

## Framework for Military Aircraft Fleet Retirement Decisions

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# **Framework for Military Aircraft Fleet Retirement Decisions**



# **Framework for Military Aircraft Fleet Retirement Decisions**

Dissertation

for the purpose of obtaining the degree of doctor  
at Delft University of Technology  
by the authority of the Rector Magnificus, Prof.dr.ir. T.H.J.J. van der Hagen,  
chair of the Board for Doctorates  
to be defended publicly on  
Monday 10 September 2018 at 10:00 o'clock

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# Summary

## Framework for Military Aircraft Fleet Retirement Decisions

Jeffrey NEWCAMP

The purpose of this work is as follows. Military aircraft are enormous investments for a nation. The systems lifecycle for aircraft spans decades wherein aging effects increase maintenance and operations costs over time. At some point, the deterioration of a fleet of aircraft erodes the capability of those assets below an acceptable threshold, thus triggering retirement planning by a military. Questions arise about how to retire a fleet, including how many aircraft should be retired, when those aircraft should be retired and which aircraft should be chosen. There are few military aircraft fleets that are retired each year, and even fewer managers who understand the aircraft retirement puzzle. This work addresses these questions. The purpose was to provide fleet managers with a comprehensive framework to guide decision-making, as well as to build tools and a standard guidance framework for fleet managers to implement.

In terms of methodology, in the absence of directly applicable existing research in this field, fleet management concepts and modelling approaches were studied in related fields and then applied to the military fleet retirement problem. The vital first approach to the problem required the baselining of military aircraft fleets given structural loading data and utilization histories. Database analysis and trending algorithms were written to draw correlations between existing data and structural fatigue effects. This work then implemented a greedy algorithm model to solve the individual aircraft retirement scheme. That led to a mixed-integer linear programming approach to optimize a fleet utilization and rotation model. Combined, these methods provided concrete steps for the fleet retirement decision framework, which followed established methods for designing a decision support framework. Throughout the work, a consistent case study fleet (United States Air Force's A-10 Thunderbolt II) was utilized to provide validation of the methods, while secondary case studies and validation techniques were employed to test applicability of the methods to other military aircraft fleets and other capital asset types.

In terms of concrete research results from the work carried out, this dissertation discovered that a framework for military aircraft fleet retirement decisions was a needed contribution

to the field. In the process of building that framework, other valuable results were obtained. It was found that aircraft utilization information could be correlated to cyclic loading data on an individual aircraft level. This revealed patterns in aircraft fleets showing which mission types and basing locations either increased or decreased structural degradation. Using that information led to the result that a fleet manager could determine which aircraft to retire prior to others while optimizing an objective function related to fleet cost, fleet utility or the ratio thereof. It was also found that a fleet manager could selectively utilize individual aircraft at particular bases flying particular missions to prolong or hasten the structural degradation of those aircraft. This led to the result that a fleet manager could therefore forecast retirement dates for an entire fleet, subpopulations within that fleet or individual assets.

From the research carried out, it is emphatically concluded that the results imply that a fleet manager beginning with only aircraft usage data can actively manage a fleet of aircraft to extract residual value from the fleet prior to retirement. This work showed that resource allocation could be improved by utilizing a mixed integer linear program to schedule asset retirements. Further, this work illustrated how a management strategy could impact future usage levels in a way to extend useful lifetime. With a capital asset as critical to national defense and as expensive to acquire, operate and retire as military aircraft, focusing on the end-of-life phase of the systems lifecycle not only promotes forward thinking but also provides potential cost savings. This work's limitations included its focus on military aircraft instead of all capital assets and that the methods were not implemented in an actual fleet environment. This dissertation demonstrated that a flexible framework with core modelling elements is a tool capable of solving the problem of aircraft fleet retirement decisions. Fleet managers both military and otherwise should investigate the applicability of the methods and findings in this dissertation to their own challenges. Future research must include application of the methods to an actual operating fleet. Also, the methods should be applied to other capital asset classes including military equipment and commercial equipment.

# Table of Contents

Acknowledgements.....	6
Summary.....	8
Nomenclature.....	14
1 Introduction .....	16
1.1 Problem Statement .....	16
1.2 Key Research Question .....	21
1.3 Research Objectives .....	21
1.4 Dissertation Overview.....	21
References .....	28
2 Aging Military Aircraft Landscape.....	30
2.1 The Aging Aircraft Problem .....	31
2.2 Background .....	33
2.3 The Case for End-of-Life Optimization .....	34
2.3.1 The Aging Aircraft Problem is Widespread.....	35
2.3.2 Aircraft are Continuing to Age With Little Remediation .....	36
2.3.3 Aging Aircraft Cost More to Maintain.....	37
2.3.4 Aircraft Utilization Directly Correlates to Aircraft Lifetime .....	38
2.3.5 Aircraft Are Retired With Unrealized Residual Value .....	39
2.3.6 Focusing on Aging Aircraft Optimization Can Realize Savings .....	40
2.4 Fleet Management Paradigm.....	41
2.5 Conclusions .....	43
References .....	45
3 Framework for Military Aircraft Fleet Retirement Decisions .....	48
3.1 Introduction .....	49
3.2 Literature Review .....	52
3.3 Elements of the Decision Support Framework.....	53
3.3.1 Understanding the structural toll caused by utilization .....	54

3.3.2	Recognizing the indicators that predispose a fleet for retirement .....	55
3.3.3	Determining an optimal fleet size and choosing which aircraft to retire.....	55
3.3.4	Optimizing end-of-life usage prior to retirement .....	55
3.4	Applying the Decision Support Framework.....	56
3.4.1	Applying a Decision Support Framework to Military Aircraft .....	56
3.4.2	Role of Expert Judgement.....	58
3.4.3	Implementing the Decision Support Framework .....	58
3.5	Evaluating the Decision Support Framework.....	59
3.6	Applying the Decision Support Framework to a Sample Fleet .....	60
3.6.1	Understanding the structural toll caused by utilization .....	60
3.6.2	Recognizing the indicators that predispose a fleet for retirement .....	60
3.6.3	Determining an optimal fleet size and choosing which aircraft to retire.....	61
3.6.4	Optimizing end-of-life usage prior to retirement .....	62
3.7	Conclusions .....	63
	References .....	65
4	Correlation of Mission Type to Cyclic Loading as a Basis for Agile Military Aircraft Asset Management.....	67
4.1	Introduction .....	68
4.1.1	Theoretical Context.....	70
4.2	Methodology .....	71
4.2.1	Data Reduction .....	71
4.2.2	Modeling the Usage Spectrum.....	72
4.2.3	Data Analysis.....	73
4.3	Results.....	74
4.3.1	Loading Environment .....	75
4.3.2	Mission Evaluation .....	79
4.3.3	Basic Fighter Maneuvers (BFM) and Surface Attack (SA) Missions Accrue the Most g-Counts.....	82
4.3.4	Close Air Support (CAS) and Navigation (NAV) Missions Are the Least Damaging.....	82

4.3.5	Aerial Refueling (AR) Missions Are Structurally Significant .....	83
4.3.6	Functional Check Flight (FCF) Missions Are the Most Extreme Flying.....	83
4.3.7	Relationship Between Aircraft Age and g-Counts .....	84
4.3.8	Relationship Between Flight Duration and g-Counts .....	85
4.3.9	Validation .....	87
4.4	Impact.....	89
4.5	Conclusions.....	90
	References .....	92
5	Time to Retire: Indicators for Aircraft Fleets .....	94
5.1	Introduction.....	95
5.2	Aspects of Fleet Retirement .....	97
5.3	Results and Discussion.....	103
5.3.1	Validating Utility Per Cost Zones.....	103
5.3.2	Asset Retirement Planning.....	105
5.4	Conclusions.....	106
	References .....	108
6	Application of a Greedy Algorithm to Military Aircraft Fleet Retirements .....	110
6.1	Introduction.....	111
6.2	Background .....	113
6.2.1	Literature Review .....	113
6.2.2	Replacement Theory.....	114
6.3	Methodology .....	115
6.3.1	Framing the Problem.....	115
6.3.2	Fleet and Aircraft Retirement Model.....	116
6.3.3	Mathematical Formulation.....	118
6.3.4	Solution Approach .....	121
6.4	Results.....	122
6.5	A-10 Case Study .....	125
6.6	Discussion .....	128

6.7	Validation.....	130
6.8	Conclusions.....	132
	References .....	134
7	Retirement Optimization Through Aircraft Transfers and Employment .....	136
7.1	Introduction.....	137
7.2	Literature Review.....	140
7.3	Methodology .....	141
7.3.1	Mathematical Formulation.....	144
7.4	Results and Discussion.....	146
7.4.1	Case Study .....	147
7.4.2	Disruption Management.....	151
7.5	Conclusions.....	154
	References .....	155
8	Conclusions .....	157
8.1	Reviewing the Research Objectives.....	158
8.2	Novelty.....	160
8.3	Main Contributions .....	160
8.4	Assumptions.....	162
8.5	Limitations .....	163
8.6	Future Work .....	163
	Curriculum Vitae .....	165
	List of Publications.....	167

## Nomenclature

ADADS	Aircraft Data Acquisition and Distribution System
AFTO	Air Force Technical Order
AHP	Analytic Hierarchy Process
ALEX	Airframe Life Extension Program
AMARG	Aircraft Maintenance and Regeneration Group
ANOVA	Analysis of Variance
AR	Aerial Refueling
ASIP	Aircraft Structural Integrity Program
AVDO	Aerospace Vehicle Distribution Officer
BFM	Basic Fighter Maneuvers
CAS	Close Air Support
CBO	Congressional Budget Office
CDF	Cumulative Distribution Function
CSL	Certified Service Life
DoD	Department of Defense
DSF	Decision Support Framework
DSS	Decision Support System
DST	Decision Support Tool
EFH	Equivalent Flight Hours
ESL	Economic Service Life
FAC	Forward Air Controller
FARM	Fleet and Aircraft Retirement Model
FCF	Functional Check Flight
FVB	Fleet Viability Board
MCDM	Multiple-Criteria Decision-Making
MDS	Mission Design Series
NAV	Navigation
OC-ALC	Oklahoma City Air Logistics Complex
OEM	Original Equipment Manufacturer
O&S	Operations and Support
OTH	Other
PAF	Project Air Force
ROTATE	Retirement Optimization Through Aircraft Transfers and Employment
SA	Surface Attack
SAB	Scientific Advisory Board
SAR	Search and Rescue
SAT	Surface Attack Tactics

USAF	United States Air Force
USD	United States Dollar



# **1 Introduction**

Aircraft age from day one and that aging comes with a cost. For the United States Air Force (USAF), the quantification includes three B-47 Stratojet bombers lost in 1958 to fatigue failures, the initiation of the Aircraft Structural Integrity Program (ASIP) in 1958 and the subsequent loss of aircraft, costly repairs and curtailment of service life estimates [1]. The effects of aging and the associated costs are critical inputs to the planning process for the usage and eventual retirement of aging aircraft. This work and resulting dissertation provides a flexible yet targeted framework for fleet managers to use when making military aircraft fleet retirement decisions. In this introduction, the problem statement will be presented, followed by the research question and the five research objectives. The context of the work will be discussed to provide an apt academic framing for the reasons behind this work. Lastly, this Introduction will provide an overview of the later chapters contained in this dissertation.

## **1.1 Problem Statement**

The current defense environment can be characterized by change. Globally, defense budgets are growing in some regions and shrinking in other regions, with the only constant being change [2]. In the USAF, defense spending for aging platforms has been under pressure as the acquisition of new capabilities demands monetary attention [3]. Aging platforms are necessary capability enablers but suffer from both the presence of newer, costlier fleets and costly aging effects [4]. The aging platform experiences a total cost increase due to rising maintenance costs as shown in Jardine's work on the economic life problem, summarized in Figure 1.1 [5].

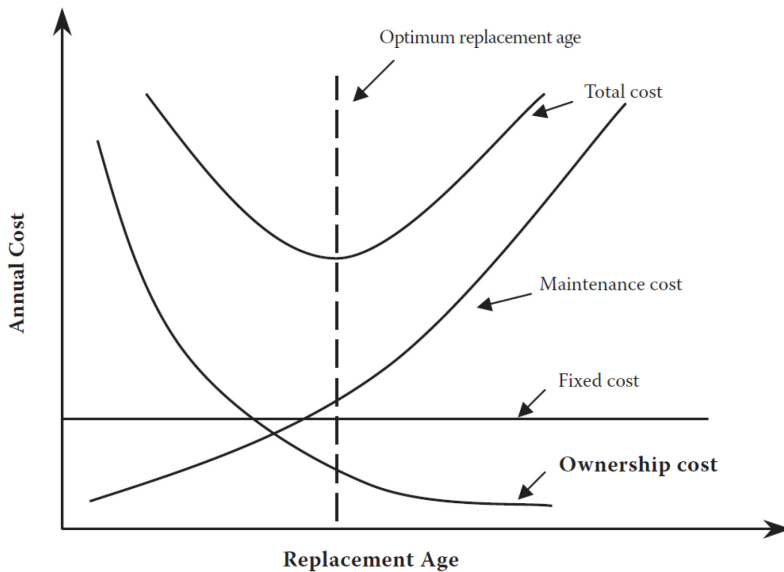


Figure 1.1: The economic life problem posed by Jardine [5]

In an analysis of alternatives, fleet managers find that they can continue to operate an aging fleet while its yearly cost increases until a point where it makes more fiscal sense to divest the aging fleet and acquire a new fleet [6, 7]. Even though a military aircraft fleet may number only in the hundreds of aircraft, the yearly operations and support costs of a fleet are staggering. This invites end-of-life optimization and management strategies, that if capable of extracting a fraction of a percent of value, may save millions of dollars annually.

There is a deceptive attractiveness to acquiring a new weapon system. Decision-makers can weigh the acquisition cost of a new aircraft platform one-to-one with the existing costs of an aging system. However, the lifecycle costs (including acquisition) of a new platform must be equitably compared to the lifecycle costs of an existing platform. Blanchard highlights the hidden costs in Figure 1.2 [8].

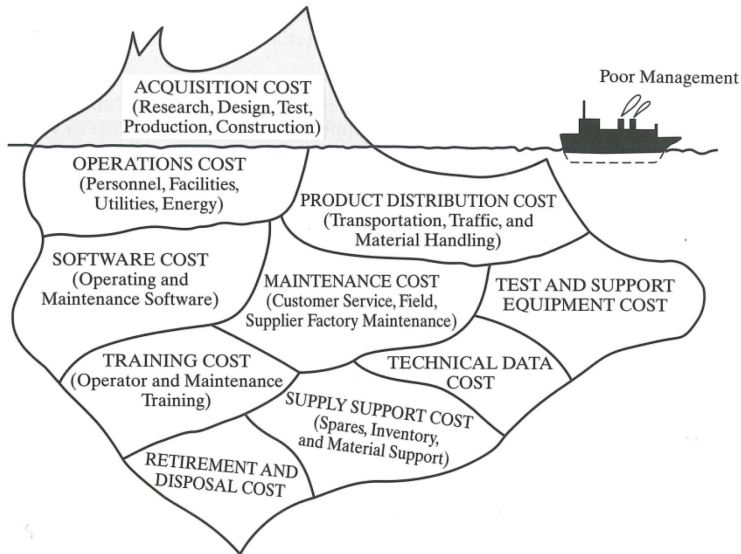


Figure 1.2: Hidden lifecycle costs for capital assets illustrated by Blanchard [8]

Fleet managers are burdened by innumerable short-term tasks that mollify long-term planning efforts [9]. A survey of current fleet ages of major aircraft types across the globe shows some average fleet ages of up to half a century [10, 11]. Therefore, fleet retirements are not frequent and fleet managers have little experience dealing with retirement decisions. There are no globally recognized tools for managing aging aircraft except the ASIP [12]. This is the context in which fleet managers can be found; making multi-billion dollar fleet management decisions while lacking the experience and the tools to make informed decisions.

This work began with the understanding that military aircraft fleet retirement decisions was an ill-defined, ambiguous topic area previously unexplored [13, 14]. The work that is conducted in this field is often conducted from within a military for that military and the results are not published openly for confidentiality reasons.

As this research matured, every objective pointed in the same direction, towards *resource allocation*. From within a military, actions feel operational in nature. A fleet of aircraft is relocated to a forward operating base to provide combat capability where it is needed. Every motive is attached to the tenet of national defense. However, from an academic perspective looking in from outside a military, fleet decisions are classically indicative of resource allocation [15]. Certainly, the end-game is to provide a combat capability but the

chess-like moves are effectively managing a fixed amount of resources to attempt to satisfy all the demands placed on the system [16].

In the chapters presented hereafter, it is critical to recognize that this context of resource allocation takes many forms. Chapter 4 reviews how structural lifetime (resource) was historically allocated to mission types. Chapter 6 looks at individual aircraft (resources) to determine which are necessary in the fleet and which should be allocated elsewhere. Lastly, the tool built to rotate aircraft between bases and missions in Chapter 7 is a set-covering tool designed to allocate resources across a network possessing demand.

Whether a military is experiencing growth or reductions, the theme of resource allocation is pertinent. The methods presented in this work are useful to militaries worldwide, but also to private industry and other government agencies. The core of these ideas is applicable outside military aircraft fleets. Many of the assumptions remain the same, just the asset type changes.

A typical fleet of military aircraft could be nearing 50 years of active service, numbering in the hundreds, valued at over \$2 billion and with a worldwide logistics footprint spanning a dozen locations. Imagine the tens of thousands of employees whose livelihood depends on that aircraft fleet, the thousands of pilots who flew it and the sole fleet manager responsible for its retirement. Retiring aircraft fleets is a titanic undertaking that happens so infrequently that a fleet manager would consider oneself lucky to retire a fleet during one's tenure. Few have direct knowledge of aircraft retirements and even fewer have developed tools to aid decision-making that has serious national defense, political and budgetary consequences. Planning for retirements is the duty of every fleet manager throughout the lifecycle of an aircraft fleet. Those who manage military aircraft fleets require methods to assist them with aircraft retirement decisions because ignoring the fact that even the newest fleet will require retirement planning is a failing course of action.

Choosing whether or not to retire a military aircraft or fleet is the fundamental question that generates many peripheral questions: deciding how many aircraft to retire, which aircraft and when to retire those aircraft shows just how quickly the procedural complexity increases. According to Grimsley, quantifying the economic burden of aging assets is a vital element of fleet planning [17]. Wilson's work showed that the lifecycle costs can be staggering, including an operations and sustainment phase that can exceed ten times more than the fleet's acquisition cost [18]. Because military aircraft are enormously expensive capital assets to acquire and operate, it is sensible to extract as much residual value prior to retirement as possible [19, 20]. This Dissertation tackles the problem by providing a framework to decision makers that can guide retirement decisions. If an Air Force can

streamline its retirement planning while optimizing the end-of-life usage of its aircraft, the air force can realize significant savings [21]. For example, the USAF's 2017 budget for operations and maintenance was over \$37.5 billion with aircraft flight hours costing \$4.6 billion of that total [22]. Retirement decisions that improve fleet planning can make better use of the operations and maintenance expenditures and make better use of aging assets.

Those making the decisions, the *military aircraft fleet managers*, are identified as the key stakeholders for this Dissertation. This can refer to a position within a military organization, a role, an individual or a group of individuals tasked with overseeing the fleet's logistical requirements. Fleet managers may possess various titles including fleet director, force programmer and operations manager. In some military organizations, the role of fleet manager is executed by a large matrix of individuals. This office in the USAF is often termed Strategic Plans, Programs and Requirements.

Some larger militaries employ analysts and operations researchers to assist with fleet management tasks. They use a quantitative approach that may include optimization techniques to better inform fleet decisions. While this work focused on optimal usage of an aircraft fleet, non-optimal solutions are also presented when expert opinion is necessarily interlaced with quantitative methods.

Within the aviation community, there is little agreement on the definition of aging aircraft and even less on aging fleets. For the purposes of this research, aging fleets are those in operational usage, even newly acquired fleets. The acquisition phase of an aircraft's lifecycle may extend well beyond 10 years so an aircraft flying its first flight may have been conceived, designed and built using antiquated technology and methods, thus contributing to an aging paradigm [23, 24].

Retirement decisions include both the choice to defer and the choice to initiate the retirement of assets. Fleet managers must also decide when to retire aircraft, how many, which ones and in what order. When the decision is made to defer retirement, there must be a valid reason such as the impact on warfighting capability and that decision must be revisited periodically [25].

Improving retirement decisions has two elements: quantitative and qualitative. The quantitative element demands that retirement decisions be benchmarked against the right objective metric which is valuable to the organization [26]. The qualitative element gives expert opinion an inroad, underscoring how a fleet decision is complex and cannot alone be decided by quantitative methods [27, 28].

## **1.2 Key Research Question**

*How can a Decision Support Framework and methodology be developed and established so that military aircraft fleet managers can optimize the use of their aging fleets and improve their retirement decisions?*

This research question guided the research objectives in this work, providing both focus and direction. This work's research question is both specific and broad. It addresses not all fleet management, but only military aircraft fleet management. Each air force worldwide must perform fleet management or the lack thereof is detrimental. Despite the number of air forces being small, within each exists fleet management functions for each aircraft type. Within the specific field of military aircraft, the research question broadly calls for both the optimization of usage and the improvement of retirement decisions. Each element is methodically addressed in the subsequent chapters of this text.

## **1.3 Research Objectives**

The goal of the work was to develop a fleet management framework to aid fleet managers with aging military aircraft fleet decisions. Cognizant of the scope of the research question, this effort was broken down into five research objectives to meet that goal.

- 1. To develop a framework for military aircraft fleet retirement decisions.*
- 2. To show that individual aircraft data can be used to link mission usage to cyclic loading.*
- 3. To illustrate the indicators that can be detected at the aircraft and fleet level that are indicative of asset degradation.*
- 4. To develop a methodology to determine which aircraft should be retired from a fleet and in what order.*
- 5. To build a tool for fleet managers to use in rotating aircraft between bases and mission sets in order to give increased control over fleet-aging prior to retirement.*

## **1.4 Dissertation Overview**

The following seven chapters answer the research question and deliver tangible outcomes for each of the research objectives. The Dissertation was arranged so that Chapter 2 provides an ample overview and context for the work. It provides motivation for the work and all necessary background to understand the aging aircraft problem. Chapter 3 then provides the overarching decision support framework that can be used by aircraft fleet

managers to better manage their fleets. Chapters 4-7 provide the necessary elements that provide substance to the decision support framework. These chapters include methodologies for solving a variety of problems related to the theme of resource allocation. Lastly, Chapter 8 is the concluding chapter, which summarizes the findings of the work and addresses the research objectives.

Four critical figures link the work between the chapters. Chapter 2's Figure 2.6 (reproduced here as Figure 1.3) distills the Dissertation's focus to the elements of usage, basing and retirements. This concept is followed in the remaining chapters, showing that aging fleet management is centered on those three ideas.

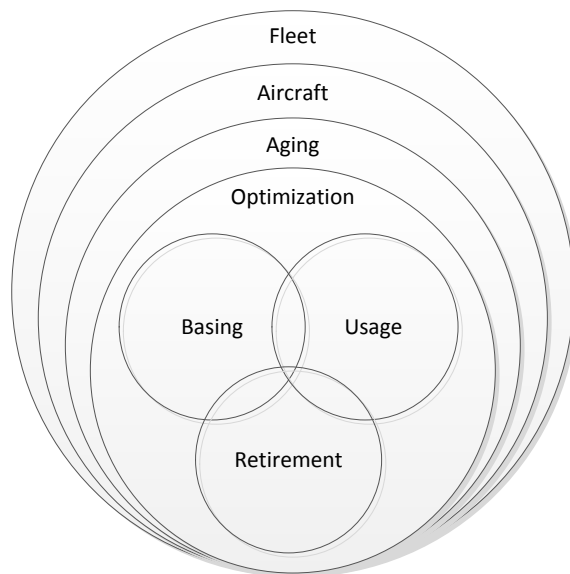


Figure 1.3: Visualization of how optimization fits into the fleet management perspective

In Chapter 3, Figure 3.2 (reproduced here as Figure 1.4) presents the decision support framework that can aid fleet managers through the complex nature of aircraft fleet retirement decisions. The numbers shown in some of the blocks represent the four primary elements of the decision support framework.

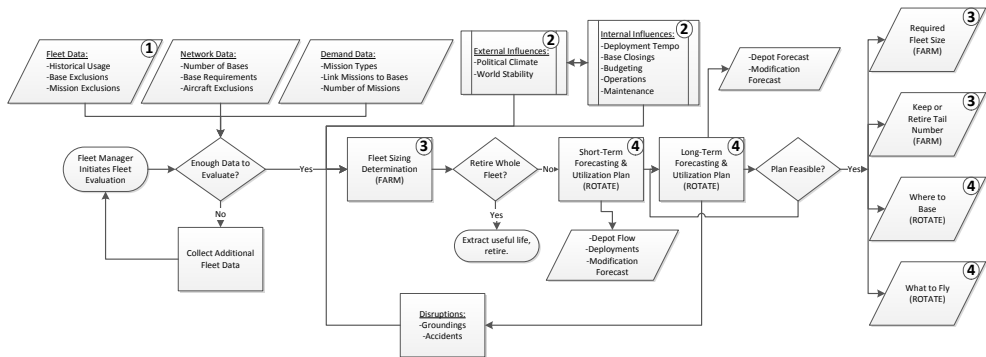


Figure 1.4: Military aircraft retirement DSF

The decision support framework employs the Fleet and Aircraft Retirement Model presented in Chapter 6's Figure 6.1 (reproduced here as Figure 1.5). This figure catalogs the critical methodological steps required to determine which aircraft to retain in an aging fleet.

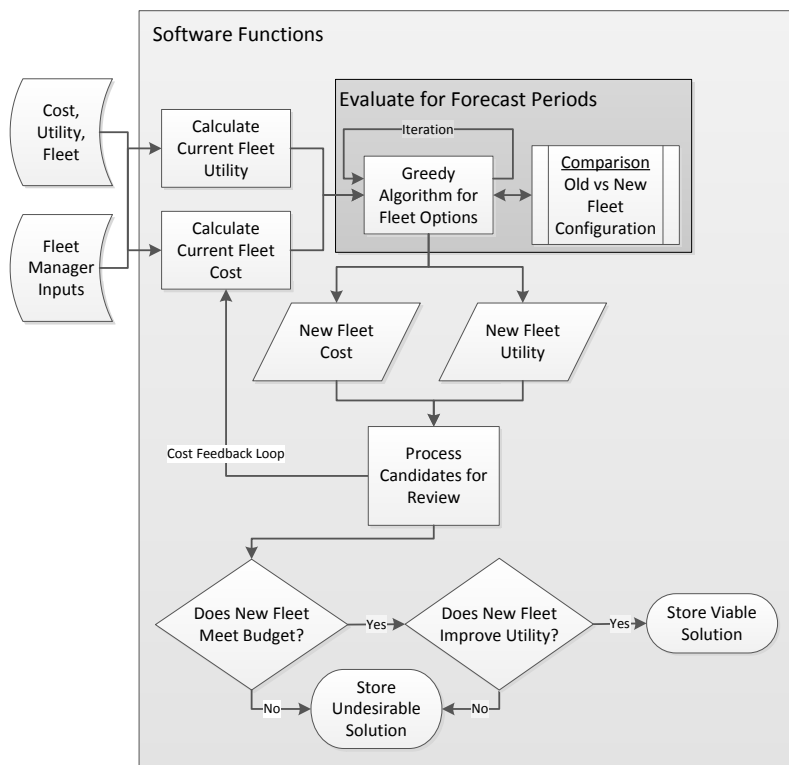


Figure 1.5: Flow chart for methodology steps



The Retirement Optimization Through Aircraft Transfers and Employment from Chapter 7's Figure 7.4 (reproduced here as Figure 1.6) is outlined in detail. The methodology shows how to make fleet reassignment decisions based on historical utilization and future forecast demand.

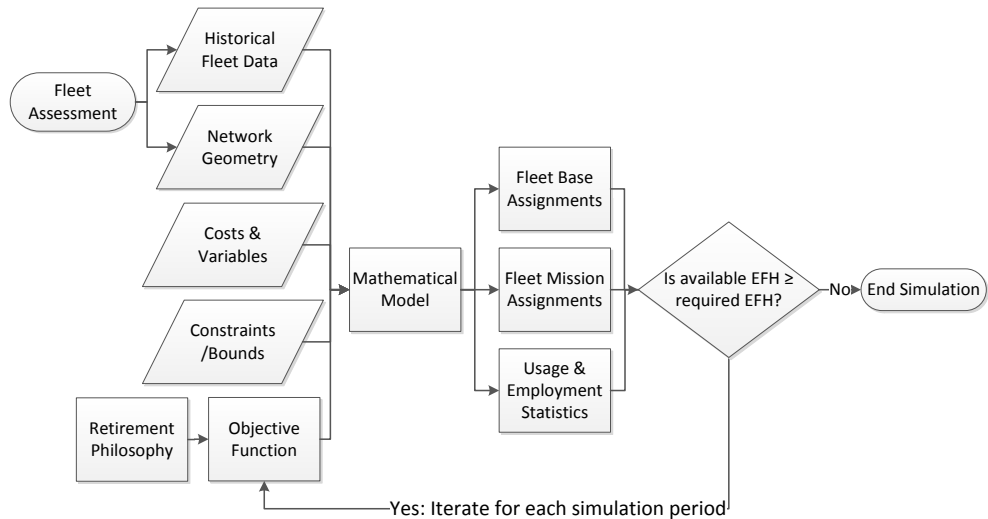


Figure 1.6: ROTATE methodology flow chart

These four figures are primary takeaways from this Dissertation. Each adds a concrete piece to the understanding of the resource allocation inherent to the problem of fleet management. The figures have been reproduced here to provide a fitting overview of the Dissertation's most important elements.

Excluding the Introduction and Conclusions chapters, the remaining six chapters were each the subject of a paper. Chapter 2 was previously published at a conference [29]. Chapter 3 is a peer-reviewed journal article awaiting a decision. Chapters 4 through 6 were published in peer-reviewed journals [30-32]. Chapter 7 is a peer-reviewed journal article awaiting a decision. Each of the previously published or publication pending articles has been reproduced here in near original form so that it is a standalone work. This by nature reveals some overlap in explanation, citations and introductory material. Each chapter includes an introductory page that provides context and links it to the overall dissertation. The chapters are described in greater detail below.

## **Chapter 2 – Aging Military Aircraft Landscape**

This chapter serves to provide background on the aging military aircraft problem. It gives context to the discussion, making a strong case for why this work's research question has been asked. A thorough review of current literature on the field is undertaken in this chapter and six premises are discussed, ranging from the assertion that the aging aircraft problem is widespread to the conclusion that focusing on aging aircraft optimization can realize savings. A fleet management paradigm for the future is presented. It is one that emphasizes a dynamic, fluid role for lifecycle managers who focus on predictive forecasting for their fleet while implementing cost-benefit analysis findings.

## **Chapter 3 – Framework for Military Aircraft Fleet Retirement Decisions**

Positioned ahead of Chapters 4-7 purposefully, this chapter presents a decision support framework built to aid fleet managers making fleet retirement decisions. The chapter illustrates the necessary data and inputs, then describes how a fleet manager and his surrogates should approach the problem of retirement. Care is taken to provide detailed implementation instructions since every fleet possesses different types of databases and has different constraints. Expert judgement is highlighted as an essential element in the decision support framework, even more important than rote quantitative fleet data. This chapter concludes with a validation effort showing the application of the decision support framework to a sample fleet, proving the flexibility of the framework even within a fleet having complex requirements and an immediate retirement requirement of 25% of its fleet.

## **Chapter 4 – Correlation of Mission Type to Cyclic Loading as a Basis for Agile Military Aircraft Asset Management**

This chapter establishes that individual aircraft tracking data can be used to define how much structural degradation an airframe has withstood in its lifetime. Many fleets already possess these types of data as aircraft sensors and recording equipment have been commonplace for decades. The data link the types of missions, lengths, altitudes, airspeeds, numbers of landings and other useful information to the cyclic loading experienced. Despite physics models being unable to predict exact lifetimes, the use of cyclic loading data can inform predictions for lifetime so that asset management may have a starting basis. This chapter concludes with a validation case study using the USAF's A-10 Thunderbolt II.

## **Chapter 5 – Time to Retire: Indicators for Aircraft Fleets**

If a fleet manager can predict when a fleet is nearing end-of-life, that knowledge can be used to more actively manage the fleet and its aircraft. This chapter shows that there are portents prior to aircraft structural failure. The motivations for aircraft retirements and the triggers for these motivations are described so fleet managers can recognize how their fleets align with known indications evidenced in other aging fleets. To illustrate a quantitative

measure for recognizing the aging effects on an aircraft, the *utility per cost ratio* is developed. This metric compares a metric of utility chosen by the fleet manager against a lifecycle cost indicator. It was shown that the utility per cost ratio is a fair predictor of where a fleet resides on the aging continuum. Three zones show a break-in period, usage period and degradation period. Six USAF aircraft types were used to validate the work.

### **Chapter 6 – Application of a Greedy Algorithm to Military Aircraft Fleet Retirements**

This chapter presents a model for identifying the right size of a fleet and which individual assets should be retained in that fleet to maximize capability. The methodology used a greedy algorithm that iteratively decided whether or not a fleet composition met fleet requirements. The mathematical model allows for the choice of an objective function based on cost minimization, utility maximization or the maximization of the utility per cost ratio. An output of this model shows in what order to retire the aircraft to preserve the most fleet capability while downsizing the fleet size. The USAF's A-10 Thunderbolt II was used as the case study fleet for model validation. This chapter concludes by showing that early retirements levy the greatest impact on lifetime fleet cost and utility.

### **Chapter 7 – Retirement Optimization Through Aircraft Transfers and Employment**

This chapter presents a mixed-integer linear programming model whose objective function maximizes remaining equivalent flight hours for aircraft. The linear program allows for a network of operating locations and a set of mission types each having different required amounts. The work seeks to achieve the fleet manager's goal, whether that is to retire all aircraft at one time, to retire aircraft in batches at multiple times or to retire aircraft in an ongoing fashion, in very small batches more frequently. This chapter tells fleet managers how to use their aircraft as they age in a way to extract more value from the fleet. This can entail both hastening aircrafts' retirement or delaying those retirements. It is shown that fleet managers can closely control their fleet's utilization to achieve the manager's desired fleet retirement profile. Disruption management scenarios (deployments, accidents, budget changes) are successfully modeled and presented. Validation of the mixed-integer linear programming model was performed using the USAF's A-10 Thunderbolt II fleet, resulting in a nearly 18% shape error improvement for retirement planning dates.

### **Chapter 8 – Conclusions**

This chapter includes three sections. The first reviews the research objectives presented in Chapter 1. Then, the main contributions of the research are summarized. Limitations of the work are stated. Lastly, suggestions for future work and extensions to this work are discussed.

Therefore, the contents in the following chapters of this Dissertation will address the key achievements concerning the main research goal.

