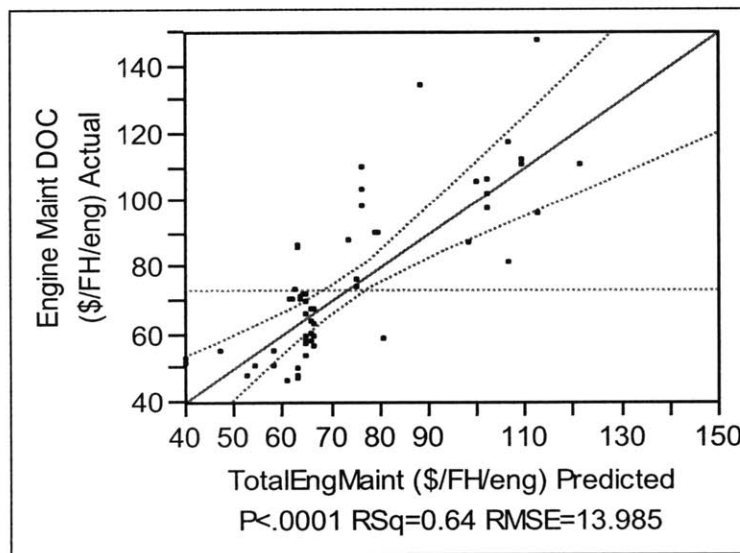


**Figure 26 Engine Maintenance DOC Regression Model 2**

The Engine Maintenance DOC Model 2, with an R-square value of 0.644, an RMSE of 13.99 and a PRESS RMSE of 16.44, represents a significant improvement over Engine Maintenance DOC Model 1. In both cases, engines with more stages tend to have higher engine maintenance DOC after accounting for weight. While accounting for the number of stages significantly improves the predictive ability, the engine maintenance DOC model is still the least satisfactory from a statistical standpoint.

The rather poor fit of an engine maintenance model to the available dataset is a major motivator for the recommendation to pursue this area as an opportunity for future work. Specifically, it may be possible to improve the predictive ability of the model by compiling data on materials, rotational speeds, operating temperatures, etc. Some of this data is not widely available, but given sufficient resources there are likely enough subsets of data to enable one to estimate the missing data points.

## 7.7  Construction of Crew Related DOC Model

After exploring the data for relationships between crew costs and the potential explanatory variables, we concluded that it is best to simply use the average pilot salary in determining the crew cost. Thus, the model contains the average pilot salary as a default. The crew cost per hour can then be calculated directly using Equation 38 presented in Section 6.3 from the input number of pilots and annual utilization.

## 7.8  Construction of Insurance Related DOC Model

As described in Section 6.4, the insurance related DOC is directly proportional to the acquisition cost of the aircraft. As a result, an estimate of the acquisition cost (selling price) of the aircraft can be used to calculate the insurance cost directly.

By building on relationships founded on the first principles and physics-based considerations, we constructed an overall TDOC model and three key sub-models: fuel related DOC, airframe maintenance DOC, and engine maintenance DOC. The modular nature of such sub-models provides additional flexibility in using the model and facilitates updates to those sub-models that benefit from future work, or require more frequent updates. Direct calculations are used for the cost subcategories where models are not required, such as in the case of crew related DOC and insurance related DOC. In addition, the TDOC model provides a quick estimate of operating costs which can then be refined as additional information becomes available.

# 8 Model Validation

The models constructed in this study are intended to be used to predict costs for future designs. As a result, the predictive ability of the models is a key measure of how well they may be expected to perform to this end. In this section, we will discuss the validation of the models by evaluating their performance on the validation data set. In addition, we will compare the performance of the model developed herein with the Lockheed-NYA model published in 1967 and described in Section 4.1.

## 8.1  Performance on Validation Data set

As mentioned earlier, it is important to ensure that the model created to predict operating costs is not overfit to our available data. Specifically, if the model is built to simply achieve the highest possible R-square value, then it will appear to perform well for the data used to construct the model, but may not be effective at predicting the response for new observations. One method to help avoid this situation is to split the dataset into two or even three groups, a training set, a validation set, and possibly a test set. One or more models are constructed using the training data. These models are then used to predict the response for the validation data. The model that performs "best" on the validation data may be selected, or the two or more models may be combined using some sort of technique such as a weighted average. In any case, performance on the validation set is used to identify a single model (which may be a combination of multiple models). This single final model is then used to predict the response for the test data set. The measures of fit and predictive accuracy on the test data set provide an estimate of how the model may perform for predicting responses to new observations.

While this segregation of data into these three subsets is ideal from the standpoint of avoiding overfitting, it has the serious drawback of requiring a relatively large set of observations. A possible alternative validation method is known as K-fold cross-validation. This technique involves randomly dividing the full data set into K different subsets, where the number K is specified by the user. Then a regression model is created K different times, where each time a different subset of the data is withheld as the test data set. Thus each time the model is generated, the data in subset K is withheld, and the remaining K-1 subsets of data are used to train the model. This process is repeated K times until all of the subsets have been withheld and used as the test data exactly once. In total, K different models are created, and each model is used to predict the response for the test data and calculate a standard error. The standard error on the data set is averaged across all K trials and is used as a measure of how well the model may perform to predict new observations. The greatest drawback of this approach is that the complete process of generating a model must be repeated K times.

The number of subsets, K, can be increased until K is equal to the number of observations, N. In this case the process generates N different models where each model uses all but one observation. The model is then used to predict the excluded observation, and an error term is calculated. This is repeated for every observation and a sum of the squared errors can be calculated. The resulting statistic is commonly called the Prediction Error Sum of Squares (PRESS). Frequently, the PRESS root mean square error (RMSE) is also calculated. This can be used as a metric to evaluate how well the model may be expect to work in predicting the response to new observations. Ideally, the value of the PRESS RMSE should be close to the RMSE for the regression model. A large PRESS RMSE relative to the regression model RMSE may suggest that the model is overfit to the data.

During construction of the models in Chapter 7, both the holdback and the PRESS methods were used as validation techniques. As described, approximately 20% of the data (15 helicopter models) were withheld from the training dataset and reserved as validation data. The performance of each model can

be compared to the validation dataset to ensure that the data is not overfit. Figure 27 shows an example of the validation dataset plotted versus the model prediction for the TDOC Model 2 which was first presented in Figure 16.
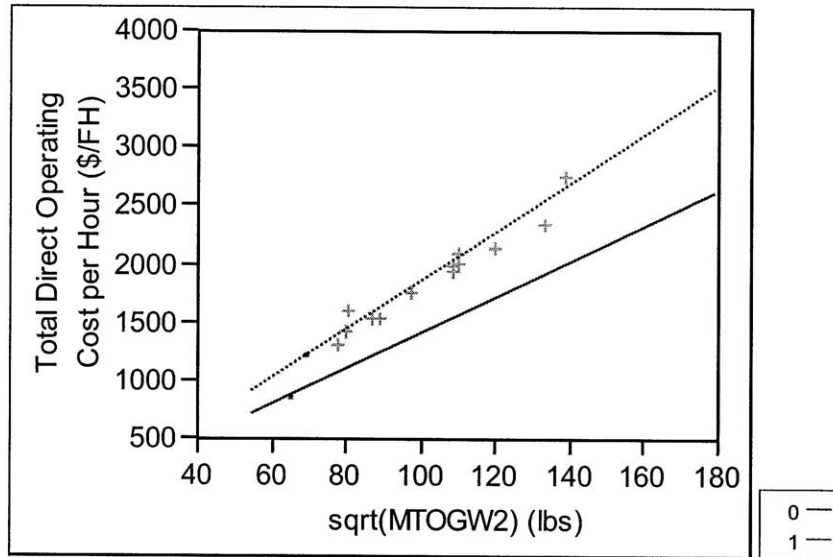


**Figure 27 Validation Dataset for TDOC Regression Model 2**

Similar plots were produced for the remaining models to check the performance of the model on the validation dataset. In addition, the cross-validation technique using the Prediction Error Sum of Squares (PRESS) calculation was used to check the models. Specifically, the RMSE values generated from predicting the models in the test dataset are consistent with the PRESS RMSE values given in the discussion of each of the sub-models in Chapter 7. These values suggest that the models presented are not overfit to the training set. As a result, the RMSE associated with each model given in Chapter 7 is consistent with how we would expect the model to perform on predicting new observations.

## 8.2  Comparison with Historical Model

In this section, we compare the performance of TDOC Model 2 developed herein described in Section 7.3, with the performance of the 1967 Lockheed and NYA model described briefly in Section 4.1 and published in reference (Stoessel and Gallagher 1-17). In order to make this comparison, some of the assumptions of the Lockheed-NYA model must be updated to be consistent with those used to construct the TDOC Model 2. Specifically, the assumptions described in Section 7 were used as inputs to the Lockheed-NYA model. In addition, an assumption for the inflation rate had to be made to correct the crew cost from 1967 dollars to 2008 dollars. The historical inflation in the US as measured by the Consumer Price Index (CPI) as well as the Gross Domestic Product (GDP) were both considered for this purpose. The difference in the results between the two is insignificant, and as a result the CPI was chosen since it is believed that this would more closely track crew salaries. Take the sum product of the CPI growth factor from 1967 through 2008 results in a value of about 6.6. This correction for inflation was only required to adjust the crew costs, as the remaining cost elements were functions of the acquisition prices, labor rates, or fuel costs, all of which are corrected for by modifying the input values.

Ten rotorcraft models included in the dataset were chosen at random. For each of these ten models, the Lockheed-NYA operating cost model was used to calculate the Total Direct Operating Cost. The

resulting values along with the predictions from TDOC Model 2 and the actual response data are shown in Figure 28.
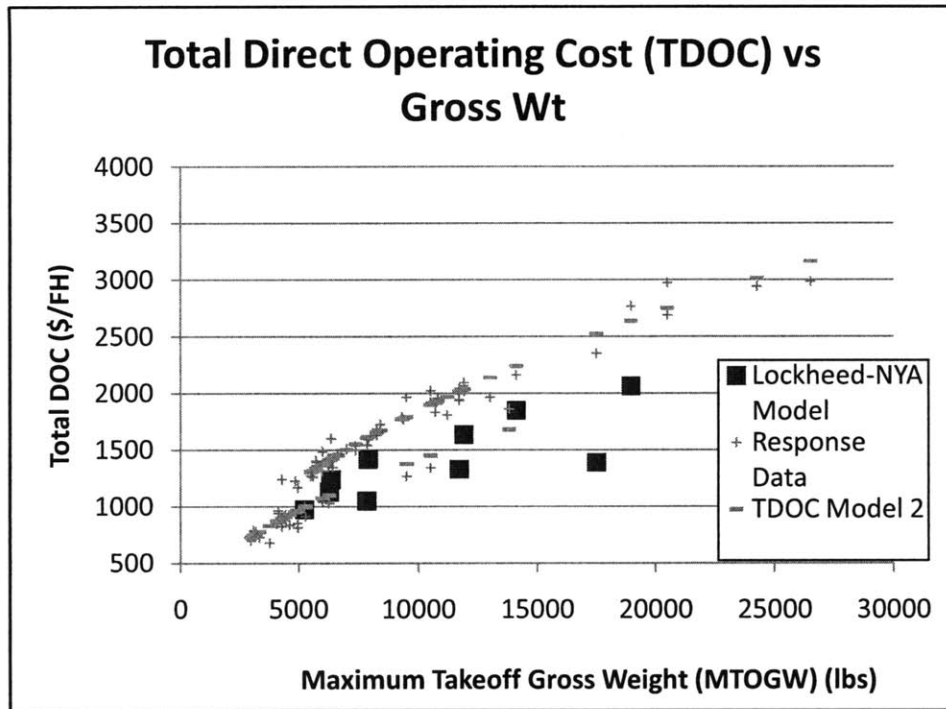


**Figure 28 Comparison of TDOC with Historical Model**

Figure 28 shows that the Lockheed-NYA model does a fairly good job at predicting TDOC for some of the smaller (lower MTOGW) aircraft. However, the Lockheed-NYA predictions tend to fall off faster with increases in gross weight and hence underestimate the operating costs by increasingly large amounts.

We see that the development of TDOC Model 2 provides a valuable improvement over the existing published model from 1967. In addition, it is worth noting that TDOC Model 2 requires knowledge of only the gross weight and number of engines. In contrast, the Lockheed-NYA model requires knowledge of additional aircraft attributes including the cost of the aircraft and the cost of the engines. These values are typically not available early in the design phase. Thus, the TDOC model developed herein provides an improvement with regards to the model's predictive ability as well as the ease of use and broader applicability.

The validation techniques used to check the models developed in this study do not reveal any areas of concern. Both the holdback and cross-validation techniques suggest that the models are not overfit to the available data. In addition, the comparison of the TDOC model with the historical Lockheed-NYA model provides a useful reference or check to confirm that the model is in line with previous efforts to model rotorcraft operating costs.

# 9 Conclusions

This project starts with historical work and case studies involving the modeling and understanding of rotorcraft operating costs. From there, a comprehensive review of publicly available sources of operating cost data is completed. Efforts are taken to engage major rotorcraft manufacturers by leveraging involvement and common interests in major trade organizations. In parallel, the laws of physics governing rotorcraft operation and first principles are discussed to identify key potential design variables affecting operating costs. This study leverages historical economic modeling work, combined with the application of first principles and physics-based considerations, to develop a robust, useful method for predicting rotorcraft operating costs early in the preliminary design phase.