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## 2 Aging Military Aircraft Landscape

*This chapter serves to provide background on the aging military aircraft problem. It reviews the state-of-the-art in the field and canvases the literature available on the aging aircraft topic, which was quite narrow. The current state of aging aircraft best practices in the United States are discussed, including an overview of the Aircraft Structural Integrity Program. This chapter gives context to the discussion, making a strong case for why this work's research question has been asked. A thorough review of current literature on the field is undertaken in this chapter and six premises are discussed, ranging from the assertion that the aging aircraft problem is widespread to the conclusion that focusing on aging aircraft optimization can realize savings. These premises are valuable to establish prior to undertaking the remaining material in this topic and are done here to serve as a preliminary chapter for the remainder. Because of the findings in this chapter, an important outcome was to establish a fleet management paradigm for the future of aircraft fleet management. It is one that emphasizes a dynamic, fluid role for lifecycle managers who focus on predictive forecasting for their fleet while implementing cost-benefit analysis findings.*

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# Aging Military Aircraft Landscape

## Abstract

Military aircraft fleets are continuing to age despite increased structural integrity concerns and rising maintenance costs. Aircraft are not being replaced or retired in large numbers but are instead having their lives extended beyond their original design service lives. Because aging aircraft cost more to maintain, this additional burden on air forces is a forcing function for smarter approaches to enhanced structural health monitoring. As data recorder technology has improved and recording capacity has increased, structural health monitoring tools have become more important in understanding aircraft life. Accrued historical data present opportunities for end-of-life fleet optimization. This paper provides a thorough review of the aging aircraft problem and suggests a direction for future end-of-life fleet optimization research. The suggestions include the alteration of aircraft utilization, optimization for aircraft basing and the prediction of structural fatigue, all of which can enable the realization of fleet-wide cost savings.

## 2.1 The Aging Aircraft Problem

Some important 1990s aircraft recapitalization programs in the United States were postponed because funding was prioritized to other appropriations [1]. This initiated a death spiral resulting in more aging aircraft in the Air Force, Navy and Marine Corps fleets: older aircraft have become more expensive to maintain leaving less defense spending for new acquisition programs, and thus fewer new aircraft have been purchased to replace the aging aircraft. This resulted in the situation seen today, where aircraft are kept in service well past their initially planned service lives. According to Pyles, to keep a fleet averaging less than 20 years of age, the United States Air Force (USAF) would need to purchase 315 aircraft per year – a feat it has not accomplished for decades [2]. The direct impact of possessing an aging aircraft fleet is the increased sustainment cost and the reduced aircraft availability due to decreased inspection and repair intervals.

While new development programs garner much of the excitement concerning military aircraft, the reality is that approximately 70%-90% of a defense program's budget is spent in the sustainment phase – not in the development phase of the system lifecycle [3], [4], [5]. Coincidentally, approximately 90% of the lifecycle costs are determined before production begins so there is a well-defined, up-front window in which designers can affect decades of sustainment cost [6]. Because some aircraft were never intended to be flown as long as they have been, lifecycle planning for the sustainment phase is inadequate thus resulting in additional cost. Essentially, 1960s and 1970s aircraft designers did not anticipate that they were designing an airplane to be flown for 50 years, so their design mentality did not



account for costly life extension programs and end-of-life problems now seen. More recent aircraft development programs have planned for anticipated lifetime extension to thwart these problems.

The term ‘aging aircraft’ is new to the aircraft lexicon so operators and maintainers are continually adapting to the needs of these aircraft [7]. The USAF Scientific Advisory Board (SAB) defined aging aircraft as those aircraft whose age exceeds 20-25 years or those aircraft that have exceeded 75% of their certified service life, whichever is less [3]. The Australian Civil Aviation Safety Authority chose to declare all aircraft ‘aging aircraft’ commencing at their date of manufacture, further suggesting that the rate of aging is the more dominant descriptor [8]. The sector of aircraft that comprise the category of aging aircraft in the USAF will continue to grow in size over the coming decades because aircraft retirement rates in the USAF are low. Since there is so much opportunity for value extraction from aging aircraft, techniques for managing these aircraft must be developed. Unfortunately, as Ribeiro and Gomes found, end-of-life aircraft research is young and there is a lack of “quantitative, transparent models about handling aircraft at the end of their lives” [9]. End-of-life strategies are worth capital investment and investigation. Fleet makeup must be optimized, economical basing strategies should be developed, fatigue and maintenance costs can be better forecast and smarter decisions about when to retire aircraft and fleets are needed.

Though this study focuses on military aircraft stakeholders with a particular emphasis on the USAF, its applicability extends to other military services, foreign militaries and even into the commercial sector. Militaries and services utilize their aircraft fleets differently, but the underlying physics of aging effects such as corrosion and structural fatigue affect all aircraft similarly. Dixon posited that military and commercial aging effects are sometimes relatable because militaries share aircraft types with the commercial sector and some mission profiles like cargo missions and aerial refueling missions are similar to airline flight profiles [10]. Therefore, this research proposes the landscape in which all aging aircraft fleets must be analyzed and suggests that opportunities for optimization must be sought.

This paper is divided into three subsequent sections. The background section contains a thorough examination of fleet concepts to include maintenance and usage costs. Section three provides the case for end-of-life optimization, a necessity if aircraft acquisition numbers are to remain, in the best case, unchanged. This section consists of six tenets, each one building on the previous. The flow begins with the assertion that the aging aircraft problem is widespread and finishes with the conclusion that a fleet can realize savings by

focusing on the aging aircraft problem. Lastly, the paper ends with a conclusions section that provides final thoughts and recommendations for fleet managers.

## 2.2 Background

Aging aircraft issues have increased in importance over the past decades, due in part to several high-visibility accidents. For the USAF, it was the 1950s in-flight structural failure of a B-47 wing that triggered the beginning stages of the Aircraft Structural Integrity Program (ASIP) [11]. The Department of Defense (DoD) wrote MIL-HDBK-1530A in 1972 to address structural concerns and the USAF wrote Policy Directive 63-10 [12], [13]. A detailed and relevant history of the ASIP and structural health monitoring is found in the work of Kudva, et al [14]. The five objectives of the ASIP are included in Table 2.1 [12]. The application of these objectives using structural health monitoring is summarized by Molent and Aktepe’s comprehensive review of the field [15].

Table 2.1: ASIP objectives

Number	Objective
1	Define the structural integrity requirements associated with meeting Operational Safety, Suitability and Effectiveness requirements.
2	Establish, evaluate, substantiate, and certify the structural integrity of aircraft structures.
3	Acquire, evaluate, and apply usage and maintenance data to ensure continued structural integrity of operational aircraft.
4	Provide quantitative information for decisions on force structure planning, inspection, modification priorities, risk management, expected life cycle costs and related operational and support issues.
5	Provide a basis to improve structural criteria and methods of design, evaluation, and substantiation for future aircraft systems and modifications.

Within the USAF, aircraft acquisition programs began to incorporate structural health monitoring (Objective 3) first as a desired feature and later as a requirement. The F-16 acquisition program required only one in six aircraft to possess structural health monitoring but the B-1B program required structural health monitoring for all serial numbers to be included as an initial design requirement [16], [17]. Similarly, Navy and Marine Corps aircraft have possessed structural health monitoring capabilities for decades. It is now common practice to require this technology for fighter, attack and bomber aircraft [18].

There are a variety of structural health monitoring techniques spanning from very basic to very complex. Molent and Aktepe's summary, shown as Figure 2.1, clearly describes the four most common techniques [19]. Simple flight hour counting has been accomplished since the beginning of flight. Counting hours merely quantifies airframe use but says nothing about utilization. Fatigue meters are simple electrical or mechanical devices that increment counts each time a specified load factor is crossed. Most fatigue meter systems are mounted at the aircraft center of gravity and therefore only record the load factor at one location, limiting their usefulness. Also, most fatigue meters do not record a time history of loading so the data show how many times a load factor was reached and not how long a load factor was sustained. Further, aircraft weight is crucial to understanding the impact of a load factor but fatigue meter systems are not capable of monitoring aircraft weight. Flight parameter monitoring became more popular with the advent of aircraft data buses. Parameters from the bus, sometimes numbering in the thousands, are recorded. This monitoring type can leave a fleet logistician with an overwhelming volume of data that can be hard to interpret. Strain gauges provide the best loading information but can be expensive to install, calibrate and interpret.

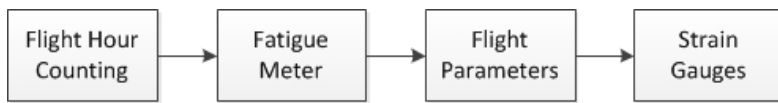


Figure 2.1: Structural health monitoring types [19]

ASIP managers use the data collected by structural health monitoring technologies to make important aircraft and fleet-wide decisions. Utilization changes, inspection intervals and retirement planning all hinge on the collected information. ASIP managers make use of work done by researchers and agencies that have spent resources studying aging aircraft problems. The major contributor to the field has been RAND Corporation's Project Air Force (PAF). Begun in 1946, PAF has solved many varieties of problems for the USAF with just a subset being focused on aging aircraft issues [20]. Major universities, the Federal Aviation Administration, the National Aeronautics and Space Administration and many others have also sought ways to contribute to this field.

### 2.3 The Case for End-of-Life Optimization

End-of-life optimization requires financial investment in structural health monitoring hardware and then takes years of data-gathering before useful patterns can be understood and exploited. This investment must see a reasonable return to warrant the risk of increased fleet management expenditure. Aircraft fleets are rapidly aging, little is being done to

rectify the aging problem and aging aircraft cost more to maintain, so fleet optimization has a valid trade space.

### 2.3.1 The Aging Aircraft Problem is Widespread

Air forces, navies and armies worldwide experience aging aircraft issues. Commercial airlines, private aircraft owners, tourism operators and airline brokers also face these problems. Structural fatigue and corrosion are widely studied but end-of-life fleet optimization sees much less academic and corporate investment. For example, Ribeiro and Gomes found the literature sparse on end-of-life alternatives [9]. Table 2.2 shows reasons why various entities do not focus their efforts on studying and publishing their findings.

Table 2.2: Reasons for sparse end-of-life literature

<b>Entity</b>	<b>Reason</b>
Military Services	Publication of efforts may jeopardize national security
Commercial Airlines	Publication of analysis can forfeit corporate advantage
Private Aircraft Owners	Organizations and individuals lack resources to study/publish on the topic
Tourism Operators	Focused on profit
Airline Brokers	Lack interest in system of systems architecture

The existing literature on aging aircraft thoroughly addresses structural and corrosion issues. The maintenance of maturing military aircraft has been discussed by the Congressional Budget Office (CBO), Skinner, Yonggang and Honglang, the Air Force Studies Board, Keating and Dixon and Hildebrandt and Sze [1], [21], [22], [23], [24], [25]. Heller and Thomsen showed that aging fleets require additional training for maintenance personnel and specialized steps to increase safety [26]. Berens et al conducted risk analyses relating to fatigue cracking in metallic structures for aging fleets and Groner addressed the corrosion issues relating to mature aircraft [27], [28].

The aging aircraft problem transcends borders and services. Kurdelski et al discuss the application of structural load monitoring systems in the Polish Armed Forces with some comparisons to the German Air Force [29]. The North Atlantic Treaty Organization is concerned about the aging aircraft problem, as is the United States Coast Guard [30], [31]. Garcia wrote about the United States Navy’s retirement planning and a novel method for optimizing fleet makeup [32]. Lincoln even posited that aging aircraft problems faced by

military aircraft often have corollaries in the commercial sector – and management of both can be enigmatic [33].

Aging aircraft operators are responding to the need for more focus in this area through enhanced structural health monitoring, as discussed by Albert et al, Connor et al, Maley et al and at length in Staszewski et al [34], [31], [4], [35]. Unfortunately, current data collection is not uniform across aircraft fleets. Even within one mission design series, multiple generations of flight data recorder technology possessing incremental capabilities exist. Therefore, historical data take many forms, making it difficult to conduct both longitudinal and horizontal studies.

### **2.3.2 Aircraft are Continuing to Age With Little Remediation**

In 1996, Groner wrote that large aircraft like bombers and aerial refueling tankers were kept flying longer than in previous decades, with average ages between 40 and 50 years [28]. In 2001, the average age of USAF aircraft was 22 years old [36]. A 2003 RAND report found that the average KC-135 refueling tanker fleet was 40 years old [24]. In 2005, the C-5A fleet averaged 30 years [37]. In 2011, the average USAF aircraft age was 26 years old [3]. Johns concluded in 2012 that the USAF fleet is the oldest it has ever been [38]. Reid's work addressed the dangers to safety when aircraft are operated beyond their original design service life [39].

Relevant studies that recommend recapitalization of fleets increased in the 1990s through the 2010s because large data sets from digital recording means became available. Unfortunately, Hall found that most aircraft programs focus more on collecting aging data than they do on using those data to make management decisions [40]. The current organizational climate suggests that fleet managers desire to recapitalize their fleets but do not do so because of high up-front development and replacement costs or because they are not trained to understand the available data. DoD data from fiscal years 2016 until 2025 show a negative trend in fleet size, as shown in Figure 2.2 [41]. These data include all planned retirements as well as all planned purchases of aircraft over the next ten years. The net loss of aircraft over the forecast period is 962 aircraft, or 7% of the force's 2016 end-strength.

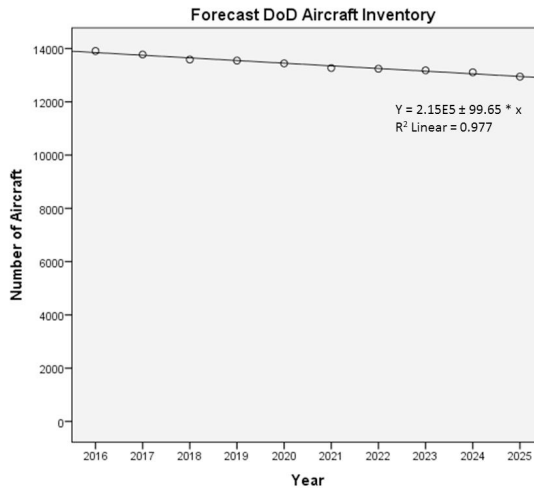


Figure 2.2: U.S. DoD aircraft inventory forecast for FY 2016-2025

### 2.3.3 Aging Aircraft Cost More to Maintain

Some analysts anecdotally describe the cost trend over time for aircraft as a bathtub-shaped curve like the one shown in Figure 2.3. Evidence exists to support the high operations and maintenance costs early in the system lifecycle but the CBO found no studies that illustrate the rapidly rising cost curve indicative of wear-out at the end of an aircraft’s lifecycle [1].

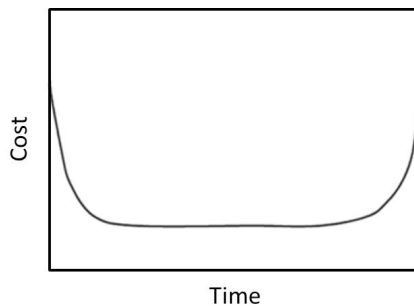


Figure 2.3: Notional bathtub curve

There is evidence, though, that after the initially high costs for maintenance there is an increase in annual operating costs between 1% and 3% per year for military services like the Air Force and Navy [24], [32]. This is due in part to decreased scheduled inspection intervals. According to Bond et al’s two case studies, these inspections alone without aircraft loading pattern knowledge add risk to the understanding of aircraft health [42].

Grimsley’s comprehensive review of the USAF aging aircraft strategy showed that unintended problems arise with aging aircraft during inspections, further increasing maintenance costs [43]. Greenfield used stochastic and deterministic modeling to show this positive relationship between aircraft age and sustainment cost [44]. He also found that operating organizations are unable to accurately predict when to begin a new aircraft acquisition program because development cycles vary greatly in length. This makes it difficult to know how to manage an aging fleet economically. Dixon’s work summarized previous studies and showed that all but Kamins found a positive age effect, which is the increase in maintenance cost as an aircraft ages [10]. Dixon’s summary is included as Table 2.3. His log-linear regression analyses used Department of Transportation Form 41 data from U.S. airlines divided into three age groups (0-6 years, 6-12 years, 12+ years). The results showed a positive age effect for the first two age groups and a non-statistically significant positive age effect for the aging aircraft in the third group [10]. Dixon’s study is added as the last row in Table 2.3. Note that Dixon’s endogenous divisions for aircraft ages do not suggest an alternative definition contradictory to that shown in this paper’s introduction.

Table 2.3: Aging aircraft age effect [10]

<b>Authors</b>	<b>Date</b>	<b>Age Effect</b>	<b>Data Level</b>	<b>Sector</b>
Kamins [45]	1970	No	Multiple	Air Force & Commercial
Hildebrandt and Sze [25]	1990	+	Aircraft	Air Force
Johnson [46]	1993	+	Aircraft	Navy
Stoll and Davis [47]	1993	+	Multiple	Navy
Ramsey	1998	+	Multiple	Air Force & Commercial
Francis and Shaw [48]	2000	+	Aircraft	Navy
CBO [1]	2001	+	Anecdotal	Air Force
Jondrow et al. [49]	2002	+	Aircraft	Navy
Pyles [2]	2003	+	Aircraft	Air Force
Boeing	2004	+	Fleet	Commercial
Dixon [10]	2006	+	Fleet	Commercial

(\*)

\*Age effect present for 0-6 and 6-12 year old aircraft, but may not exist for those 12+.

#### 2.3.4 Aircraft Utilization Directly Correlates to Aircraft Lifetime

Military aircraft fleets are disposed of when they become too costly to maintain at a desired level of availability. For most platforms, flight hours, effective flight hours or cycles are used as the independent variable for this decision with the dependent variable being

maintenance costs. Flight hours are calculated from liftoff to touchdown in most flight organizations. Some organizations add a token amount of time for taxiing operations (USAF standard is 0.3 hours), which may skew loading estimations for those aircraft flying short-duration missions. Effective flight hours is an algorithm-based number typically derived from flight condition severity factors. Cycles are an important metric for life-limited components and for fatigue concerns. Original Equipment Manufacturers (OEM) test aircraft to these metrics and make recommendations to aircraft operators based on test results. Therefore, if a flying organization reaches the recommended aircraft lifetime in flight hours, effective flight hours or cycles, aircraft disposal or overhaul must be discussed.

Boyd asserted that the greatest impact on the aging process comes from post-manufacturing decisions [8]. Maintenance policies are important, as is flight utilization. More austere operating conditions can shorten an aircraft's lifetime. Khoo and Teoh wrote that how an airline uses its aircraft for an optimum level of service will determine its profitability [50]. The military fleet corollary to profitability is the availability of combat capability. Once a commercial aircraft is no longer profitable or a military aircraft can no longer provide combat capability, the utilization has hastened the aircraft's lifetime.

### **2.3.5 Aircraft Are Retired With Unrealized Residual Value**

Monitoring the structural health of individual tail numbers and then predicting the risk of continued flight is difficult. Military fleet managers often make group retirements based on OEM recommendations. This methodology ensures that some aircraft possess residual life, which is helpful if a fleet is pulled from desert storage for continued use in the future but not helpful if a fleet manager is trying to maximize aircraft lifetime. The clusters in Figure 2.4 show evidence that aside from outliers (hard landings, over-g incidents and crashes), this particular DoD aircraft type has had parts of its fleet retired at planned intervals ( $n = 246$ ). The ordinate shows normalized flight hours and the abscissa shows normalized arrival time at the Aerospace Maintenance and Regeneration Group (AMARG; desert storage). Both axes are normalized to unity to show representative data. In this case, the concentrated data points show three separate retirement events, all correlating to flight-hour threshold retirements instead of retirement decisions based on individual aircraft structural lifetime calculations.



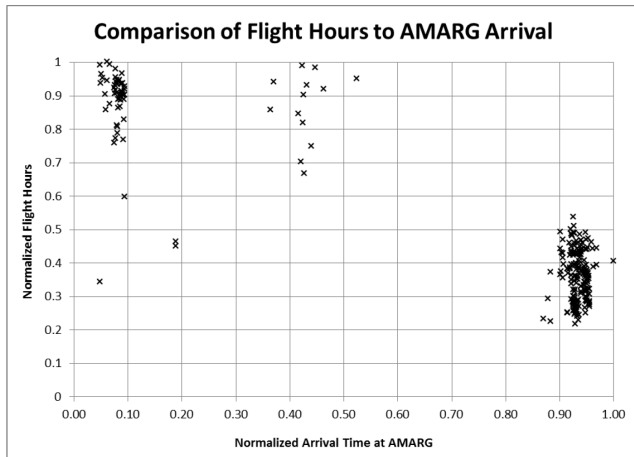


Figure 2.4: Normalized retirement schedule for USAF attack type aircraft

What is seen in Figure 2.4 represents poor end-of-life planning and a loss of unrealized residual value. It shows a failure to utilize individual aircraft tracking for the benefit of fleet longevity. Greenfield showed that the USAF has great flexibility in choosing retirement windows, thus encouraging end-of-life fleet optimization [44]. This approach would result in more scatter on a retirement plot, retiring each tail number when appropriate.

### 2.3.6 Focusing on Aging Aircraft Optimization Can Realize Savings

Optimization is widely discussed in literature, but there are few published works with applications as narrowly focused as military aircraft end-of-life optimization. Baker’s work on C-17 Pacific basing optimization stands nearly alone as a work that addresses USAF basing optimization [51]. He concluded that there was a more optimal solution to placement of C-17s to minimize yearly flight hours, but he conceded that any changes would be met with intense political opposition. Other works discussing optimization include availability optimization from a maintenance viewpoint and availability during simulation of combat [52], [53].

Keating and Dixon used a parameter model to evaluate repair versus replacement decisions for two USAF aircraft, the C-21A distinguished visitor transport and the KC-135 aerial refueling tanker. They found that an aging system should be repaired “if and only if the availability-adjusted marginal cost of the existing aircraft is less than the replacement’s average cost per available year” [24]. Understanding an aircraft fleet’s real cost as it relates to availability can aid decision makers when evaluating retain versus retire discussions. Potential savings exist. Hsu et al conducted a related study about commercial aircraft and

concluded that there exists a threshold for maintenance costs above which an airline should retire an aircraft [54]. The appropriate use of optimization in this trade space can allow fleet managers to find savings.

#### **2.4 Fleet Management Paradigm**

DoD aircraft programs follow the all-encompassing Systems Engineering Lifecycle. The management of each aircraft's lifecycle is conducted by a responsible System Program Office. This office receives inputs and tasking from the DoD, then provides combat capability to the Combatant Commanders (also DoD). Headquarters-level discussions dictate which stateside and overseas bases receive aircraft and DoD-level discussions dictate when those aircraft will be tasked for contingency operations worldwide.

Traditionally, the needs of the military service has determined how legacy aircraft fleets are managed. With the advent of fifth-generation aircraft possessing data recording capabilities, the ASIP manager has been able to advise fleet movements. This methodology is useful but does not take full advantage of endogenous engineering capabilities. The current state is reactive based on fatigue life and severity factors, but future aircraft movements will be dynamic. Figure 2.5 proposes the author's novel vision of future fleet management. The legacy block illustrates that assigning aircraft to bases and missions was conducted at a high level with little insight into specific aircraft detail. This method was binary in nature, meaning that an aircraft would move or not move. The fifth-generation block shows the current state, where ASIP managers use some fleet metrics to make informed decisions about the movements of aircraft. The future should hold a system where lifecycle managers are the ones who decide what is best for the aircraft's mission assignment and basing. Predictive forecasting, instead of existing data, should inform fleet movements. This dynamic paradigm is more in line with modern analysis capabilities. The DoD may override the lifecycle manager's recommendations to provide critical combat capability when needed. These deviations from the optimum solution are the reason for maintaining a flexible fleet optimization.

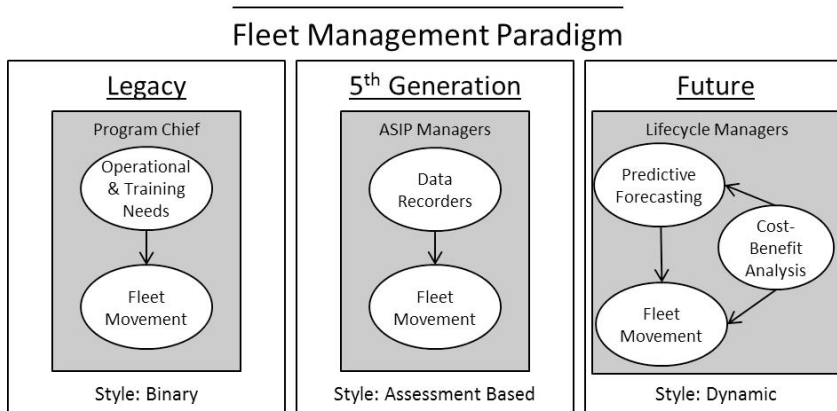


Figure 2.5: Fleet management paradigm from legacy to future

Aircraft historically have not moved from base-to-base primarily because difficulties with moving paper-based maintenance records and having local tail-number expertise trumped the unknown benefits of a more dynamic fleet management technique. Maintenance records are now digital, which makes fleet optimization more practical. A more fluid fleet management technique may be economically valuable. As found by Bond et al, fleet-wide management decisions carry risk and uncertainty, so managing by tail number can offer advantages [42]. Molent et al found that averaging across a fleet is inappropriate [18]. Glaessgen and Stargel reviewed the concept of the digital twin, which is an “integrated multiphysics, multiscale, probabilistic simulation” of an aircraft that encompasses digital models, analyses, usage history and more [55]. They recommended continuous fleet health management.

Figure 2.6 shows the organizational trade-space for the future fleet management paradigm. Within the framework of aging aircraft fleet optimization, the three possibilities for change include usage, basing and retirement. It is likely that all three are part of the optimum solution for an aging aircraft fleet, making this a very difficult problem to solve. Complicating this framework further are operational demands and political climate. Having some aircraft in use for wartime needs significantly impacts an optimization routine. It is difficult to predict the location of conflict, the intensity and the duration. Also, despite having a good solution, politicians may argue against efficiency changes based on economic concerns in base communities. Regardless of the challenges, there needs to be a strong focus on end-of-life optimization strategies. The opportunity is present and the timing is ideal.

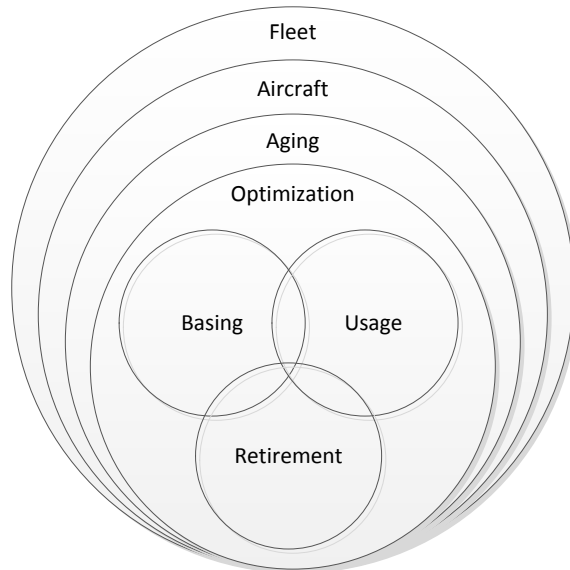


Figure 2.6: Visualization of how optimization fits into the fleet management perspective

## 2.5 Conclusions

Aging aircraft are an enigma for fleet managers. At the same time that some military fleets are the oldest they have ever been, replacement acquisitions programs are on hold or have not been initiated. Managers have a wealth of structural information available to them but most individual aircraft types have different monitoring programs with different conclusions. There is no unity across fleets because aircraft mission types are different, each having a unique loading history. Similar aircraft across militaries may have similar loading histories but sharing such information is not commonplace. All of these situations leave fleet managers with hordes of data but no practical outlet for their usage.

This paper has explored the case for end-of-life optimization through six tenets. First, this paper addressed how the aging aircraft problem is widespread. This tenet associates the problem well beyond the scope of military operations as a way to increase the number of stakeholders for the problems. An isolated military problem does not reach as many interested parties as a problem that plagues military and civilian aircraft would. Next, this paper used DoD data to show that the aging problem is not improving with time. While it was a 10-year snapshot in time representing today's paradigm of world conflict dangers, it showed that replacement programs are not a strong focus. Investment is focused less on aircraft replacement and more on other areas of the defense budget. With the help of Dixon's study, a positive correlation between aircraft age and maintenance costs was

shown. This is the critical argument for aging aircraft replacement. At a point in time, the cost increases of an aging aircraft will outgrow the replacement cost and that point is the time to retire an aircraft. The actual observed retirement point may be scheduled earlier or later, but both incur a lost opportunity cost. The fourth tenet related aircraft utilization to aircraft lifetime. This common-sense tenet underscores that the primary degradation component for aircraft is usage. The more an aircraft is used, the less lifetime it possesses. Aircraft are retired with residual value. For most organizations, the cost of predicting exact lifetime and the risk of getting the prediction wrong is too great for individual aircraft retirement forecasting. Tighter controls and optimization in basing and usage can lead to a more focused retirement plan. The paradigm must shift so that aircraft residual value is less at retirement across tail-numbers. Lastly, this paper underscored the importance of focusing on aging aircraft. Fleet optimization techniques will remain a topic of the future until they become commonplace. Predictive forecasting can inform fleet movements, which will yield a more well understood aircraft history. This information can then be used to affect smart retirements.

This work looked at the existing aging aircraft literature as a way to provide direction to future end-of-life optimization research. The body of knowledge for traditional maintenance and aging studies is vast but the specific application of structural health monitoring data to fleet extension is quite lacking. Future research must be done in this area. Similar fields of study can inform this topic. Basing, usage and retirement optimization also relate to railroad cars, shipping containers, ferries and many other industrial applications. Aging aircraft are unique from the aspects of increased risk to the user with age and necessity for combat needs, but are otherwise task-built vehicles. Specific future research should address the real costs of moving aircraft between bases, the effects of combat on a usage optimization algorithm and the sensitivity of retirement dates to mission utilization. It is in these areas that advancements could drive the future of aging aircraft optimization.

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### **3 Framework for Military Aircraft Fleet Retirement Decisions**

*Positioned ahead of Chapters 4-7 purposefully, this chapter presents a decision support framework built to aid fleet managers making fleet retirement decisions. Chapter 4-7 then provide detail for the elements of the decision support framework. The outputs of Chapter 2, principally the six premises discussed and the recommendation for a more dynamic fleet management paradigm, are vital inputs to this chapter. The premises that aging aircraft are more costly to maintain, aircraft are retired with unrealized residual value and end-of-life optimization can realize savings are the most vital inputs to this chapter. The chapter illustrates the necessary data and inputs, then describes how a fleet manager and his surrogates should approach the problem of retirement. Care is taken to provide detailed implementation instructions since every fleet possesses different types of databases and has different constraints. Expert judgement is highlighted as an essential element in the decision support framework, even more important than rote quantitative fleet data. This chapter concludes with a validation effort showing the application of the decision support framework to a sample fleet, proving the flexibility of the framework even within a fleet having complex requirements and an immediate retirement requirement of 25% of its fleet.*

This chapter is a journal article awaiting decision.

# Framework for Military Aircraft Fleet Retirement Decisions

## Abstract

A decision support framework is proposed to solve the aging military aircraft retirement problem. It integrates four steps for fleet managers to simplify the decision-making process: (i) Understanding the structural toll caused by utilization, (ii) Recognizing the indicators that predispose a fleet for retirement, (iii) Determining an optimal fleet size and choosing which aircraft to retire and (iv) Optimizing end-of-life usage prior to retirement. An example using a sample military fleet is used to illustrate the effectiveness of the decision support framework, integrating both computational results and manager judgement. It is shown that fleet managers can utilize a decision support framework to positively impact their decision-making for full-spectrum aging aircraft retirement decisions.

## 3.1 Introduction

Computerized decision support tools are necessary because of the complexity of managing a fleet of aircraft. The high number of alternatives for fleet managers and the high cost of making the wrong choice both complicate the process. Decision support is traditionally necessary when one of four conditions is met for the problem: large databases, necessity for a computational strategy, time pressure or expert judgement is required [1]. When addressing a fleet of aircraft that could reach into the hundreds with a yearly operational budget in the tens of millions (USD), all four conditions are met. Aircraft usage and management data are catalogued in dozens of independent database systems no one manager could fully understand. Determining which aircraft to retire quickly becomes a problem requiring a computer-based computational strategy. Clearly in a military aviation application, there is great time pressure to solve the problem but solving quantitatively without a qualitative element cannot satisfy all stakeholders. Expert judgement must be a key element in the analysis of alternatives. For these four reasons, a decision support framework is required.

Decision support frameworks (DSF), decision support tools (DST) and decision support systems (DSS) are sometimes defined interchangeably but do have subtle differences [1-3]. Decision support systems may encompass multiple DST and the DSF provides the structure for either a DST or DSS. We choose to follow Keen and Scott-Morton's definition of DSF, "Decision support frameworks couple the intellectual resources of individuals with the capabilities of the computer to improve the quality of decisions" [4].

Turban's landmark work lists the four hallmarks that describe a DSS but also apply to a DSF [5]:

1. They include both data and models
2. They assist managers for semi-structured tasks
3. They support, not replace, managerial judgement
4. A DSF improves effectiveness of decisions

A DSF can be used for tactical as well as strategic decisions, which makes it the ideal architecture for aiding commanders, fleet managers and top military leaders. This work will focus on providing fleet managers with a robust DSF. Applying Mintzberg’s landmark work on the classification of managerial roles reveals the depth of responsibility placed on a fleet manager [6, 7]. Mintzberg’s ten management roles are shown in Table 3.1, grouped by their types and each with its application to fleet management outlined. It is in this context that we can understand the breadth of authority of a fleet manager to guide the future of a fleet and the necessity for a DSF.

Table 3.1: Mintzberg’s management roles applied to fleet managers

Type	Management Role	Fleet Manager Application
Interpersonal	Figurehead	Identified as the symbolic leader of the fleet.
	Leader	Maintains organization of employees tasked with managing the fleet.
	Liaison	Liaises with other fleet managers and interprets intent of Major Command and Headquarters decisions.
Informational	Monitor	Evaluates aircraft data and fleet statistics to determine health of the fleet.
	Disseminator	Conveys messages from Major Command and Headquarters. Works to ensure organization is informed.
	Spokesperson	Speaks for the organization in peacetime, during mishaps and during wartime.
Decisional	Entrepreneur	Cultivates improvements to the fleet’s operations and maintenance activities.
	Disturbance Handler	Manages grounding events, budgetary fluctuations and retirement planning.
	Resource Allocator	Receives manpower and budget from Major Command and works to equitably distribute resources within the organization.
	Negotiator	Compromises with interested parties to ensure fleet viability within resource constraints.

The strategic planning and long-term forecasting involved in fleet management decisions means that they can demand multiple management roles [4, 8]. Fleet decisions blend knowns with unknowns, requiring both data and judgement by the manager. Managers must have mastery of all three of Mintzberg's types: Interpersonal, Informational and Decisional.

In the United States Air Force (USAF), fleet managers possess a variety of backgrounds that may or may not include extensive experience with decisional types of managerial roles or complex decision support tools. Fleet managers therefore must rely on their surrounding incumbent expertise and the tools available to them. This research's goal was to provide fleet managers with a comprehensive framework for making military aircraft fleet retirement decisions.

Decision support framework (DSF) is a generic term, similar to decision support tools (DST) and decision support systems (DSS) used to describe computerized systems that aid an organization with decision-making [9]. For this work, DSF will be the term employed to describe the combination of analytical models and best practices. Fleet managers already use DSF for a multitude of tasks that include depot planning and structural integrity monitoring, for example. However, the aperiodicity of major fleet retirements has left a DSF gap for fleet managers planning fleet retirements.

The focus of this paper is technical decision-making for aging military aircraft retirement decisions. The objective of this paper is to provide a decision support framework to fleet managers that synergizes computer tools along with managerial opinion to aid decision-making. This work is the first known DSF for aging military aircraft and reduces the problem complexity in a novel way by emphasizing the fleet manager's experience to reduce uncertainty.

The remainder of this paper is divided into six sections. The Literature Review summarizes current research in the DSF field. Then the Elements of the DSF section presents the DSF both graphically and with explanatory text. Next, the Applying the DSF section addresses military aircraft specifics, the role of expert judgement and implementing the DSF. The Evaluating the DSF section posits a method to evaluate the value of the DSF. The Applying the DSF to a Sample Fleet section provides an example for fleet managers to use to better understand how to apply the DSF. Finally, the Conclusions section summarizes the research and includes areas for future research.