## 9.1 Principle Findings – Operating Cost Models

In Chapter 7, we combined the physics and first principles considerations with statistical analysis using regression to develop simple, effective, models for predicting direct operating costs for new rotorcraft applications. Previous economic modeling work, such as that published by Stoessel et. al. and Ausrotas et. al., described in Chapter 4, show that the number of flying hours, also referred to as utilization, is a key *operating parameter* affecting DOC for a given period (month, quarter, year, etc.). Since this project focuses on relating rotorcraft *design parameters* to operating costs, the response is in units of cost per flight hour ($/FH). This section summarizes the models developed during this project and highlights a few of the major insights revealed during this work. A total of seven models are developed in this project as summarized in Table 5.

**Table 5 Summary of DOC Models**

| DOC Category | Model | Explanatory Variables | $R^2$ | RMSE | PRESS RMSE | $R^2$-adj |
|---|---|---|---|---|---|---|
| Total Direct Operating Cost (DOC) ($/FH) | TDOC Model 1 | MTOGW | 0.931 | 166.558 | 169.030 | 0.930 |
| Total Direct Operating Cost (DOC) ($/FH) | TDOC Model 2 | MTOGW, Number Engines | 0.974 | 104.553 | 114.450 | 0.972 |
| Fuel Related DOC ($/FH) | Fuel DOC Model 1 | MTOGW | 0.977 | 18.268 | 18.798 | 0.976 |
| Airframe Maintenance Related DOC ($/FH) | Airframe Maint. DOC Model 1 | MTOGW | 0.834 | 87.742 | 89.569 | 0.832 |
| Airframe Maintenance Related DOC ($/FH) | Airframe Maint. DOC Model 2 | MTOGW, Rotor Type, Landing Gear Type | 0.915 | 66.252 | 71.860 | 0.907 |
| Engine Maintenance Related DOC ($/FH) | Engine Maint. DOC Model 1 | Engine Weight | 0.369 | 21.446 | 21.907 | 0.356 |
| Engine Maintenance Related DOC ($/FH) | Engine Maint. DOC Model 2 | Engine Weight, No. LPT Stages, No. HPT Stages | 0.644 | 13.985 | 16.442 | 0.605 |

The total DOC models can be used to quickly estimate TDOC for new rotorcraft designs early in the design process while many parameters are still unknown. The simplest model requires only the maximum takeoff gross weight for the new design as an input to the model. After accounting for maximum takeoff gross weight, the second most significant explanatory variable considered for this data

set is the number of engines. Overall rotorcraft designs incorporating two engines have higher TDOC than those with a single engine.

For the fuel related DOC, the maximum takeoff gross weight is the best explanatory variable. After accounting for gross weight, no other variables provided a statistically significant improvement in the prediction of fuel related DOC. Thus, the simple consideration of maximum takeoff gross weight is an effective predictor for fuel related DOC.

The maintenance related DOC is an area of focus for this project. These costs have historically shown the greatest difference from fixed-wing applications and were an area of focus for previous studies performed at MIT by Ausrotas et. al. as described in Chapter 4. The maximum takeoff gross weight is the strongest explanatory variable for the airframe maintenance DOC. In addition, two key attribute design parameters show a strong relationship to airframe maintenance cost. Specifically, the type of rotor hub employed in the design is an important parameter where this design choice can lead to a difference of over 100 ($/FH) in airframe maintenance DOC by using a bearingless design versus an articulated design as described in Section 7.5. The type of landing gear chosen for a new design also has a significant impact on airframe maintenance DOC. The use of retractable wheels rather than skids for the landing gear design leads to higher maintenance DOC by approximately 70 ($/FH).

The engine maintenance related DOC subcategory shows the greatest amount of variation. The engine weight is the strongest explanatory variable, and the number of LPT and HPT stages are also important design parameters relating to engine maintenance DOC. However, this model is the least statistically satisfactory. Engine maintenance DOC estimation is identified as a key area for future research described in Section 9.5.

The models developed herein share the general theme that a relatively small number of explanatory variables can be used to account for the majority of the variation in direct operating cost. In all of the models developed, an appropriate measure of weight provides the greatest explanatory power with a single variable. In most cases, this is the maximum takeoff gross weight, while in the case of engine maintenance DOC, the engine weight is used. By knowing or estimating the appropriate weight, an estimate of the DOC can be made using the appropriate model in Table 5. The accuracy of the DOC prediction for each model can be quantified using the RMSE for the model or the PRESS RMSE values provided in the appendices and summarized in Table 5. While the weight explains most of the variation in DOC, the estimates can be refined by accounting for key design attributes such as the type of rotor hub and landing gear type in the case of airframe related DOC.

## 9.2 Specific Recommendations

The creation of a rotorcraft economics model addresses a growing need to improve the understanding of the relationship between design parameters and rotorcraft operating costs early in the process of designing new helicopters and major subsystems such as the engine. The work performed during this project provides new capability to the preliminary design group at a major rotorcraft engine manufacturer This capability enables rotorcraft economic analysis to be incorporated with existing aircraft and engine performance methods to provide a more holistic representation of the effects of major system design decisions. Specifically, the capability enables quantitative comparisons between various candidate configurations early in the helicopter and engine design process.

The modular nature of the models developed and presented in Chapter 7 enables designers to select the appropriate model based on the amount of available design data as well as the available time and required level of accuracy. For example, a quick, rough, estimate of TDOC for a proposed design can be

generated is less than ten minutes using the simple TDOC model presented in Section 7.3 based on knowing only the maximum takeoff gross weight. As additional information on the proposed rotorcraft design becomes available, the prediction of operating costs can be refined to improve the accuracy. For example, if the number of engines to be used in the new design is known then the second TDOC model presented in Section 7.3 can be used to improve the estimate.

An example of the potential use of this model involves predicting TDOC for the complete aircraft to help put the operating costs associated with individual subsystems in context with the TDOC that the operator may face. Consider a study in which an engine manufacturer were proposing to use an existing "off-the-shelf" engine for a new rotorcraft application. The historical data pertaining to the operation of this engine enables a very accurate prediction of the engine related maintenance DOC. In addition, engine performance models that have been validated with engine test data result in a thorough understanding of the engine operation. Assume that the helicopter manufacturer proposing the new rotorcraft design only specifies the maximum takeoff gross weight. The engine design team needs to know how the engine related maintenance DOC will compare to the TDOC for the proposed new helicopter. The models developed in this project enable the preliminary design group to quickly respond to this type of request. Specifically, the engine maintenance DOC can be put in context with the TDOC by using the estimate from the TDOC model presented in Section 7.3. Knowing whether the engine related maintenance costs make up a small or large proportion of the total operating costs will help guide trade-offs and design decisions.

The models developed in this project provide the flexibility and modularity to provide both quick estimates as well as more detailed predictions of the various subcategories of operating costs for new designs. In addition to enabling an engine or subsystem design group to respond to specific requests such as the example above, simply improving the awareness of operating costs experienced by commercial helicopter operators improves the understanding of the customer's perspective and needs. The appropriate application of this model will lead to better aircraft system designs.

## 9.3 Integration with Existing Preliminary Design Processes

In order to facilitate the widespread use of this new model, it is important that it be integrated with the current design processes in place within the preliminary design group at the host company. Figure 29 shows a high level map of a typical process used to complete the preliminary design of a new rotorcraft engine.
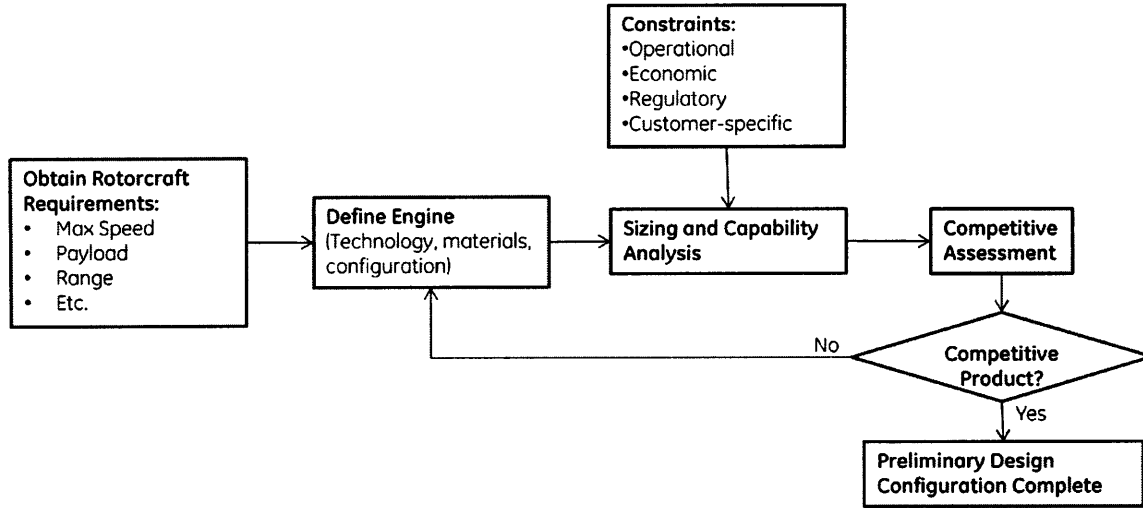
Constraints:
•Operational
•Economic
•Regulatory
•Customer-specific

Obtain Rotorcraft
Requirements:
• Max Speed
• Payload
• Range
• Etc.

Define Engine
(Technology, materials,
configuration)

Sizing and Capability
Analysis

Competitive
Assessment

No

Competitive
Product?

Yes

Preliminary Design
Configuration Complete

**Figure 29 High Level Preliminary (Conceptual) Design Process**

More details on the design of rotorcraft and engines are described in Chapter 3. Figure 29 provides a simplified, high-level map of a possible process used in the Preliminary Design group to design new engines for rotorcraft applications.

The purpose of the figure is to illustrate how the models developed in this project fit in to the overall process. The steps involving the sizing and capability analysis as well as the competitive assessment both involve operating cost considerations. Some of these considerations stem from constraints and others may be incorporated with the figure of merit for design optimization as described in Section 3.2.5.

Typically the economic analysis and assessment is included as part of the Aircraft Performance function in the Preliminary Design group at the host company. Currently this function performs the economic analysis for some fixed-wing design studies using an existing operating cost model to provide economic estimates. A logical way to implement the models developed herein is to use a process analogous to that currently in use for fixed-wing applications. As such, the most convenient platform for implementing this prototype model is simply in the form of a MS Excel template with empty fields for the inputs and the relevant equations linking these inputs to the resulting output in operating costs. The rotorcraft models developed here will be handled analogously to the models in use for fixed-wing applications. As such, if a different platform or implementation method is identified for performing economic analysis for fixed-wing applications, the same will be used for rotorcraft.

By benchmarking and leveraging the existing process for performing economic analysis as part of the preliminary design process, we can directly integrate the models developed in this project with existing design processes and tools. While these tools and processes continue to evolve over time, the economic analysis and importance of predicting operating costs will continue to be relevant.

## 9.4 Applicability to Overall Rotorcraft Design

In addition to providing value to the preliminary design group who hosted this LGO internship and project, the results of this study are applicable to a broad audience involved in rotorcraft design and

operations. Taken a step further, the methodology employed is applicable to a variety of product design applications.

In Chapter 3 we described the major considerations encountered during the design of new rotorcraft and engines. The models developed in this study are directly related to enabling the use of operating costs as a figure of design merit as described in Section 3.2.5. At the preliminary design phase, any of the proposed simple models, such as TDOC Model 1, could be incorporated with the preliminary design process shown in Figure 3 and described in Section 3.2.1 to predict operating cost for each design considered. The predicted cost could then be compared to the requirements, or it could be used in the objective function during design optimization. One possible example of the addition of operating cost estimation to this process is shown in Figure 30. The additional steps added to account for DOC consideration during the preliminary design process are shown in red with dashed lines and boxes.
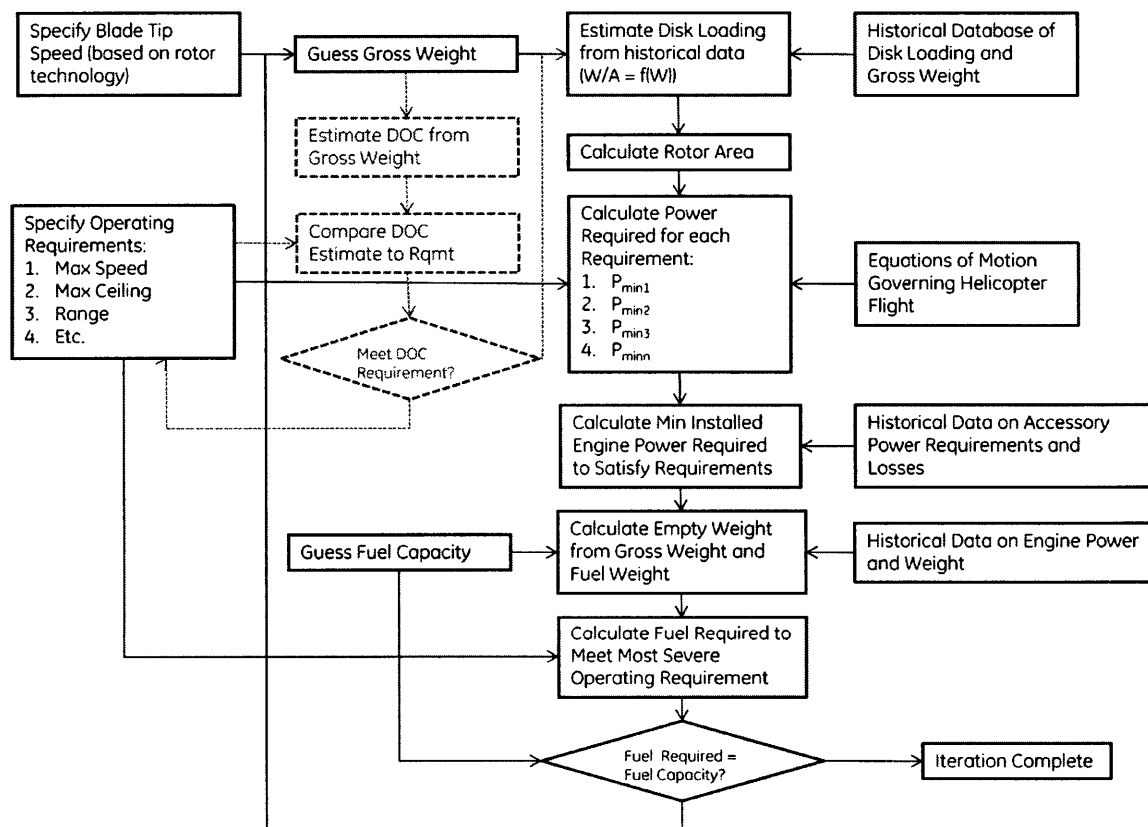


**Figure 30 Rotorcraft Preliminary Design Process with DOC**

In this simplest example, the TDOC could be estimated directly from the gross weight and compared to a given requirement. Using TDOC Model 1 as an example, this would effectively limit the maximum takeoff gross weight for the design. In that case, as the iteration progresses, it may turn out that it is not possible to satisfy all of the performance requirements while adhering to the DOC requirement. Thus, there is a feedback from the "Meet DOC Requirement" decision block to the requirements block. This indicates that some of the requirements, either DOC or performance requirements, may have to be relaxed to find a design. Alternatively, maintaining the DOC requirement in combination with the performance requirements may shed some light on how much better the new design must be when

compared to historical relationships.  For example, the design process could be used to identify the fact that in order for the design to meet all the requirements (including DOC), then the power to weight ratio of the engine must be 20 percent higher than the historical relationship would suggest.  This type of process can be used to set design goals for the engines or various aircraft subsystems.

In addition to integrating the models developed in this report with preliminary design processes, it is possible to use some of the results inferred during the statistical analysis in Chapter 7 to guide design decisions.  In Section 7.5 while discussing ways to improve the airframe maintenance DOC model, we drew inferences regarding how different design attributes affect airframe maintenance DOC.  For example, the data analyzed in this study suggest that after accounting for max gross takeoff weight, the use of retractable landing gear in place of skids adds about 70 ($/FH) to the airframe maintenance DOC.  With a DOC value for this feature in hand, it is possible to perform a quantitative trade-off to see if the benefits of including retractable landing gear in a design outweigh the costs.

As mentioned in Chapter 4, it is likely that most rotorcraft manufacturers have extensive, proprietary, models to estimate operating costs and life cycle costs for new products.  However, these models are not likely to be released for public dissemination.  The models developed in this project provide a starting point for anyone in the rotorcraft design community to estimate operating costs and start thinking about how designs can be improved to minimize these costs.

## 9.5 Remaining Questions and Opportunities for Further Research

The opportunities for further research and improvements to this study can be categorized into three major subsets:

- Improve response data
- Increase integration and collaboration between engine manufacturer and aircraft manufacturer early in the design phase
- Additional modeling work

The greatest opportunity for improving the actual operating cost model involves obtaining higher quality and a greater quantity of response data (operating cost data).  As discussed in Chapter 5, the best data is that from the field, meaning the actual realized costs from operators.  While there are many challenges associated with obtaining this data due to the competitively sensitive nature, future opportunities to engage operators should be considered and pursued.  It is extremely important for engine manufacturers to be aware of operator requirements and to anticipate the propulsion system needs of future aircraft.  Any efforts to improve the relationship between the engine manufacturers and operators will help improve the dialogue between the two parties as well as the understanding of customer needs.  In addition, increased involvement in trade organizations and conferences related to the rotorcraft industry will help achieve this end.

Additional potential public sources for improving the response data that were identified during the course of this study include:

- Analysis of quarterly (and annual) financial statements filed by operators
- Compilation and analysis of flight hours data from FAA and other agencies which can be used to estimate the number of flight hours on each aircraft in a given fleet

The data contained in financial filings alone is not sufficient to draw significant conclusions related to operating costs.  The most important piece missing from such data is typically the exact composition of

the operator's fleet, and the number of hours flown for each model of aircraft. Although extremely time consuming, and hence expensive, it is conceptually possible to obtain the number of flight hours on each aircraft based on public records with the agency required to prove the airworthiness of the aircraft. This data could be collected and compiled based on the aircraft registration number. The flight hours could then be combined with the revenue and expense data from financial filings to obtain operating costs.

The second opportunity identified for future efforts involves increased integration between the engine and aircraft design functions, which boils down to improved collaboration between the aircraft manufacturers and the engine manufacturers. "It is extremely important that the preliminary design process take into account as many controlling variables as possible. Clearly an integrated treatment of the engine and the airframe is essential(Kerrebrock )."

In seems that there is ample opportunity to improve the understanding of the customer requirements and discussion between the helicopter manufacturers and engine manufacturers to find the most effective way for the whole aircraft system to meet those requirements. In the day-to-day operations at an engine manufacturer it is important to clearly articulate who the customer actually is. Specifically, in some cases the aircraft manufacturers may be the immediate customer, but the helicopter operator is the final customer who will be using the aircraft. There are many instances where improved collaboration between the airframe and engine manufacturers could improve their ability to provide an integrated system to exceed the requirements and wishes of the operators.

The third area identified for additional operating cost modeling work covers opportunities for improving the treatment of operating costs without requiring additional response data. The first opportunity is to improve the engine maintenance sub-model, with a more detailed model. Early in the process of selecting the object for this project, there were two possible models under consideration: an engine maintenance cost model and a rotorcraft economics model. The rotorcraft economics model was chosen for the purpose of this internship and thesis. If the engine maintenance model project is completed in the future, then the results of that model can be directly integrated with this overall treatment of rotorcraft operating costs. The modular structure of the sub-models used in this operating cost model make it easy to update or replace a given sub-model as more information or additional efforts are undertaken to improve key areas.

Another opportunity for future modeling work that is independent from, yet closely related to, operating costs, involves modeling to investigate, describe and quantify the complexity of aircraft and engine designs. Specifically, various techniques based on entropy concepts exist for developing quantitative methods for measuring part and system complexity. Typically this complexity is driven directly by product requirements. The complexity can then often drive both initial cost and operating costs. A defined way of quantifying complexity and performing such analyses could be very beneficial to the aircraft and engine design community. Specifically, such information could be used to link requirements to cost. This data could then be used to help both suppliers and customers reach a set of performance requirements (and hence design requirements) that create the greatest value for the customer.

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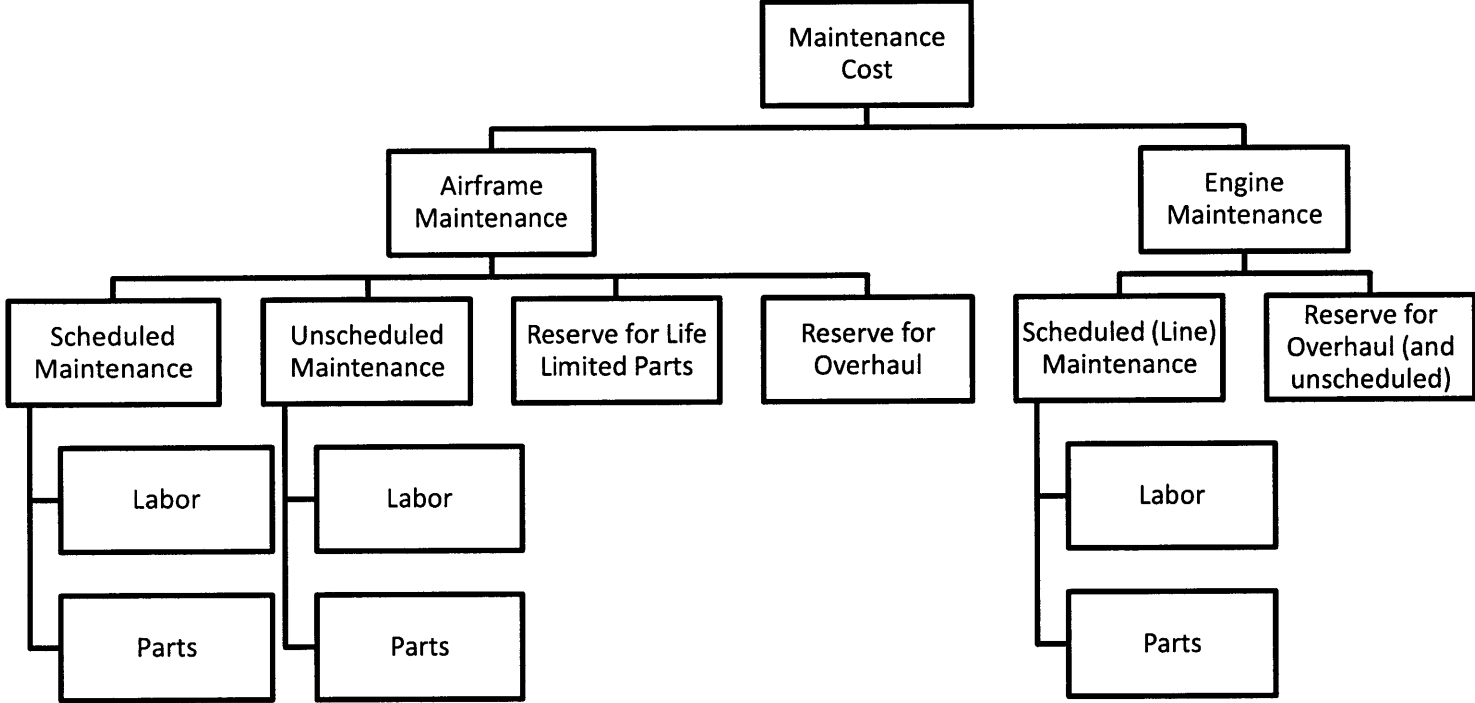Sims, Chester T., and William C. Hagel . The Superalloys. New York: Wiley-Interscience, 1972.

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# 11 Appendices

**Appendix A Diagram of Rotorcraft Operating Cost Breakdown**
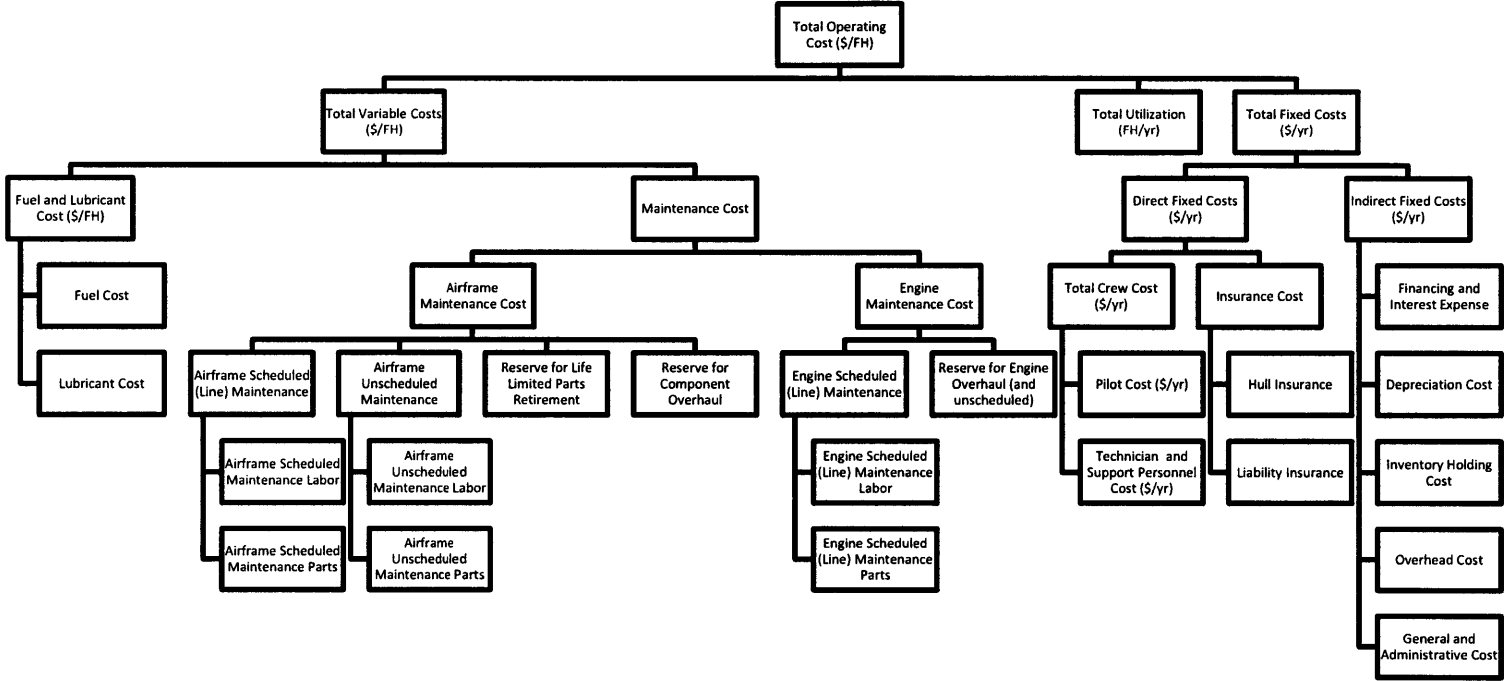
**Appendix B Hierarchical Diagram of Maintenance DOC**

```
                          ┌──────────────┐
                          │ Maintenance  │
                          │     Cost     │
                          └──────┬───────┘
              ┌──────────────────┴────────────────────┐
      ┌───────┴────────┐                        ┌──────┴───────┐
      │    Airframe    │                        │    Engine    │
      │  Maintenance   │                        │ Maintenance  │
      └───────┬────────┘                        └──────┬───────┘
  ┌─────┬─────┴─────┬──────────┐            ┌──────────┴──────────┐
┌─┴───┐ ┌─┴───┐ ┌──┴────┐ ┌────┴───┐   ┌────┴─────┐     ┌─────────┴──────┐
│Sched│ │Unsch│ │Reserve│ │Reserve │   │Scheduled │     │   Reserve for  │
│uled │ │edul │ │for Life│ │for     │   │(Line)    │     │ Overhaul (and  │
│Maint│ │Maint│ │Limited │ │Overhaul│   │Maintenance│    │  unscheduled)  │
└─────┘ └─────┘ │Parts   │ └────────┘   └──────────┘     └────────────────┘
                └────────┘
```