### 3.2 Literature Review

Sorensen and Bochtis resolved that an effective fleet management system can aggregate disparate data and documentation for a manager [10]. Their work focused on agricultural equipment resource allocation where each asset's location and assigned tasks could be optimized. They found that the agricultural community desired a fleet management framework so their proposed conceptual framework filled a gap.

Andersson and Varbrand built decision support tools for ambulance relocation and dispatching to increase readiness inside an area of responsibility [11]. This role is analogous to military aircraft fleet management's role of ensuring the fleet is available to meet peacetime and wartime demands in similarly conceptualized areas of responsibility. Their work found that an integrated framework for managers could increase preparedness.

Decision support frameworks must combine data-driven analysis with expert opinion. As Fagerholt concluded in his work on the DSS named TurboRouter, the optimization backbone of a problem is perhaps less important than the user and system under development [3]. Military fleet planning's focus is often on the exact solution instead of on finding a feasible solution that satisfies stakeholder desires. Fagerholt's work with sea-based shipping vessels uncovered the need to convert the industry's decision support systems from a paper-based approach to one that capitalizes on computer technology. Similarly, military aircraft decision support systems have lagged behind the ground transport and airline industries.

The United States Coast Guard approached its cutter scheduling with a decision support system [12]. Darby-Dowman et al found not only usefulness for the day-to-day scheduling of assets with their model but they also found incredible value in the investigative capabilities of the tool. Their decision support framework could be used to detect problems in the future utilization plan.

Abdelghany et al built a decision support tool for airline disruption operations that could be employed by an airline's operations control center [13]. Their work synergizes a simulation model with optimization models to resolve hard problems.

The team of Vaidya and Rausand tackled the issue of decision-making for life extension versus retirement for undersea oil and gas systems [14]. They emphasized the multi-disciplinary nature of their problem, concluding that technical data, computational results and manager opinion together could yield a satisfactory solution. Their model found that service life estimates for undersea equipment were too conservative – similar to military

aircraft service life forecasts – which is a driving force behind needing a DSF that can determine the effects of retaining aging capital equipment.

Couillard developed a decision support system for vehicle fleet planning, tackling the problems of adjusting fleet size and assigning assets to operations [15].

### 3.3 Elements of the Decision Support Framework

The four elements of the DSF include (i) Understanding the structural toll caused by utilization, (ii) Recognizing the indicators that predispose a fleet for retirement, (iii) Determining an optimal fleet size and choosing which aircraft to retire and (iv) Optimizing end-of-life usage prior to retirement. These four actors are presented in the following subsections, including their tie-in to the overall framework.

The DSF must be capable of taking the fleet manager from understanding the status of the fleet using a fleet health snapshot to a place where decisions can be made about the future of the fleet. The approach to understand the current fleet capability is prescribed in Figure 3.1.

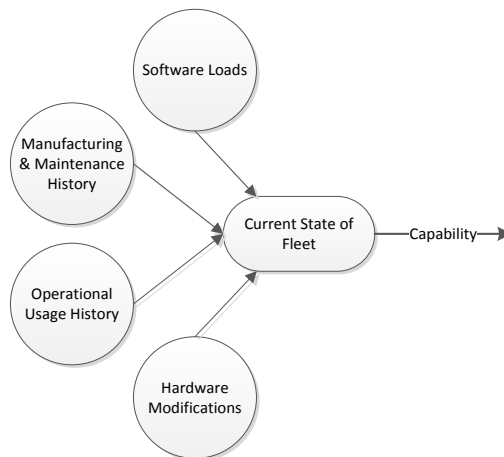


Figure 3.1: Factors contributing to the fleet health snapshot

Software loads, manufacturing and maintenance history as well as hardware modifications are well documented knowns. However, the operational usage history’s impact on the current state of the fleet is a rather large unknown because individual aircraft tracking data and the particular physics behind aircraft structural degradation are difficult problems.

Hence, this DSF emphasizes only one numerical input from Figure 3.1, the operational usage history. Expert opinion is critical for the remaining inputs.

Focusing on how the DSF fits together to help decision-makers, Figure 3.2 shows a start-to-finish flow. On the left, a fleet manager initiates a fleet evaluation. Fleet data, network data and demand data allow the four main DSF elements to proceed (numbered). Element one is represented in the “Fleet Data” process block. Element two is represented by the sub-process blocks labelled “External Influences” and “Internal Influences.” Element three is represented by those process and data blocks that utilize the FARM software (discussed in Chapter 6). Element four is represented by the process and data blocks that utilize the ROTATE software (discussed in Chapter 7).

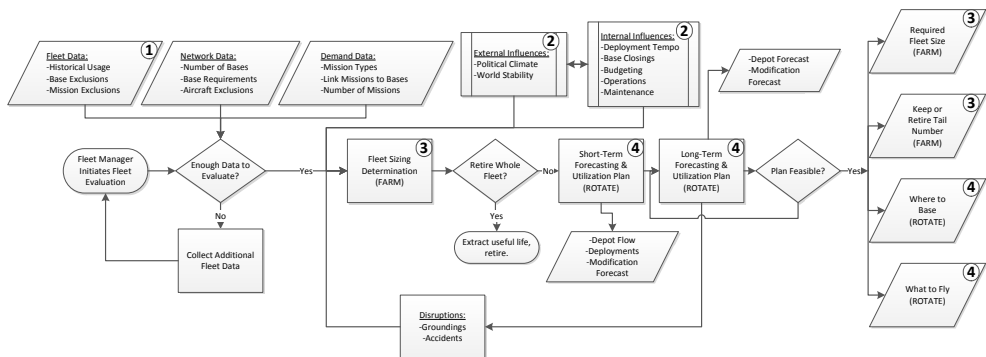


Figure 3.2: Military aircraft retirement DSF

### 3.3.1 Understanding the structural toll caused by utilization

This phase of the DSF is a preliminary step for decision-makers because its purpose is to inform the starting point for the determination of retirement eligibility. Absent a budgetary requirement for retirement, accumulated usage drives fatigue-based or corrosion-based retirement. Fleet managers must recognize the amount of expended lifetime in their fleet to make important decisions, which is addressed thoroughly by Newcamp et al [16]. If the data are insufficient with which to make structural health decisions, a fleet manager would need to find a workaround because the quality of the inputs to the framework in this respect directly impact the quality of the outputs. If the data available provide no solid link between utilization and structural degradation (such as through crack severity indices), then it is difficult to understand future lifetime. This managerial work represents the informational type of management where a manager must absorb structures data to determine health impact. Fleets already possess many tools to report on structural health of a fleet. Most are specific to individual aircraft, leaving a fleet manager to aggregate information at the fleet

level. It is this link, being able to interpret the trends in each asset at the system level that requires the second element of the DSF.

### **3.3.2 Recognizing the indicators that predispose a fleet for retirement**

Individual aircraft are now tracked closely in air forces across the globe but what hints can be seen in the fleet that should warn fleet managers about waning fleet health? Newcamp et al found a series of aging aircraft milestones that predispose a fleet for retirement consideration [17]. Furthermore, the co-mingling of fleet utility and fleet cost can be an early indicator of degrading fleet health. If a fleet manager does not fully understand the indicators for his fleet, the quality of the framework here can be degraded. Fleet managers must maintain an informational type approach to management because fleet health indicators are an input to the information-gathering process. Managers must marry the structural degradation information gained in the first element of the DSF with the fleet-indicators from this element to form a full-spectrum view of their fleet.

### **3.3.3 Determining an optimal fleet size and choosing which aircraft to retire**

Optimal fleet size is not solely dependent on fleet health – rather, fleet size is a product of available budget and required capability [18]. Choosing which aircraft to maintain in a fleet is a product of past usage, which is an output of the first DSF element. This element outputs the number of aircraft that should be retired to remain within budget and capability. This element also outputs which aircraft, giving actual tail numbers, that should be divested based on past usage and performance [19]. It is important to account for the future unknowns for the fleet. This DSF element in no way encourages fleet sizing based on current utilization, rather, the basis should be maximum expected utilization plus a wartime reserve buffer. The risk of retiring too much of the fleet when it might be needed in the future can outweigh the cost of maintaining spare capability. With this element of the DSF, a fleet manager can imagine his ideal fleet and then work to achieve that state. Now a fleet manager can understand how many aircraft and which aircraft can be retired. If the economic determination to retire the whole fleet is made, the DSF then instructs fleet managers to extract any residual value from the fleet. This element can be the conclusion of the DSF if a fleet manager is unwilling to invest additional resources to optimize the remaining fleet's usage. Fleet managers deal with the composition of their fleet in this element using Mintzberg's decisional leadership types.

### **3.3.4 Optimizing end-of-life usage prior to retirement**

This element of the DSF describes how a fleet manager can use the knowledge he has gained through the other elements of the DSF to create fleet savings through optimizing



usage. Knowing the aircraft that are pending retirement from the third element gives fleet managers the opportunity to utilize those aircraft in a way to preserve useful life for the remaining fleet. Fleet managers exercise both the decisional and informational leadership types in this DSF element, requiring judgements as well as actions to gain buy-in from stakeholders. Outputs from this element include a basing strategy and utilization plan (Newcamp et al, 2017, Submitted). Aircraft can be allocated to operational locations with consideration of usage history and expected future utilization rates. The aircraft most vulnerable to structural failures can be assigned to low-impact mission types at low-usage bases, information derived from the first DSF element. This element of the DSF is where a disruptions feedback loop is shown in Figure 3.2 because no retirement plan is without problems.

Expert judgement is applied throughout the DSF, but it is particularly essential at the feasibility decision diamond. A feedback loop allows the expert judgement to impact the long-term plan, which is necessary to arrive at a feasible and desired solution.

The decision maker can expect the DSF to provide both a starting place and structure during the decision-making process. The inputs directly influence the outputs and also the quality of the inputs are important to the DSF. Several generalizable, sensible tenets should be noted. First, some fleets are incapable of meeting threshold requirements set by the fleet manager. In these cases, the only solutions are to acquire new aircraft or to transfer some fleet requirements to another fleet. The second generalizable tenet is that when faced with a retirement scenario, the aircraft with the lowest residual value as measured by the fleet manager must be the first aircraft to be retired. Rare exceptions include aircraft with special mission equipment.

### **3.4 Applying the Decision Support Framework**

#### **3.4.1 Applying a Decision Support Framework to Military Aircraft**

DSF are not immune to faults like group member biases or conflicting interests, but military aircraft present some peculiar challenges. Military assets exhibit long forecast horizons because they are designed, built and flown over spans of decades. Because of this a DSF is even more useful but for the same reason, a DSF has fewer chances to refine iteratively and is thus a less precise solution. A second peculiarity with DSF for military applications is that military conflicts trump standard business practices. While equipment replacement policy may seem germane in a corporate environment, the military may make economically irrational choices in the name of national defense.

The military fleet decision structure is illustrated in Figure 3.3, an adaptation of the work of Aronson, Liang and Turban [8]. The decision environment is contained in the outer ring of the figure. This is where national defense posture impacts the decision process – as well as the other external influencers. Inside the decision system boundary, it is clear that the inputs, processes and outputs yield a very complex problem formulation for the decision maker. A DSF for military aircraft is essential due to this complex decision structure.

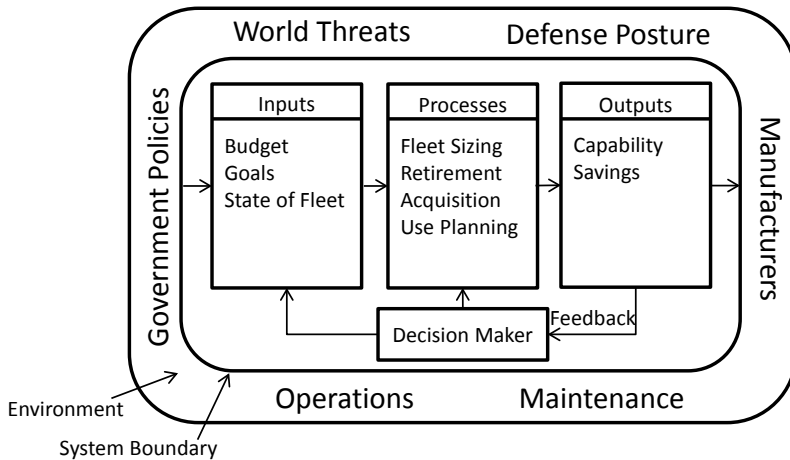


Figure 3.3: Structure of the military fleet decision

Military aircraft fleet retirement decisions are nonprogrammed problems conducted in a semi-structured environment. The decisions do not recur and each is a new occurrence, but they occur in an environment that has some rigid elements such as timelines and budgets and some judgemental aspects [1]. The fleet manager is the problem owner, but there are a multitude of stakeholders and higher authorities. Complicating facets of military fleets are that no standing, published heuristics or frameworks exist that are specific to military fleets. Further, refinement of a DSF is difficult since the ability for trial and error is limited.

Given the inherent complexity of retirement decisions, it is vital to reduce the number of decision variables to only those that impact the decision process. The Air Force’s Fleet Viability Board valued fleets based on 74 metrics but found approximately six of those metrics to be important resulting from a principal component analysis. The team dramatically reduced the complexity of their problem by reducing their decision variables. The decision variables chosen for each fleet should be unique to that fleet’s peculiarities [20].

A DSF for aircraft retirements must be supported by human judgement as well as computer-based optimization. The previous work for this project has focused on the optimization component whereas this effort synthesizes the computer models and provides a framework approach.

### **3.4.2 Role of Expert Judgement**

Expert judgement must be combined with quantitative assessment for DSF success. Requiring a formal, defined process ensures that expert judgement can be more dependable in the decision-making environment [21]. While the formalization of expert judgement is unique to each problem, some generalizable rules persist. Expert judgement must originate from qualified sources possessing relevant backgrounds. For aircraft retirements, fleet managers can delegate judgement to the appropriate managerial level. Structural health questions should be answered by an aircraft structural integrity program manager while budget questions should be answered by a budget analyst, for example. Fleet managers must determine how many experts should be involved in the DSF – too many stakeholders risks an inability to reach consensus while too few or the wrong experts risks making an ill-informed decision [22].

Expert judgement suffers from conflicting stakeholder inputs therefore DSF outputs are subject to stakeholder priorities. Fleet managers must adopt a process to evaluate and weigh stakeholder inputs, however no relevant work for this niche application can be found in literature. Analytic hierarchy process (AHP) is just one recommended option for what should be a problem-specific choice [23, 24]. Fleet managers may recognize the financial analyst as holding the greatest weight for stakeholder input, but it is still valuable to assemble alternatives not constrained by budget for purposes of discussion and analysis.

### **3.4.3 Implementing the Decision Support Framework**

Promulgation of a DSF in an immensely large organization such as the USAF is a particular challenge. Though the USAF follows a hierarchical structure, disseminating a new vision for fleet decisions is a near impossible task. Instead of a vertical integration, a horizontal integration is proposed. Fleet managers and Aerospace Vehicle Distribution Officers (AVDO) meet yearly to discuss retirement planning. This group is led by a chief AVDO who is the focal point for a potential DSF implementation. This is the most sensible avenue toward institutionalization. The challenge of infrequent retirements means there must remain a cadre of DSF proponents within the organization to voice support for the continued evolution and use of the DSF. The implementation strategy should follow an evolutionary approach, where feedback from each retirement is implemented in the DSF. The disadvantage to this approach is that the users must deal with continuous change.

Little's work on managerial models emphasizes the need for a model to be "simple, robust, easy to control, adaptive, as complete as possible, and easy to communicate with" [25]. There exist several major challenges for DSF implementation within the USAF, both technical factors and behavioral factors. For institutionalization to take hold, the DSF must not require special software. It must be freely accessible to all parties with no confidentiality concerns. The DSF also must have a low level of complexity – it must be a framework anyone can pick up and understand. Lastly on the technical side, the DSF must be flexible enough to adapt to multiple fleet types or military services.

The primary behavioral factor of concern with DSF implementation is resistance to change, especially within the civilian employee population. Employees and managers will be unwilling to change their paradigm from the ad-hoc approach to aircraft retirements to a structured system. The second behavioral factor is the slow organizational climate in the USAF. While it is sensible to think that a military service so reliant on advanced technology would have a fast-moving organizational climate, the opposite is true. The sheer size of the USAF is the reason that makes it hard to change paradigms. Lastly, apathy could be detrimental to DSF implementation. Many will feel that making change will be more trouble than it is worth.

### **3.5 Evaluating the Decision Support Framework**

Since the biggest challenge to managerial models is in getting them used, it is also important to evaluate the likelihood that a DSF would be used. Regan et al developed a simulation framework to evaluate fleet management systems and found gaps between simulation and realism must be addressed [26]. Their technique for evaluation compared different operating strategies to outcomes. Regan et al addressed the effectiveness of the decision support framework but did not assess the manager's subjective opinion of the system.

#### *Usage*

Usage of this DSF must be evaluated long-term to determine if the ideas were valuable to actual retirement scenarios. The DSF must stand up to time – meaning that it was structured broadly enough to maintain pertinence even when technology and management techniques progressed.

#### *Return on Investment*

Determining whether a DSF has been valuable relative to its cost may involve measuring the potential savings between a DSF solution and a non-DSF solution. While many

uncertainties exist when making cost projections of fleets, there are well-established baseline costs for a fleet. Deltas from these values can be more easily established.

#### *Fleet Manager's Input*

The best evaluation tool for a DSF is assessing whether the fleet manager found value in the framework. The DSF is designed to help the manager make better decisions. Assuming the model was constructed properly, any decision utilizing the DSF would be a better decision than those made without the DSF. Thus, if the DSF makes the job of the fleet manager easier, then a net benefit exists.

### **3.6 Applying the Decision Support Framework to a Sample Fleet**

This section discusses the practical steps a fleet manager would take to apply this DSF to a fleet of military aircraft. It is organized to mirror the steps presented in Section 3, where the elements of the DSF are presented here in Section 6.1 through Section 6.4.

#### **3.6.1 Understanding the structural toll caused by utilization**

The sample fleet comprised 200 generic transport aircraft acquired over a period of 20 years and possessing ages normally distributed with mean,  $\mu = 10$  and standard deviation,  $\sigma = 3$ . It was assumed that fleet data, network data and demand data were all available. For this application, a normal distribution of flight hours was assumed with  $\mu = 1000$  yearly flight hours and  $\sigma = 300$  yearly flight hours with a lower cut off at 250 yearly flight hours. It was assumed that future utilization would match current-year utilization. The aircraft were randomly assigned to their current yearly usage levels. The basing network was assumed to have four equally equipped locations,  $loc = \{A, B, C, D\}$  each possessing a corresponding utilization severity factor which represents different mission types (one per base) having different structural degradation of the aircraft,  $SF = \{0.25, 0.50, 0.75, 1.0\}$ . The equivalent flight hours (EFH) were calculated by multiplying flight hours by the severity factor. Service life was set to 20,000 EFH. No specific basing or mission restrictions were included.

#### **3.6.2 Recognizing the indicators that predispose a fleet for retirement**

The sample fleet was assumed to have been flown during contingency operations, thus resulting in the overuse of some airframes. Additionally, a fleet could include aircraft with undesirable existing damage, antiquated modifications or could fail to meet mission capable rate thresholds. Fleet managers may quantify this recognition process by evaluating trends in fleet data over time. Increased structural crack detection, increased evidence of corrosion

and decreased mission capable rates are examples of indicators fleet managers should assess.

### 3.6.3 Determining an optimal fleet size and choosing which aircraft to retire

The capability threshold for the fleet was set to 75% of current, resulting in the fleet manager making a fleet sizing determination to retain 150 aircraft and retire 50. In this simple implementation, those aircraft already over the 20,000 equivalent flight hour service life were immediately slotted for retirement and are shown as x's in Figure 3.4. To reach 50 total aircraft for retirement, the remainder were the aircraft with the highest equivalent flight hour utilization. These are shown as circles in Figure 3.4. Because of the random distribution of aircraft to bases and missions, the aircraft in the list of 50 to retire were not solely those that were oldest by age. The aircraft slated for retirement were generally older aircraft with the greatest equivalent flight hour accumulations. The short-term plan for this fleet is to immediately retire those above the service life limit, to use the remaining equivalent flight hours of the remaining identified retiring aircraft and to move the lowest equivalent flight hour aircraft to the highest severity factor bases. This strategy is fleet manager dependent based on fleet needs and management preferences.

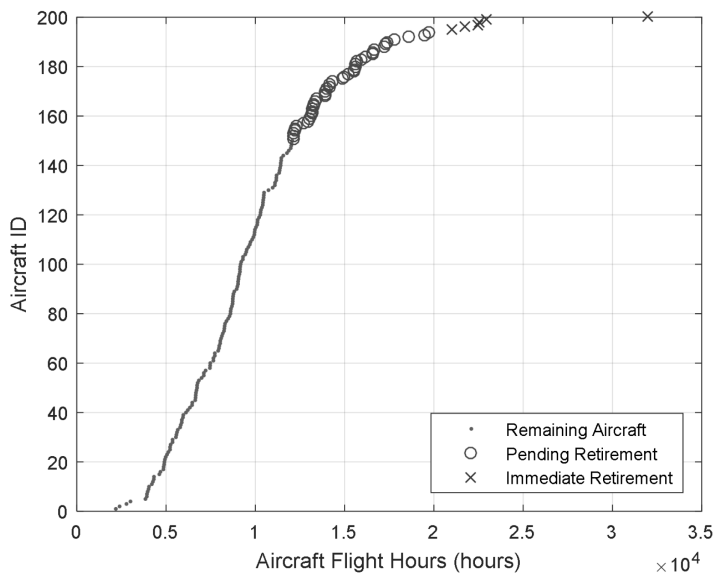


Figure 3.4: Equivalent flight hours for sample fleet, showing retirement eligible aircraft

### 3.6.4 Optimizing end-of-life usage prior to retirement

The long-term utilization for this simple fleet was then readjusted to ensure set coverage for the four bases. High-time aircraft were shifted to low severity factor bases and vice versa. As each aircraft at the high severity factor base surpasses the mean equivalent flight hour accumulation, they are rotated to the less severe bases. The long-term management strategy implemented in this example was to maintain the remaining 150 aircraft as long as possible. Consequently, the remaining 150 aircraft were distributed among the four bases in this way: split the population into flight hour quartiles based on remaining aircraft equivalent flight hours (20,000 less current equivalent flight hours) and assign the lowest remaining flight hour quartile to the base with the lowest severity factor, the second lowest remaining flight hour quartile to the second lowest severity factor base and on. Figure 3.5 shows the initial base assignments (right side) and the fleet after 11 years of base reassignment and usage (left side). Aircraft IDs 151-200 are not shown in Figure 3.5 because they are assumed retired and the minimum number of aircraft at each base was fixed:  $loc = \{A = 38, B = 37, C = 38, D = 37\}$ .

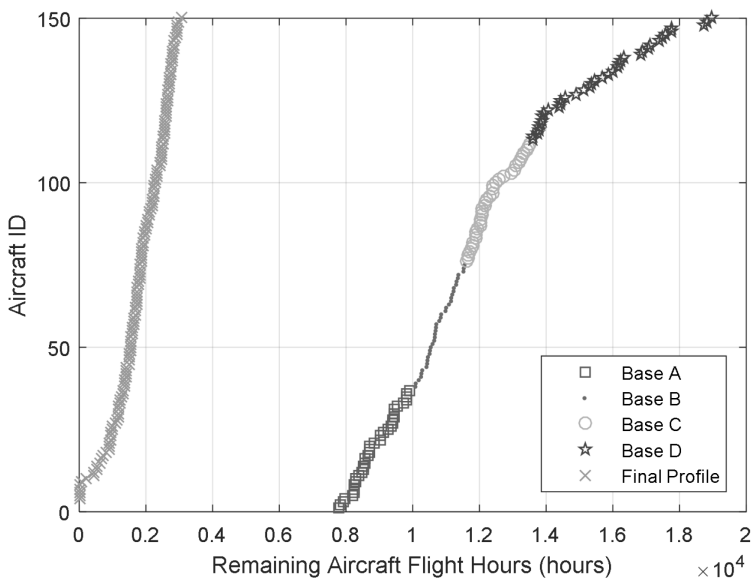


Figure 3.5: Remaining aircraft base reassignment quartiles

This management strategy used the aircraft with the lowest remaining equivalent flight hours in the least severe (lowest severity factor) missions over the 11 years in the simulation, thereby maintaining a larger standing fleet as long as possible. In the twelfth year, aircraft reached zero remaining equivalent flight hours and therefore the fleet would need to shrink smaller than 150 aircraft. The baseline case allowing no aircraft rotations

would have resulted in the next aircraft retirement in the seventh year, so the methodology correctly prolonged the fleet's desired size for four years. This application of the DSF used simulated fleet data, simulated network data and simulated demand data to build a notional fleet. Enough data were present for a fleet sizing determination that resulted in 50 aircraft being retired in the short-term. The long-term forecasting and utilization plan called for the rotation of the aircraft between the four locations to equalize remaining equivalent flight hours. External and internal influences, while ignored, can be injected into the short and long term planning horizons and dealt with as disruptions. The DSF successfully directed the fleet manager to proceed through the steps resulting in a methodological approach to sizing and utilizing the fleet. The DSF emphasized common sense decisions such as retiring aircraft that have overflown their safe life limit first, then rotating the aircraft within the base network to maximize fleet longevity. The most important aspect of the DSF is that it is not a static framework, but should adapt through time and be referenced repeatedly.

### **3.7 Conclusions**

This paper presented a decision support framework for military aircraft fleet retirement decisions. Military fleets retirement decisions are infrequent and the supporting discussions are not published nor widely shared, resulting in a very small body of knowledge. Fleet managers often view their decisional tasks as one-off for which they are underprepared and ill-experienced. The presented DSF was built with flexibility in mind, able to represent decisions across military services worldwide. The DSF accounts for internal and external factors while allowing the fleet manager flexibility in deciding what is important to his fleet. The role of expert opinion was held paramount in this work because numerical solutions ignore the prescient inputs from many key stakeholders like operators and maintainers.

To illustrate the efficacy of the DSF, a sample application problem was considered. This scenario used a fleet of 200 aircraft within a network of four base locations. The desired future capability was 75% of the current capability, resulting in the retirement of 50 aircraft. The remainder of the fleet was managed using the DSF's short term and long term functions to prolong fleet longevity. The result was 11 years of utilization before the next aircraft consumed its flight hour lifetime. The baseline case, with no change to current operating patterns, would have resulted in a first retirement in the seventh year of utilization. This approach ensured fleet viability for an additional four years. This application study showed the ease of applying the DSF to a transport aircraft fleet of nominal size.

It was shown that the developed decision support framework was useful to solve the complex problem of aircraft fleet retirement for fleet managers. Future work in this area



should focus on the development of tools and database concepts that more fully integrate the existing data sources for military aircraft. Further, this DSF should be applied to a military aircraft fleet to gain pragmatic insights for its use. Fleet managers who implement this DSF can further refine the methods and uncover more fleet-specific problems that arise during retirement discussions.

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## **4 Correlation of Mission Type to Cyclic Loading as a Basis for Agile Military Aircraft Asset Management**

*This chapter establishes that individual aircraft tracking data can be used to define how much structural degradation an airframe has withstood in its lifetime. Many fleets already possess these types of data as aircraft sensors and recording equipment have been commonplace for decades. The data link the types of missions, lengths, altitudes, airspeeds, numbers of landings and other useful information to the cyclic loading experienced. Despite physics models being unable to predict exact lifetimes, the use of cyclic loading data can inform predictions for lifetime so that asset management may have a starting basis. This chapter concludes with a validation case study using the USAF's A-10 Thunderbolt II. Outputs from this chapter are vital to Chapters 5-7 because this chapter makes the link between utilization and cyclic loading. It shows that there are differences in missions and subsequently in bases which can be exploited in fleet management decisions.*

This chapter was previously published as:

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# **Correlation of Mission Type to Cyclic Loading as a Basis for Agile Military Aircraft Asset Management**

## **Abstract**

Military attack aircraft are susceptible to the harmful effects of widespread fatigue damage caused by cyclic loading of structural components, which leads to airframe retirement. Modern structural health monitoring techniques use a multitude of sensors and high data collection rates. Some legacy airframes, which are most susceptible to fatigue damage due to their age, possess a counting accelerometer technology with few sensors and low data capture rates. The data provided by these 40-year old devices are crucial to understanding fleet health and can be used to extend structural lifetime for aging aircraft. Existing literature has addressed counting accelerometer usefulness, but a profound three-decade gap in research has led to a chasm between the current wealth of available data and tool development for utilizing those data. This research uses 11 years of A-10 Thunderbolt II counting accelerometer data to prove that mission type, mission duration and aircraft type correlate to aircraft loading patterns. It is shown that a mission type model can therefore influence fleet management strategies and the structural lifetime extension for aging aircraft.

## **4.1 Introduction**

Mission type usage for military attack aircraft varies widely and the particular utilization pattern is important for determining an airframe's lifetime. As an aircraft fleet ages, the initial lifetime estimate must be updated to reflect usage patterns. These calculations are especially important in a fiscal climate where air forces are retaining aircraft longer than initially projected. For example, the United States Air Force (USAF) employs a fleet averaging 26 years old, with an average age of 21 years for the attack/fighter aircraft subgroup [1]. A 2012 study concluded that the USAF fleet is the oldest it has ever been with no strategy in place to reverse the trend [2], [3]. The problem of aging aircraft is not new and accordingly, the Department of Defense's (DoD) policy has evolved through time. MIL-HDBK-1530 and the USAF Policy Directive 63-10 are two examples of how serious the DoD has taken aging aircraft issues [4], [5]. The Aircraft Structural Integrity Program (ASIP) has implemented inspections and enhanced monitoring to decrease the effects of aircraft aging [6], [7]. While there is a strong emphasis on monitoring for structural deterioration, there is much less emphasis on how mission type impacts loading.

For this research on aircraft loading, the A-10 Thunderbolt II was chosen as the case study aircraft. It is an aging aircraft, first reaching initial operating capability in 1977 [8]. The A-10 was built by Fairchild Republic to fill the close air support role for the USAF. It is a

single-seat, twin-turbofan engine aircraft with a low wing, low-tail configuration possessing advanced survivability characteristics [9]. The structure is mostly aluminum with the primary exception of titanium armor shielding the cockpit from ground fire. Base weight is 28,000 pounds and normal operating weight is 35,000 to 50,000 pounds. Though categorized as an attack aircraft, zero-g or negative-g maneuvers greater than 10 seconds are forbidden. The maximum airspeed is 450 knots indicated airspeed, or Mach 0.75, whichever is lower. At a nominal weight of 30,000 pounds at sea level, the normal load factor ( $N_z$ ) limits are +7.3g/-3.0g. The A-10 possesses a basic structural health monitoring system known as a counting accelerometer governed by a now rescinded military specification [10], [11].

The A-10 System Program Office of the USAF provided data from its Aircraft Data Acquisition and Distribution System (ADADS) for this study. Each A-10 has a counting accelerometer unit that records counts in discrete bins each representing an  $N_z$  loading (0.3g, 2.5g, 3g, 4g, 5.5g and 7g). These counts are unidirectional, meaning that an aircraft maneuver to 4.8g would accrue one count in each of the 2.5g, 3g and 4g bins. The system does not provide a time-history nor does it provide aircraft weight information. For each mission, the counting accelerometer data were transcribed by maintenance ground crews onto an Air Force Technical Order (AFTO) form 278. The mission pilot then hand-carried the form into maintenance debrief and handed off the data to a support person who inputted the data into a digital storage service managed by the Oklahoma City Air Logistics Complex (OC-ALC). The ASIP manager is responsible for analyzing loading pattern data and for implementing fleet-wide changes. This data collection process is shown in Figure 4.1.

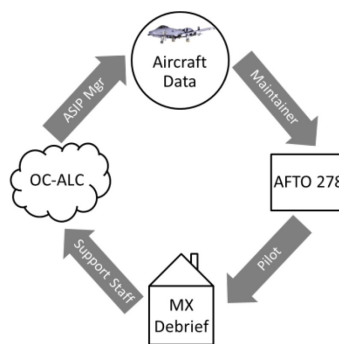


Figure 4.1: Aircraft Data Acquisition and Distribution System data flow

This research analyzed two important hypotheses about aircraft loading. The first was that the type of flying mission impacts the loading pattern experienced by a military attack

aircraft. Second, some mission types account for greater loading accumulation. These two hypotheses are essential first steps for future phases of this effort which aim to develop a fleet optimization model for assigning military aircraft to operational locations while maximizing aircraft availability and extending useful life.

#### **4.1.1 Theoretical Context**

The A-10's counting accelerometer technology originated in the 1950s so there exists a plethora of related work in the 1950s, 1960s and 1970s but a dearth in the 1980s through present. Accordingly, the theory and methodologies developed at the outset of counting accelerometer usage have not been updated since the 1970s. The seminal work in counting accelerometers was conducted by Taylor who discussed counting accelerometer technology from a design perspective in 1954 [12]. Gray's work applied counting accelerometer systems to individual aircraft tracking for fatigue crack growth prediction [13]. Lambert's work in 1973 applied tracking data to life predictions and fleet optimization [14]. He suggested fleet basing optimization as a way to extend aircraft lifetimes because his work showed a theoretical relationship between aircraft stress and sortie pattern combination. Lambert did not propose ways to optimize fleets or basing and his theoretical calculations used generic data, not collected data.

De Jonge's 1989 work using counting accelerometer data was among the most recent published. He studied Royal Netherlands Air Force F-104G operational data and used a Weibull distribution to represent load factor cumulative occurrence distributions, which were different for reconnaissance, strike and air defense mission categories [15]. De Jonge's study followed 15 counting accelerometer instrumentation kits that were installed on various aircraft over a 10-year period. His data comprised 9,500 flights but did not have the tail-number specificity that the A-10 data in this study possesses. The Netherlands Aerospace Center (NLR) conducted F-16 work in this area but their work was not available from a published, releasable source.

Aging aircraft operators are responding to aging aircraft fleet problems through enhanced structural health monitoring, as discussed by Albert et al, Connor et al, Maley et al and at length in Staszewski et al [16], [17], [18], [19]. Boyd wrote that the greatest impact on the aging process comes from post-manufacturing decisions [20]. This implies that combining structural health monitoring with usage decisions can impact fleet health. Unfortunately, current data collection is not uniform across aircraft fleets. Even within one mission design series, there exist multiple generations of flight data recorder technology possessing incremental capabilities. Therefore, historical data take many forms, making it difficult to conduct both longitudinal and horizontal studies. This research evaluated existing structural health monitoring data to draw correlations that are useful to different aircraft types.

The author recognizes the inferiority of a counting accelerometer system, as outlined by De Jonge, but the author understands the importance of developing tools to use these data [21]. The USAF has decades of counting accelerometer data that can be used for lifetime optimization but few established tools for analysis. Despite the failings of the data type, there still exists opportunity to use the data.

The remainder of this paper will address the two hypotheses listed in this introduction. This unprecedentedly large analysis of the entire A-10 fleet will show a new look at how mission type impacts aircraft loading patterns. The next section discusses the methodology used to analyze the data provided by the USAF, including the practice of data reduction and the established norms for analyzing counting accelerometer data. Then, the results section presents a thorough treatment of counting accelerometer data both in aggregate form and in population subsets. The relationship between g-count occurrences and mission type is analyzed, exponential usage models for each mission type are presented and an analysis of important findings is presented. Data verification then shows the relationship between this study's data and existing studies. Lastly, the conclusions section summarizes the findings from this study.