- Maintenance Cost
  - Airframe Maintenance
    - Scheduled Maintenance
      - Labor
      - Parts
    - Unscheduled Maintenance
      - Labor
      - Parts
    - Reserve for Life Limited Parts
    - Reserve for Overhaul
  - Engine Maintenance
    - Scheduled (Line) Maintenance
      - Labor
      - Parts
    - Reserve for Overhaul (and unscheduled)

**Appendix C Sample TBO Data for Current Production Helicopter (MD500E)**

## Limited-Life Parts {{53 MD Helicopters 2009}}
Component Finite Time (hr)

| Component | Finite Life (hrs) |
|---|---|
| Main Rotor Blade | 3,530 |
| Blade Pin | 7,600 |
| Main Rotor Hub | 8,900 |
| Pitch Housing/MR | 9,100 |
| Retention Strap/MR | 2.770 |
| Bolt-Lead Lag/Mr | 6,120 |
| Lead Lag Link/MR | 11,080 |
| Drive Shaft | 5,020 |
| Mast | 10,450 |
| Transmission Coupling | 4,300 |
| T/R Drive Shaft | 13,900 |
| T/R Transmission Input Shaft | 12,000 |
| T/R Transmission Output Shaft | 7,290 |
| T/R Blade | 5,140 |
| T/R Hub | 3,450 |
| T/R Retention Strap | 5,100 |
| Tail Boom Bolts | 21,950 |
| Tail Boom | 10,300 |
| Vertical Stabilizer | 12,700 |
| Horizontal Stabilizer | 7,700 |
| Idler Bellcrank | 6,500 |

## Overhaul Systems
Component Finite Time (hr)

| Component | Finite Life (hrs) |
|---|---|
| Transmission/MR | 5,000 |
| M/R Swashplate | 2,770 |
| M/R Hub | 2,770 |
| Overrunning Clutch | 1,800 |
| T/R Transmission | 4,800 |
| Starter, Generator | 1,200 |
| Blower Bearings | 1,200 |
| Blower Belt | 1,200 |

## Appendix D Full Regression Output for TDOC Model 1

### Response Total Direct Operating Cost per Hour ($/FH)
### Whole Model
### Regression Plot
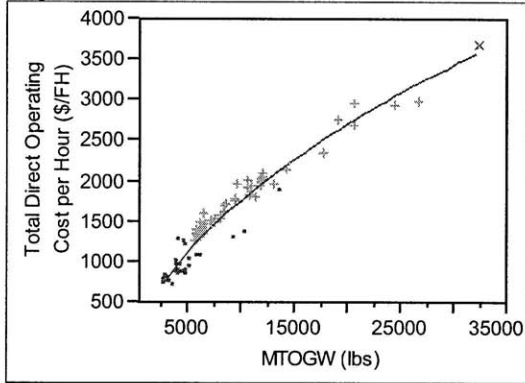


### Actual by Predicted Plot
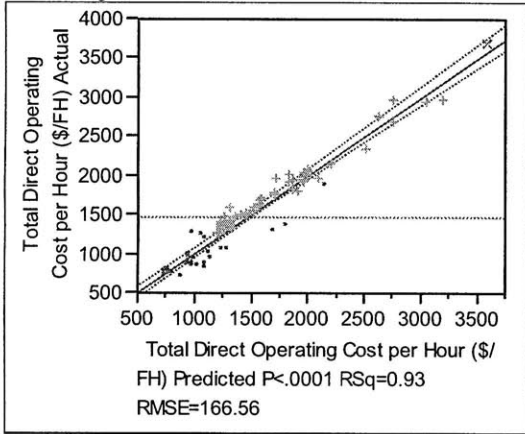


### Summary of Fit

| | |
|---|---|
| RSquare | 0.931221 |
| RSquare Adj | 0.930075 |
| Root Mean Square Error | 166.5577 |
| Mean of Response | 1466.609 |
| Observations (or Sum Wgts) | 62 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 22536154 | 22536154 | 812.3632 |
| Error | 60 | 1664489 | 27741.477 | **Prob > F** |
| C. Total | 61 | 24200643 | | <.0001 |

### Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 42 | 1207534.3 | 28750.8 | 1.1325 |
| Pure Error | 18 | 456954.4 | 25386.4 | **Prob > F** |
| Total Error | 60 | 1664488.6 | | 0.3999 |
| | | | | **Max RSq** |
| | | | | 0.9811 |

## Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|
| Intercept | -504.0182 | 72.30341 | -6.97 | <.0001 |
| Sqrt(MTOGW (lbs)) | 22.687139 | 0.795985 | 28.50 | <.0001 |

## Residual by Predicted Plot
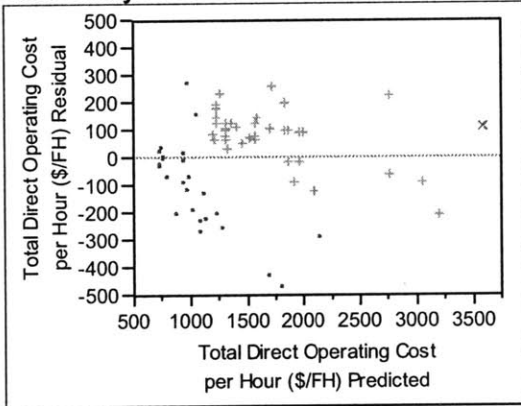


## Prediction Expression

$$-504.01817190077$$

$$+22.6871393995447 * \sqrt{\text{MTOGW (lbs)}}$$

## Press

| Press | Press RMSE |
|---|---|
| 1771428.91 | 169.030867 |

## Sqrt(MTOGW (lbs))
## Leverage Plot



Leverage, P<.0001
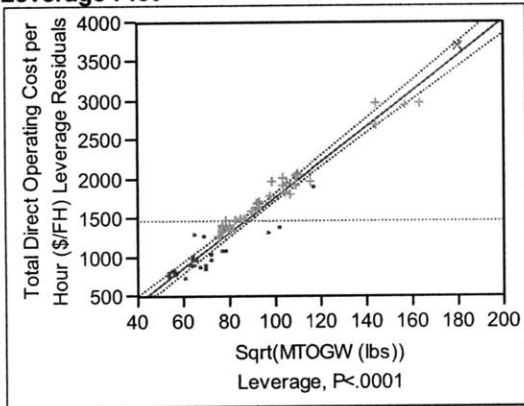
## Appendix E Full Regression Output for TDOC Model 2

### Response Total Direct Operating Cost per Hour ($/FH)
### Whole Model
### Regression Plot
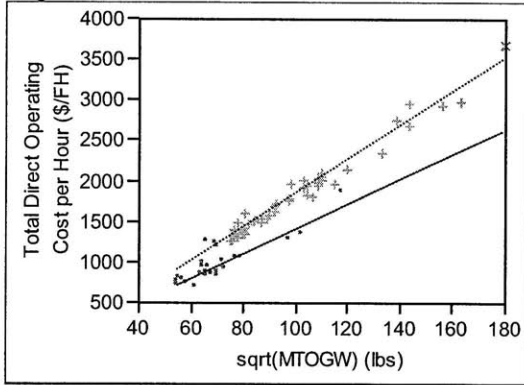


### Actual by Predicted Plot
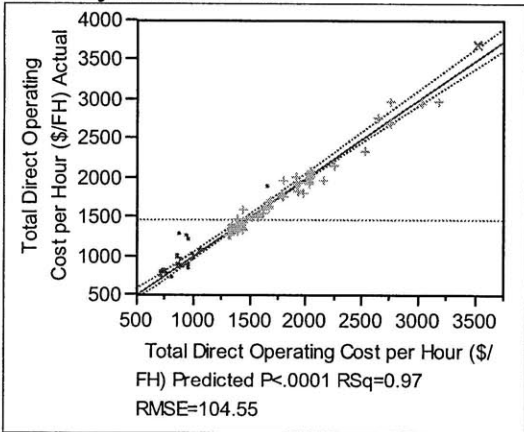


### Summary of Fit

| | |
|---|---|
| RSquare | 0.973802 |
| RSquare Adj | 0.972447 |
| Root Mean Square Error | 104.5528 |
| Mean of Response | 1466.609 |
| Observations (or Sum Wgts) | 62 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 3 | 23566628 | 7855543 | 718.6289 |
| Error | 58 | 634015 | 10931 | Prob > F |
| C. Total | 61 | 24200643 | | <.0001 |

### Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 42 | 540706.62 | 12874.0 | 2.2076 |
| Pure Error | 16 | 93308.38 | 5831.8 | Prob > F |
| Total Error | 58 | 634015.00 | | 0.0441 |
| | | | | Max RSq |

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| Source | DF | Sum of Squares | Mean Square | F Ratio |
|--------|-----|----------------|-------------|---------|
| | | | | 0.9961 |

## Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|------|----------|-----------|---------|----------|
| Intercept | -176.2454 | 59.0669 | -2.98 | 0.0042 |
| sqrt(MTOGW2) (lbs) | 18.051317 | 0.75793 | 23.82 | <.0001 |
| OneEngine?[0] | 177.09618 | 18.33635 | 9.66 | <.0001 |
| (sqrt(MTOGW2) (lbs)-86.861)*OneEngine?[0] | 2.9255489 | 0.75793 | 3.86 | 0.0003 |

## Residual by Predicted Plot
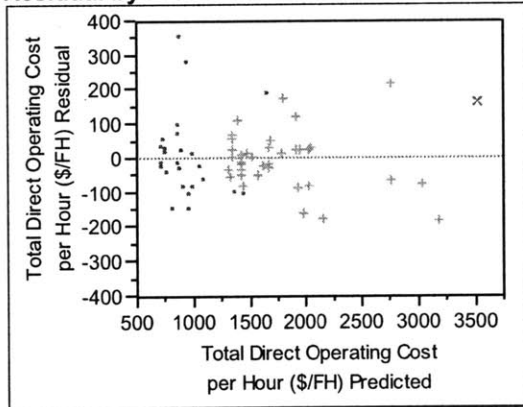


## Prediction Expression

$$-176.24535047591$$
$$+18.0513166231697 \cdot \text{sqrt(MTOGW2) (lbs)}$$

$$+\text{Match}\left[\text{OneEngine?}\right] \begin{bmatrix} 0 & \Rightarrow 177.09618420788 \\ 1 & \Rightarrow -177.09618420788 \\ \text{else} \Rightarrow . \end{bmatrix}$$

$$\left[\text{sqrt(MTOGW2) (lbs)} - 86.8609852206451\right]$$

$$+ \cdot \text{Match}\left[\text{OneEngine?}\right] \begin{bmatrix} 0 & \Rightarrow 2.9255489197753 \\ 1 & \Rightarrow -2.9255489197753 \\ \text{else} \Rightarrow . \end{bmatrix}$$

## Press

| Press | Press RMSE |
|-------|------------|
| 812173.19057 | 114.453342 |

## sqrt(MTOGW2) (lbs)
## Leverage Plot
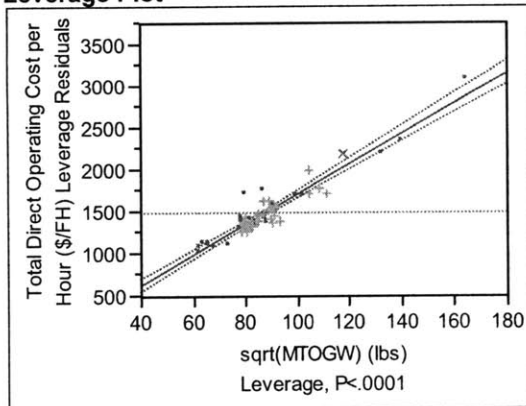
**OneEngine?**
**Leverage Plot**
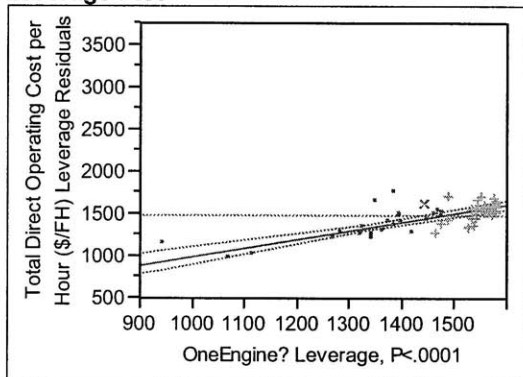


**Least Squares Means Table**

| Level | Least Sq Mean | Std Error | Mean |
|-------|---------------|-----------|------|
| 0 | 1568.8060 | 18.799438 | 1812.85 |
| 1 | 1214.6136 | 31.487588 | 954.18 |

**sqrt(MTOGW2) (lbs)*OneEngine?**
**Leverage Plot**
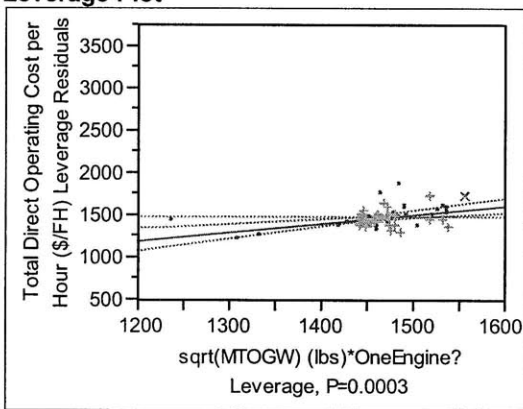


**Correlation of Estimates**

| Corr | Intercept | sqrt(MTOGW2) (lbs) | OneEngine?[0] | (sqrt(MTOGW2) (lbs)-86.861)*OneEngine?[0] |
|------|-----------|--------------------|----------------|-------------------------------------------|
| Intercept | 1.0000 | -0.9627 | 0.5980 | 0.4914 |
| sqrt(MTOGW2) (lbs) | -0.9627 | 1.0000 | -0.6687 | -0.6271 |
| OneEngine?[0] | 0.5980 | -0.6687 | 1.0000 | 0.4894 |
| (sqrt(MTOGW2) (lbs)-86.861)*OneEngine?[0] | 0.4914 | -0.6271 | 0.4894 | 1.0000 |

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## Appendix F Full Regression Output for Fuel Related DOC

**Response Fuel Cost ($/FH)**
**Whole Model**
**Regression Plot**



**Actual by Predicted Plot**



P<.0001 RSq=0.98 RMSE=18.268
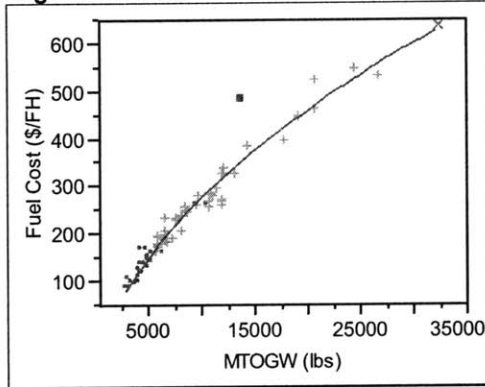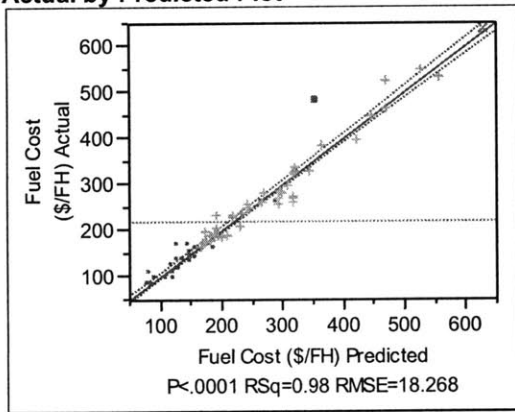
### Summary of Fit

| | |
|---|---|
| RSquare | 0.976728 |
| RSquare Adj | 0.976333 |
| Root Mean Square Error | 18.26828 |
| Mean of Response | 218.1148 |
| Observations (or Sum Wgts) | 61 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 826388.13 | 826388 | 2476.218 |
| Error | 59 | 19690.07 | 334 | **Prob > F** |
| C. Total | 60 | 846078.20 | | <.0001 |

### Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 41 | 18526.371 | 451.863 | 6.9894 |
| Pure Error | 18 | 1163.700 | 64.650 | **Prob > F** |
| Total Error | 59 | 19690.071 | | <.0001 |
| | | | | **Max RSq** |
| | | | | 0.9986 |

### Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|

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| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|
| Intercept | -161.2143 | 7.973706 | -20.22 | <.0001 |
| Sqrt(MTOGW (lbs)) | 4.3924599 | 0.08827 | 49.76 | <.0001 |

## Residual by Predicted Plot
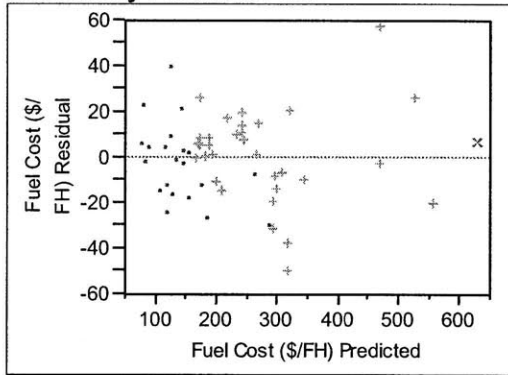


## Prediction Expression

$$-161.21431372772$$

$$+4.39245987825421 * \sqrt{MTOGW\ (lbs)}$$

**Press**

| Press | Press RMSE |
|---|---|
| 21556.181971 | 18.798405 |

**Sqrt(MTOGW (lbs))**
**Leverage Plot**



Leverage, P<.0001
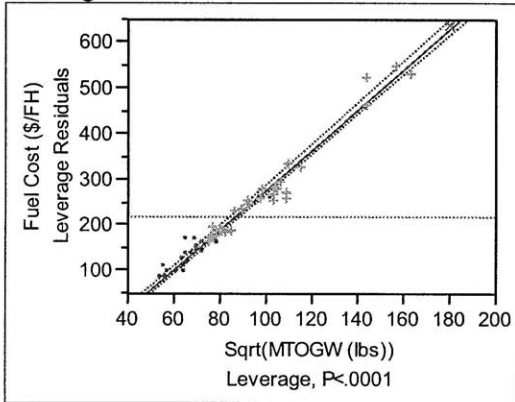
**Appendix G Select Scatter Plots for Airframe Maintenance DOC**

### Airframe Maintenance ($/FH) By MTOGW lbs)
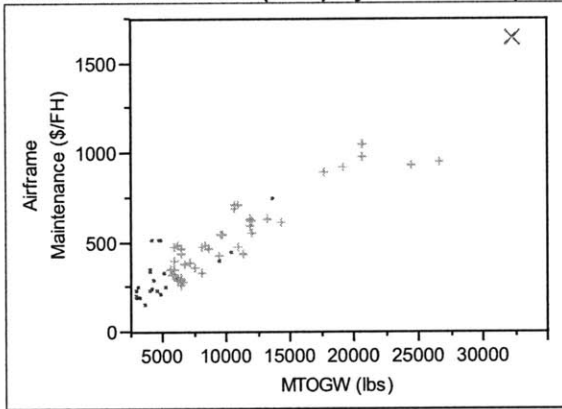


### Airframe Maintenance ($/FH) By RotorArea
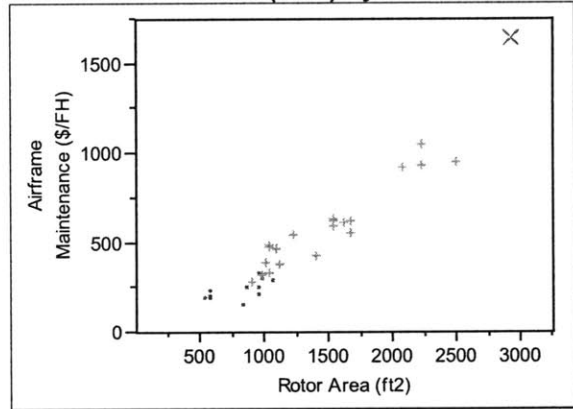


### Airframe Maintenance($/FH) By Sqrt(MTOGW)(lbs)
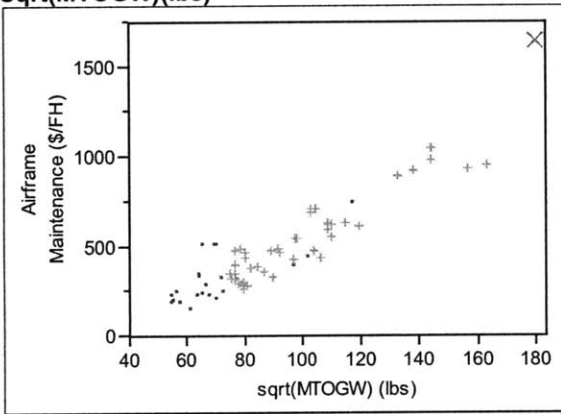


### Airframe Maintenance ($/FH) By Last Yr Produced
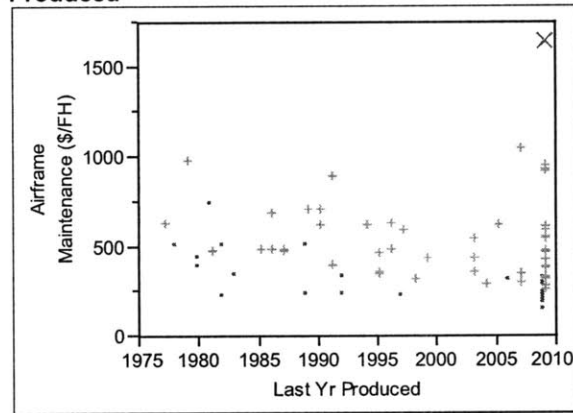


### Airframe Maintenance ($/FH) By AcqCost
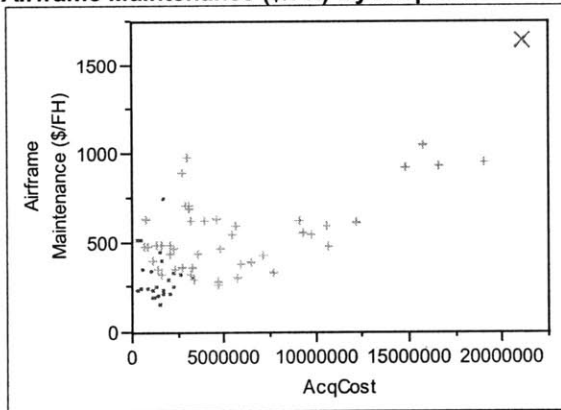


### Airframe Maintenance ($/FH) By InstalledPower
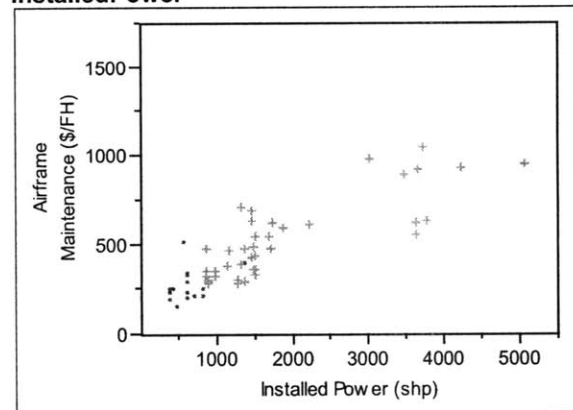
**Response Airframe Maintenance ($/FH)**
**Whole Model**
**Regression Plot**



**Actual by Predicted Plot**



P<.0001 RSq=0.83 RMSE=87.742
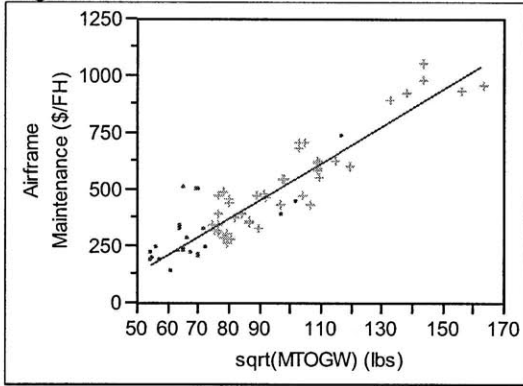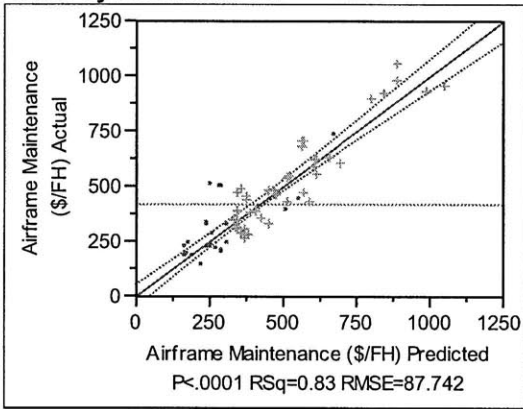
### Summary of Fit

| | |
|---|---|
| RSquare | 0.834324 |
| RSquare Adj | 0.831515 |
| Root Mean Square Error | 87.74242 |
| Mean of Response | 415.396 |
| Observations (or Sum Wgts) | 61 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 2287414.6 | 2287415 | 297.1157 |
| Error | 59 | 454225.2 | 7699 | Prob > F |
| C. Total | 60 | 2741639.9 | | <.0001 |

### Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 41 | 343679.62 | 8382.43 | 1.3649 |
| Pure Error | 18 | 110545.63 | 6141.42 | Prob > F |
| Total Error | 59 | 454225.25 | | 0.2413 |
| | | | | Max RSq |
| | | | | 0.9597 |

### Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|

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| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|
| Intercept | -273.763 | 41.52964 | -6.59 | <.0001 |
| sqrt(MTOGW2) (lbs) | 8.075088 | 0.468473 | 17.24 | <.0001 |

## Residual by Predicted Plot
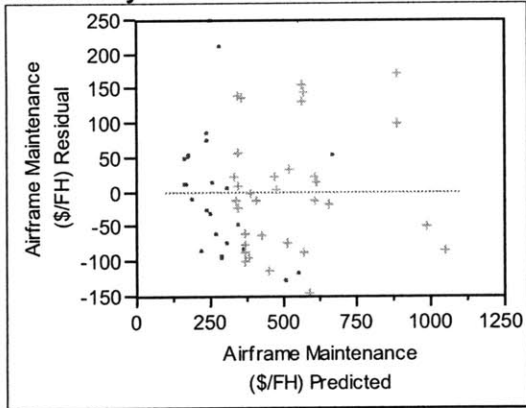


## Press

| Press | Press RMSE |
|---|---|
| 489374.89337 | 89.5686286 |

**Prediction Expression**

-273.76298686363

+8.07508804024326*sqrt(MTOGW2) (lbs)