## **4.2 Methodology**

### **4.2.1 Data Reduction**

The dataset from the USAF ADADS database contained 456,847 unique entries spanning from January 2002 to August 2015. The counting accelerometer data capture rates were low during 2002 and 2003 so data from those years were removed from the dataset. Only half of the collection year for 2015 had occurred at the start of this study, so 2015 data were excluded. These exclusions resulted in 407,634 viable sorties. Because the data collection was subject to many failure modes (missing data, human error and accelerometer malfunctions), there resulted 278,678 useful entries after multiple filtering algorithms were applied. These algorithms removed clear errors: sortie durations  $d$  outside the reasonable range of  $0.3 < d < 15$  hours, sorties firing more rounds than capacity allows and sorties with counting accelerometer failures indicated by discontinuities. Further reduction of the population was undertaken to remove eight infrequently flown mission types. Figure 4.2 illustrates the data reduction process.



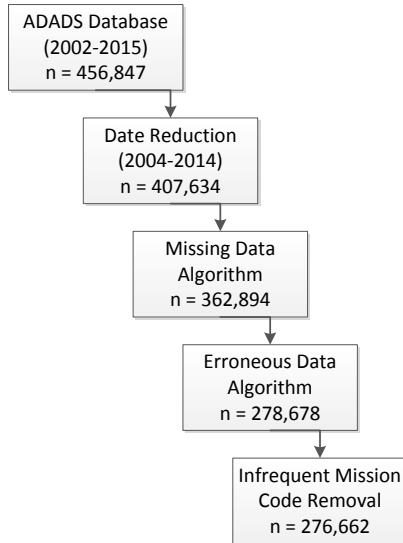


Figure 4.2: Data reduction process steps

Descriptive statistics of the full dataset and the edited dataset show that the reduction steps did not skew the data. The means for flight duration and number of rounds fired only show minor shifts between the full dataset and the edited dataset (0.40% and 4.42% losses, respectively). These outcomes are reasonable. Only six of the original 365 tail numbers were removed and those six aircraft only represented seven missions in the original 2002-2015 dataset.

Because this research relies on understanding fleet usage, losing a portion of the dataset would have resulted in an underestimation of yearly usage. To correct for this the associated number of sorties and mission types from the full dataset were reserved for analysis alongside the edited dataset. The erroneous counting accelerometer data were not replaced or corrected.

#### 4.2.2 Modeling the Usage Spectrum

Two assumptions were required during the modeling effort. The first was that data collected for mission types are representative of those missions. For example, if a pilot states that his mission was Close Air Support (CAS), then that pilot flew CAS for the majority of the mission. The second assumption was that the data contained in the study population from 2004-2014 is representative of the entire lifetime for the aircraft analyzed.

Since there were not significant differences found between the years in the study, this assumption is reasonable.

The ADADS database accepts 18 unique mission codes, however the top 10 mission codes represented 99.33% of all missions and the remaining eight codes were antiquated. Table 4.1 shows the 10 currently used mission codes along with the percentage of missions each represented in the dataset. One can see that the six most frequent mission codes account for 96.33% of all missions. Codes SAR, FAC, NAV and FCF were still included in the model despite their low representation because of their relevance to overall A-10 operations and loading spectra. For example, the Functional Check Flight (FCF) code only accounts for 0.58% of all A-10 missions, but an FCF is a full-envelope check of the aircraft and greatly contributes to the width of the loading spectrum envelope.

Table 4.1: Mission types retained for analysis

<b>Mission Code</b>	<b>% of Dataset</b>	<b>Cumulative %</b>	<b>Median Missions In Fleet (1 yr)</b>
CAS	48.95	48.95	17,966
SAT	14.00	62.95	5,182
OTH	13.83	76.78	5,250
BFM	7.26	84.04	2,543
SA	7.10	91.14	2,866
AR	5.19	96.33	1,472
SAR	1.00	97.33	351
FAC	0.74	98.07	254
NAV	0.68	98.75	203
FCF	0.58	99.33	211
<b>Sum:</b>	<b>99.33</b>		<b>36,298</b>

A *typical* year for the A-10 fleet flies this mix of missions. It is from these data that one can understand the demands placed on the fleet. To simplify the usage data to a *typical* year, the medians of each mission code shown in Table 4.1 were calculated over the 11-year population. Fleet-wide, the median number of missions per year was 36,298. This number is subject to a variety of influences: political changes, budgetary climate and combat needs.

### 4.2.3 Data Analysis

The edited database contained these factors: aircraft tail number, six levels of counting accelerometer data, an elapsed time indicator, mission type, base of assignment, rounds fired, date, flight duration and cumulative flight hours. Principal component analysis

showed that mission type, mission duration, rounds fired and base of assignment had high eigenvalues and were the factors that impacted counting accelerometer occurrences and therefore explained the variance in the dataset. Each of these factors except rounds fired is discussed in this paper.

The established approach for analyzing aging aircraft counting accelerometer data is discussed by both Denyer and Gray [22], [13]. The calculation of normal load factor occurrences per 1,000 flight hours is used as the standard for comparison with historical studies (Equation 4.1). Normal load factor,  $N_{z_j}$  represents the counting accelerometer bins where  $j = (0.3, 2.5, 3, 4, 4, 5.5, 7)$ .

$$C_j = \frac{\sum_1^n N_{z_j} \text{ Occurrences}}{\sum_1^n \text{ Flight Hours}} \times 1,000 \quad (4.1)$$

Aircraft within one mission design series experience a range of loads, but that variability can be considered stochastic. De Jonge's work with counting accelerometers acknowledges this, allowing the methodological use of Equation 4.1 for comparisons between different mission types [21]. Holpp and Landy also followed this approach using generic, DoD fighter data to assess aircraft loading spectra [23]. They showed counting accelerometer cumulative occurrence plots from a government study that highlighted differences between air-to-air, air-to-ground and loiter mission type categories. Holpp and Landy did not analyze the differences between mission types nor did they assess the reasons for the differences because their objective was to develop an overarching usage spectrum. De Jonge's later work on fighter aircraft shows a difference in load experience for different mission types [15]. In this approach, he reduces counting accelerometer data to a singular parameter per flight, labeled the load severity factor (calculated from a combination of recorded parameters and Miner's rule).

### 4.3 Results

To address the first hypothesis stating that the type of mission impacts the loading pattern, it must be shown that there exists a measurable difference in counting accelerometer occurrences for each mission type. This will be shown through the distillation of the dataset into mission type subgroups with a subsequent between-subjects treatment using ANOVA. Then to address the second hypothesis, that some mission types account for greater loading accumulation, the mission type subgroup data are parsed. Then their exponential decay model coefficients are compared. Lastly, bivariate correlation and the Pearson product-moment correlation coefficient are used to show the relationship between flight hours and

g-count occurrences to demonstrate that the established relationships have a positive correlation with increasing time.

#### 4.3.1 Loading Environment

To understand the loading environment differences between missions, it is critical to first establish the loading environment for an individual sortie. The median yearly loading accumulations for the fleet are shown in Table 4.2. The median g-count occurrences per flying hour represent the distillation of the population data into a tangible cost for each hour an A-10 flies. For example, an A-10 will accumulate the g-count occurrences shown in Table 4.2 in a 2.26-hour sortie, which is the average sortie duration during the data collection period. The A-10 fleet accumulated 748,812 counts on its 3g counters in a median year. Any candidate tail number accumulated 9 counts (integer scale) on the 3g counter in one flight hour. For the average A-10 sortie duration of 2.26 hours, a candidate aircraft would receive 20 counts on its 3g counter. This is the real structural loading cost of one hour of flight.

Table 4.2: Distribution of g-counts

<b>Counting Accelerometer</b>	<b>Median Yearly g-Counts</b>	<b>Mean g-Counts Per Flight Hr</b>	<b>Mean g-Counts Per Avg Sortie</b>
0.3g	194,472	2.31	5.22
2.5g	1,267,447	15.42	34.85
3g	748,812	9.21	20.81
4g	298,941	3.62	8.18
5.5g	32,078	0.42	0.95
7g	2,166	0.03	0.07

These medians and means are powerful tools for fleet managers. Knowing how much loading accumulation occurs in a typical flight hour can help managers predict useful lives for their fleets. Figure 4.3 is a box plot of the counting accelerometer data, showing the means, 25<sup>th</sup> and 75<sup>th</sup> percentiles as well as outliers. The boxplot whiskers are set to 2.7 standard deviations, so all data beyond them are shown as individual datum points. The box plot shows the relationship between counts on each counting accelerometer for a typical flying hour.

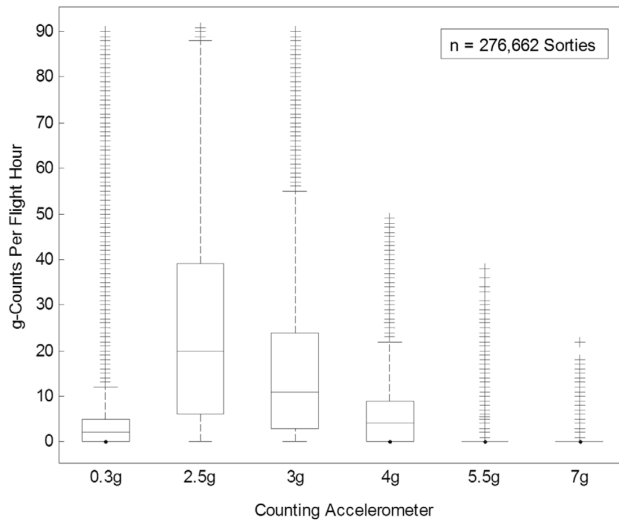


Figure 4.3: Box plot of g-counts per flight hour

Understanding the loading spectrum for a *typical year* and a *typical flying hour* are important, but it is essential to know how each mission code affects the loading patterns. Each mission code was isolated in the population to determine its contribution to loading patterns. The g-counts per flight hour for select mission codes are summarized in Figure 4.4. Surface Attack (SA), Functional Check Flight (FCF) and Navigation (NAV) were chosen for inclusion because they represent a broad range of the mission type subgroups, thus emphasizing the variability. Because the counting accelerometers are discrete, not continuous, connecting lines were merely added for clarity of presentation.

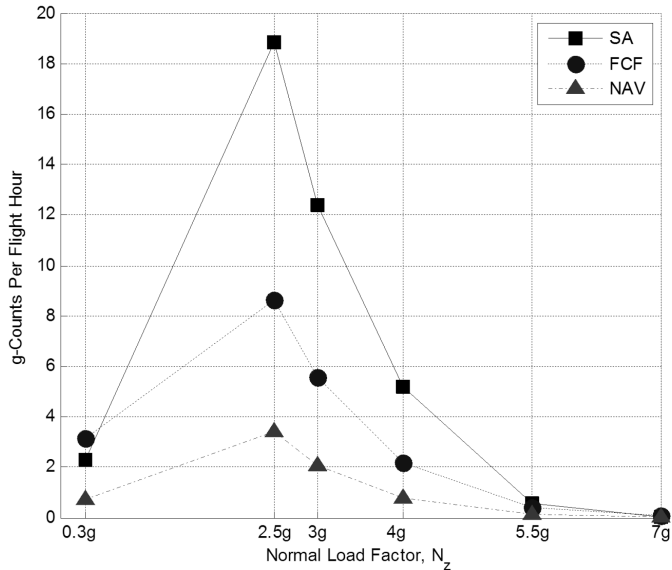


Figure 4.4: Loading pattern per flight hour for mission types

These data answer several important questions. First, the type of mission impacts the loading pattern experienced by the aircraft. The types of missions flown impact how many g-count occurrences are accumulated on the fleet. The stratification in the data is more visible at the lower g-levels with less variance at the 5.5g and 7g levels. In the full dataset not shown here, some mission types stand out compared to the others. Close Air Support (CAS) and Surface Attack Tactics (SAT) both have greater counts per flight hour than the other mission types. Other (OTH) is found close to the median at each bin. OTH is the catch-all mission code when a pilot felt that he did not predominantly fly one of the other mission codes, so this code is less valuable and serves as a proxy median. Consequently, fleet managers cannot use the data provided by OTH to devise fleet optimization algorithms.

Applying Equation 4.1 to these data allows for comparison to legacy aircraft and across time. The cumulative normal load factor occurrences per 1,000 flight hours for the same selected mission types are shown in Figure 4.5. Connecting lines were again added for clarity of presentation. The logarithmic ordinate best represents the differences between mission type usage severity across the full spectrum of recorded normal load factors and confirms the result that mission type impacts the loading pattern.

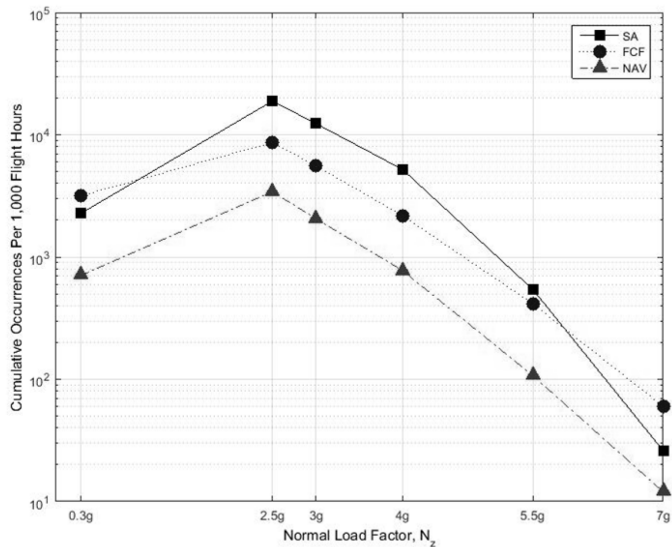


Figure 4.5: Usage severity shown for select mission types

The underlying data used for Figure 4.4 and Figure 4.5 showed that the SAT and OTH g-count loading patterns are similarly shaped. An ANOVA to detect between-subjects effects shows significance for four of the six normal load factors, shown in Table 4.3: SAT-OTH ANOVA comparison. Fleet managers cannot be certain that the SAT and OTH 5.5g and 7g trends are distinct due to their high p-values.

Table 4.3: SAT-OTH ANOVA comparison

Counting Accelerometer	f-Statistic	p-Value
0.3g	24.603	0.000
2.5g	15.222	0.000
3g	36.924	0.000
4g	326.662	0.000
5.5g	0.750	0.386
7g	0.140	0.708

The counting accelerometers were analyzed for variance using an ANOVA. Table 4.4: Summary of mission code ANOVA shows that the variance present within the counting accelerometer subgroups (0.3g, 2.5g, 3g, 4g, 5.5g and 7g) are significant and should therefore be treated as different in further analyses.

Table 4.4: Summary of mission code ANOVA

<b>Counting Accelerometer</b>	<b>f-Statistic</b>	<b>p-Value</b>
0.3g	364.988	0.000
2.5g	1609.144	0.000
3g	2063.013	0.000
4g	2373.582	0.000
5.5g	285.735	0.000
7g	26.870	0.000

### 4.3.2 Mission Evaluation

To show the correlation of loading pattern to mission type, it was required to map each mission code to the counting accelerometer data. Counter occurrences per sortie were evaluated, as were the percentages of counter occurrences with respect to the sum for each mission code. Both of these approaches presented factual but incomplete results because neither depicted usage in terms useful to aircraft managers. Since flight hours are the basic unit of aircraft usage, counter occurrences per flight hour best represented the loading patterns. All values higher than the mean in the counter subgroups (columns) are bolded.

Table 4.5: Counting accelerometer occurrences per hour for each mission type

<b>Mission Code</b>	<b>Counts Per Hour</b>					
	<b>0.3g</b>	<b>2.5g</b>	<b>3g</b>	<b>4g</b>	<b>5.5g</b>	<b>7g</b>
SAT	<b>2.28</b>	<b>15.90</b>	<b>9.83</b>	<b>3.68</b>	<b>0.36</b>	0.02
AR	<b>2.50</b>	<b>13.76</b>	<b>8.67</b>	<b>3.44</b>	0.32	0.02
BFM	<b>3.21</b>	<b>15.97</b>	<b>10.87</b>	<b>4.86</b>	<b>0.48</b>	<b>0.04</b>
CAS	1.31	8.26	4.84	1.82	0.19	0.01
FAC	1.50	9.93	5.65	2.08	0.23	0.01
FCF	<b>3.17</b>	8.65	5.58	2.18	<b>0.41</b>	<b>0.06</b>
NAV	0.71	3.42	2.06	0.77	0.11	0.01
OTH	<b>2.24</b>	<b>14.37</b>	<b>9.43</b>	<b>3.86</b>	<b>0.33</b>	0.02
SA	<b>2.28</b>	<b>18.86</b>	<b>12.37</b>	<b>5.20</b>	<b>0.54</b>	<b>0.03</b>
SAR	1.62	12.02	6.65	1.95	0.18	0.01

Bolded values are above the column mean.



The data in Table 4.5 were transformed to cumulative occurrences per 1,000 flight hours for each counting accelerometer. These data are shown graphically in Figure 4.6, where the curve fits are all one-term exponential distributions calculated by Equation 4.2. Exponential fits were expected because each positive, lesser accelerometer must serially receive a count to register a higher count during a maneuver from 1g. The 0.3g counting accelerometer was masked from this data representation because data between the 0.3g and 2.5g counters are significantly impacted by the asymptotic nature of the function near 1g. The value  $x$  represents the normal load factor and  $a$  and  $b$  are coefficient terms. All values of  $b$  are negative resulting in exponential decay for increasing load factor. Table 4.6 shows the coefficients used to build each exponential model.

$$f(x) = ae^{bx} \quad (4.2)$$

The number of occurrences of a particular normal load factor may now be calculated. Then algebraic manipulation yields Equation 4.3 where the value  $y$  represents the number of occurrences per 1,000 flight hours of a normal load factor,  $x$ . The values  $a$  and  $b$  are both coefficients.

$$x = \frac{\ln\left(\frac{y}{a}\right)}{b} \quad (4.3)$$

These equations and the exponential models show the differences in loading accumulation for each of the ten mission types. The limitation to this approach is that the counting accelerometers are discrete. Continuous data from a digital data recorder could reveal more information about the occurrences experienced at all load factors. Thus, these exponential fits assume exponential behavior between counting accelerometers.

It must be noted that the chosen fit type consistently over-predicts the 5.5g counting accelerometer occurrences. The reason for this is not known, but was discussed in conversations with pilots. Many A-10 maneuvers require a 5g pull and it is assumed that pilots try not to overshoot that mark, resulting in sub-5g maneuvering. However, this explanation does not adequately address why the exponential fit remains accurate for the 7g counting accelerometer occurrences. Despite the poor fit for the 5.5g counting accelerometer occurrences, the exponential fit was deemed the best approach.

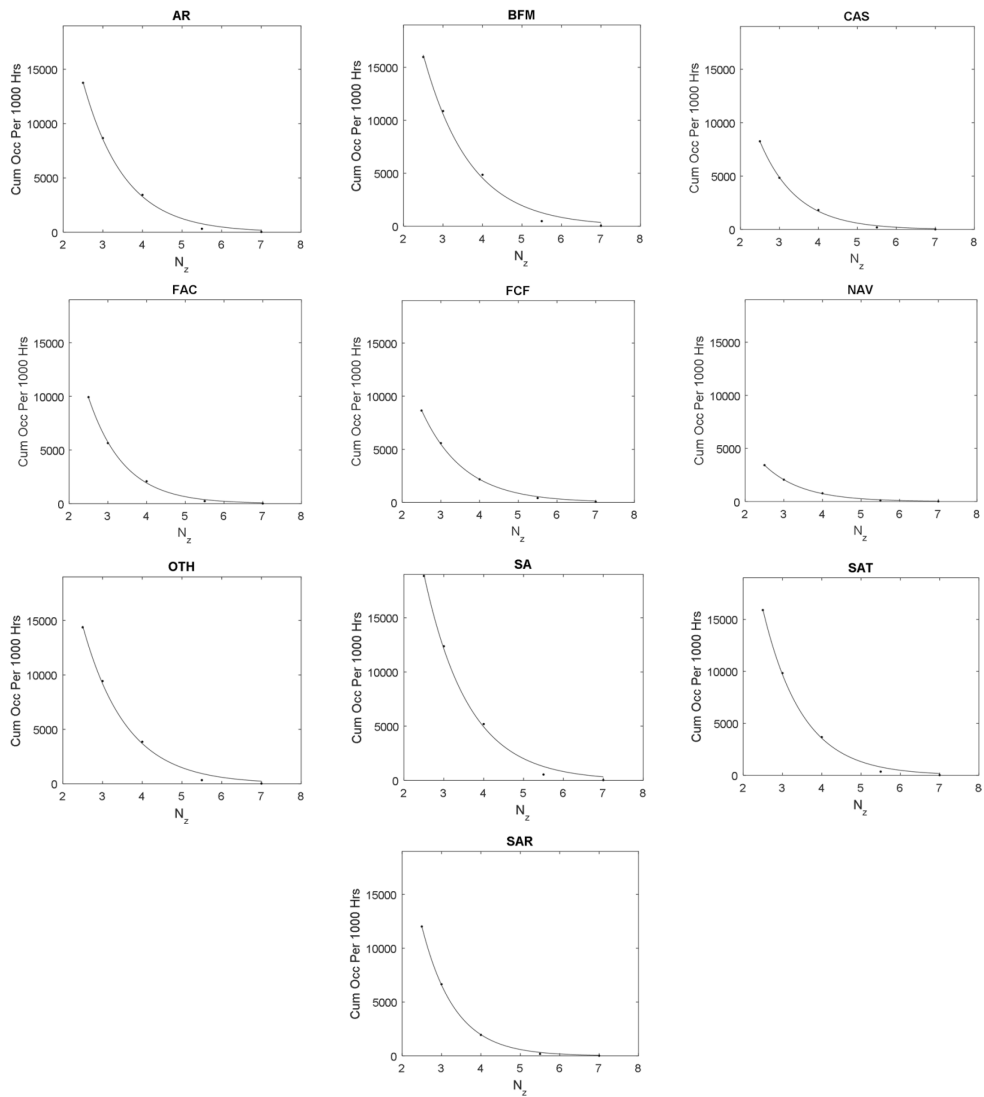


Figure 4.6: Exponential fits for mission types

Table 4.6: Coefficients for mission type exponential fits

<b>Mission</b>	<b>a</b>	<b>b</b>	<b>R<sup>2</sup></b>	<b>RMSE</b>
AR	1.521e+05	-0.959	0.9980	306.2
BFM	1.34e+05	-0.8457	0.9950	562.2
CAS	1.137e+05	-1.049	0.9991	119.5
FAC	1.513e+05	-1.091	0.9992	138.8
FCF	8.743e+04	-0.9231	0.9993	108.4
NAV	4.351e+04	-1.017	0.9995	38.4
OTH	1.417e+05	-0.9115	0.9966	415.8
SA	1.797e+05	-0.8983	0.9970	514
SAR	2.461e+05	-1.207	0.9997	94.6
SAT	1.938e+05	-0.9982	0.9986	292.5

### 4.3.3 Basic Fighter Maneuvers (BFM) and Surface Attack (SA) Missions Accrue the Most g-Counts

These two mission types have g-count occurrences per hour above the mean for each counting accelerometer subgroup. Tangibly, this means that these mission types have more g-transients and therefore contribute more to structural degradation [24]. Because the counting accelerometer system increments each time a normal load factor is surpassed, the aircraft is experiencing more departures from the normal acceleration of gravity in both the positive and negative directions. Since fatigue damage is caused by the accumulation of loading, BFM and SA missions contribute the most to aircraft lifetime usage. This assumes stores weight, stores location and aircraft fuel load for BFM and SA missions are similar to those of other mission types.

This result is sensible. BFM is an aggressive mission type because it simulates an air-to-air engagement. As the data show, pilots will utilize all regions of the flight envelope to gain an energy advantage against an opponent. SA missions are characteristically aggressive because the run-in and safe-escape phases of an engagement with a ground asset are designed to evade enemy ground fire.

### 4.3.4 Close Air Support (CAS) and Navigation (NAV) Missions Are the Least Damaging

CAS and NAV missions experience fewer g-transients compared to other mission types. These sorties spend more time at 1g. For CAS, this means more time orbiting an engagement area waiting for orders to engage an enemy position. Pilots flying CAS avoid excessive maneuvering and flight under elevated g-loads because of increased fuel burn for

those actions and therefore decreased loiter time. NAV missions are generally flown over long distances where fuel consumption is closely monitored. Therefore, the likelihood for elevated g-loading is decreased.

#### **4.3.5 Aerial Refueling (AR) Missions Are Structurally Significant**

Pilot tendency to code a mission as AR is greatest for those missions whose primary purpose is practicing aerial refueling with a tanker aircraft. These missions may include multiple rejoins, boom connects/disconnects and simulated breakaways. Maneuvering near a tanker aircraft is usually in the middle of the flight envelope, near 1g. Simulated breakaways, where the refueling aircraft expeditiously separates from the tanker aircraft, often transit below 1g. This is shown in the data. AR missions account for a high number of 0.3g counts.

#### **4.3.6 Functional Check Flight (FCF) Missions Are the Most Extreme Flying**

FCF missions are required after major maintenance actions. These missions are designed to test the aircraft in all regions of the flight envelope to ensure the aircraft is capable of full functionality. Table 4.5 shows that FCF missions have the highest 7g occurrences per flying hour. FCF missions also have the second highest occurrences per hour for the 0.3g counter. This occurs because FCF missions are required to fly at the extremes of the flight envelope. BFM and SA accrue more counts than the mean, but FCF is also an important mission type for fleet managers because of its contribution to loading at the extremes of the loading spectrum.

Three sample mission types (SA, FCF and NAV) are shown in a spider plot as Figure 4.7, which is a different representation of the data shown in Figure 4.4. This plotting technique best shows the differences between an aggressive mission type (SA), a more docile mission type (NAV) and a mission type with skewed loading (FCF). The skewness best illustrated by the FCF data trace shows the abundance of 7g counts accrued in FCF. The lines between each datum point were added for visual convenience and do not suggest continuous data.

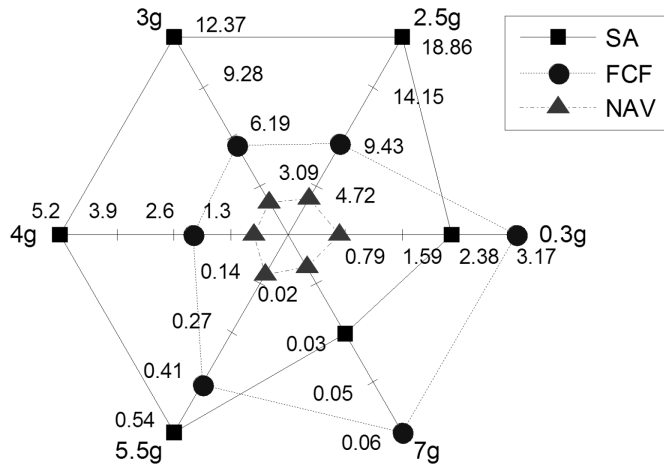


Figure 4.7: Spider plot of normal load factor occurrences per flight hour

#### 4.3.7 Relationship Between Aircraft Age and g-Counts

Median counting accelerometer counts were tabulated for each age-ranked tail number to determine if aircraft age had an impact on an aircraft’s g-count accumulation. The resulting linear trend equations are listed in Table 4.7, where  $y$  represents g-count occurrences and  $x$  represents aircraft age. Not enough non-zero data from the 5.5g and 7g counting accelerometers existed so their linear trend equations were omitted from Table 4.7. The low coefficients of determination, measures of the total variance of the dependent variables that can be explained by the equations, are due to the large sample size. These equations show there to be no significant aircraft age effect on g-count accumulation rate. This implies that the reason for aircraft retirement must not be because older aircraft were flown harder in bygone days but might be because older aircraft have merely accumulated more structural loading through time.

Table 4.7: Counting accelerometer linear trend relating aircraft age

Counting Accelerometer	Linear Trend Equation	R <sup>2</sup>
0.3g	$y = 0.0009x + 1.689$	0.0069
2.5g	$y = -0.0014x + 20.937$	0.0003
3g	$y = -0.0019x + 12.156$	0.0014
4g	$y = -0.0018x + 4.5616$	0.0073

### 4.3.8 Relationship Between Flight Duration and g-Counts

If older aircraft accumulate more structural loading through time, it must be shown that increased flight time correlates to increased loading. Figure 4.8 illustrates the pattern comparing increasing flight duration to g-counts for one representative counting accelerometer (5.5g). Only flight durations between 0.6 hours and 5.0 hours were plotted to best show the typical data and to exclude outliers. These exclusions reduced the number of samples compared to other plots in this section. As flight duration increases to the center of the distribution the tendency for higher g-counts increases. After the center, the tendency for higher g-counts decreases. The shape of the data shows that there is a flight duration effect, which was expected. A longer flight duration gives a pilot more opportunity to maneuver the aircraft through the range of counting accelerometers. A density plot of the same data confirmed the relationship shown in Figure 4.8. Excessive maneuvering increases g-counts but also consumes more fuel. During a sortie without aerial refueling, excessive maneuvering would lead to a shorter sortie duration. Therefore, sorties shown in the right-tail of the distribution represent two categories: sorties with minimal maneuvering to extend sortie duration and sorties where aerial refueling took place. These classes of missions are skewed towards long-distance flights, during which pilots refrain from excessive maneuvering. This result was verified through an interview with an A-10 test pilot [25]. For reference, the max endure label indicates the approximate maximum sortie duration without aerial refueling.

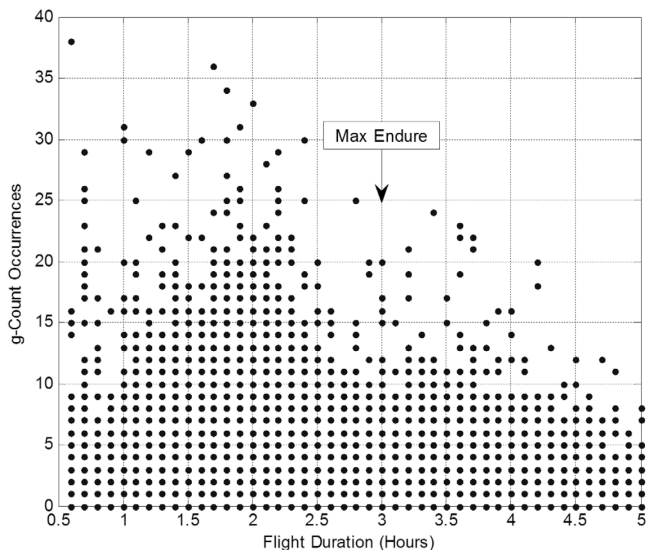


Figure 4.8: Relationship of flight duration to g-count occurrences,  $n = 265,680$

Assuming a stochastic makeup of flight assignments, it follows that aircraft with more flight hours, regardless of flight duration, would have accumulated more g-counts through time. Figure 4.8 shows this relationship using data from the 4g counting accelerometer for all 356 aircraft in the study. Aircraft with lower flight hours in the dataset tend to have shorter duration sorties, but higher g-counts (indicative of some mission types). Still, a natural scatter in the data confirms the stochastic nature of mission assignments across the fleet. A bivariate correlation of each of the counting accelerometer data revealed that all but the 7g accelerometer had a positive correlation. The results, along with relationship and strength are contained in Table 4.8 [26].

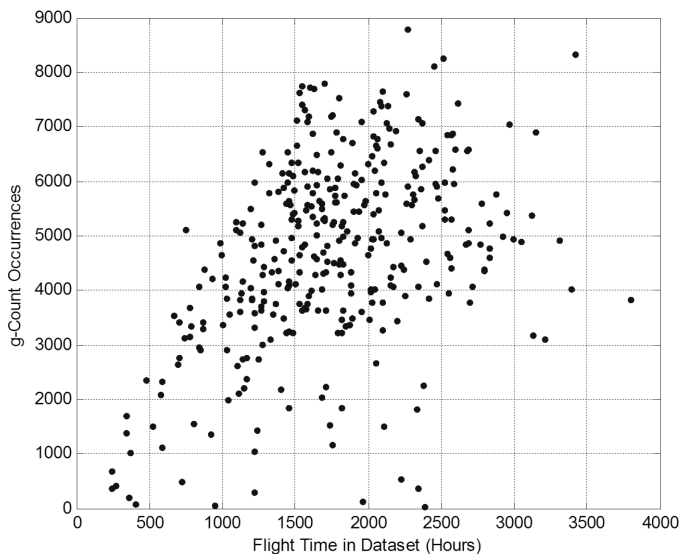


Figure 4.9: Cumulative flight hours compared to g-counts for the 4g counting accelerometer, n = 356 aircraft

Table 4.8: Bivariate correlation of g-counts to flight time in dataset

Counting Accelerometer	Pearson Corr. (r)	Relationship - Strength	Sig.
0.3g	0.289	Pos – Sm	0.000
2.5g	0.488	Pos – Med	0.000
3g	0.460	Pos – Med	0.000
4g	0.426	Pos – Med	0.000
5.5g	0.211	Pos – Sm	0.000
7g	-0.100	Neg – Sm	0.058

### 4.3.9 Validation

To verify the aforementioned data reduction and analysis methods, previous study data were evaluated for similarity. Benchmark A-10 cumulative occurrence data collected during a 6,000 flight hour usage profile in 1992 was provided by Grumman Aerospace Corporation [27]. The A-10 data from this 2016 study matched the profile data curvature from the 1992 collection showing a decrease in occurrence magnitude at the 7g load factor (Figure 4.10).

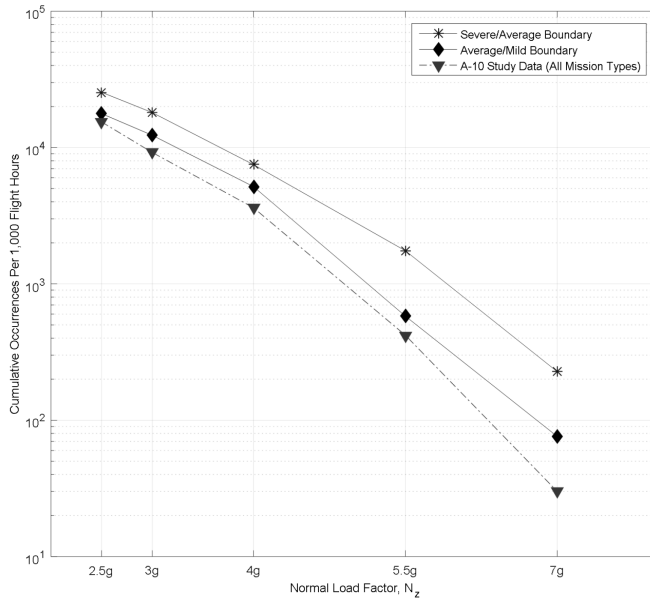


Figure 4.10: 1992 Grumman A-10 severity spectrum compared to 2016 study data

Other unclassified counting accelerometer data exist for a variety of aircraft but the work done by De Fiore, Leikach and Bohannon and Kaniss provided the most relevant military attack aircraft data [28], [29], [30], [31]. Navy Blue Angels A-4F data recorded in 1975 had a usable data retention rate of 73.68%, which was comparable to this study's 68.36% retention rate [29]. The B-1B capture rate has been as high as 75% and as low as 60% [22]. De Fiore's analysis showed that increasing  $N_z$  increases the coefficient of variation in the data, similar to what was found in this study's data [28]. Also, De Fiore found differences in loadings by mission type, a primary hypothesis of this study [15]. He concluded that air-to-ground missions were the most severe and navigation missions were nearly the least severe. However, De Jonge's Weibull distribution fits possessed a lower coefficient of determination than this study's exponential distribution fits. The reason for the small



difference could be from the difference in sample size or operational reporting techniques. It is sensible to fit an exponential function to data collected in an incremental fashion.