## sqrt(MTOGW2) (lbs)
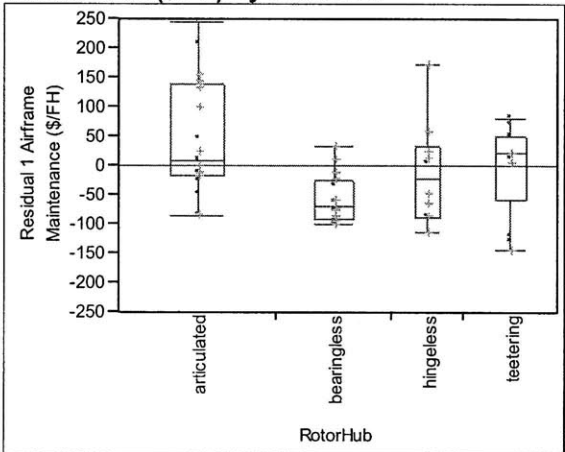## Leverage Plot
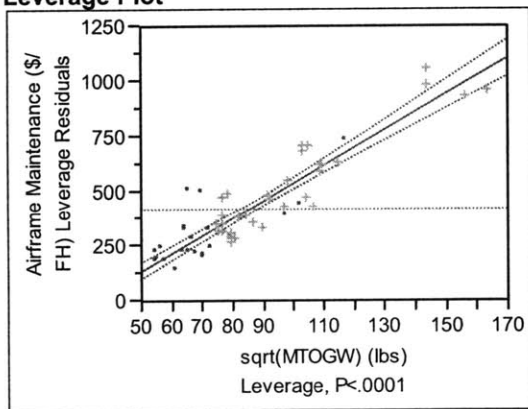
**Appendix I Select Plots of Maintenance DOC Model 1 Residuals**

**Oneway Analysis of Residual Airframe Maintenance ($/FH) By Gear**
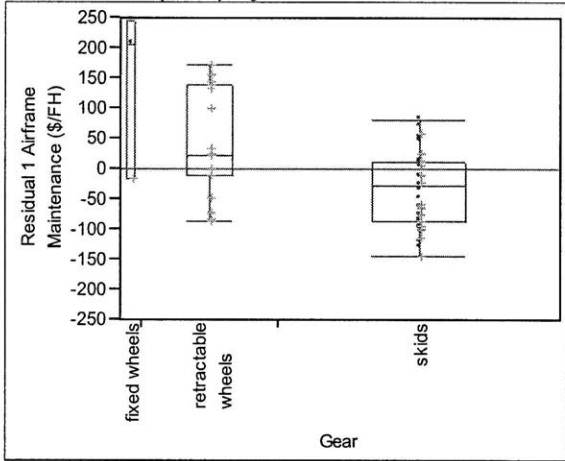


**Oneway Analysis of Residual Airframe Maintenance ($/FH) By TailRotor**
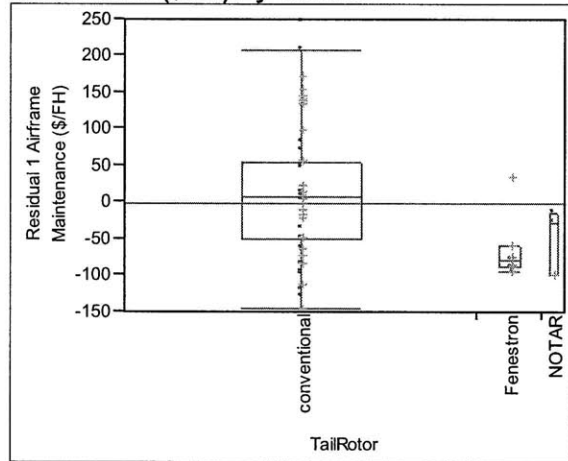


**Oneway Analysis of Residual Airframe Maintenance ($/FH) By RotorHub**



**Oneway Analysis of Residual Airframe Maintenance ($/FH) By BladeMaterial**
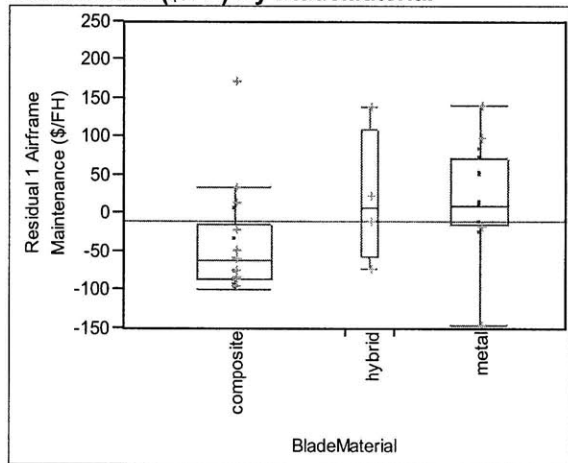
**Appendix J ANOVA Output for Maint. DOC Model 1 Residual vs Landing Gear**

**Oneway Analysis of Residual Airframe Maintenance ($/FH) By Gear**
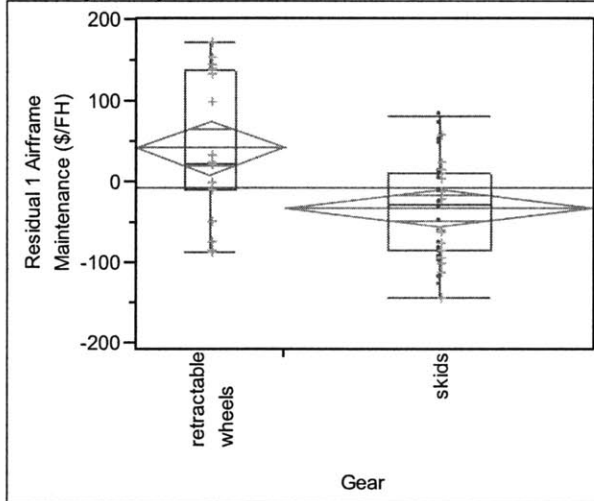


Missing Rows
3Excluded Rows
16

## Oneway Anova
## Summary of Fit

| | |
|---|---|
| Rsquare | 0.198647 |
| Adj Rsquare | 0.184338 |
| Root Mean Square Error | 70.57892 |
| Mean of Response | -7.50066 |
| Observations (or Sum Wgts) | 58 |

## t Test
skids-retractable wheels
Assuming equal variances

| | | | |
|---|---|---|---|
| Difference | -73.57 | t Ratio | -3.72584 |
| Std Err Dif | 19.75 | DF | 56 |
| Upper CL Dif | -34.01 | Prob > \|t\| | 0.0005 |
| Lower CL Dif | -113.13 | Prob > t | 0.9998 |
| Confidence | 0.95 | Prob < t | 0.0002 |
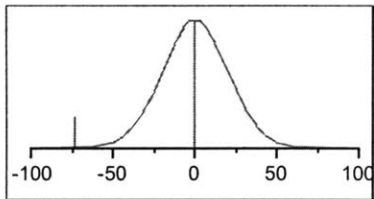


## Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Gear | 1 | 69150.86 | 69150.9 | 13.8819 | 0.0005 |
| Error | 56 | 278957.53 | 4981.4 | | |
| C. Total | 57 | 348108.39 | | | |

## Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| retractable wheels | 19 | 41.969 | 16.192 | 9.53 | 74.41 |
| skids | 39 | -31.601 | 11.302 | -54.24 | -8.96 |

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**Appendix K ANOVA Output for Maint. DOC Model 1 Residual vs Rotor Hub Type**

## Oneway Analysis of Residual Airframe Maintenance ($/FH) By RotorHub
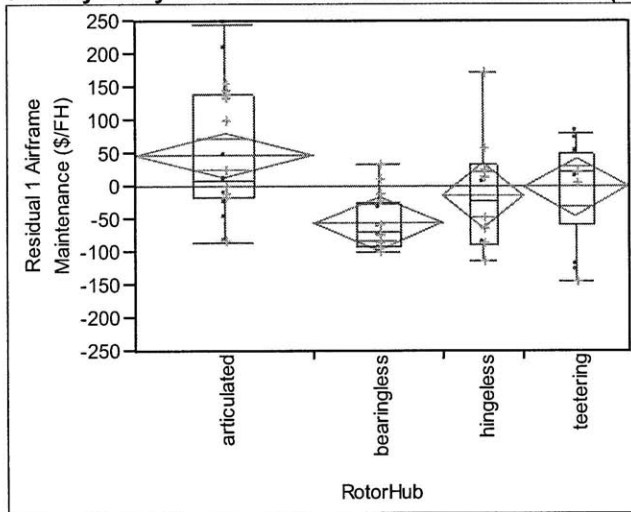


Excluded Rows
16

### Oneway Anova
### Summary of Fit

| | |
|---|---|
| Rsquare | 0.227926 |
| Adj Rsquare | 0.187291 |
| Root Mean Square Error | 78.43821 |
| Mean of Response | -5.5e-14 |
| Observations (or Sum Wgts) | 61 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| RotorHub | 3 | 103529.77 | 34509.9 | 5.6090 | 0.0019 |
| Error | 57 | 350695.48 | 6152.6 | | |
| C. Total | 60 | 454225.25 | | | |

### Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| articulated | 22 | 47.810 | 16.723 | 14.32 | 81.30 |
| bearingless | 16 | -56.761 | 19.610 | -96.03 | -17.49 |
| hingeless | 10 | -12.956 | 24.804 | -62.63 | 36.71 |
| teetering | 13 | -1.084 | 21.755 | -44.65 | 42.48 |

Std Error uses a pooled estimate of error variance

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**Appendix L ANOVA Output for Maint. DOC Model 1 Residual vs Blade Material**

**Oneway Analysis of Residual Airframe Maintenance ($/FH) By BladeMaterial**
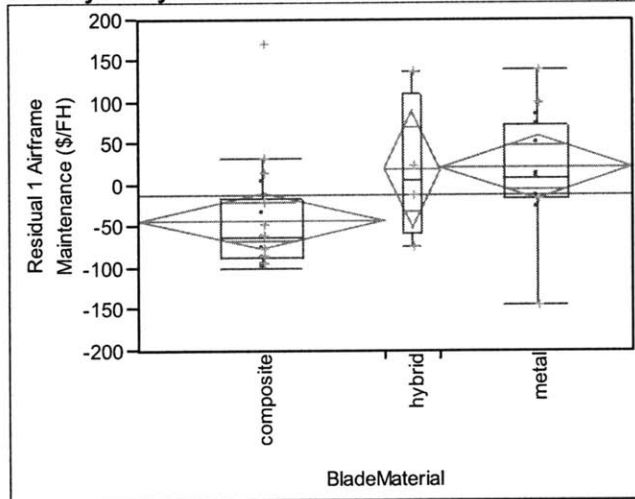


Missing Rows
25Excluded Rows
16
### Oneway Anova
### Summary of Fit

| | |
|---|---|
| Rsquare | 0.190017 |
| Adj Rsquare | 0.140927 |
| Root Mean Square Error | 69.784 |
| Mean of Response | -10.2704 |
| Observations (or Sum Wgts) | 36 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| BladeMaterial | 2 | 37700.08 | 18850.0 | 3.8708 | 0.0309 |
| Error | 33 | 160703.60 | 4869.8 | | |
| C. Total | 35 | 198403.68 | | | |

### Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| composite | 18 | -42.622 | 16.448 | -76.09 | -9.16 |
| hybrid | 4 | 20.076 | 34.892 | -50.91 | 91.06 |
| metal | 14 | 22.655 | 18.651 | -15.29 | 60.60 |

Std Error uses a pooled estimate of error variance

# Appendix M Regression Details Airframe Maintenance DOC Model 2

## Response Airframe Maintenance ($/FH)
## Whole Model
## Actual by Predicted Plot



P<.0001 RSq=0.91 RMSE=66.252
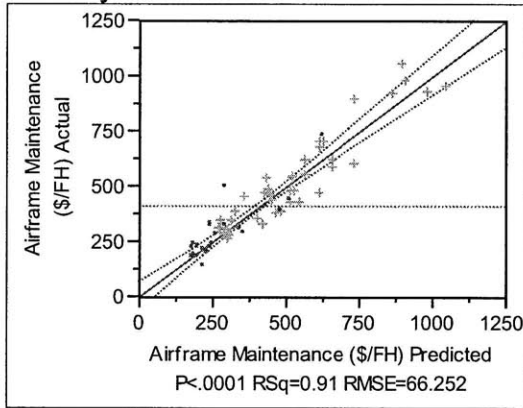
## Summary of Fit

| | |
|---|---|
| RSquare | 0.914809 |
| RSquare Adj | 0.906618 |
| Root Mean Square Error | 66.25192 |
| Mean of Response | 408.8417 |
| Observations (or Sum Wgts) | 58 |

## Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 5 | 2450971.0 | 490194 | 111.6789 |
| Error | 52 | 228244.5 | 4389 | Prob > F |
| C. Total | 57 | 2679215.5 | | <.0001 |

## Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 38 | 224713.92 | 5913.52 | 23.4495 |
| Pure Error | 14 | 3530.53 | 252.18 | Prob > F |
| Total Error | 52 | 228244.46 | | <.0001 |
| | | | | Max RSq |
| | | | | 0.9987 |

## Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|
| Intercept | -209.7623 | 37.58427 | -5.58 | <.0001 |
| sqrt(MTOGW2) (lbs) | 7.1294743 | 0.481302 | 14.81 | <.0001 |
| RetractableWheels? | 87.186249 | 25.90867 | 3.37 | 0.0014 |
| HingelessRotor? | -11.37563 | 28.13469 | -0.40 | 0.6876 |
| BearinglessRotor? | -58.21847 | 24.45999 | -2.38 | 0.0210 |
| TeeteringRotor? | -5.477242 | 25.2627 | -0.22 | 0.8292 |

## Effect Tests

| Source | Nparm | DF | Sum of Squares | F Ratio | Prob > F |
|---|---|---|---|---|---|
| sqrt(MTOGW2) (lbs) | 1 | 1 | 963110.72 | 219.4216 | <.0001 |
| RetractableWheels? | 1 | 1 | 49705.30 | 11.3242 | 0.0014 |
| HingelessRotor? | 1 | 1 | 717.57 | 0.1635 | 0.6876 |
| BearinglessRotor? | 1 | 1 | 24866.01 | 5.6651 | 0.0210 |
| TeeteringRotor? | 1 | 1 | 206.33 | 0.0470 | 0.8292 |

## Residual by Predicted Plot



## RetractableWheels?
## Leverage Plot
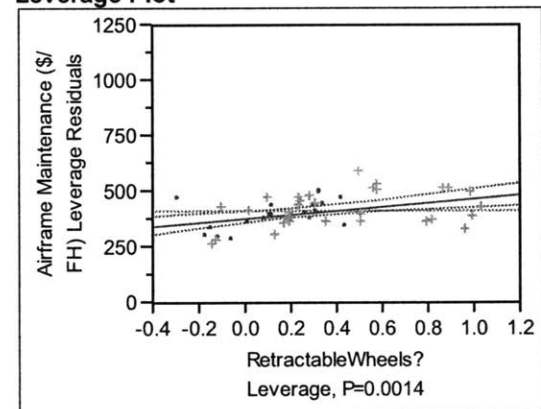


## Prediction Expression

-209.76228802664

+7.12947430276411*sqrt(MTOGW2) (lbs)

+87.1862489996329*RetractableWheels?