Counting accelerometer bin frequencies in other aircraft studies mirrored the data in this study. Figure 4.11 shows data from the Royal Australian Navy’s A-4G Skyhawk (16 aircraft representing 15,502 flight hours, 1962-1977) and the U.S. Navy’s A-7A Corsair II (194 aircraft representing 197,869 flight hours, 1932-1974) alongside A-10 data [31], [28]. The exponential fit equation is shown in Equation 4.4 where  $x$  is defined as the normal load factor. This exponential fit appears to be a poor fit because of the logarithmic ordinate, but the  $R^2$  is 0.9967.

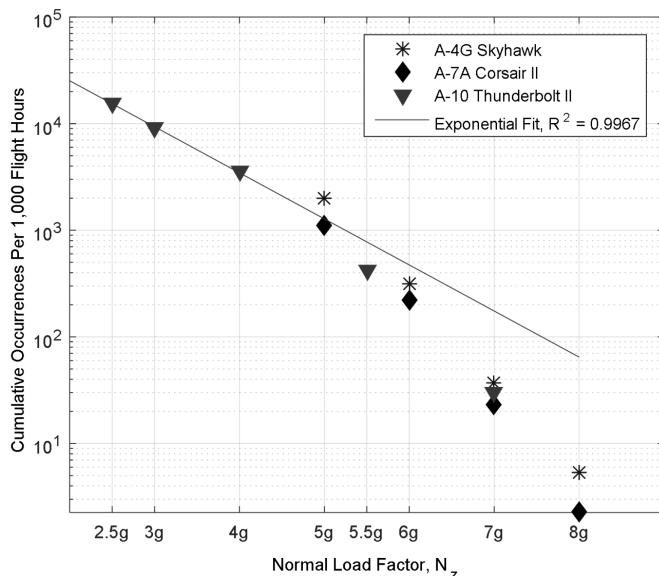


Figure 4.11: Comparison of counting accelerometer data for multiple attack aircraft

$$f(x) = 1.85 \times 10^5 e^{-0.9949x} \quad (4.4)$$

The comparison studies showed evidence that model variations (A-7A versus A-7B, for example) led to usage differences and within model mission assignments (lead versus chase, for example) led to usage differences. In the case of the latter, the chase aircraft is subjected to greater loading than the lead aircraft. Unfortunately, there is no designator or derived parameter in this study’s dataset that defines lead versus chase aircraft roles.

Looking at mission design series designations and data compiled by the United States Navy, the USAF and Fokker aircraft, it is clear that each aircraft type experiences different

loading patterns. Attack aircraft usage spectra fall toward the middle of aircraft usage for the types identified in Figure 4.12. Fighter aircraft and flight demonstration aircraft accrue more damaging flight hours while bomber, cargo and passenger aircraft accrue less damaging flight hours. This validation step shows that the macroscopic discussion of aircraft type matters just as mission types matter within an aircraft type. Figure 4.12 was constructed using representative aircraft possessing counting accelerometer technology from each type category. All data were previously published [22], [32], [28].

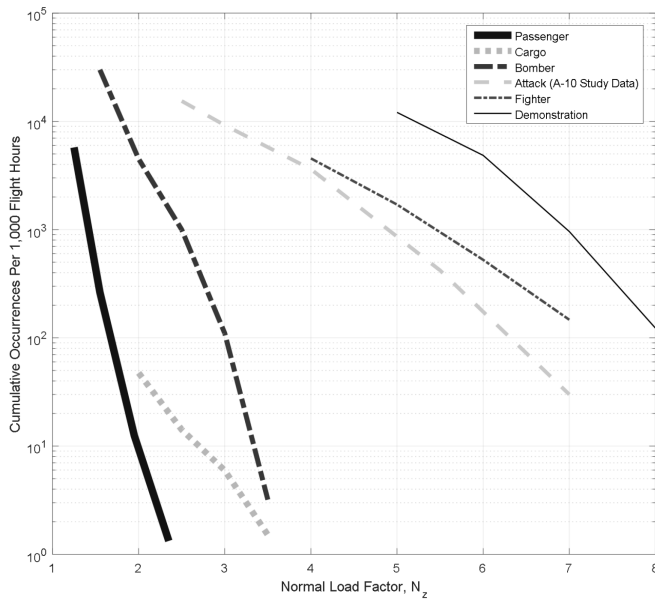


Figure 4.12: Comparison of counting accelerometer data for aircraft types

Lastly, the finding that flights longer than some peak lead to fewer g-counts is supported by De Jonge and Hol's analysis of Fokker F27 and F28 commercial aircraft hourly damage calculations [32]. They found a decreasing trend in loading accumulation per flight hour because the percentage of flight time consisting of high loading takeoffs and landings is less for a long flight [32].

#### 4.4 Impact

The correlation between mission type and structural loading is a bridge between structural health monitoring data collection and implementation of those findings. This result is directly useful for military aircraft fleet operators and will impact the assignment of aircraft to varying mission roles. Fleet managers faced with the retirement decision may opt to

reassign aircraft to less structurally damaging mission types thereby prolonging fleet viability.

Some nations and military services do this as standard practice, as discussed by Simpson [33]. The dialogue about extending service lives of aircraft now has a study that shows how closer mission type management can realize fleet lifetime extension. Military aircraft outside of the attack genre and commercial aircraft fleets can benefit from these results through use of the presented assessment strategy with their fleet-specific input data.

#### **4.5 Conclusions**

This study has answered two hypotheses relating to the correlation of mission type to aircraft loading using case study data from the A-10 attack aircraft. The A-10 was chosen because it is wholly representative of attack aircraft worldwide. The A-10 dataset matched attack aircraft from the United States Navy and the Royal Australian Navy, proving these findings are not limited to USAF aircraft alone. Further studies would be needed to confirm the applicability of the conclusions of this study for other aircraft types and for those in the commercial sector.

The first hypothesis posited that the type of mission impacts the loading pattern experienced by an attack aircraft. Data showed that there is a marked difference in g-counts for aircraft flying dissimilar mission types. This result was seen for each of the 10 mission types analyzed in the A-10 dataset. The differences were found to be statistically significant. Exponential decay models showed differences in the mission types and form the underlying equations for future optimization methods. Fleet managers can use these equations for fleet planning and mission allocation strategies.

The second hypothesis stated that some mission types account for greater loading damage accumulation. This was shown to be true. For the analyzed dataset, Basic Fighter Maneuvers and Surface Attack accrued the greatest elevated g-counts while Close Air Support and Navigation accrued the least elevated g-counts. ASIP managers interested in prolonging aircraft lifetime can use these results to prioritize mission types that accrue the least number of elevated g-counts. For example, an aircraft's lifetime could in practice be prolonged by flying fewer Basic Fighter Maneuvers or Surface Attack and more Close Air Support or Navigation.

These conclusions are vital for future research in this area. Because mission types are a distinct variable for aircraft loading history, there will exist an optimization for aircraft mission utilization. Accordingly, because military aircraft bases are often mission-specific, basing optimization will result in a change to fleet-wide loading accumulation.

The plethora of available counting accelerometer data is underutilized by researchers because they have focused on more modern structural health monitoring techniques. There is a lot to be gained from legacy data because it shows usage patterns over a much longer lifespan than more recent monitoring technologies. This paper has shown the intrinsic value in using existing data to show correlations in aircraft usage, which leads to potential for structural lifetime extension.

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## **5 Time to Retire: Indicators for Aircraft Fleets**

*If a fleet manager can predict when a fleet is nearing end-of-life, that knowledge can be used to more actively manage the fleet and its aircraft. This chapter shows that there are portents prior to aircraft structural failure. The motivations for aircraft retirements and the triggers for these motivations are described so fleet managers can recognize how their fleets align with known indications evidenced in other aging fleets. To illustrate a quantitative measure for recognizing the aging effects on an aircraft, the utility per cost ratio is developed. This metric compares a metric of utility chosen by the fleet manager against a lifecycle cost indicator. It was shown that the utility per cost ratio is a fair predictor of where a fleet resides on the aging continuum. Three zones show a break-in period, usage period and degradation period. Six USAF aircraft types were used to validate the work. Outputs of this chapter are important to the decision support framework, Chapter 3, showing both the quantitative and the qualitative inputs that fleet managers must consider.*

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# Time to Retire: Indicators for Aircraft Fleets

## Abstract

It is well known that aircraft fleets are aging alongside rising operations and support costs. Logisticians and fleet managers who better understand the milestones and timeline of an aging fleet can recognize potential savings. This paper outlines generalized milestones germane to military aircraft fleets and then discusses the causes that lead to retirement motivations. Then this paper develops a utility per cost metric for aging aircraft fleet comparison as a means for determining when to retire a fleet. It is shown that utility per cost is a pragmatic metric for gauging the desirability of an existing fleet because of naturally occurring zones. Historical data from the United States Air Force's fleet are used to validate the existence of these zones. Lastly, this work highlights the need for increased vigilance during the waning years of a fleet's lifecycle and discusses the intricacies of asset divestment planning.

## 5.1 Introduction

The operations and sustainment phase of a system's lifecycle can span several decades [1]. Within that span, an aircraft fleet can undergo multiple management changes. Historical and corporate knowledge of the airframe can be lost, leading to the necessity for developing and managing a plan for an aging fleet's extended care.

The United States Air Force's (USAF) Aircraft Structural Integrity Program (ASIP) manages aging aircraft with a particular focus on structural concerns. Three acronyms used in the ASIP are important: EFH, ESL and CSL. Equivalent flight hours (EFH) are calculated by multiplying actual flight hours by a severity factor based on loading conditions during a flight. Economic service life (ESL) is the EFH ceiling below which a fleet is economical to operate. Certified service life (CSL) is the EFH limit that has been approved for operations, based on aircraft analysis, risk forecasting and a full scale durability test. Regardless of aircraft age, a fleet may not fly beyond the CSL because airworthiness is not assured. ESL can be exceeded but the ESL is the point at which it may be more beneficial to divest and replace a fleet. This paper focuses on aircraft age because ESL and CSL are fleet dependent and change with time. EFH is aircraft-dependent and while it is useful to investigate effects on tail numbers, this paper will seek to develop age-based patterns.

Objective measures are required to benchmark a fleet's aging process. A fleet's average age, despite accumulation of EFH, indicates the onset of particular milestones. Milestones occur even though the fleet's relevance and ability to meet mission requirements may



remain strong. Figure 5.1 proposes a notional timeline from initial operating capability through retirement and delivery to an aircraft boneyard. Several example aircraft fleets are shown at approximate positions on Figure 5.1 to illustrate the span of a typical aircraft’s system lifecycle. These fleets, each known as a mission design series (MDS) do not experience every milestone pictured and the milestones may not occur in the order presented, but the events bound the position of a fleet on the aging aircraft timeline. Fleet managers must be continually cognizant of these indicators because proper planning and forecasting can mitigate aircraft safety risks and decrease lifecycle costs.

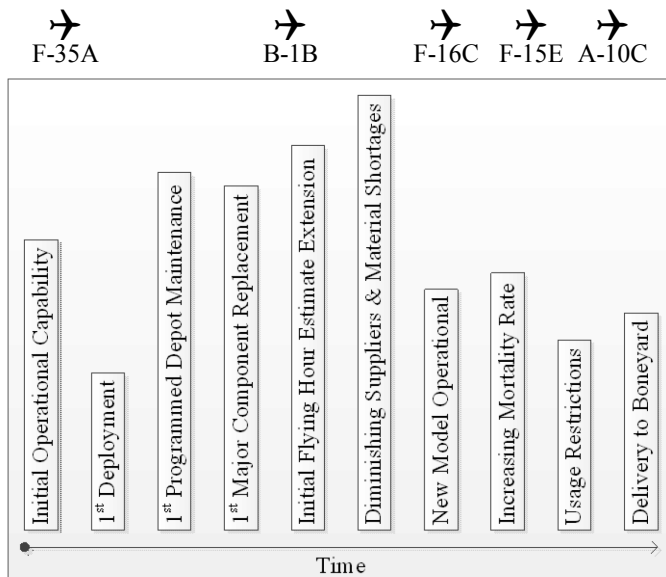


Figure 5.1: Notional aging aircraft fleet milestones

Each of the events in Figure 5.1 taken alone does not draw a pattern for an aging aircraft fleet. However, when viewed consecutively these events are seen as steps during aging. A major component replacement like a new wing or engine is an isolated event whose meaning enhances when shown next to a service life extension or supply chain disruptions. Similarly, airworthiness concerns manifest in multiple milestones such as increasing mortality rate and usage restrictions. It is incomplete to view any milestone in a vacuum. Each event may be separated by years and could be handled by a new fleet manager, so it is important to view the aging timeline at the appropriate level of fidelity.

The USAF’s organization tasked with evaluating the fleet milestones on the Figure 5.1 timeline was the Fleet Viability Board (FVB), which operated from 2003 until its

deactivation in 2012. At its largest, the board employed 60 contractors and civilians who were divided between four assessment teams responsible for reporting on the future options for an MDS [2]. The board completed 15 fleet assessments before closing after a robust and impactful eight years. While the board's goal was to determine the future viability of each fleet, the FVB also developed concepts germane to aircraft retirement philosophy. For example, the FVB presented decision makers with a range of options, suggesting that given enough funding some aging aircraft could maintain relevancy and airworthiness regardless of physical age [3]. Unfortunately, no equivalent to the FVB currently exists in the USAF. Its functions are now conducted by disparate organizations.

This look at aging aircraft indicators is necessary for the fleet management community. The purpose of this work is to continue the development of retirement planning best practices because divestment decisions are inherently imperfect and uncoordinated [4]. The work is novel because it develops the utility to cost ratio metric, a quantitative measure that can be used to position an aircraft fleet on the aging aircraft timeline. The remainder of this paper is organized into three sections: Aspects of Fleet Retirement, Results and Discussion and Conclusions. In the Aspects of Fleet Retirement section, the motivations for retiring a fleet and the associated causes will be presented. Then, a utility per cost metric will be developed to quantitatively identify the relative goodness of a fleet. In the Results and Discussion section, the utility per cost metric is validated using historical data from six USAF aircraft fleets. Asset retirement planning is also addressed. Lastly, the Conclusions section highlights the major findings from this research, lists the limitations of the work and then suggests areas for future work.

## **5.2 Aspects of Fleet Retirement**

One of the most basic questions about aircraft retirement is simply, "When should we retire the fleet?" Understanding when an MDS should be retired is a question whose answer hinges on a range of factors within and outside of a fleet manager's control. The most practical place to start is with the motivation for the retirement. Figure 5.2 shows three retirement motivations (effects) in the left column and associated triggers (causes) for each in the boxes on the right side. These causes and effects were derived from literature, subject matter experts and operational experience [5], [6], [7], [8], [9], [3]. An example using Figure 5.2 might be an MDS that is considered for retirement when its system life has been consumed (CSL). The causes suggest reasons why the fleet manager may have come to the conclusion that the system life is consumed. In this example, perhaps the MDS has experienced widespread fatigue damage or major corrosion, has mission restrictions due to airworthiness concerns or has experienced catastrophic failures. It is the causes that must be addressed to prolong the efficacy of a fleet.

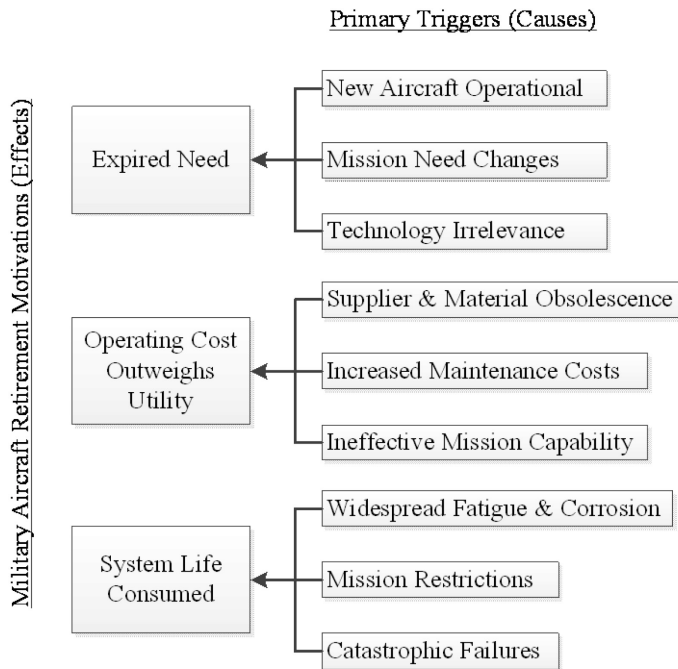


Figure 5.2: Retirement motivations and their associated triggers

In practice, aircraft retirement planning is far more complex than represented in Figure 5.1 and Figure 5.2, especially in the absence of the FVB. To understand the complexity, the A-10 Thunderbolt II will serve as an example. This aging aircraft, produced by the Fairchild Republic Company during the years 1975-1984, has undergone multiple upgrades and extensions to maintain an effective fleet [10], [11]. Several small batch retirements have occurred during the lifecycle of the A-10 and the fleet-wide retirement plan has been proposed, delayed and cancelled several times [12]. Divesting the A-10 was proposed for fiscal reasons, but opponents have questioned the capability-gap that would be left in the close air support of ground personnel mission area [13]. There are two elements of interest from this example. Picking an end-date for an aircraft fleet hinges on the capability need as well as the funding accessibility. The Air Force's close air support needs can be satisfied by other weapon systems (F-16, F-15), but transitioning aircrew and tactics requires time and funding. Waiting for the build-up of F-35 Joint Strike Fighter operating locations and the transfer of the close air support role also has complicated timing. Meanwhile, the budget appropriations for the A-10 are threatened each year and are uncertain in future years. This uncertainty can negatively impact maintenance operations and much needed upgrade programs.

Because of the A-10's age, it is a useful aircraft to map to the milestones identified in Figure 5.1. Initial operational capability occurred in 1977, aircraft were first deployed in 1978, depot maintenance has occurred periodically and most notably the main wing has been changed. The initial design life was 6,000 flight hours but the fleet average has eclipsed 10,000 hours per aircraft (2015) [10]. The CSL is 12,000 EFH and the ESL is 16,000 EFH, both fast approaching. The original equipment manufacturer as known in 1977 has disappeared, the supply base has contracted, the newer model A-10C reached initial operational capability in 2007 and other aircraft can perform the A-10's mission. Lastly, hundreds of A-10s (309 A-10A models and 49 A-10C models) have been delivered to the USAF's aircraft boneyard [14]. Usage restrictions for the remaining active fleet have been avoided primarily through extensive modifications.

Despite being at the far right end of Figure 5.1, the A-10 remains actively flying at nine permanent operating locations. This is because the A-10 has not met any of the retirement motivations shown in Figure 5.2. There is great need for a close air support aircraft in today's threat environment. The aircraft has been able to adapt to changing needs through system upgrades, including Global Positioning System capabilities, targeting pod integration, Joint Direct Attack Munitions and cockpit upgrades. The operating costs are lower than replacement aircraft (ESL not yet reached) and commanders maintain that the A-10 is their most useful air asset during engagements with enemy ground forces [11]. Despite rising maintenance costs, the A-10 is still operationally useful. Lastly, the system life or CSL of the A-10 has been largely consumed, but timely modifications and repairs have ensured airworthiness, preventing catastrophic failures or mission restrictions. Until one of the triggers (causes) drives greater attention to the retirement motivations, the A-10 will continue to operate unless budgetary or political conditions force fleet retirement.

Choosing when to retire a fleet will have a different answer depending on whom you ask. The USAF's status quo decision making for retirements starts with Headquarters Air Force, which tasks the major commands with force structure planning. With the many weapon systems across the military services, constantly changing global threats and political implications, picking the right time to retire assets is difficult and it is questionable whether an optimal solution exists [15].

Making several assumptions can reduce the complexity of the problem but still yield beneficial results. Assume that an aircraft type is single-role and that it is replaced by a like, single-role aircraft. Replacing an aging aircraft type with a multi-role aircraft type requires cost and performance trade-offs that entangle the decision process. Further, assuming that an aging aircraft fleet is replaced by a new but similar fleet allows for a less complicated amortization of procurement cost. To quantify the retirement planning problem, we must

develop equations that allow comparisons within a fleet and between fleets. The place to start is with the premise that assets should be replaced when the operating cost grows beyond the replacement cost [16], [17].

Amortizing the lifecycle cost of a new acquisition over the projected lifecycle duration allows comparison of the existing fleet cost (with remaining amortization) to a candidate replacement fleet's cost. Because the existing system has less remaining acquisition cost to amortize than does a new system, the time at which the existing system becomes more costly than purchasing/operating a new system will be at a time after the old system is simply more costly to operate than the new system. Said another way, acquisition cost of a new system delays the point at which it is fiscally advantageous to replace an aging system.

Measuring cost independently does not fairly address the value of an MDS. For example, if  $C_{F16} < C_{F35}$  that does not imply that the F-16 is a more desirable aircraft in all scenarios. Another factor, like utility, must balance what could otherwise be an overreliance on cost metrics [18]. Utility here is any suitable metric for an aircraft's usefulness to the fleet manager. Therefore, focusing on utility per cost leads to Equation 5.1.

$$\frac{U(t_p)}{C(t_p)} = \frac{\text{Utility During Lifecycle}}{\text{Cost During Lifecycle}} \quad (5.1)$$

where  $t_p$ , the replacement interval, is assumed to be the aircraft's useful lifetime. Utility represents an amalgamation of availability and capability. It is an objective measure unique to each fleet, therefore it may be calculated from metrics. For most aircraft types, utility is commonly represented by available aircraft. This metric is the product of each aircraft's mission capable rate and each aircraft's field possessed rate, both sampled monthly, summed across the fleet and normalized by the fleet size. Equation 5.2 shows instantaneous available aircraft for a fleet of size,  $N$ .

$$U \equiv AA = \frac{\sum_{i=1}^N MC_i \times FP_i}{N} \quad (5.2)$$

where  $FP$  is the field possessed rate and  $MC$  is the mission capable rate. The field possessed rate is the fraction of time an aircraft is available at home station. The field possessed rate excludes time when the aircraft is at a repair depot or in modification status. Mission capable rate is defined as the percentage of possessed hours that an aircraft can perform at least one of its assigned missions [19]. Available aircraft can be viewed relative to cost, as shown in Equation 5.3.

$$C_{AA} = \frac{C(t_p)}{\sum_{i=1}^{t_p} AA_i} \quad (5.3)$$

where  $C_{AA}$  is the cost per available aircraft. This was the principal metric used by the FVB because it included cost and available aircraft [20]. For this analysis, Equation 5.1 will be discussed because of its wider applicability to fleet managers.

Even in cost per available aircraft, the mission capable rate plays a dominant role. Utility for some aircraft types may be better represented by a blend of metrics, including mission capable rate, sorties per day, maintenance man hours per sortie, ton-miles per flight hour or others. This dichotomy highlights the difficulty of comparing dissimilar aircraft types. While available aircraft may be an ideal metric for determining viability of a cargo aircraft fleet, for example, available aircraft may not help differentiate between the utility of a single-role versus a multi-role fighter aircraft. These comparisons may require the use of additional metrics. This paper will use mission capable rate as a proxy for utility but will not draw comparisons across MDS.

Implementing Equations 5.1 and 5.2, utility per cost during a military fleet's lifecycle can be generically represented as Figure 5.3 where the data show a fleet's instantaneous, discretized utility per cost ratio. Cost data for this figure were derived from Dixon's 2006 RAND Corporation study while the utility data were derived from a 1997 Congressional Budget Office study [21], [22]. The ordinate has been normalized to one while the abscissa represents a 50-year operational phase. Integrating these results from fleet inception until a defined point in the operations and sustainment phase of the system lifecycle results in an objective measure of utility per cost that can be used for comparisons. This approach, while objective and simple, ignores some valuable intricacies of retirement planning. Utility per cost cannot tell you everything about a fleet but it can be used as a primary motivation to encourage fleet retirement.

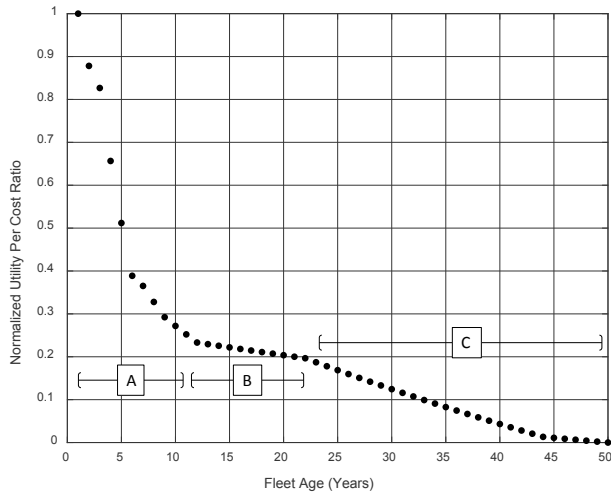


Figure 5.3: Notional utility per cost ratio for 50-year outlook

The general shape of Figure 5.3 is impacted by the operational demands put on a military aircraft fleet, the effectiveness of the fleet’s maintenance practices and total obligation authority (budget). Figure 5.3 has three labels, each drawing attention to a different region. Figure 5.4 shows how utility and cost act and the resultant slopes that are produced. While it is possible for there to be a positive slope locally, the utility and cost terms will produce various negative slopes from near aircraft infancy until aircraft retirement. Label *A* marks a zone of rapid utility per cost depreciation caused by rising cost during early operations. There is no evidence of an infancy effect in Dixon’s RAND data but it is reasonable to assume other models may include one. Label *B* evidences a zone where cost increases have subsided and utility is at its peak. Lastly, label *C* shows the onset of a steady decline. This zone is caused by a rapid decrease in utility despite a reduced cost increase rate.

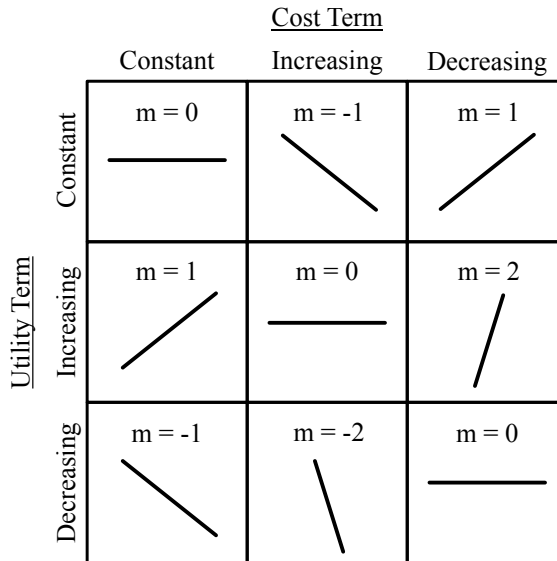


Figure 5.4: Resultant slope options for utility per cost ratio

Replacement asset acquisition cost, if amortized across a useful lifetime, would drive a fleet manager to accept a lower utility per cost ratio as a trade-off to absorbing the high cost of new asset acquisition. Therefore, a fleet manager could overlay a new fleet’s projected utility per cost curve on Figure 5.3 to help determine the optimal replacement time. The zones, labelled as *A*, *B* and *C* are valuable markers for comparison between old and new fleets.

### 5.3 Results and Discussion

#### 5.3.1 Validating Utility Per Cost Zones

Data obtained from the USAF’s Logistics, Installations and Mission Support-Enterprise View database were used to validate the model shown in Figure 5.3. Mission capable rate was used as the metric for utility because it was the most consistently collected metric throughout a fleet’s lifecycle. Total maintenance man hours were used as a proxy for cost, eliminating the need to correct for inflation. All data were averages for the fleet and were assessed discretely, for each fiscal year available in the database from database inception through fiscal year 2016. Monthly data were also evaluated and the results were similar. Six aircraft fleets were chosen for analysis: the C-130H cargo aircraft, the F-15E multirole fighter, the T-6A turboprop trainer, the F-16C fighter, the MQ-9 and the MQ-1 unmanned



aerial systems. These fleets were chosen because they represented a variety of aircraft roles and ages, which increased the robustness of the model validation.

The utility per cost ratio data for each aircraft fleet were normalized with respect to the model data. For example, the F-15E data available for years three to twenty-eight were normalized according to the values in the model in years three to twenty-eight. Figure 5.5 shows the six validation aircraft fleets compared to the model.

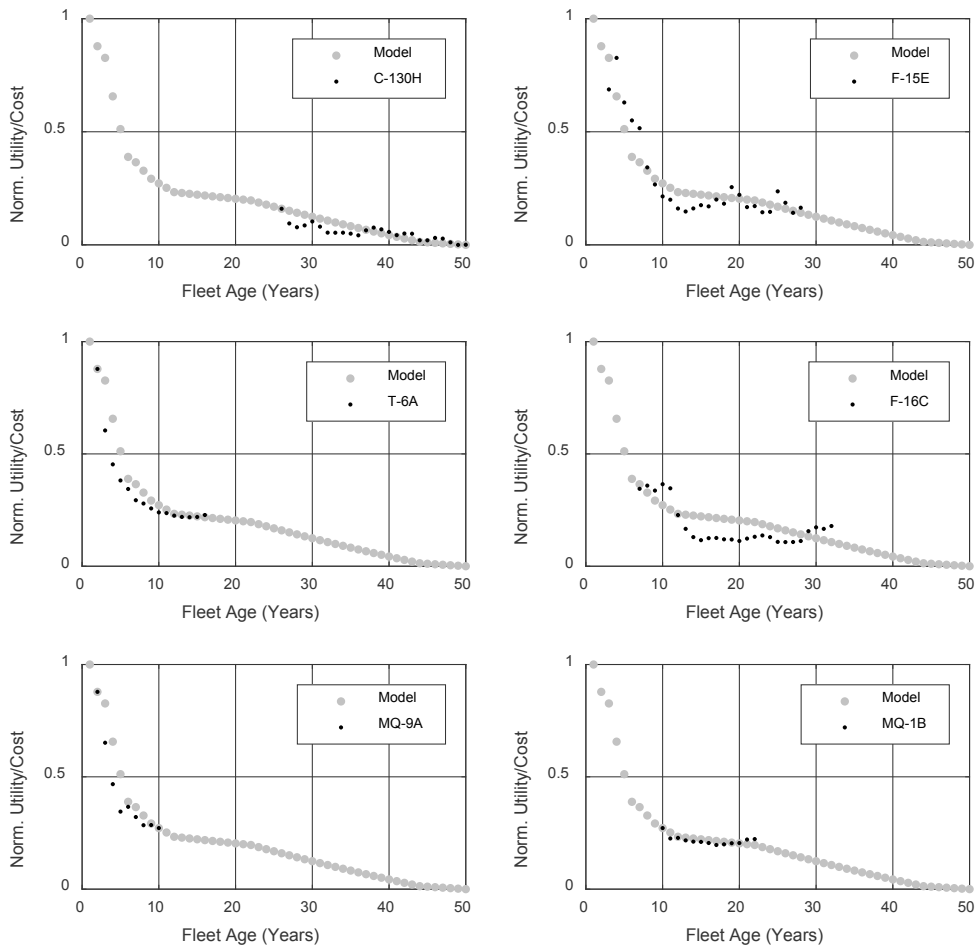


Figure 5.5: Aircraft data comparison to the normalized utility per cost ratio model

Figure 5.5 shows that some aircraft types match Dixon’s model and experience zone changes. A closer look at the C-130H and T-6A fleets will help to illustrate the value of

these results. The C-130H data span an average fleet age of 26 years through 50 years. These data fall entirely within Dixon's zone *C* and are valuable because they show no change within a zone. The T-6A data span an average fleet age of two years through sixteen years, crossing the boundary between zones *A* and *B*. A very clear slope change occurred. The F-15E data may show a transition from zone *B* to *C* but the research team was not confident of this assertion. Some fleets like the F-16C and others not shown do not follow the model. They show evidence of changing utility per cost over time, but do not fit the model with a high coefficient of determination. The F-16C appears to have a flat zone *B* instead of a negative slope as the proposed model suggests. While a flat zone *B* is good for a fleet manager, it is bad for model fit. The reasons for this mismatch may include changes in maintenance, changes in operations or changes in data collection practices, among others.

Because this is a broad snapshot of the overall fleet's lifecycle using aggregated metrics, the data do not map seamlessly to the notional data presented in Figure 5.3, but there is evidence of zones. This method has shown mission capable rate and maintenance man hours, via Equation 5.1 and Equation 5.2 can be used to show zone transition. This is important because asset retirement planning hinges on understanding the position of a fleet in its system lifecycle.

### **5.3.2 Asset Retirement Planning**

Retirement planning can be as important as acquisition planning and should be conducted simultaneously [4]. Without an effective asset divestiture plan, potential savings from a fleet's retirement can be lost. Worse, maintaining a failing fleet whose utility per cost ratio is in continual decline can divert focus and funding away from a replacement fleet [23]. Some reasons for poor divestiture planning are programmatic and budgetary while others reveal human nature. Divestiture planning exposes employees to questions about future employment stability but also forces employees to adapt their skills to a new fleet or new project. A fleet manager must recognize the human element to divestiture planning and assess the effects on the team [24].

Those responsible for retirement planning must also be aware of psychological biases that exist, such as escalating commitment. Managers may continue to invest in a failing system and ignore alternative options because of their previous commitments to the existing system [25]. For example, an aircraft fleet that has recently undergone a modernization program should not be immune from divestment discussions on the basis of renewed financial commitment. Also, retirement planning must not be fickle. Changes to planned fleet retirement dates are inherently inefficient and must be avoided through structured planning efforts.

While the optimal time for new asset acquisition depends on the specific factors for a particular fleet, two generalizable findings from this research are important. The first finding is that the divestment decision should be made using the utility per cost ratio because utility and cost are dependent factors. Either utility or cost can be artificially adjusted using the other factor. If a fleet experiences low utility, an influx of funding can increase utility. Similarly, budget decreases can be absorbed by allowing a fleet's utility to falter. The ratio of utility to cost tells stakeholders the exact usefulness of an aircraft fleet for the cost of that fleet. The second finding is that the optimal time to acquire a new aircraft fleet is dependent on the naturally occurring inflection points of the existing fleet's utility per cost ratio curve. The model derived from literature and proposed in Figure 5.3 is not representative of all aircraft types or all fleet management practices. However, the model is a starting point for comparisons. The relatively flat portion of the curve (Figure 5.3, *B*) is analogous to what has traditionally been termed the trough of the cost bathtub curve. This region reflects a low cost increase with age and a stable utility. New asset acquisition must begin after region *B*'s slope becomes more negative (Figure 5.3, *C*). This will always be the case because a like challenger asset carries a cost amortization penalty that an aging system does not have. Aircraft are complex capital assets and have a lengthy acquisition timeline. The length of this timeline can drive an acquisition decision years ahead of the need for those assets, forcing a fleet manager to make a prediction of when the utility per cost ratio decline will occur despite the manager having incomplete data. The model presented herein can be used as a guide for fleet managers attempting to predict the more rapid decline. However, caution must be exercised to avoid making premature decisions. Fleet-specific operations and maintenance practices may cause yearly fluctuations in aircraft metrics.

Looking at a fleet in aggregate and ignoring the infancy years, the utility decreases with time and the cost increases with time. The rates may change with asset type and overhauls can cause step functions in the values, but the gross patterns are set. Tracking utility and cost alongside the retirement milestones in Figure 5.1 can help identify or predict the triggers discussed in Figure 5.2. This work can indicate patterns in the fleet and prompt a more advanced look at the fleet retirement plan.