+-11.375631865718*HingelessRotor?

+-58.218468751287*BearinglessRotor?

+-5.477241897626*TeeteringRotor?

## Press

| Press | Press RMSE |
|---|---|
| 299501.71929 | 71.8597436 |

## sqrt(MTOGW2) (lbs)
## Leverage Plot



## HingelessRotor?
## Leverage Plot
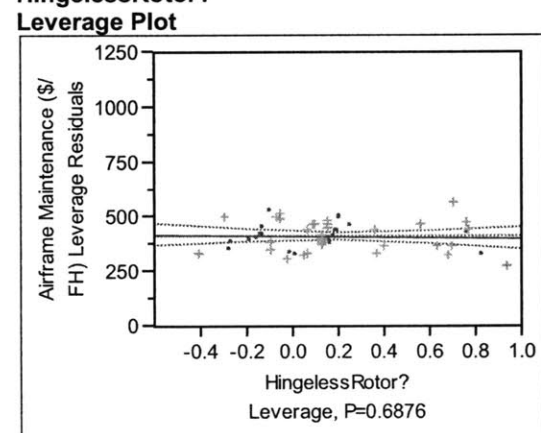


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## BearinglessRotor?
## Leverage Plot



Airframe Maintenance ($/FH) Leverage Residuals vs BearinglessRotor?
Leverage, P=0.0210

## TeeteringRotor?
## Leverage Plot



Airframe Maintenance ($/FH) Leverage Residuals vs TeeteringRotor?
Leverage, P=0.8292
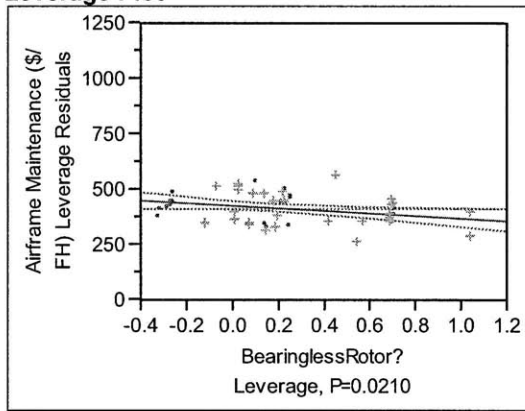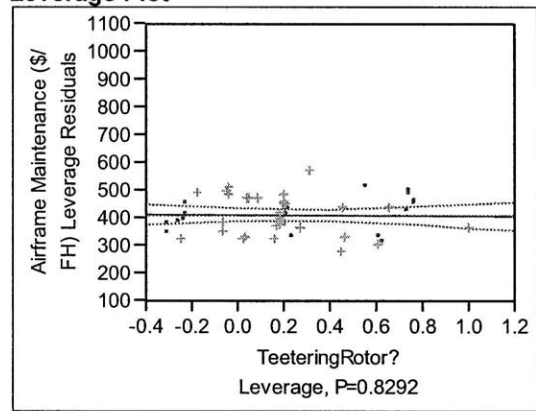
### Correlation of Estimates

| Corr | Intercept | sqrt(MTOGW2) (lbs) | RetractableWheels? | HingelessRotor? | BearinglessRotor? | TeeteringRotor? |
|---|---|---|---|---|---|---|
| Intercept | 1.0000 | -0.8602 | 0.2980 | 0.0094 | -0.2615 | -0.1765 |
| sqrt(MTOGW2) (lbs) | -0.8602 | 1.0000 | -0.6276 | -0.3371 | -0.1234 | -0.1780 |
| RetractableWheels? | 0.2980 | -0.6276 | 1.0000 | 0.3673 | 0.3689 | 0.3282 |
| HingelessRotor? | 0.0094 | -0.3371 | 0.3673 | 1.0000 | 0.4521 | 0.4406 |
| BearinglessRotor? | -0.2615 | -0.1234 | 0.3689 | 0.4521 | 1.0000 | 0.4999 |
| TeeteringRotor? | -0.1765 | -0.1780 | 0.3282 | 0.4406 | 0.4999 | 1.0000 |

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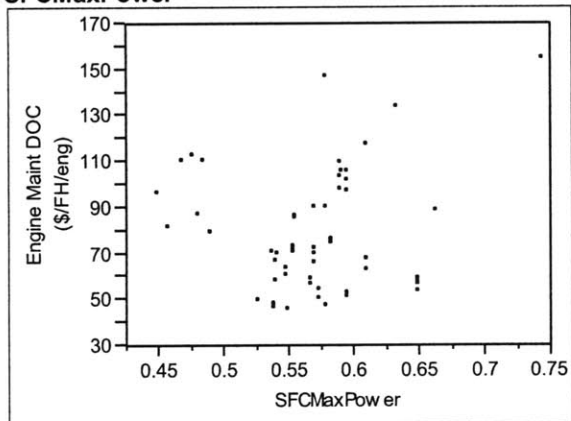**Appendix N Scatter Plots of Engine Maintenance DOC**

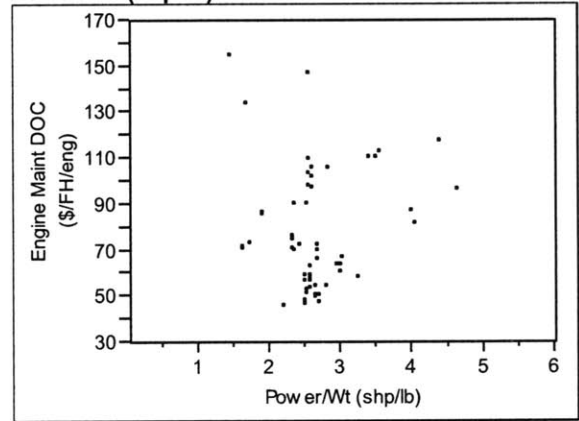**Bivariate Fit of TotalEngMaint ($/FH/eng) By SLSMaxPower**
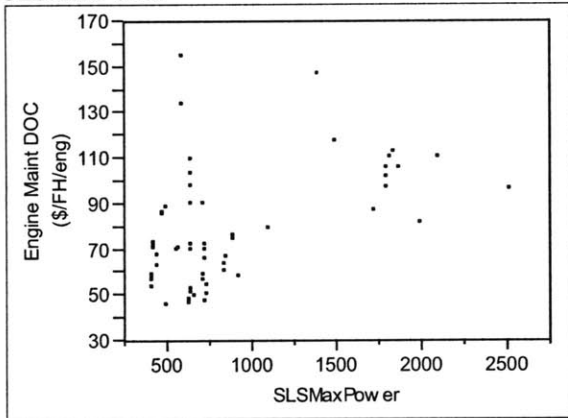


**Bivariate Fit of TotalEngMaint ($/FH/eng) By DryWtLessTailpipe**
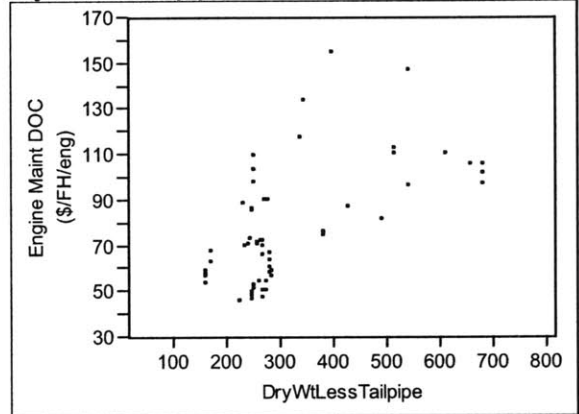


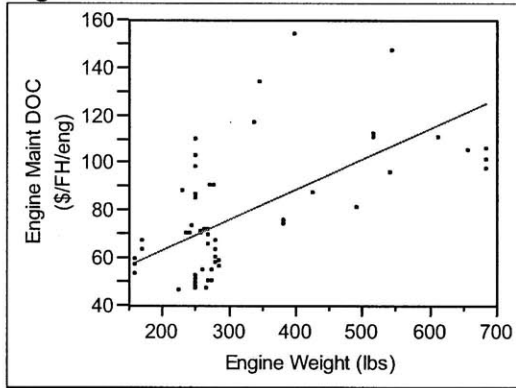**Bivariate Fit of TotalEngMaint ($/FH/eng) By SFCMaxPower**



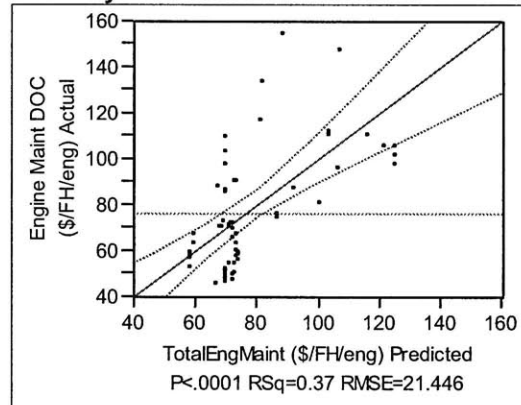**Bivariate Fit of TotalEngMaint ($/FH/eng) By Power/Wt (shp/lb)**

## Appendix O Full Regression Output for Engine Maintenance DOC Model 1

### Regression Plot



### Actual by Predicted Plot



### Summary of Fit

| | |
|---|---|
| RSquare | 0.368658 |
| RSquare Adj | 0.356279 |
| Root Mean Square Error | 21.44563 |
| Mean of Response | 76.09793 |
| Observations (or Sum Wgts) | 53 |

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 13696.433 | 13696.4 | 29.7804 |
| Error | 51 | 23455.660 | 459.9 | Prob > F |
| C. Total | 52 | 37152.092 | | <.0001 |

### Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 24 | 18561.347 | 773.389 | 4.2665 |
| Pure Error | 27 | 4894.313 | 181.271 | Prob > F |
| Total Error | 51 | 23455.660 | | 0.0002 |

| | |
|---|---|
| | Max RSq |
| | 0.8683 |

### Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|
| Intercept | 38.069312 | 7.565647 | 5.03 | <.0001 |
| DryWtLessTailpipe | 0.1274111 | 0.023348 | 5.46 | <.0001 |

**Residual by Predicted Plot**
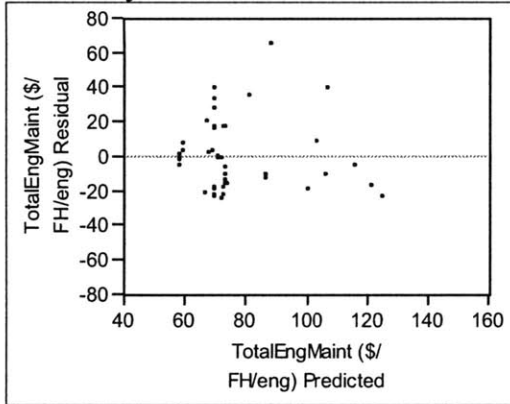


**Prediction Expression**

38.0693115833649

+0.12741112114683*DryWtLessTailpipe

**Press**

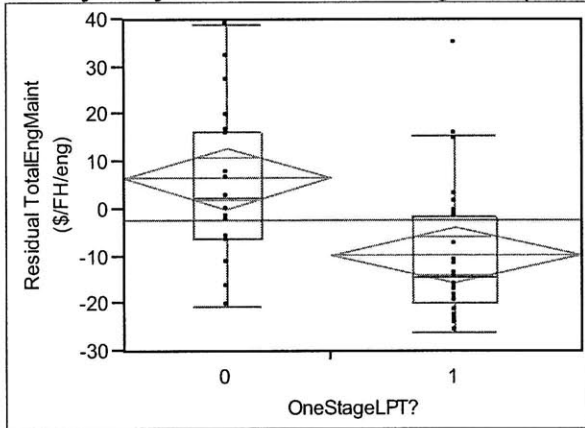| Press | Press RMSE |
|---|---|
| 25435.800472 | 21.9070939 |