#### **5.4 Conclusions**

System program offices employ analysts who are experts on their fleets. Major commands also employ analysts who assess fleet capability and costs at an aggregate level. However, the number of these positions is shrinking and additionally, the loss of the USAF Fleet Viability Board in 2012 means that there are fewer experts invested in the aircraft retirement puzzle. The complexity inherent to retirement decisions is itself evidence that

logistical decisions can lead to savings. As shown herein, even the most basic question asking when a fleet should be retired is a difficult logistical query. Through the difficult aspects, simplifications can be made to show patterns and generalized retirement suggestions.

This paper presented the timeline aspect of the aircraft retirement and replacement question. Then, the utility per cost ratio metric was developed. The three regions evident in the utility per cost metric were shown and then validated using USAF data. The aircraft types C-130H, F-15E, T-6A, F-16C, MQ-9A and MQ-1B were used to study normalized utility per cost data. Most types evaluated matched the general trends suggested in literature while some did not match as closely. The problem was simplified using several key assumptions that led to the formulation of two findings. Using the utility per cost ratio is an important tool and knowing that the retirement time should occur after the middle zone of the utility per cost curve is vital to understand. This limited study was exploratory in nature. The methods should be tested with other aircraft types and verified using additional case study aircraft. Additional metrics or a blend of metrics should be evaluated to determine if they are better measures for utility than the mission capable rate.

Future work could address specific case study fleets or could apply these ideas to other capital asset types such as locomotives or wind turbines. Also, researchers could investigate metrics relevant to the primary causes presented in Figure 5.2. While the method presented herein utilized maintenance metrics for recognizing changes in the utility per cost metric, other metrics and methods could be applied to the other retirement causes.

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## **6 Application of a Greedy Algorithm to Military Aircraft Fleet Retirements**

*This chapter presents a model for identifying the right size of a fleet and which individual assets should be retained in that fleet to maximize capability. Outputs from Chapters 4 and 5 provided the measures for deciding the relative utility and cost of each aircraft in the analysis. The methodology used a greedy algorithm that iteratively decided whether or not a fleet composition met fleet requirements. The mathematical model allows for the choice of an objective function based on cost minimization, utility maximization or the maximization of the utility per cost ratio. An output of this model shows in what order to retire the aircraft to preserve the most fleet capability while downsizing the fleet size. This output is useful for Chapter 7 where the remaining aircraft will be tasked differently. The USAF's A-10 Thunderbolt II was used as the case study fleet for model validation. This chapter concludes by showing that early retirements levy the greatest impact on lifetime fleet cost and utility.*

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# Application of a Greedy Algorithm to Military Aircraft Fleet Retirements

## Abstract

This article presents a retirement analysis model for aircraft fleets. By employing a greedy algorithm, the presented solution is capable of identifying individually weak assets in a fleet of aircraft with inhomogeneous historical utilization. The model forecasts future retirement scenarios using user-defined decision periods, informed by a cost function, a utility function and demographic inputs to the model. The model satisfies first-order necessary conditions and uses cost minimization, utility maximization or a combination of the two as the objective function. This study creates a methodology for applying a greedy algorithm to a military fleet retirement scenario and then uses the United States Air Force A-10 Thunderbolt II fleet for model validation. It is shown that this methodology provides fleet managers with valid retirement options and shows that early retirement decisions substantially impact future fleet cost and utility.

## 6.1 Introduction

Military aircraft fleet managers are responsible for providing strategic capability to their owning command. Thus, aircraft are based around the globe to perform various roles under a variety of operating conditions. As these individual aircraft are flown over time, each develops a historical utilization profile that is related to its fatigue life expended [1]. When a fleet of individual assets nears projected end-of-life, it is imperative that the fleet manager plan for retirement so that operational demand can be satisfied. Retirement planning varies greatly across military services and within service fleets [2]; [3]. It can be proactive and data-driven but at times has been reactionary, driven by changing budgetary conditions or critical aircraft failures. As the average age of aircraft fleets is increasing, retirement planning tools and methodology are necessary to aid fleet managers through the retirement decision process [4].

The objective of this research was to develop a tool to provide fleet managers with a list of aircraft serial numbers that should be considered for retirement, sorted by precedence and timing. This tool is called the Fleet and Aircraft Retirement Model (FARM). FARM provides a list of aircraft indicating which should be retired first and when each should be retired. To improve the applicability of the tool, its interface is simplistic, the greedy algorithm implementation is clear and the inputs are accepted in a variety of formats. FARM was built for the spectrum of fleet managers including those who seek to minimize lifecycle cost, those who seek to maximize aircraft utility and those who prefer to maximize



the fleet's utility to cost ratio. The methodology also supports a fleet manager who wishes to use his own objective function that might be based on a variety of weighted metrics.

Prior to discussing retirement, a fleet manager must understand the fleet's demands and historical utilization [5]. A precursor to this work analyzed this opportunity using operational data from the United States Air Force (USAF) A-10 Thunderbolt II fleet [6]. The next step in retirement thinking is to develop replacement policy for a fleet utilizing the operations research methodologies contained in the study of replacement theory [7].

Unfortunately, current fleet retirement schemes are primarily based, after an initial objective screening, on subjective means because economic life calculations are exceedingly complex [8]; [9]; [10]. For example, the USAF gathers maintenance and logistics experts to decide which aircraft get retired, however the decision is very complex and the decision makers lack suitable tools [11]. Aircraft can be identified for retirement based on flight hours, repairs that limit usability, limits exceedances, corrosion or owning unit capabilities among many other factors. While the bulk of replacement theory literature discusses the replacement of current (defender) assets with more modern (challenger) assets, this study ignores challenger assets because their acquisition does not directly hasten defender retirements [12]. Also, the authors treat military aircraft as parallel assets that independently contribute to supply [13]. This allows for the specificity of individual serial numbers in the fleet.

A military aircraft fleet's assets do not continually operate at maximum capacity. Since retirement schedules depend on utilization, a fleet manager may alter utilization patterns leading to a more optimal retirement schedule. Testing various retirement schedules with an objective tool is necessary to quantify the net present value of each scheme. This work contributes a methodology that answers this need and enables fleet managers to make utilization decisions now that will affect future fleet statuses.

The novel contribution of the FARM methodology is the use of individual serial number utilization histories and cost data as a basis for future year predictions. Traditional replacement models have used fleet-wide utilization averaging or ignored asset utilization altogether, which has led to non-optimal solutions [14]. To overcome the limitation of basing forecasts on outdated information, fleet managers can periodically use FARM to update their fleet retirement forecasts, including updated cost and utility data for each iteration. This approach also allows fleet managers to alter their utilization levels across a fleet to optimize their retirement scheduling.

The remainder of this article will discuss the methodology employed in the FARM software. The background section contains relevant literature on asset retirement plus a discussion of capital asset replacement theory. In the methodology section, the greedy algorithm approach to the retirement problem and the mathematical formulation for FARM are described. Then the results section shows data from a simulation run using FARM for a virtual fleet. The discussion section highlights the usefulness of a serial number specific retirement tool and shows validation of FARM using the real USAF A-10 fleet. Lastly, the conclusions section emphasizes the major findings from this work.

## **6.2 Background**

### **6.2.1 Literature Review**

A military aircraft fleet retirement methodology must connect the domains of replacement theory, capital asset economics and military operational analysis. Relevant studies concerning asset replacement include the work by Jones, Rajagopalan, Bethuyne and the thorough treatment of capital equipment replacement in Jardine [15]; [16]; [17]; [18]. While insights can be gained from other domains, two considerations are important to aircraft replacements. First, aircraft lifecycles and planning/construction timelines are much greater than for some other asset categories. Second, upgrades and overhauls significantly alter the capability and lifetime projection [8].

Tang's work on replacement schedules discussed a time-space network approach for helicopters [8]. The study concluded that cost parameters like fixed and variable operating costs can be simplified for benefit of the model's approach. Tang assumed all helicopters were homogenous regardless of age and utilization history. Tang also excluded variable staff costs from the model. This research advances the work of Tang by accommodating variable staff costs in the variable cost function and also allows an inhomogeneous fleet input. Hartman's complementary work on replacement schedules showed that replacement schedules are highly dependent on asset utilization through time [19]. Hartman's integer programming method used a cost minimization technique for asset replacement over a finite horizon [14]. His work suggested that future work should address fleet management and fleet sizing options.

Jin and Kite-Powell's important work relied on system utilization and replacement decisions to meet the demands of a profit-maximizing manager [5]. Jin and Kite-Powell looked at operating cost trends and the cost of replacement as factors for the retirement decision for ships. The primary contribution of this existing work is the conclusion that an asset should be retired if its net benefit in a fleet is less than the salvage value.

Evans studied ship replacement theory basing his approach on costs rather than profits and concluding that replacement should occur when it becomes cheaper to purchase a replacement than to continue operating an aging system [20]. His work has many similarities to aircraft fleet replacement work, mainly that replacement should only be affected by costs in real terms. Additionally, Evans posited that replacement decisions should focus on the existing fleet and not on the costs or capabilities of the replacement assets. This study uses the same approach, suggesting that retirement is based on the current operating costs of the fleet. Since ship replacement requires years for contracting, construction and testing, ships are more similar to aircraft than assets in the motor vehicle, farm machinery and locomotive industries. As Evans posited, ships are often replaced with like replacements. However, aircraft are commonly replaced with newer assets with greater capability [21].

Malcomson worked to determine replacement rules for capital equipment and concluded that an iterative approach was the most efficient [22]. Like this work, Malcomson also assumed that the replacement trigger point must be when the operating cost of aging assets is greater than operating new equipment. Further, Malcomson noted that finite answers to the replacement problem are more desirable than approximate answers, and given modern computing power, finite solutions are attainable at very low cost.

Landry's work analyzed multiple courses of action for maintaining the aging fleet of Canadian CF188 (F-18) and CP140 (P-3) aircraft [23]. His work treated the problem as a business case analysis with the aim of providing a fleet manager with objective data for a retirement decision. His Airframe Life Extension Program (ALEX) software used fatigue test control point data to forecast early retirement dates.

Lu and Anderson-Cook concluded that future reliability estimations can be improved when assets of the same age are not treated homogeneously, but are rather based on historical usage [24]. The authors used an automobile example to illustrate that two cars of the same age do not possess the same reliability. Understanding mileage and usage conditions can improve maintenance and replacement decisions, just as understanding aircraft demographics can improve retirement decisions.

### **6.2.2 Replacement Theory**

Replacement theory is a decision making process from operations research dealing with substitute system selection conducted by an agent. For a group of assets, the formulation becomes a parallel replacement problem. If the goal is to minimize lifecycle cost, replacement theory can help determine a capital asset's optimum life. As capital assets age, increasing maintenance costs and reduced utility draw attention to the necessity for

replacement [17]; [24]. Retiring assets is half of the parallel replacement puzzle and the subject of this research. It is assumed that the selection of replacement equipment occurs outside the scope of this methodology.

Generally, new equipment with better capability replaces older equipment [25]. For aircraft, replacement theory might suggest two courses of action: upgrades/overhauls or retirement. As Landry's research concluded, the crux is deciding whether it is more fiscally responsible to upgrade aircraft structure or to replace the aircraft altogether [23]. This work only addresses the retirement course of action, which is termed the replacement model. It is believed that providing a fleet manager with the best replacement model will yield the most sensible economic replacement policy.

A parallel replacement problem, by its nature, addresses a set of assets. Unlike the single asset case, assets under consideration for parallel replacement can have their utilization levels adjusted to prolong or accelerate deterioration [17]. This can be an invaluable approach for fleet managers trying to meet operational requirements or retirement mandates.

## **6.3 Methodology**

### **6.3.1 Framing the Problem**

This problem assumed that a fleet manager desired to reduce his fleet size and desired to maintain the best aircraft in that fleet. To determine the optimal aircraft to retire at a point in the future, managers could use previous aircraft information as the best predictor for residual aircraft life [26]; [27]. Customer requirements therefore forced a certain formulation approach, which was to iteratively assess each aircraft's value to the fleet while decreasing the fleet size one-by-one.

To solve the problem of determining which aircraft to retire, it was necessary to analyze the current fleet and each smaller fleet size for each decision period. This approach was not computationally feasible for fleet sizes greater than approximately 15 assets because the number of decision variables grew beyond the capability of a desktop optimization solver to provide a solution within a reasonable timeframe. A greedy algorithm formulation was chosen because the selection problem relies on sequential decisions that impact the objective function. Each interim retirement decision must seek the local optimum instead of the global optimum, a facet of the greedy algorithm. There is no future guarantee of additional retirements so it is a must to maintain the local optimum solution after each retirement decision. Other formulations were evaluated but the greedy algorithm was deemed the most computationally efficient.

Calculating every permutation was not necessary since a greedy algorithm provides the same global optimum if the problem is appropriately bounded and local optima are avoided through logic [28]. This model consisted of a fleet of  $n$  aircraft with each subsequent fleet size,  $n-1$ , dependent on the previous reduction. This methodology was grounded in the assumption that a fleet manager desiring to retire two or more aircraft would always choose the worst asset to retire at each iteration. Therefore, all smaller fleet size problems became  $n-1$  easier until  $n-(n-1)$ , when the single remaining aircraft was the least desirable option. This iterative approach resulted in a Pareto front of fleet cost, fleet utility or the ratio of fleet utility to cost. Changing from a minimization model to a maximization model, a second Pareto front could be found. The space between the Pareto fronts indicates the relative goodness or inferiority of retirement choices.

### **6.3.2 Fleet and Aircraft Retirement Model**

FARM uses a greedy algorithm to determine which aircraft in an inhomogeneous fleet should be retired and in what order. For each smaller fleet size, the algorithm chooses the current optimal solution before analyzing the next smaller fleet size. FARM's methodology is outlined in Figure 6.1. The multi-year outlook makes retirement decisions using projected asset cost and utility. The model is valid for any initial and final fleet sizes. FARM operates with user inputs (decision periods, min/max aircraft ages, rate of yearly budget increase) and three user functions (fixed cost, variable cost, utility). The fixed cost is distributed evenly across assets while the variable cost and utility are both functions of aircraft age. FARM is flexible enough to offer these inputs as functions of equivalent flight hours or structural condition. Costs are modeled as equivalent costflow. Inflation and the effects of various methods for cost reporting were removed from the model by using maintenance man hours as a proxy in the variable cost calculations. Utility is analogous to aircraft availability, is a number between zero and one and is computed as the number of available days out of 31. However, individual FARM users may alter the format of input functions as necessary.

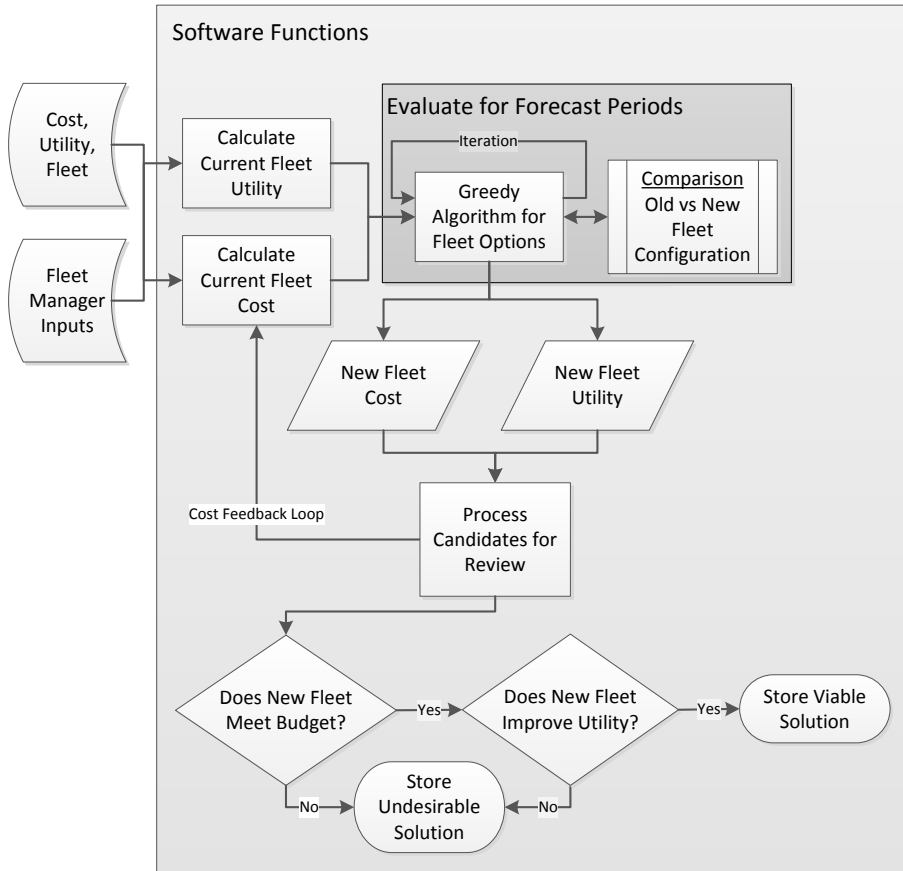


Figure 6.1: Flow chart for methodology steps

The methodology underlying FARM is useful for modeling a real fleet of aircraft as well as a virtual fleet of aircraft. Virtual fleet modeling follows the conventions found in literature: aircraft operations and support (O&S) costs are high in the first few years of operation, then they decrease sharply as the fleet matures and finally the costs increase at approximately 3% per year of age into the future [29]. Utility begins low for a new aircraft, then quickly peaks, followed by a decrease with age. An example of the cost and utility models used for FARM's development are shown in Figure 6.2. Step functions in utility levels and costs that occur due to major overhaul or repairs were not added to the model. Real fleets were modeled with actual cost and utility functions, which in general were found to follow the published conventions. To forecast future fleet conditions, the most recent cost and utility

were extrapolated through time. Otherwise, depending on the age distribution of the fleet, FARM would suggest retiring very young aircraft with high cost and low utility.

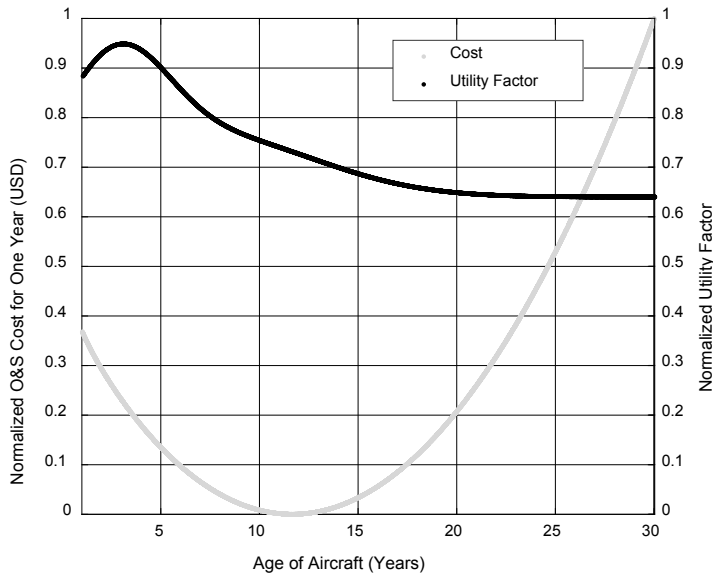


Figure 6.2: Representation of cost and utility models in FARM

For each decision period, FARM outputs the recommended serial numbers to retain for all fleet size options with associated metrics for each option. Fleet managers may use these data to identify their ideal fleet size and makeup. Fleet changes with time can then be evaluated. The limitations of this methodology and associated software model are few but important. The methodology is only valid for one mission design series. For example, a mixed fleet of KC-135s and F-15s cannot be evaluated. Second, the methodology does not allow for subjective valuations or weighting factors for the aircraft. Lastly, FARM does not provide a time-sequence of retirement decisions. Rather, FARM forecasts future asset cost and utility to support a retirement decision forecast.

### 6.3.3 Mathematical Formulation

This section presents the optimization model that the greedy algorithm solves in each of its iterations for a given year of interest. Table 6.1 shows the notation that was used to develop the methodology, then the decision variables and objective function are defined. Lastly, the calculation equations and problem constraints are presented.

Table 6.1: Indices, sets and variables for mathematical formulation

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Indices:

a	aircraft of interest
i	iteration
t	year of interest

Basic Sets:

A	aircraft type, $a$
T	decision period, $t$

Variables:

$\overline{B}_t$	max budget in year $t$
$C_a$	annualized cost function of aircraft $a$
$C_t$	cost of operating the fleet in year $t$
$C_{ta}$	cost of aircraft $a$ in year $t$
$F_t^i$	fleet size in year $t$ in iteration $i$
$\overline{NA}_t$	max number of operational aircraft in year $t$
$\underline{NA}_t$	min number of operational aircraft in year $t$
$R_{ta}^i$	if aircraft $a$ is retired in year $t$ in iteration $i$
$S_{ta}^i$	solution of aircraft $a$ in year $t$ in iteration $i$
$U_a$	annualized utility function of aircraft $a$
$U_t$	utility of the fleet in year $t$
$\underline{U}_t$	min utility threshold of the fleet in year $t$
$U_{ta}$	utility of aircraft $a$ in year $t$
$X_{ta}^i$	if aircraft $a$ is operating in year $t$ in iteration $i$
$W_c, W_u, W_r$	weighting (cost, utility, utility/cost ratio)

---

The decision variables are:

$$X_{ta}^i = \begin{cases} 1, & \text{operating,} \\ 0, & \text{not operating.} \end{cases}$$

$$R_{ta}^i = \begin{cases} 1, & \text{retired,} \\ 0, & \text{not retired.} \end{cases}$$

The objective function, Equation 6.1, seeks to maximize:

$$Z = -W_c \int_0^a \int_0^t C_{ta} X_{ta}^i dt da + W_u \int_0^a \int_0^t U_{ta} X_{ta}^i dt da + W_r \int_0^a \int_0^t \frac{U_{ta} X_{ta}^i}{C_{ta} X_{ta}^i} dt da \quad (6.1)$$



where:

$$W_c, W_u, W_r \in \{0,1\}, W_c + W_u + W_r = 1 \quad (6.2)$$

The objective function contains three terms. The first is the cost calculation, a combination of all fixed and variable costs for operations and sustainment. The second term is the utility calculation, measured as wished by the fleet manager. The third term is the utility per cost ratio, a way to balance the cost associated with changes to utility. It is assumed that only one term can be optimized at a time in the model. That is, one and only one of the weights is equal to one each time the optimization model is solved, as shown in Equation 6.2.

The calculation equations are subject to several constraints:

The sum of aircraft  $a$  in year  $t$  must be between the bounds of operational aircraft in year  $t$  Equation 6.3):

$$\underline{NA}_t \leq \sum_{a \in A} X_{ta}^i \leq \overline{NA}_t \quad (6.3)$$

The sum of the cost of aircraft  $a$  times inventory must be less than or equal to budget in year  $t$  (Equation 6.4):

$$\sum_{a \in A} C_{ta} X_{ta}^i \leq \overline{B}_t \quad (6.4)$$

The sum of utility of aircraft  $a$  times inventory must be greater than or equal to the minimum acceptable utility threshold in year  $t$  (Equation 6.5):

$$\sum_{a \in A} U_{ta} X_{ta}^i \geq \underline{U}_t \quad (6.5)$$

The opportunity to retire an aircraft  $a$  in year  $t$  is contingent upon the existence of aircraft  $a$  in the fleet in the previous year (Equation 6.6):

$$R_{ta}^i \leq X_{(t-1)a}, \forall a \in A \quad (6.6)$$

The presence of an aircraft  $a$  in year  $t$  given knowledge of previous years of interest and the decision made in year  $t$  is represented in Equation 6.7:

$$X_{ta}^i = (X_{(t-1)a}^i - R_{ta}^i), \forall a \in A \quad (6.7)$$

where upon initialization all aircraft are operational (Equation 6.8):

$$X_{0a}^i = 1, \forall a \in A \quad (6.8)$$

The fleet size in year  $t$ , Equation 6.9, is the summation of the operating aircraft:

$$F_t^i = \sum_{a \in A} X_{ta}^i \quad (6.9)$$

where the fleet size, Equation 6.10, must be one smaller each iteration:

$$F_t^i = F_t^{i-1} - 1 \quad (6.10)$$

and the initial fleet size, Equation 6.11, is the summation of the operating aircraft in the initial year:

$$F_{0a}^i = \sum_{a \in A} X_{0a}^i \quad (6.11)$$

### 6.3.4 Solution Approach

To ensure the problem was formulated correctly, a build-up approach was used. The problem was initially visualized and built on a small scale using Microsoft Excel's (version 14.0.7208.5000) solver function. This enabled fast troubleshooting for fleet sizes up to six aircraft. The constraints and bounds could be verified more efficiently with this approach.

For full fleets, the commercially available optimization software, ILOG CPLEX version 12.6.3, was chosen to solve the optimization formulation because of its Branch and Cut capability. Other open source optimizers were discounted because they are less powerful than a commercially available optimizer. The MATLAB version R2015b CPLEX connector was used because of the necessity to reformulate the fleet for each subsequent retirement decision. All pre- and post-processing was accomplished in MATLAB while optimization functions could be more efficiently computed by CPLEX. Sensitivity analysis was conducted to ensure the correct solution was being presented. Fleet cost and utility factors were used to assess whether the suggested solution was in accordance with the objective function.

Using MATLAB's linear programming functions alone were not appealing because CPLEX has evolved for three decades and provides pre-processing algorithms useful for this work's formulation. CPLEX's algorithms identify unnecessary variables and eliminate them to reduce the problem's size and thus decrease the solution time. Within CPLEX, there are multiple linear programming optimizers (mixed integer, dual simplex, primal simplex, et al). CPLEX calls the appropriate optimizer for the problem type in the name of solution speed. This work did not force a particular optimizer.

Heuristic methods were discounted for this solution approach because they do not provide a global optimum solution like algorithms guarantee. Nor do the heuristic formulations match with the problem type generated in this work.

## 6.4 Results

This section presents results from the FARM program. A virtual fleet is used for simulation and simplified output plots show representative results. Then, to validate the methodology, A-10 case study FARM results are shown with plots showing detail to the tail number level.

To evaluate FARM, this discussion uses a simulated aircraft fleet of size,  $n = 100$ , over a period of five years with cost and utility data similar to those represented in Figure 6.2. Aircraft ages were drawn from a uniform distribution. Budget was set at the current budget plus a 1% yearly budget increase to mimic the defense budgeting process. Minimum acceptable utility was set to 45% of the existing utility. Three objective functions are used: cost-minimization, utility-maximization and utility per cost maximization.

Figure 6.3 shows simplified simulation cost results for a sample fleet in year five for fleet size options from  $1:n$ . The two lines represent the feasible solutions, which include only those results meeting budget and utility requirements. The bottom curve represents the cost-minimization solutions. These solutions show the cost of the fleet for  $n$  aircraft,  $n-1$  aircraft, et cetera. The top curve shows fleet cost for cost-maximization or worst case retirement choices made for each fleet size. The vertical gap between the curves is the cost delta that can be saved by making the cost-minimization serial number retirement decisions. The curves are cut off at both ends, caused by the budget and utility constraints.

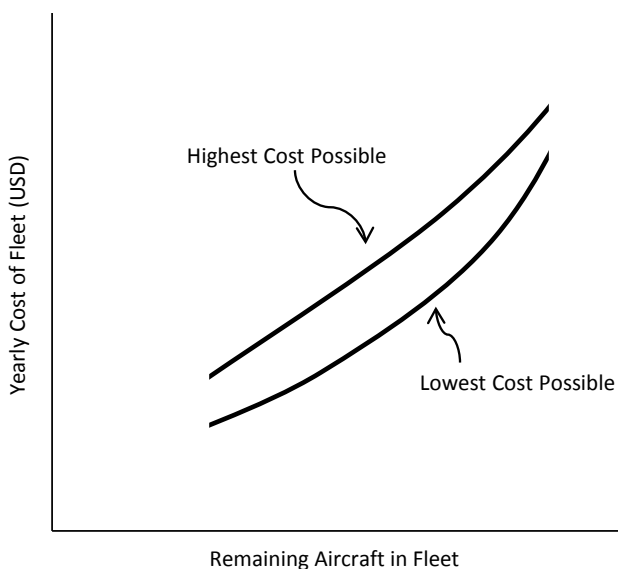


Figure 6.3: High and low cost options for fleet of various fleet size options

Figure 6.4 is an expanded view of a small portion of the lines in Figure 6.3. This expanded view shows that the Figure 6.3 lines are composed of many discrete points. At each fleet size,  $n$ , FARM calculates all of the possible options. These are shown in Figure 6.4 between the most expensive and least expensive options. Knowing the range of options is useful because it is not always practical for a fleet manager to retire the optimum aircraft.

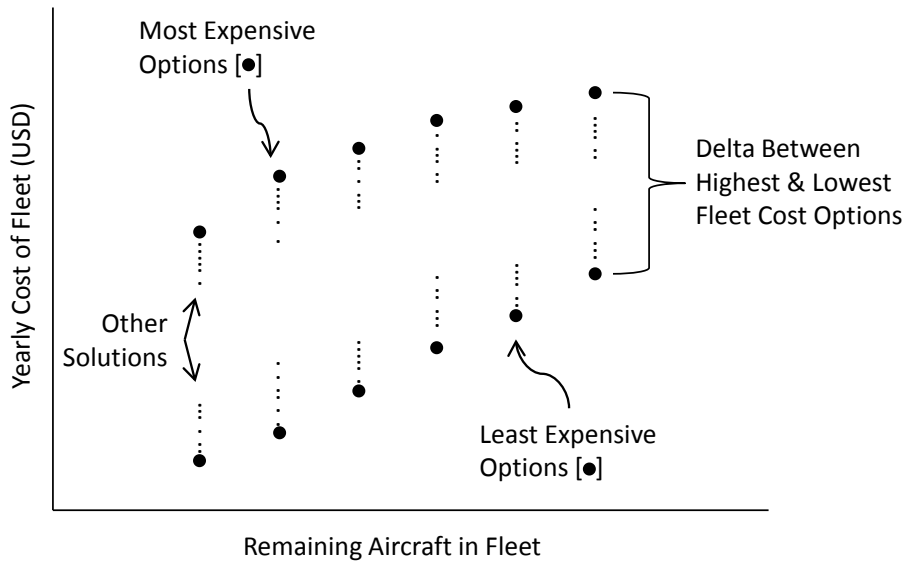


Figure 6.4: Expanded view of cost options showing all solutions

Figure 6.5 shows the simplified simulation results for the same scenario, but with a utility-centered management focus. These results inform the fleet manager which serial numbers to retire if the fleet goal was to maximize the utility factor, which for this scenario is the sum of aircraft days available per month for the existing fleet. The expanded view shows that for each fleet size, there are  $n-1$  utility outcomes. The shapes of the curves shown in Figure 6.3 – Figure 6.5 are the manifestation of the cost and utility input data.

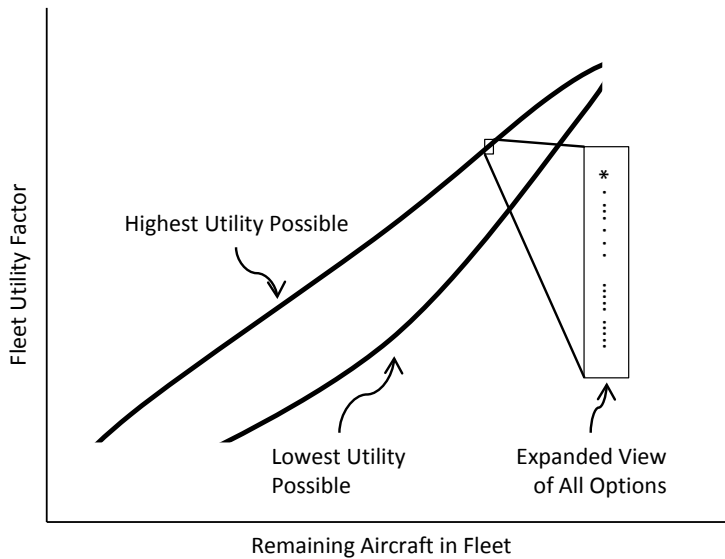


Figure 6.5: High and low utility options for various fleet size options with expanded view of all options

The curves in Figure 6.6 show the Pareto fronts for the utility per cost ratio calculations for the sample fleet. As aircraft are retired from the fleet (right to left), the curves diverge, showing that a fleet manager can make poor retirement decisions that impact the fleet's utility per cost ratio. As the fleet size shrinks, the shape of the Pareto curves shifts which is due to the fixed cost distribution function. Maintaining a constant fixed cost distribution function but varying the fleet retirement scenarios results in there always being a local maxima (optimality condition). This result is valuable to fleet managers because it recommends a minimum practical fleet sizing solution that conforms to the minimum utility requirement. For example, this simulation shows a maximum utility per cost ratio can be achieved for a fleet size of 30 aircraft.

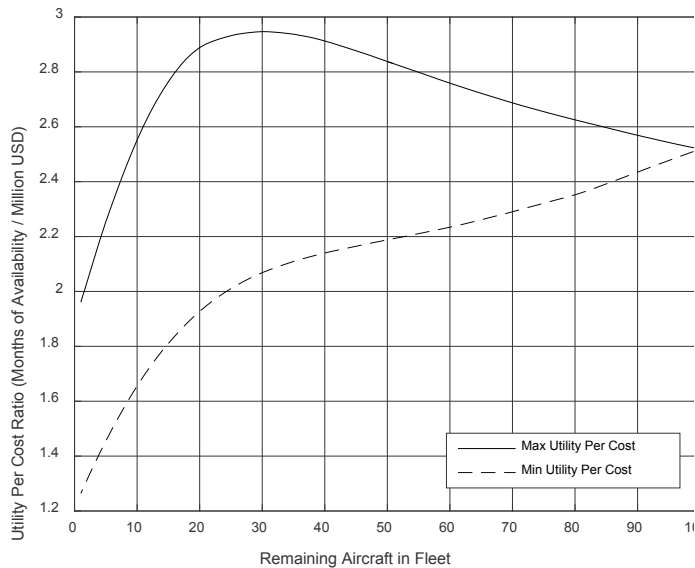


Figure 6.6: High and low utility per cost Pareto fronts for various valid fleet size options

### 6.5 A-10 Case Study

A realistic retirement scenario for the USAF A-10 fleet (2016 active fleet) sought to reduce the fleet size to simulate the closure of a base. Right-censored A-10 data were provided by the USAF and were used as demographic data for FARM. Maintenance man hour data were provided for each active tail number for each month for fiscal years 1995 through 2015 (66,172 total observations). Figure 6.7 shows two different percentile categories for the distribution of man hours and the median line of the aircraft in the set. These values are from individual aircraft, meaning the variation shown is due to variation in man hours per aircraft, not because of fleet size fluctuations. For example, the median number of maintenance man hours for a 14-year old A-10 was approximately 100 hours per month. The dashed line is a 3% growth prediction, which validates the relationship between aircraft age and maintenance burden for agile aircraft investigated by Dixon [29]. The A-10 maintenance man hour data increased at a rate of approximately 3% per year. A one-way ANOVA confirmed this age effect (factor: aircraft age; dependent variable: maintenance man-hours, p-factor = 0.014). A 159 USD labor cost rate derived from USAF depot cost data was applied to the man-hour data for illustrative purposes in the case study. Fixed cost and variable cost values were derived from the USAF's Total Ownership Cost tool [12]. The USAF provided maintenance activity data but there was no recorded link between a maintenance activity and man hours on a particular aircraft. Thus, maintenance could not be

correlated to utility measurements or mission capable rates with even the smallest amount of confidence. This amounted to an inability to show any relationship between maintenance activities and lagging increases or decreases in maintenance load.