**DryWtLessTailpipe**
**Leverage Plot**



Leverage, P<.0001
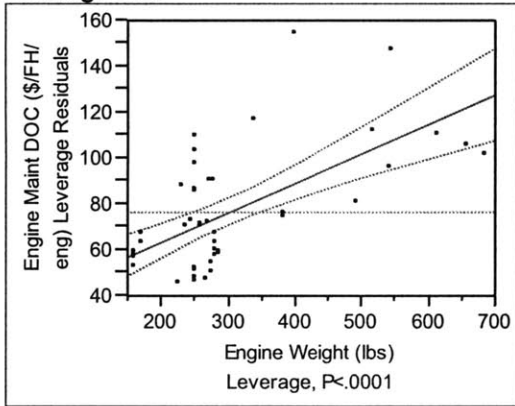
## Appendix P ANOVA for Number of LPT Stages vs. Engine Maint. DOC

**Oneway Analysis of Residual TotalEngMaint ($/FH/eng) By OneStageLPT?**



Missing Rows
9Excluded Rows
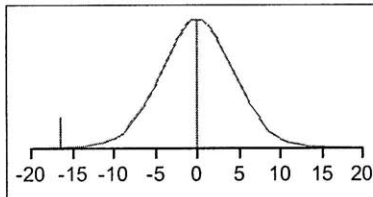17
### Oneway Anova
### Summary of Fit

| | |
|---|---|
| Rsquare | 0.228297 |
| Adj Rsquare | 0.212548 |
| Root Mean Square Error | 15.29977 |
| Mean of Response | -2.52144 |
| Observations (or Sum Wgts) | 51 |

### t Test
1-0

Assuming equal variances

| | | | |
|---|---|---|---|
| Difference | -16.393 | t Ratio | -3.80735 |
| Std Err Dif | 4.306 | DF | 49 |
| Upper CL Dif | -7.740 | Prob > |t| | 0.0004 |
| Lower CL Dif | -25.045 | Prob > t | 0.9998 |
| Confidence | 0.95 | Prob < t | 0.0002 |



### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| OneStageLPT? | 1 | 3393.247 | 3393.25 | 14.4959 | 0.0004 |
| Error | 49 | 11470.065 | 234.08 | | |
| C. Total | 50 | 14863.312 | | | |

### Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| 0 | 23 | 6.4785 | 3.1902 | 0.06747 | 12.89 |
| 1 | 28 | -9.9142 | 2.8914 | -15.72 | -4.10 |

Std Error uses a pooled estimate of error variance

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**Appendix Q ANOVA for Number of HPT Stages vs. Engine Maint. DOC**

## Oneway Analysis of Residual TotalEngMaint ($/FH/eng) By OneStageHPT?
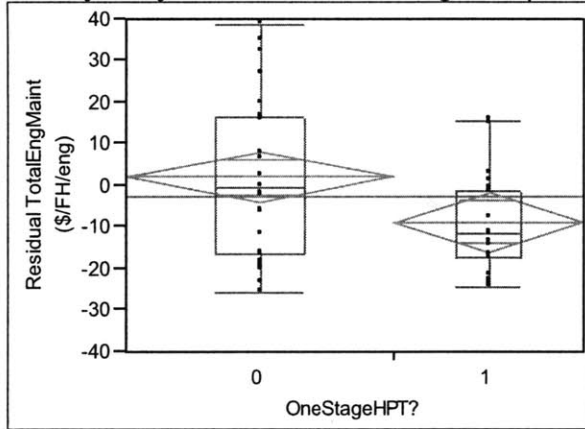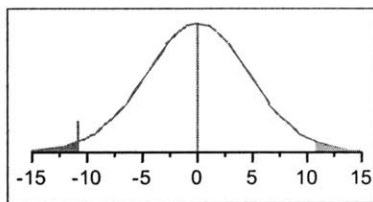


Missing Rows9
Excluded Rows17

### Oneway Anova
### Summary of Fit

| | |
|---|---|
| Rsquare | 0.098665 |
| Adj Rsquare | 0.08027 |
| Root Mean Square Error | 16.53495 |
| Mean of Response | -2.52144 |
| Observations (or Sum Wgts) | 51 |

### t Test
1-0
Assuming equal variances

| | | | |
|---|---|---|---|
| Difference | -10.896 | t Ratio | -2.31598 |
| Std Err Dif | 4.705 | DF | 49 |
| Upper CL Dif | -1.442 | Prob > \|t\| | 0.0248 |
| Lower CL Dif | -20.350 | Prob > t | 0.9876 |
| Confidence | 0.95 | Prob < t | 0.0124 |



### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| OneStageHPT? | 1 | 1466.482 | 1466.48 | 5.3638 | 0.0248 |
| Error | 49 | 13396.831 | 273.40 | | |
| C. Total | 50 | 14863.312 | | | |

### Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| 0 | 30 | 1.9650 | 3.0189 | -4.10 | 8.032 |
| 1 | 21 | -8.9306 | 3.6082 | -16.18 | -1.680 |

Std Error uses a pooled estimate of error variance

**Appendix R Full Regression Analysis for Engine Maint. DOC Model 2**

**Response TotalEngMaint ($/FH/eng)**
**Whole Model**
**Actual by Predicted Plot**



Engine Maint DOC ($/FH/eng) Predicted
P<.0001 RSq=0.64 RMSE=13.985
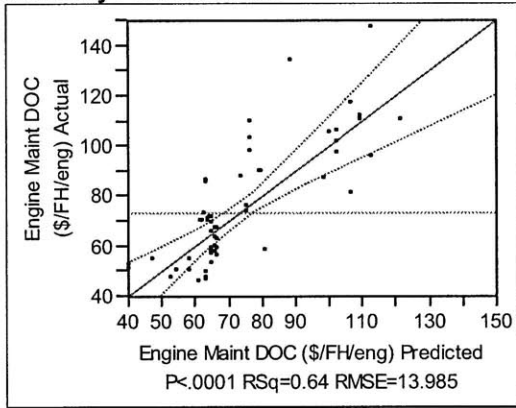
## Summary of Fit

| | |
|---|---|
| RSquare | 0.644467 |
| RSquare Adj | 0.604964 |
| Root Mean Square Error | 13.98496 |
| Mean of Response | 73.0692 |
| Observations (or Sum Wgts) | 51 |

## Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 5 | 15953.505 | 3190.70 | 16.3141 |
| Error | 45 | 8801.055 | 195.58 | Prob > F |
| C. Total | 50 | 24754.560 | | <.0001 |

## Lack Of Fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Lack Of Fit | 21 | 7129.5291 | 339.501 | 4.8746 |
| Pure Error | 24 | 1671.5258 | 69.647 | Prob > F |
| Total Error | 45 | 8801.0549 | | 0.0002 |
| | | | | Max RSq |
| | | | | 0.9325 |

## Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|---|---|---|---|---|
| Intercept | 42.975232 | 5.254282 | 8.18 | <.0001 |
| Engine Weight (lbs) | 0.1077318 | 0.015961 | 6.75 | <.0001 |
| OneStageHPT?[0] | -96.13543 | 27.0875 | -3.55 | 0.0009 |
| OneStageLPT?[0] | 98.412694 | 26.95031 | 3.65 | 0.0007 |
| Engine Weight (lbs)*OneStageLPT?[0] | -0.318218 | 0.096026 | -3.31 | 0.0018 |
| Engine Weight (lbs)*OneStageHPT?[0] | 0.3353963 | 0.096307 | 3.48 | 0.0011 |

## Residual by Predicted Plot
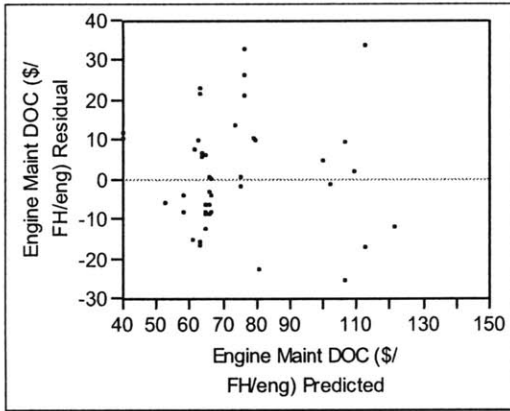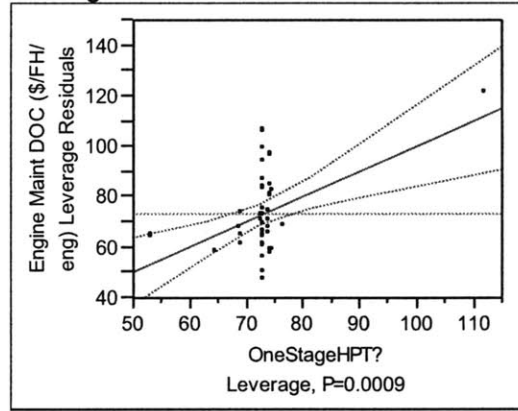


## Prediction Expression

42.9752322369316
+0.10773177122957*Engine Weight (lbs)

$+\text{Match}\left[\text{OneStageHPT?}\right]\begin{cases}0 \Rightarrow -96.135425633819 \\ 1 \Rightarrow 96.1354256338186 \\ \text{else} \Rightarrow .\end{cases}$

$+\text{Match}\left[\text{OneStageLPT?}\right]\begin{cases}0 \Rightarrow 98.4126940754822 \\ 1 \Rightarrow -98.412694075482 \\ \text{else} \Rightarrow .\end{cases}$

Engine Weight (lbs)

$^+*\text{Match}\left[\text{OneStageLPT?}\right]\begin{cases}0 \Rightarrow -0.3182179239784 \\ 1 \Rightarrow 0.3182179239784: \\ \text{else} \Rightarrow .\end{cases}$

Engine Weight (lbs)

$^+*\text{Match}\left[\text{OneStageHPT?}\right]\begin{cases}0 \Rightarrow 0.3353963282175 \\ 1 \Rightarrow -0.3353963282175 \\ \text{else} \Rightarrow .\end{cases}$

## Press

| Press | Press RMSE |
|---|---|
| 13787.723715 | 16.4422481 |

## Engine Weight (lbs)
## Leverage Plot



Engine Weight (lbs)
Leverage, P<.0001

## OneStageHPT?
## Leverage Plot



OneStageHPT?
Leverage, P=0.0009

## Least Squares Means Table

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| 0 | 77.336687 | 3.3698757 | 75.8496 |
| 1 | 72.065678 | 4.5711351 | 69.0972 |

## OneStageLPT?
## Leverage Plot



OneStageLPT?
Leverage, P=0.0007
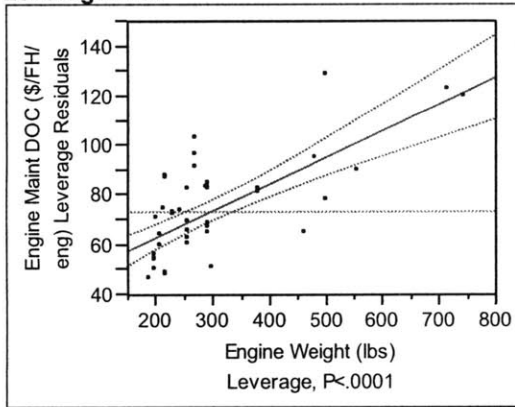
## Least Squares Means Table

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| 0 | 79.401818 | 4.4907766 | 80.4500 |
| 1 | 70.000547 | 3.4057005 | 67.0064 |

## Engine Weight (lbs)*OneStageLPT?
## Leverage Plot



Leverage, P=0.0018
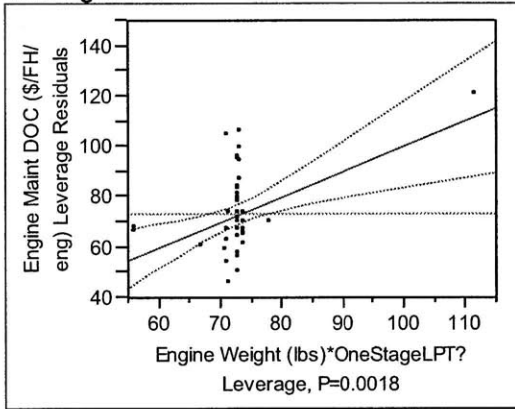
## Engine Weight (lbs)*OneStageHPT?
## Leverage Plot



Leverage, P=0.0011
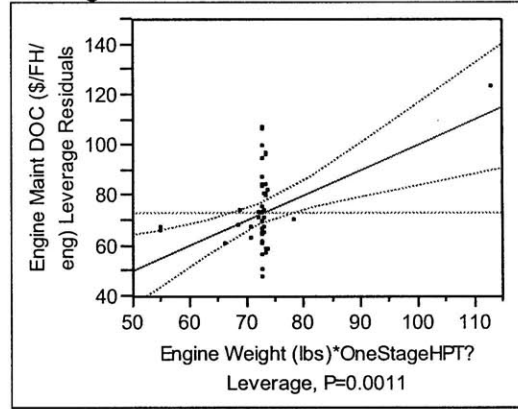
### Correlation of Estimates

| Corr | Intercept | Engine Weight (lbs) | OneStageHPT?[0] | OneStageLPT?[0] | Engine Weight (lbs)*OneStageLPT?[0] | Engine Weight (lbs)*OneStageHPT?[0] |
|---|---|---|---|---|---|---|
| Intercept | 1.0000 | -0.9146 | -0.1230 | 0.0713 | -0.0561 | 0.0957 |
| Engine Weight (lbs) | -0.9146 | 1.0000 | 0.1120 | -0.0658 | 0.0655 | -0.1004 |
| OneStageHPT?[0] | -0.1230 | 0.1120 | 1.0000 | -0.9811 | 0.9778 | -0.9935 |
| OneStageLPT?[0] | 0.0713 | -0.0658 | -0.9811 | 1.0000 | -0.9937 | 0.9799 |
| Engine Weight (lbs)*OneStageLPT?[0] | -0.0561 | 0.0655 | 0.9778 | -0.9937 | 1.0000 | -0.9862 |
| Engine Weight (lbs)*OneStageHPT?[0] | 0.0957 | -0.1004 | -0.9935 | 0.9799 | -0.9862 | 1.0000 |