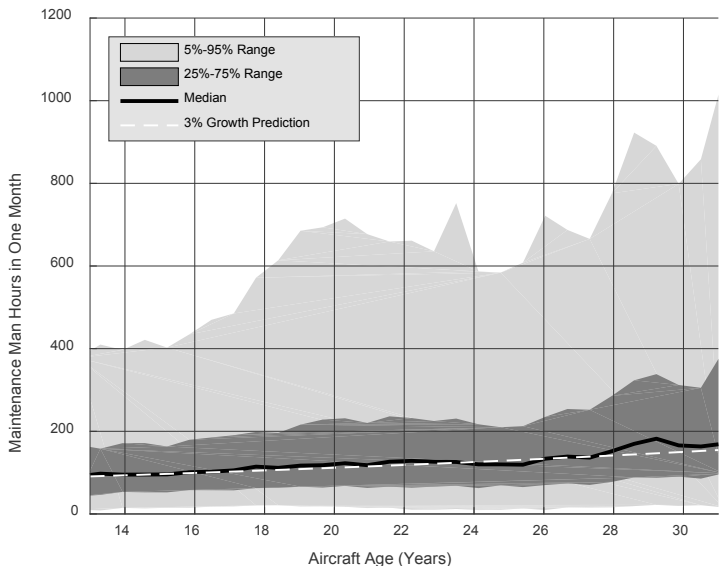


Figure 6.7: A-10 maintenance man-hours historical look

The USAF also provided mission capable rates as a utility measure for use in FARM simulations (not shown for security reasons). These data were recorded monthly for each active tail number for the years 2009-2015 (2,792 observations). The mission capable rate was a reasonable utility metric to use for the A-10 because it is a function of failure frequency, which represents asset reliability [30]. The mission capable rate data fluctuated in response to funding changes, upgrades and operational conditions. Similarly, it is assumed that maintenance man hours fluctuated in response. However, too many factors existed to draw a direct link between maintenance activities and mission capable rate. During the data collection period the A-10 fleet underwent a system life extension program (SLEP) that altered the mission capable rates of the fleet but isolating the SLEP as the principal cause was not possible from the data provided. However, these fluctuations in the data were useful for testing the software.

The maintenance man hour (cost) data and the mission capable rate (utility) data were input functions to FARM. Given these data, simulations were run to determine which aircraft would be chosen for retirement. For the active fleet of 349 A-10 aircraft, FARM produced

the cost minimization output shown as Figure 6.8 and the utility maximization output shown as Figure 6.9 for the decision period of five years. While not shown here, the accompanying outputs list the serial numbers that should be retired for each desired end-strength fleet size.

In Figure 6.8, the maximum budget line forms the horizontal border under which acceptable cost options can be chosen. Changing the budget in FARM directly shifts the maximum budget line up or down. The minimum utility cutoff is the vertical line near the middle of the figure. This line is moved to the left or right based on the utility requirement. Options to the left do not meet the user-input minimum utility requirement while options to the right of the line consist of fleets with enough aircraft to meet the utility requirement. The desired options, meeting both utility and cost, are black while the bad options are shown in gray.

Figure 6.9 is similar except that the utility measure is shown horizontally and the budget cutoff is visible in the top-right of the figure.

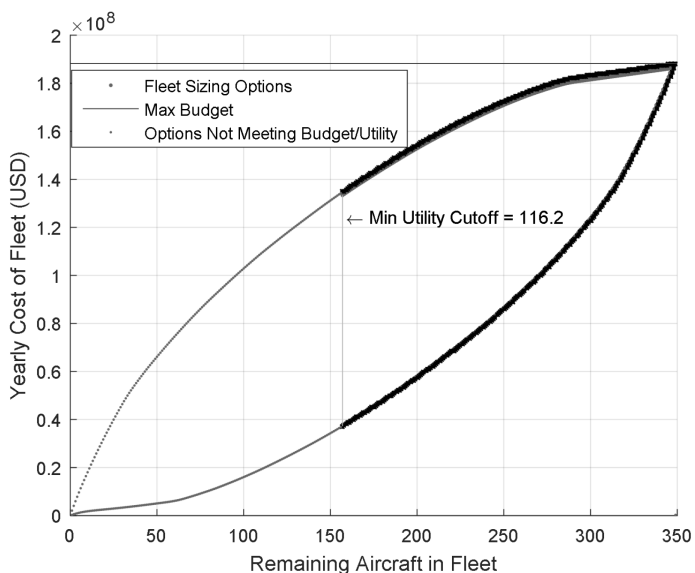


Figure 6.8: A-10 cost of fleet for various valid fleet size options



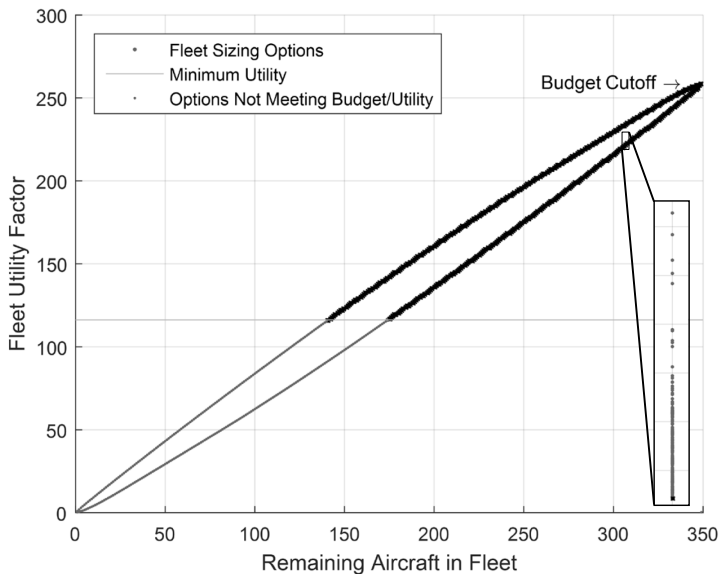


Figure 6.9: A-10 utility of fleet for various valid fleet size options

The cost minimization objective function results shown in Figure 6.3 and Figure 6.8 exhibit different shapes. This is due to the variance in the cost data inputs ( $\sigma_{A-10} > \sigma_{model}$ ) and emphasizes the potential advantage to this method's approach to identifying weak assets in a capital equipment fleet. Also, the expanded view in Figure 6.9 highlights the inhomogeneity of utility factors in the actual A-10 fleet. The groupings of solutions in the expanded view result because the utility input data possess groups of aircraft with low factors, probably due to major corrective maintenance on some serial numbers during the data collection period. Fleet managers must be aware that a low utility factor may be the result of corrective maintenance or upgrades, which may make an asset less desirable in the interim but more desirable in the future. This is reason for necessitating a human-in-the-loop methodology for aircraft retirement decision making. Expert opinion is crucial because all fleet metrics suffer from disadvantages. Additionally, using periodic fleet assessments can help fleet managers understand the effects of short-term fleet changes. FARM allows managers to cater the utility function so that recently improved aircraft are not identified for retirement.

## 6.6 Discussion

FARM experiments revealed several tenets important for retirement policy analysis, namely that the inputs drive the results, uncertainty dramatically reduces the model accuracy and

the earlier retirement decisions have the greatest impact on lifetime fleet cost and utility. Further, using the greedy algorithm enabled a computationally fast asset retirement model so that each of these tenets could be explored.

The shapes of the input functions directly impact the results. For example, if aircraft cost linearly increases as a function of age then the oldest aircraft (the most costly) are indicated by the greedy algorithm for retirement first. However, real fleets exhibit more complex input functions so FARM's value increases as a fleet's complexity increases.

Once uncertainty is entered into the retirement model framework, a fleet manager must be careful about forecasting which aircraft would be candidates for retirement in future years. In year one, the retirement suggestion is a direct representation of the initial cost and utility inputs. In future years, uncertainty in cost and utility forecasts grows, therefore making future year retirement decisions mere predictions, worsening with time. Cost uncertainty is shown in Figure 6.10. One facet of this uncertainty is the effect of short production runs. For a wide distribution of aircraft ages, FARM results show a finite solution. As the aircraft production timespan decreases, however, retirement prediction confidence decreases. This occurs because the cost differences between individual capital assets decreases thus making assets less distinguishable, particularly with confidence intervals. Retirement planning should be updated yearly with more recent cost and utility functions to lessen the uncertainty.

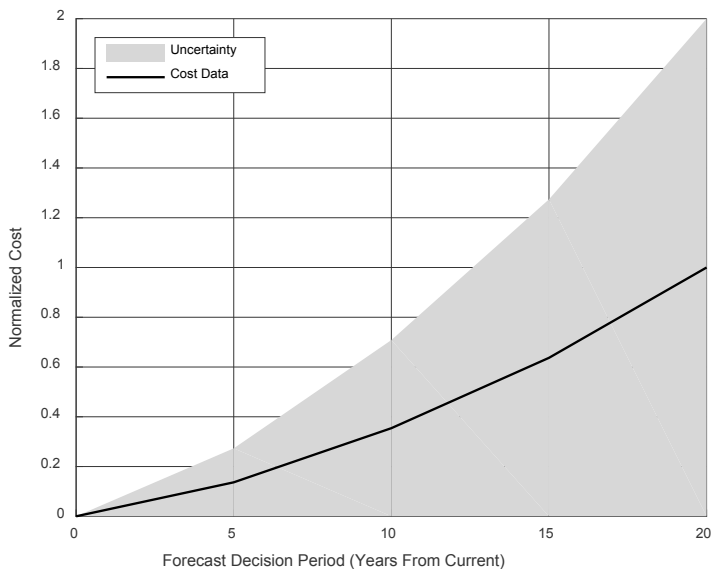


Figure 6.10: Uncertainty growth for FARM decision periods

FARM shows that it is more important to make the right retirement choices from the start. Retirement policy errors propagate through time, making the initial net present value decision an assumption of future net present value. Retiring an asset with more future potential than a neighboring asset will affect the cost baseline in each subsequent year.

For generic fleets, FARM shows that the costliest aircraft possessing the lowest utility should be retired first. Actual fleet data show that the oldest serial numbers sometimes are not the costliest, least useful aircraft because of usage variation. This is the most basic reason for using a methodology like the one developed for FARM for retirement analysis.

### 6.7 Validation

Sensitivity analysis showed accurate model response to a wide range of reasonable variable and function inputs. FARM was capable of calculating fleet retirement options for both very large and very small fleets but the results were most valuable to real-world fleet sizes in the tens to hundreds of aircraft. Computation time for all scenarios described in this article was below 60 seconds and the principal component affecting run time was the fleet size. A summary of run times for relevant USAF fleet sizes is shown in Table 6.2. The model's big O notation is:  $O(n^2)$ .

Table 6.2: Model run times for sample fleet sizes

Fleet Size	Run Time (sec)*
16	3.2
100	4.2
160	5.5
320	11.3
500	22.5
1000	95.2
2000	567.6

\*Intel Core 2 Duo, 3 GHz, 16 GB RAM

The model was developed using assumed values from previous studies but was validated using data from the United States Air Force's Logistics, Installations and Mission Support Enterprise View repository. F-16 Fighting Falcon and A-10 Thunderbolt II data validated the general forms of the cost and utility models. One necessary step of validating the model was to catalog and analyze the aircraft serial numbers recommended for retirement to ensure the model accurately identified the weak assets. The model was found to produce repeatable results, recommending the same serial numbers for retirement given static input

conditions. Likewise, whether the fleet manager wanted to retire  $n$  aircraft or some multiple of  $n$ , the sequence of retired serial numbers remained the same.

To determine model efficacy for an actual retirement scenario, the fiscal year 2013 retirement of 41 A-10s was analyzed. More aircraft were retired during this wave, but this validation effort focused on the 41 aircraft sent to retirement and ignored those aircraft reassigned as maintenance and egress trainers. The decision process to retire the 41 aircraft began in December 2011 and continued until early 2013. The FARM model was fed cost, utility and demographic data about the fleet in the years preceding and including 2012. Using the utility per cost ratio metric and allowing FARM to choose 41 aircraft for retirement, 19 (46%) of the FARM choices matched the USAF choices. Using just the cost metric resulted in 17 matches (41%) and using just the utility metric resulted in 15 matches (37%). These validation results do not necessarily suggest that the aircraft chosen in the 2013 retirement wave were chosen based on a utility per cost metric. The stakeholders involved in the retirement used a risk-based analytical process followed by other metrics and subjective determinations to select aircraft [31].

A second A-10 retirement population was evaluated to test the model. However, the 2011 retirement wave only consisted of nine serial numbers. Of that group, seven were reassigned to non-flying duties allowing only two serial numbers for model validation. The model would have retired one of those two aircraft, but the small population size limits the value of the finding. Due to the lack of additional aircraft fleet retirement data, no further validation analyses could be conducted. Retirement decisions are complex with many subjective factors, but having a simple tool that can provide decision makers with a starting point for choosing serial numbers shows the value of this methodology. In the case of the 2013 retirement wave, FARM would have provided an initial list that was nearly 50% accurate when compared to the final list.

A fleet manager could employ any of the three retirement strategies (cost minimization, utility maximization or utility per cost maximization) used in this study. To show validity, each strategy was compared to the others for both the A-10 case study and for a virtual fleet. In each case and as expected, the named strategy outperformed the remaining strategies. Figure 6.11 shows how the three strategies for the A-10 fleet compare with each other for the utility per cost maximization strategy. The similarity between the utility per cost maximization and cost minimization strategies in Figure 6.11 evidences why the 2013 retirement data match well for those two strategies.

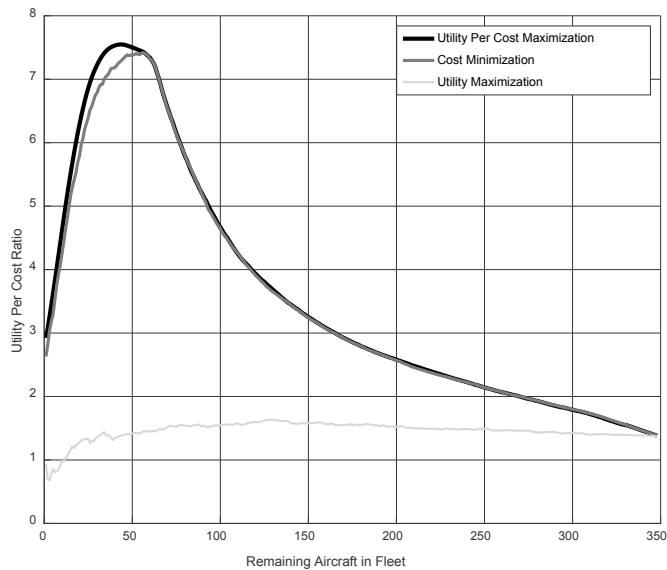


Figure 6.11: Comparison of retirement strategies for utility per cost ratio

Other validation plots show greater stratification between the three strategies. This shows the value of giving the fleet manager multiple objective function options.

## 6.8 Conclusions

This study applied a greedy algorithm to an aircraft fleet retirement decision. It answered the question of which individual aircraft serial numbers should be retired and in what order. The hallmarks of this study were the use of inhomogeneous utilization histories for parallel assets in addition to decision period forecasting. The methodology developed herein showed applicability to a virtual fleet as well as to the current USAF A-10 fleet. It was found that the correlation between usage history and retirement susceptibility could be better understood by fleet managers. The managers have the ability to control utilization levels of their assets to prolong or accelerate deterioration, which ultimately impacts the retirement schedule. Because fleet planning is a multi-year forecast, using a tool like FARM to make forecasts and periodically update them is more useful than a tool with a limited or finite horizon. Since suboptimal early retirement decisions cannot be remedied, a robust retirement policy is necessary.

This methodology can inspire future work in several ways. First, the methods may be extended to similar fields where parallel assets have unique usage histories. Though the

objective function may change and the greedy algorithm may not present the globally optimal solution, this approach may fit into other domains. Further, other domains may also wish to study the retirement problem with non-like assets. Second, this methodology did not accommodate decision-makers with complex needs. Only cost-minimization, utility-maximization and utility per cost ratio maximization were considered. An amalgamation of weighted fleet priorities could be applied to this methodology, which might better satisfy some fleet managers. Lastly, future work might expand the scope of this methodology to include multiple aircraft mission designs in the retirement analysis. The F-35A Joint Strike Fighter, for example, was designed to replace both the USAF's F-16 and A-10 aircraft. Fleet managers may be interested in evaluating which mission design to retire first and in what quantities.

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## **7 Retirement Optimization Through Aircraft Transfers and Employment**

*This chapter presents a mixed-integer linear programming model whose objective function maximizes remaining equivalent flight hours for aircraft. It accepts inputs created in Chapters 4-6 that are then used as logic for the model. The linear program allows for a network of operating locations and a set of mission types each having different required amounts. The work seeks to achieve the fleet manager's goal, whether that is to retire all aircraft at one time, to retire aircraft in batches at multiple times or to retire aircraft in an ongoing fashion, in very small batches more frequently. This chapter tells fleet managers how to use their aircraft as they age in a way to extract more value from the fleet. This can entail both hastening aircrafts' retirement or delaying those retirements. It is shown that fleet managers can closely control their fleet's utilization to achieve the manager's desired fleet retirement profile. Disruption management scenarios (deployments, accidents, budget changes) are successfully modeled and presented. Validation of the mixed-integer linear programming model was performed using the USAF's A 10 Thunderbolt II fleet, resulting in a nearly 18% shape error improvement for retirement planning dates. The outputs of this chapter are vital to the decision support framework presented in Chapter 3 as they are the source of savings first reported in Chapter 2.*

This chapter is a journal article awaiting decision.

# Retirement Optimization Through Aircraft Transfers and Employment

## Abstract

Military aircraft retirements are an afterthought for many lifecycle planners. More active management of end-of-life fleets can yield increased confidence in fleet capability and retirement timelines. This work aims to provide fleet managers with a tool to manage aircraft retirement forecasts. It solves an equivalent flight hour minimization problem using a mixed-integer linear programming model for a military aircraft fleet having a network with basing and mission type constraints. The model minimizes differences in remaining equivalent flight hours for individual aircraft in future years, thereby allowing a fleet manager to alter the timeline for retirement of individual aircraft. A relocation cost is applied to discourage excessive, costly aircraft relocations. The United States Air Force A-10 Thunderbolt II aircraft is used as a case study while disruptions such as deployments are modeled to show the methodology's robustness. This work proves that a fleet of aircraft with dissimilar utilization histories and varying amounts of remaining useful lifetime can be actively managed to change the time at which individual aircraft are ready for retirement. The benefit to fleet managers is the ability to extract additional lifetime out of their aircraft prior to retirement.

## 7.1 Introduction

Military aircraft fleets are retired with little regard to remaining flight hours, which leads to unused residual life in multi-million dollar capital assets [1], [2]. An end-of-life fleet's retirement is triggered by political motivation, technological obsolescence or budgetary necessity. These triggers are often outside the control of a fleet manager. Previous work by the authors shows that these triggers can be forecast [3]. Fleet managers wishing to extract additional usage from their fleet can more actively manage the transfers of aircraft between bases and the employment of those aircraft at the bases. The Retirement Optimization Through Aircraft Transfers and Employment (ROTATE) tool gives fleet managers the ability to optimize end-of-life aircraft usage while seeking a desired retirement date profile.

Since the United States Air Force (USAF) collects immense amounts of individual aircraft tracking data, the motivation for this work is to use those data to provide better fleet lifespan utilization. The USAF manages most of its fleets using equivalent flight hours (EFH). This measure combines flight hours with usage severity information. For example, a particularly strenuous one-hour mission may register as 1.3 EFH while a docile one-hour mission could be 0.8 EFH. Four separate USAF fleets with normalized remaining EFH are shown as cumulative distribution functions (CDF) in Figure 7.1

**not found.** This general CDF shape is similar for other aircraft fleets and is representative of the procurement rates of the aircraft

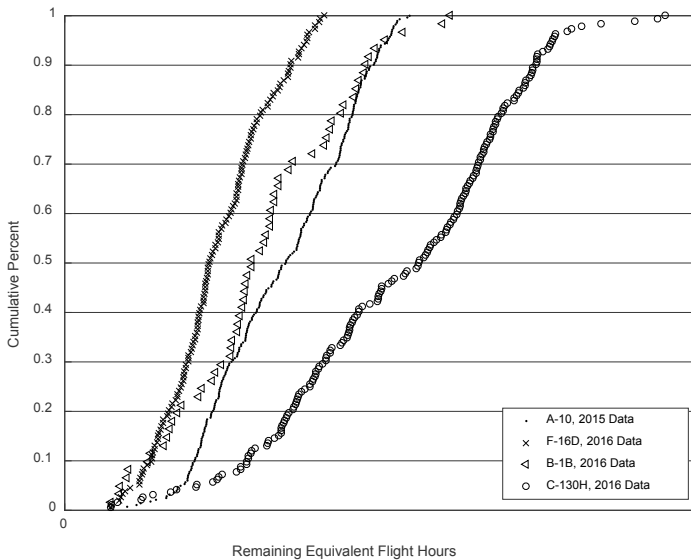


Figure 7.1: Remaining EFH curves for four USAF aircraft types

Assuming no change in usage patterns in coming years, each fleet’s CDF will shift to the left until each aircraft in that fleet reaches zero remaining EFH. Fleet managers may continue to fly aircraft after reaching zero remaining EFH on formal waivers, otherwise an aircraft should be retired when its useful lifetime reaches zero remaining EFH. Since a new aircraft fleet is built over years, it is natural for a fleet’s CDF to appear like the shapes in Figure 7.1. Consequently, each individual aircraft tends to reach retirement along an equally spaced timeline. If no interference occurs, this type of retirement pattern is called “Ramp” (Figure 7.2). However, in practice it is impractical to frequently retire single aircraft, so like-aged groups are selected for retirement [4]. This retirement pattern is called “Multi-Step” (Figure 7.2). “Cliff” is a profile where all aircraft retire at one forecast time (Figure 7.2). It occurs when increased usage is assigned to those assets with less accumulated usage. The Ramp pattern is achieved with little interference from the status quo while the Multi-Step pattern can be modeled by repeating the Cliff pattern with subsets of the fleet population.

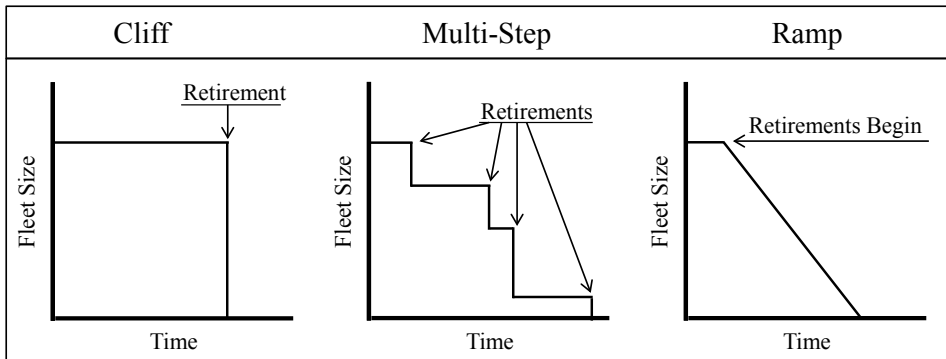


Figure 7.2: Retirement philosophy types

To alter a fleet’s CDF shape to more closely mimic a desired shape, a fleet manager may employ two approaches. Aircraft may be transferred from one base to another and aircraft may be assigned to a different mix of mission types. Previous work showed that aircraft experience different EFH demands at each base in a fleet’s network and that mission types flown also impact EFH accumulation [5]. A fleet manager may therefore choose to transfer aircraft between bases and alter the expected mission type assignments to change the aircrafts’ expected utilization. These ideas are termed SmartBasing.

This work proposes a single-period mixed integer linear programming model to alter the remaining EFH CDF of a fleet. A multi-period simulation of this model is used to transform a fleet from an existing Ramp pattern to a Cliff (and by association Multi-Step) pattern. The scope of this optimization problem is:

1. Only one fleet considered during the simulation.
2. Aircraft transfers only considered once per simulation period.
3. The number of aircraft, bases and required number of missions only changes once per simulation period.

In this problem, demand is modeled as the set of mission requirements at an air base. Supply is modeled as the set of capital assets and their corresponding remaining EFH. Because the network demands change with time, the single-period model is employed in a multi-period simulation. Inputs to the model are free to change for each simulation period. The problem is stated as follows: given an existing fleet of aircraft and an existing network of basing locations, minimize the distribution of EFH subject to realistic operational constraints. A relocation cost (in EFH) is included in the objective function to realistically model the trade-off fleet managers encounter when deciding to relocate aircraft. This

methodology is novel because it uses mixed integer linear programming to influence the remaining useful life of a fleet of aircraft. Further, the ideas of SmartBasing represent a new way to view the utilization of aging aircraft.

The remainder of this article is split into four sections. The Literature Review describes similar work in this field. Then the Methodology section presents the mathematical formulation and describes the inputs to the model. The Results and Discussion section shows actual A-10 Thunderbolt II case study results and also highlights the model's robustness given unplanned disruptions to the model. Lastly, the Conclusions section synthesizes the findings and highlights areas for further research using this approach.

## **7.2 Literature Review**

This section reviews previous work that enhances the understanding of capital equipment replacement and how an optimization formulation can aid a fleet manager when making usage and retirement decisions. A large sum of work is conducted on assigning aircraft to origin-destination pairing and maintenance routing in: [6], [7], [8], [9], [10], [11]. Sherali et al's review of fleet assignment work is a sufficient introduction [12]. Since little work has been published for military fleet base and mission pairing optimization given a realistic network architecture, literature from the airline industry and for other capital assets is included.

To account for realistic demand in a parallel replacement study, Hartman's integer programming model accepts a population of assets that have varying ages and histories [13]. His model contains a decision point after each period, asking whether or not each asset should be retired, based on the available lifetime. Hartman's work permits storage of unneeded assets, which is only economical for an aircraft application wherein the forecast period is multiple years. Parallel replacement decisions are generally economic decisions so utilization rates become a factor in useful lifetime [14].

Başdere and Bilge's work on the aircraft maintenance routing problem considers aircraft that undergo maintenance activities with remaining useful time a loss [15]. Their model tracks remaining time on aircraft for the purpose of maximizing remaining useful time utilization. Their integer linear programming model accounts for operational considerations for commercial aircraft fleets. One such consideration is the cost of asset relocations. Sriram and Haghani include aircraft relocation costs into their model by penalizing extra or inappropriate assignments [9].

Retirement planning and fleet optimization are not unique to aircraft fleets. Sethi and Chand develop algorithms for generalized machine replacement given technological

improvements through time [16]. Their models emphasize cost minimization but the real impact of their work is the recognition that an optimal first-period decision does not require accurate all-period forecasting. In aircraft fleet management, first-period knowledge is high but full lifecycle knowledge is low. Similarly, Narisetty et al develop a model to optimize empty railroad freight car assignment across the Union Pacific network given first-period demand information [17]. Hopp and Nair emphasize that using minimal forecast data for capital equipment replacement decisions could reduce future uncertainty [18]. Jin and Kite-Powell conclude that parallel replacement problems must be informed by first optimizing utilization levels [19]. Only then can effective lifecycle planning take place.

Karabakal et al's work with vehicle fleet replacement illustrates the differences between serial replacement (Ramp) and parallel replacement (Cliff, Multi-Step), showing the challenges inherent to parallel replacement [20]. Karabakal's later work deals with realistically sized problems whose budget considerations force a portfolio-level perspective [21].

Litvinchev et al use a Lagrangian heuristic for solving the many-to-many assignment problem [22]. This work is important because it allows for agent and task capacity limits which are necessary for a military fleet assignment problem.

Size impacts a fleet's capacity while the specificity of aircraft roles impacts the ability of a fleet to meet demand. Beaujon and Turnquist explore this interaction between fleet size and utilization decisions, observing that while demand can exhibit regular changes over time, future demand forecasting is difficult and requires a management-based solution [23].

Several tenets important to this work have been previously addressed for aircraft fleets. First, base location impacts what is flown as well as the costs associated with operations [24], [25]. Second, Zak shows that despite ample mathematical tools, there is still no surrogate for a fleet's decision maker [26]. Third, life cycle cost estimation is necessary for managers to make informed decisions [27]. These ideas are important to consider as the methodology for ROTATE is described in the following section.

### **7.3 Methodology**

This optimization model assumes an available pool of capital assets at an initial state. All assets possess dissimilar utilization histories. This methodological approach assigns aircraft to bases to satisfy demand as represented in Figure 7.3. Here, only two bases are shown, the first having a maximum number of seven aircraft and the second having a maximum number of four aircraft. The minimum number of aircraft are six and two, respectively. Both bases require a minimum, known number of flights of five different mission types to

be flown. Actual mission types and amount flown may be greater than or equal to the required, but not less.

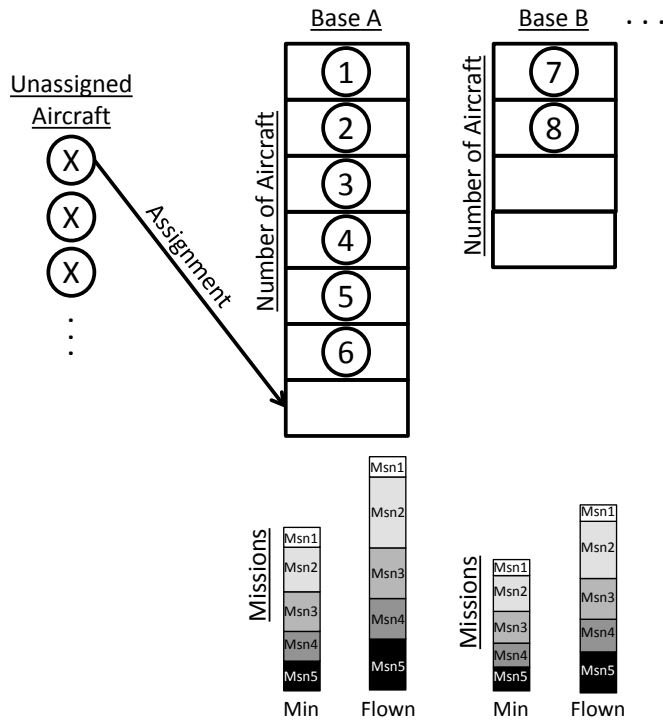


Figure 7.3: ROTATE fleet assignment logic

Simulation periods can represent any timeframe, but this paper treats each simulation period as one calendar year. In simulation period one, all aircraft are assigned to bases and to a number of missions of varying types. In each subsequent simulation period, aircraft are permitted to relocate to a different base to perform a different amount and mix of mission types. All relocations are assessed using a relocation cost, dependent on the origin-destination pairing. Actual flown EFH in a simulation period are deducted from each aircraft's remaining EFH [28]. Any aircraft that reach zero EFH are removed from the fleet. More preference is given to fly aircraft possessing higher remaining EFH than aircraft possessing lower remaining EFH because this reduces the standard deviation in EFH among the aircraft. This aligns a fleet more closely to a Cliff retirement philosophy. The Multi-Step and Ramp philosophies can also be implemented using this methodology but the optimization model presented in this work focuses only on the Cliff retirement philosophy.

It is important to build the methodology in a way to allow fleet managers to input their fleet’s peculiarities. For example, not all aircraft in a fleet can be located at all the bases in a network nor can all aircraft fly all mission types. Realistic concerns like bases that are forecast to close in the future must also be modeled. These complex relational dependencies are formatted as matrices for the solver.

There are three core assumptions made in the formulation of this methodology:

1. Each asset is able to perform its assigned tasks during a simulation period.
2. Deployment usage mimics home station usage.
3. The decisions made for the fleet being studied do not impact the remainder of a larger fleet or enterprise.

The methodology is implemented using MATLAB version 2015b with all optimization tasks computed by IBM’s CPLEX Optimization Studio version 12.6.3. CPLEX’s branch and cut approach is sufficient for this formulation and other commercially available solvers are not tested. Figure 7.4 shows the flow chart for ROTATE. As shown at the bottom left of Figure 7.4, retirement philosophy is an input to the methodology. While this article discusses the Cliff philosophy, the model’s objective function can be changed to accommodate any desired retirement philosophy.

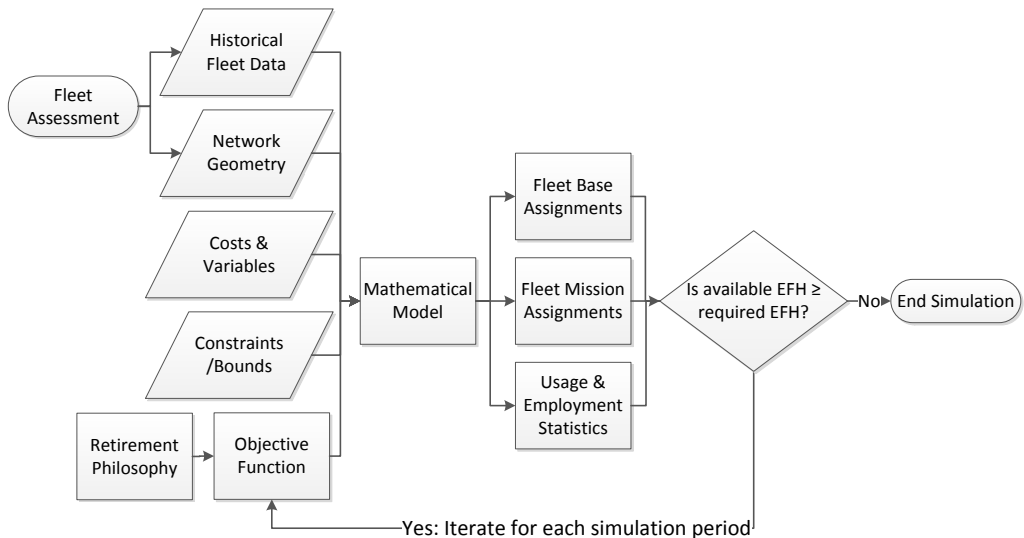


Figure 7.4: ROTATE methodology flow chart



ROTATE uses a mixed integer linear programming formulation because the assignment problem demanded both binary (assigned versus not assigned) and integer (number of flight hours assigned) variables. The formulations are designed to solve the problems most efficiently for the class of problem. In other words, the formulations are the problems built in mathematical terms. Formulating the problem in a different way would have required inefficient transformations.

### 7.3.1 Mathematical Formulation

This single-period mixed-integer linear programming model is formulated with the objective of changing the retirement timeline for a fleet of aircraft. As a generalized assignment problem that links assets (aircraft) to tasks (bases, mission types), the approach is formulated using two sets of decision variables. Flight hours are continuous variables but base assignments are binary, thereby making the problem harder to solve.

This work focuses on the Cliff retirement philosophy, which is achieved through the denominator of the objective function. By utilizing aircraft with higher remaining EFH, the objective function can impact the lifetime estimate of aircraft. Table 7.1 shows the mathematical notation used by ROTATE for each simulation period.

Table 7.1: Mathematical notation

<u>Indices:</u>	
$a$	index for aircraft
$b$	index for base
$m$	index for mission type
<u>Basic Sets:</u>	
$A$	fleet
$B$	bases
$M$	mission types
<u>Decision Variables:</u>	
$L_{ba}$	if aircraft $a$ is assigned to base $b$
$X_{mb}^a$	number of flight hours flown of type $m$ at base $b$ by aircraft $a$
<u>Parameters:</u>	
$AC_a^b$	administrative cost for moving aircraft $a$ to base $b$ (translated into) EFH

$\overline{CSL}_a$	maximum certified service life in flight hours for aircraft $a$
$iEFH_a$	initial equivalent flight hours for aircraft $a$
$\underline{FH}$	minimum flight hours per aircraft
$\underline{FH}_{mb}$	minimum flight hours for mission $m$ at base $b$
$\overline{FH}$	maximum flight hours per aircraft
$FHR_b^a$	flight hours required for relocation of aircraft $a$ to base $b$
$SF_{mb}$	severity factor for mission $m$ at base $b$
$\underline{W}_b$	minimum number of aircraft at base $b$
$\overline{W}_b$	maximum number of aircraft at base $b$

The mathematical formulation is outlined in Equation 7.1 through Equation 7.8. Equation 7.1 shows the objective function necessary for achieving the Cliff retirement philosophy, using the difference between CSL and initial EFH in the denominator to encourage higher utilization for aircraft possessing larger remaining EFH [29]. The initial EFH is the total accumulated EFH for an aircraft,  $a$ , at the beginning of a simulation period. For a subsequent simulation period, the initial EFH is reduced by the EFH flown in the previous period and reduced by the relocation flight hours, if applicable. The administrative costs and the flight hours for relocation of each aircraft are precomputed for each simulation period, based on the location of the aircraft at the end of the previous simulation period. The assignment variable,  $L$ , is represented in the objective function to apply the relocation cost, in EFH. If the aircraft remains at the same base, both the relocation flight hours and the administrative costs are assumed to be equal to zero.

Equation 7.2 mandates assigned EFH to be less than the remaining EFH for a particular aircraft. Equation 7.3 ensures each aircraft flies within the bounds of allowed flight hours in a simulation period. Equation 7.4 ensures that the flight hour requirement (demand) is met for each base/mission type combination. Equation 7.5 links the decision variables to ensure an aircraft can only fly missions at a base if it is assigned to that base. Equation 7.6 bounds the number of aircraft assigned to a base and Equation 7.7 states that an aircraft can only be assigned to one base in each simulation period. Lastly, Equation 7.8 stipulates that negative flight hour assignments are not permitted.

The decision variables are:

$$X_{mb}^a \text{ (continuous)}$$

$$L_{ba} = \begin{cases} 1, & \text{assigned,} \\ 0, & \text{not assigned.} \end{cases}$$

The objective function is shown as Eq. 7.1:

$$\min: Z = \sum_{a \in A} \frac{\sum_{m \in M} \sum_{b \in B} (X_{mb}^a \times SF_{mb}) + \sum_{b \in B} (FHR_b^a + AC_b^a) \times L_{ba}}{\overline{CSL}_a - iEFH_a} \quad (7.1)$$

Subject to:

$$EFH_a < (\overline{CSL}_a - iEFH_a), \forall a \in A \quad (7.2)$$

$$\overline{FH} \geq \sum_{m \in M} \sum_{b \in B} X_{mb}^a \geq \underline{FH}, \forall a \in A \quad (7.3)$$

$$\sum_{a \in A} X_{mb}^a \geq \underline{FH}_{mb}, \forall b \in B, \forall m \in M \quad (7.4)$$

$$X_{mb}^a \leq \underline{FH}_{mb} \times L_{ba}, \forall a \in A, \forall b \in B, \forall m \in M \quad (7.5)$$

$$\overline{W}_b \geq \sum_{a \in A} L_{ba} \geq \underline{W}_b, \forall b \in B \quad (7.6)$$

$$\sum_{b \in B} L_{ba} = 1, \forall a \in A \quad (7.7)$$

$$X_{mb}^a \geq 0, \forall a \in A, \forall b \in B, \forall m \in M \quad (7.8)$$

#### 7.4 Results and Discussion

ROTATE's decision variable output shows which aircraft are assigned to each base during each simulation period and the number of flight hours assigned to each aircraft for each mission type at each base. These data are cataloged for each simulation period in the simulation. Further, the MATLAB interface calculates the number of aircraft relocations per simulation period and the standard deviation of EFH in the fleet.

This methodology is scalable to large network sizes and large fleet sizes. The scaling configurations and associated run times for sample fleet configurations are shown in Table 7.2. Run times are computed for a Microsoft Windows 7 machine operating dual 2.93 GHz processors with 16 GB of memory. The input data for this table is from historical USAF data (1992-2015). Because utilization forecasts do not extend far into the future, historical trends are used to project future needs. This includes aggregate numbers of missions each year and standard fluctuations from lost aircraft. The last entry represents the F-35 Joint Strike Fighter acquisition [30]. The USAF plans to order 1763 F-35s, making it the foreseeable natural limit for this class of problems. Assuming 15 base locations and 6 mission types for the F-35 fleet yields 185,115 decision variables.

Big O computational complexity is  $O(n^2)$  due to nested iterations in the methodology. The number of decision variables is calculated by Equation 7.9 while constraints are calculated by Equation 7.10.

$$DV \propto (Aircraft \times Bases \times Missions) + (Aircraft \times Bases) \quad (7.9)$$

$$C \propto (Bases \times Aircraft \times Missions) + Aircraft \times Missions \quad (7.10)$$

Table 7.2: Network scaling computation run times

Bases	Aircraft	Mission Types	Variables	Run Time (s)
1	1	1	2	0.4397
2	8	2	48	0.5151
3	10	3	120	0.7006
4	10	4	200	0.8327
6	30	6	1260	1.392
8	50	8	3600	2.806
12	100	12	15600	17.39
20	400	20	168000	942.6
15	1763	6	185115	3529.7

#### 7.4.1 Case Study

The USAF's A-10 Thunderbolt II is chosen for study because it is nearing end-of-life [31]. The fleet's EFH CDF in 2015 was roughly aligned with the Ramp retirement philosophy. The goal of this case study is to show that ROTATE can optimize the A-10 fleet's usage over time to produce an EFH CDF that mimics the Cliff retirement philosophy. Table 7.3

shows the settings for this case study. The settings are derived from A-10 fleet metrics from 2015 data provided by the USAF. The relocation cost consists of two parts: the flight hour expenditure for a relocation and an administrative cost. The flight hour expenditure is zeroed out for an aircraft remaining at its origin base. The administrative cost for this case study includes the origin base’s ground inspection of the aircraft, a destination base’s ground inspection and a two-hour induction sortie.

Table 7.3: ROTATE settings

Parameters	Setting
Number of bases	9
Number of aircraft	283
Number of mission types	6
Max flight hours per aircraft per sim. period	504
Min flight hours per aircraft per sim. period	50
Min/Max aircraft per base, bounds	[14,84]
Administrative cost in EFH	8
Permitted moves per aircraft per sim. period	1

\*Large matrices were used but were not reproduced here.

With the actual A-10 fleet architecture and future-years utilization forecast input (obtained from the USAF’s Logistics, Installations, and Mission Support-Enterprise View database), ROTATE optimizes the base and mission assignment for each aircraft. For example, the output data show that aircraft  $X$  is assigned to base  $Y$  in simulation period one where it will fly  $Z_1$  EFH of mission type  $Q$ ,  $Z_2$  EFH of mission type  $R$  and  $Z_3$  EFH of mission type  $S$ . For this study, each simulation period represents one calendar year for the A-10 fleet.

Figure 7.5 shows the remaining EFH for the A-10 case study for each aircraft in the fleet for each simulation period. The various slopes of the lines from left to right show that the methodology acts to utilize the low EFH outliers more in the first simulation periods of the simulation, within the maximum flight hours constraint. Once all aircraft possess roughly the same number of EFH (occurring between simulation periods 15 and 20), the methodology then rotates aircraft between bases and missions to continue utilizing the fleet’s aircraft at similar levels. The right-side axis shows the standard deviation for the EFH of the fleet. Because the objective function seeks to minimize the variation in the CDF to result in a Cliff, the standard deviation for the fleet declines after each simulation period. The standard deviation begins high but then decreases as the outlier aircraft expend or conserve EFH to align more closely with the median usage rate. This phenomenon can alternatively be observed in the decreasing ‘bandwidth’ of the remaining EFH set of curves.

Because the case study fleet uses real inputs instead of a uniform demand, there is no perfect convergence of the standard deviation to the ideal value of zero despite there being a cost for relocations. Zero standard deviation would mean that all aircraft in the fleet have the same remaining EFH, which would be a perfect match of the Cliff philosophy. Basing restrictions, aircraft model types, software versions and other network peculiarities prevent the achievement of the ideal Cliff and at times can cause spikes.

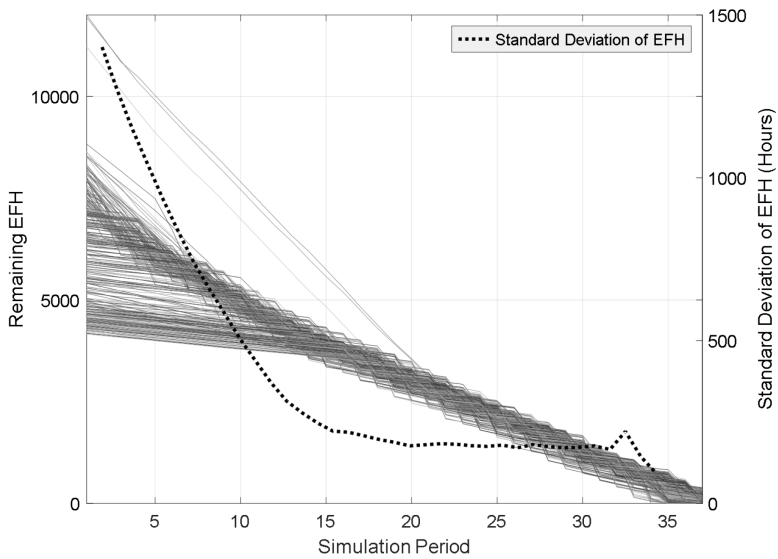


Figure 7.5: Remaining EFH and EFH standard deviation change for each simulation period

To visually check the fleet’s adherence to the desired retirement philosophy shown in Figure 7.2, a CDF representing each aircraft’s remaining EFH can be generated. Figure 7.6 shows a CDF for each simulation period produced by ROTATE. The A-10 fleet’s initial EFH CDF, labeled “Starting CDF” is shown on the right. Each successive simulation period’s CDF flows to the left. With the Cliff philosophy as the goal, the bulk of change occurs in this simulation in the first ten simulation periods. The bunching effect seen at the bottom of the CDFs is a visual depiction of the low remaining EFH aircraft flying the minimum number of flight hours allowed per simulation period. A vertical line would map perfectly to the desired shape from Figure 7.2 but that is not achieved for aforementioned reasons.

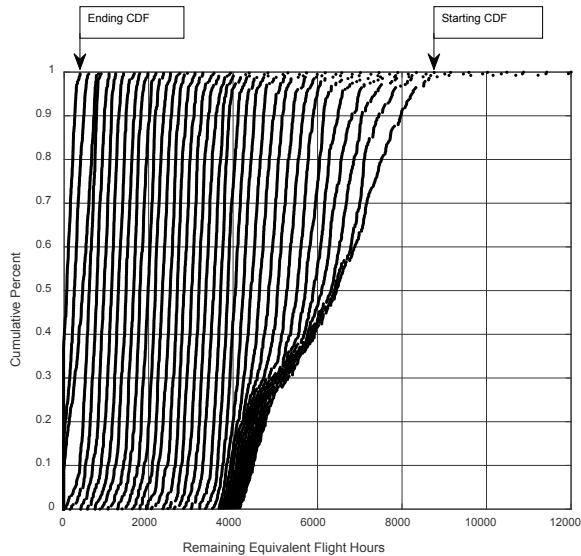


Figure 7.6: CDF for each simulation period in simulation

ROTATE’s ability to match the Cliff retirement shape is evaluated using the mean percent deviation between desired and achieved. Shown in Figure 7.7, three sets of data are represented. “Forecast” shows the case study data fleet progressing each simulation period with no changes to current utilization levels. This assumes no utilization changes or network changes over time. “Desired” shows the ideal, benchmark retirement shape, which is Cliff in this simulation. Lastly, “Achieved” shows ROTATE’s results. The “Forecast” results mimic historical patterns, are reasonable and give a mean percent deviation of 18.86%. ROTATE’s “Achieved” solution reduces the deviation to 1.65%. ROTATE cannot match a desired shape perfectly for a real fleet because of the constraints inherent to the problem. In this case study, some bases required very high utilization rates of very damaging mission types. This caused a residual delta in any simulation period after rough EFH convergence is accomplished, thereby resulting in non-perfect matching of the desired retirement shape.

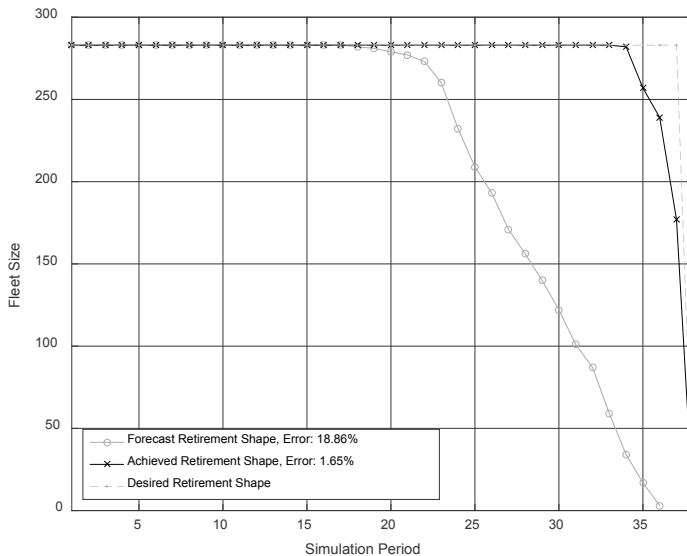


Figure 7.7: Fleet size per simulation period; forecast, achieved and desired

The number of aircraft relocations represents a benefit or cost for the retirement shape improvement. While the baseline historical transfer rate is 0.1110 relocations per aircraft per year, the ROTATE solution requires only a transfer rate of 0.1061 relocations per aircraft per year. With a fleet size of 283 aircraft and a lifetime of 35 simulation periods until the fleet can no longer meet demand, ROTATE’s solution for this case study reduces the number from 1099 transfers to 1050 transfers. This drop is less than 5% and is small compared to the benefits of retiring more of the fleet at once or expending residual EFH prior to retirement .

The managers in the USAF surveyed for this study represent fighter, attack and cargo aircraft fleets. Each believes their fleet’s intricacies must be addressed in a rotation model. Aircraft models, software versions and special maintenance procedures, however, can all be modeled using a SmartBasing approach. While results will vary, there exists no fleet too complicated to be represented by quantitative input data.

#### 7.4.2 Disruption Management

Testing the methodology using sample data results in a broad study of the simulator’s sensitivity. ROTATE successfully optimizes fleets within the range of reasonable inputs. ROTATE’s robustness is also tested using real-world scenario inputs such as deployments, base realignments and closures, aircraft mishaps and fleet groundings. In each scenario,



ROTATE is able to continue optimizing the retirement shape. This section showcases one example, represented in Table 7.4. Four disruption periods are chosen within which 32 randomly selected aircraft are assigned a one-year deployment that increases usage by 200 EFH. All other variables are set to the values shown in Table 7.3.

Table 7.4: Disruption timing, size and impact

Simulation Period	Number of Aircraft	Impact
6	32	-200 EFH
11	32	-200 EFH
13	32	-200 EFH
23	32	-200 EFH

Figure 7.8 shows the remaining EFH burndown for the entire fleet. The disruptions are clearly visible at simulation periods {6, 11, 13, 23}, represented by decreases in the remaining EFH traces as well as increases in the EFH standard deviation trace. Similarly sized disruptions have a larger impact on the fleet’s EFH standard deviation when they occur in later simulation periods. This is relevant to fleet managers and analysts – reducing disruption uncertainty in far-afield simulation periods can improve retirement shape convergence.

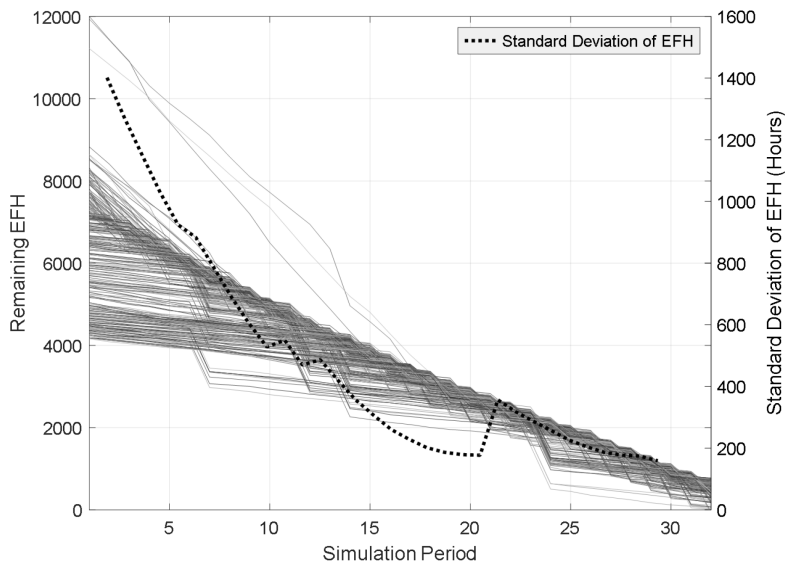


Figure 7.8: Remaining EFH and EFH standard deviation changes for each simulation period with four simulated deployment disruptions

The cumulative distribution function shows a disruption as a shift in a portion of a trace. Figure 7.9 shows the four disruptions for this simulation. Disruptions that involve more assets have a larger impact on the fleet and require more simulation periods for the objective function to correct the usage discontinuity.

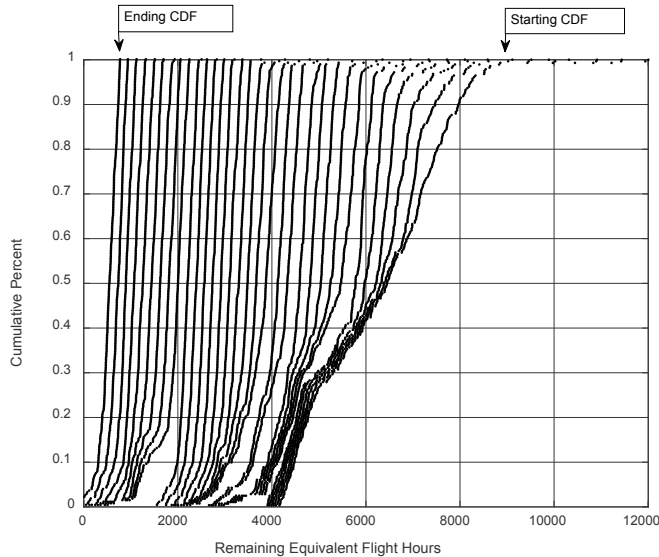


Figure 7.9: CDF for each iteration in simulation with four simulated deployment disruptions

Disruptions are not limited to deployment scenarios that increase EFH usage. Historically, some deployments have actually reduced yearly usage rates so ROTATE can also model a slower EFH accumulation rate. Base realignments and closures at future periods have the effect of shifting the demand profile for the simulation. Closures require a redistribution of the fleet, which increases transfer costs that are accounted for in this simulation. Aircraft mishaps are simulated by removing assets during the simulation. Since the demand profile is driven by the base and mission requirement inputs, any asset loss decreases the supply margin for the objective function. Lastly, fleet groundings (for impoundments, mishap investigation or time-compliant technical orders) effectively decrease usage levels in one simulation period. A secondary effect of increased usage levels in a secondary simulation period may be seen, but can also be modeled.

## 7.5 Conclusions

This work develops an optimization model to minimize the deviation of aircraft EFH within a fleet. A realistic base network and forecast mission demand are used as model inputs. This methodology handles actual fleet-sized problems and effectively alters fleet CDFs to more closely mimic the Cliff retirement philosophy desired by USAF fleet managers. At each simulation period, aircraft are permitted to relocate, an approach termed SmartBasing. The additional cost of these aircraft relocations is considered within the single-period optimization. A sensitivity analysis shows that the calculated network average relocation cost impacts the relocation frequency. A disruption management study shows this methodology's robustness despite planned or unplanned changes to fleet utilization. The A-10 fleet case study shows that ROTATE could achieve a retirement shape approaching a perfect CLIFF while decreasing the aircraft relocation frequency by a small amount from the baseline.

It is shown that SmartBasing as a concept is feasible. Also, ROTATE is a powerful tool with which to model future usage plans. Lastly, this work shows that one can achieve a desired retirement shape within reasonable accuracy. Herein, the Cliff philosophy is proven feasible and by proxy, the Multi-Step.

The benefit of this work to air forces is the practical application of health and usage monitoring data to future fleet management decisions. This may lead to savings for fleets either from the perspective of aligning a fleet to a retirement plan or by ensuring less useful life remains in a fleet at retirement. Better lifespan forecast information can aid decision makers in their procurement and divestment planning.

Future work includes applying ROTATE to a multi-period optimization problem. This would allow a fleet manager to optimize the usage and relocations for each aircraft for the remaining useful life of the fleet and could increase utilization [32]. Future work will also focus on investigating the transfer of this methodology to other fields. The ideas of SmartBasing extend beyond fighter aircraft to fleets where similar ideas have been proposed and some are in use. Additionally, researchers interested in this topic can test the validity of this model through time with a candidate fleet of capital assets. More work can be done using the Ramp methodology, potentially implementing the Gini Coefficient from the field of economics as a quantitative measure for EFH equality.

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## **8 Conclusions**

*This chapter reviews the research objectives presented in Chapter 1. Then the novelty of the work is discussed. Next, the main contributions of the research are summarized. Limitations of the work are stated. Lastly, suggestions for future work and extensions to this work are discussed.*

## 8.1 Reviewing the Research Objectives

Five research objectives were addressed throughout this research and the following are the key conclusions.

### *1. To develop a framework for military aircraft fleet retirement decisions.*

Chapters 4-7 alone represent a quantum leap in the tools available to fleet managers, but Chapter 3 provides the decision support framework necessary to understand and implement the tools in the subsequent chapters. The presented methodology gives structure to the fleet management task and provides the first data-driven, comprehensive approach to retirement. Written last, the work in Chapter 3 followed the convention for describing a complex technical process with many subtleties, such as fleet retirement decision-making. Each step in the decision support framework was crafted for flexibility to multiple aircraft types and management styles. The framework gives a fleet manager a starting point, the key steps, inputs and outputs as well as an ending point. The decision support framework was validated using a sample fleet composed of the traits discovered in Chapters 4-7. Identifying these traits and applying them to the fleet management problem was a foundational methodological contribution. This objective was met with no caveats.

### *2. To show that individual aircraft tracking data can be used to link mission usage to cyclic loading.*

Chapter 4 detailed this research objective by proving two hypotheses. The first was that the type of mission flown by an aircraft impacts the cyclic loading experienced by that aircraft. This hypothesis was proven using case study data consisting of 10 mission types for the A-10 Thunderbolt II aircraft. This finding was further validated using published United States Navy and Royal Australian Navy data. The second hypothesis stated that some mission types contribute more to the cyclic loading than other mission types. Again using A-10 Thunderbolt II data for validation, it was shown that there were significant differences in accumulated loading in different groups of aircraft, some flying more aggressive mission types and some flying less aggressive mission types. It was shown that an aircraft's lifetime could be extended if that aircraft flew more Close Air Support and Navigation missions while flying fewer Basic Fighter Maneuver and Surface Attack missions. The methodological contribution was the approach of using structural loading data to measure mission profile severity. Analysis of Variance tests verified real differences between mission types. Figure 4.6 catalogues those differences. This objective was met with no caveats.

### *3. To illustrate the indicators that can be detected at the aircraft and fleet level that are indicative of asset degradation.*

Chapter 5 showed generalized milestones an aging fleet experiences throughout its lifecycle. Five active duty fleets were analyzed to show their relative positions amidst these milestones in an effort to illustrate their progress along the aging timeline. The process of reckoning a fleet amidst these milestones, as listed in Figure 5.1, is a methodological contribution that provides a starting point for analysts to start to understand the relationship between fleet and aging. Using real aircraft data, Chapter 5 developed a metric for recognizing changes in the utility and cost of a fleet. Changes in the utility per cost metric revealed aging zones *A*, *B*, and *C*, making visible to fleet managers patterns their fleet would likely experience in the future. Chapter 5 used six USAF case study aircraft to validate the zones. It was concluded that the utility to cost metric and aircraft milestones were adequate indicators to inform fleet managers about their fleet's aggregate health. This objective was met with no caveats.

*4. To develop a methodology to determine which aircraft should be retired from a fleet and in what order.*

Chapter 6 showed a methodology to identify which aircraft should be retired and in what order. The FARM software then implemented the methodology using a greedy algorithm. It was shown that the outputs of Chapters 4 and 5 were critical inputs to FARM. The software showed not only that it was possible to pick which aircraft should be retired but that the objective function could be tuned to a fleet manager's desires whether that be cost minimization, utility maximization or maximizing the utility per cost metric developed in Chapter 5. This objective was met by testing the methodology on an active fleet, then it was validated using historical retirements. The software provided a nearly 50% match in minutes for a retirement decision that spanned two years. This objective was met with no caveats.

*5. To build a tool for fleet managers to use in rotating aircraft between bases and mission sets in order to give increased control over fleet-aging prior to retirement.*

In Chapter 7 the ROTATE software was built to give fleet managers a flexible, functional tool for aircraft rotations. It used the critical results from Chapters 4, 5 and 6 to prove that tasking aircraft with a different mission set in the future could change the projected lifetime of those aircraft. It was shown that a fleet manager could observe existing basing requirements and restrictions and still effect significant lifetime projection across the fleet in just a few rotation iterations. Fleet managers could choose to hasten retirement of their entire fleet, prolong the longevity of their entire fleet or select groups of aircraft to retire at different forecast points in the future. These abilities increase a fleet manager's control over his fleet and stand to increase the efficient use of aging aircraft fleets. The methodological contribution for this objective was the development of the process for fleet rotations –



avoiding pitfalls and illustrating the methods for effectively rotating aircraft. This objective was met with no caveats.

## **8.2 Novelty**

This dissertation significantly advances the current practice of fleet management for military aircraft. It specifically addresses the intricacies of making difficult decisions and the peculiarities of defense assets. No known work has previously undertaken the task of developing a framework for military aircraft fleet retirement decisions nor does there exist significant literature in the field of military fleet retirement decisions. The uniqueness of the field and the ingenuity of applying optimization methods and management tools to the problem resulted in a novel approach. This is the first known framework that encompasses aging aircraft retirement decisions.

Existing methods for understanding machine replacement theory are advanced through the application of the methods to the aircraft domain, thereby resulting in domain novelty. Though only aircraft are addressed in this dissertation, the methods presented herein may apply with minor modification to army equipment, naval equipment and by extension most capital equipment.

Using optimization to extract residual value from aging aircraft prior to retirement was a critically important idea in this work. This recommendation combined with the methodology backing it up ensures that fleet managers can implement a core part of this work. This can be implemented immediately and need not wait for an aging fleet to be retirement eligible. Rotating aircraft between bases and mission sets was previously undertaken in the 1990s by at least one known air force, though no public records were made available by that air force. However, modern computational power enables the methodology of rotating aircraft to be packaged for fleet managers to employ and iterate at the manager and analyst level.

## **8.3 Main Contributions**

This work has made significant contributions to the fields of engineering and fleet management, as set out in Section 8.1, with specific benefits for those involved in logistics and management of military aircraft. Since very little previous work has been published in this area, this dissertation raises awareness for the field and encourages future projects of similar nature. Throughout the execution of this research, five core contributions were made to the scientific body of knowledge. Herein, each is listed along with its context to the aging aircraft problem.

*Individual Aircraft Tracking (IAT) data contribute to the understanding of fleet health*

IAT data provide valuable understanding for one asset, allowing maintenance planners and operational organizations to predict and plan for the future. In aggregate, IAT data unveil trends in fleet health that can be used for whole fleet health management. This work illustrated the link between even the most basic IAT data and advanced planning techniques for aircraft fleets.

*There exists a correlation between base locations, mission types and aircraft loading*

When aircraft loading data are collected, they contribute to a fingerprint for that aircraft. The data show differences between mission types and base locations. It was shown that some mission types accumulate elevated g occurrences more rapidly than other mission types, leading to different rates of aircraft loading accumulation. Similarly, some bases accrue loading at different rates. This contribution to the field made the link between IAT collection and implementing management strategies to effect aircraft and fleet loading profiles.

*A greedy algorithm can be used to determine optimal fleet size*

A principal component analysis showed that a few maintenance and operations metrics could be used to differentiate between the most useful aircraft in a fleet and those less useful. This work then showed that a greedy algorithm could be employed to iteratively assess each smaller fleet size until an optimal fleet composition was reached. This contribution also identified by tail number which aircraft should be retired and in what order.

*A rebasing algorithm can optimize a fleet's end-of-life usage*

Knowing about the impending retirement of a subpopulation of a fleet provides an opportunity for fleet managers to alter fleet usage patterns. This approach of relocating aircraft and changing their mission assignments can further hasten *or* delay the expiration of existing useful structural lifetime. The rebasing algorithm presented in this work also applies to other capital asset fleets, showing that management can influence retirement timelines.

*A decision support framework for military aircraft fleet retirement decisions is useful*

Fleet retirement decisions for military aircraft fleets occur infrequently and there are few fleet managers experienced in retiring military aircraft. A decision support framework was designed to guide fleet managers through this task. This contribution enables better fleet retirement decisions through a set of defined best practices.

The research question for this dissertation was: *How can military aircraft fleet managers optimize the use of their aging fleet and improve their retirement decisions?* The quick answer to the research question is that fleet managers should more closely manage their aircraft to optimize the use of their aging fleet. Further, retirement decisions can be improved by following a structured decision making process such as the decision support framework developed by this work. Therefore, the five aforementioned main contributions not only provide a framework for improving retirement decisions but the main contributions also provide some of the steps within that framework.

Better understanding of the lifecycle processes of aging aircraft will lead to better lifecycle management. Fleet managers can improve fleet decisions, resulting in the optimization of lifespan utilization and therefore monetary savings. Every stepwise improvement for an air force ripples through a state's defense infrastructure and leads to a stronger defense posture for that state at a lower cost.

#### **8.4 Assumptions**

Programming aircraft fleet usage years into the future is rife with complexity. To combat the errors and uncertainty inherent to future forecasting, assumptions were made in the course of this work. Each published chapter listed assumptions important to those pieces of work, but several pertain to the whole scope of the work.

Most critically, this work assumed that future year utilization requirements would mimic current year utilization. While the work presented in Chapters 6 and 7 allows for changes to yearly utilization, all simulations presented used static utilization levels. This assumption was shown to be valid because the best predictor of  $n+1$  utilization is  $n$  for aircraft fleets. If future year utilization levels change, projected savings may decrease, but the software models should account for the changes.

The second global assumption for this work was that fleet managers could nearly unilaterally impact aircraft fleet usage and basing. This assumption removed layers of bureaucratic processes and enabled the development of a framework for retirement decisions with few roadblocks to implementation. In reality, many aircraft fleets suffer from political and societal pressures that would impact certain decisions. For example, there could be political pressure to maintain the newest aircraft at *Base X* that no efficiency improvement could change.

Lastly, it was assumed that no vastly significant technological improvements were made in future years. In modern military aircraft history, improvements have added low observability, electronic warfare and more to our vernacular. However, recent

improvements do not compare to the step function borne from the invention of the jet engine. A disruptive new technology like a new propulsion system could make this assumption false, but there would still be a great need for this work's retirement framework.

## **8.5 Limitations**

This work has several limitations, due to the breadth, scope and challenge in the practical application of this field. First was the scope of the research. The scope, while multi-national, did not specifically look at air forces worldwide. Nor did the research address capital assets other than aircraft. Naval and marine corps aircraft were studied, but army aircraft were not. Many fleet managers, logisticians, analysts, database managers, program managers, senior leaders, operators and maintainers were interviewed. However, politicians and budget makers were left outside the scope.

The core ideas in this work apply beyond military services and beyond aircraft, but the ideas were not tested in these ways. Further, no civilian aircraft case studies or commercial capital asset case studies were executed.

Lastly, the greatest limitation is that the main contributions have not been implemented in an existing air force fleet. The true test of efficacy is indeed analyzing the ideas in practice and measuring the results. Due to the limited timeframe of a doctoral research program and the effort involved in launching a new paradigm for fleet management strategy, this work remains untested. All efforts were undertaken to prove the ideas using analytical validation techniques and numerous experts were consulted, but the limitation remains.

## **8.6 Future Work**

The conclusions presented in this dissertation should raise more questions than they answer. The youth of this research area makes it an exciting field for study and creates opportunities in a few key areas for future work. The first direction for future work is to apply these methods to other asset classes. Fleet management for military aircraft bears great specificity but similar asset classes can be found in the civilian sector. Aging commercial aircraft, solar collection devices, wind farms, railroad rolling stock or sea shipping vessels can be managed in similar ways to military aircraft. Care must be taken to address the limitations of this work with respect to new asset classes.

The second direction for future work is the implementation of the main contributions in an operating military aircraft fleet. The challenges and costs of implementation must be outweighed by the projected benefits, thus it would be sensible to find a first fleet projected

to have high benefits. A phased rollout could give opportunity to identify flaws in the decision support framework before they become costly errors. Implementation of this work should be conducted in an environment capable of measuring the costs and benefits using existing database products. Wider implementation using riskier fleets and those with higher complexity would prove the effectiveness of the methods. Because this work was validated using USAF fleets, it is sensible to implement this work first using a USAF fleet. Assumed values, trends and utilization forecasts would need to be replaced with actuals. The software models would need to be adapted to account for any fleet peculiarities.

The primary software tools developed during this project, namely FARM and ROTATE, can be tested under different conditions and with different fleet types. While each tool was validated in multiple ways, one future work suggestion involves stretching these platforms in new directions. Can FARM's retirement date prediction algorithm receive more inputs and blend them using a weighting scheme? Perhaps FARM can be improved using a genetic algorithm to dynamically react to future world threat condition predictions. Can ROTATE manage the movements and mission assignments for an entire air force? If so, how would the input requirements shape the output? With the available computation abilities, computers may not be the limitation for modelling an entire air force's usage. Collecting necessary inputs and designing analysis of alternatives logic may be the barriers to full-scale implementation. This work found a large subjective element in fleet management, which would lead to differing opinions about the usage and implementation of fleet resources.

Lastly, future work should continue to blend the fields of engineering and management. Purely management science or purely engineering studies are of great value, but the combination of the two can reveal fascinating challenges. This work used engineering techniques and management techniques to solve a complex problem. Future researchers should heed the advantages inherent to a multidisciplinary approach.

## Curriculum Vitae



Major Jeffrey Michael Newcamp, United State Air Force, was born on October 12, 1981 in Erie, Pennsylvania. He graduated from the University of Notre Dame in 2004, where he was commissioned through the Air Force Reserve Officer Training Corps program and earned Distinguished Graduate and Top Cadet honors. His first assignment was graduate school at the Air Force Institute of Technology. There, he earned a Master's degree with a focus on plasma flow control physics and graduated first in the Department of Aeronautics and Astronautics.

Then Major Newcamp worked as an aerospace engineer at Warner Robins Air Logistics Center, Air Force Materiel Command, Robins Air Force Base, Georgia. He was responsible for worldwide engineering support for all C-130 aircraft. Maj Newcamp provided on-site and liaison engineering solutions to an aging aircraft fleet and deployed as an Aircraft Battle Damage Repair engineer during the Global War on Terrorism in Southwest Asia. There he designed and constructed over 100 nonstandard aircraft repairs for more than fifteen types of aircraft at five coalition bases.

Major Newcamp graduated from Test Pilot School in 2009 where he earned a Master's degree in Flight Test Engineering and logged 116 flying hours in 27 different DoD, foreign and civil aircraft types. After Test Pilot School, he was a Lead Flight Test Engineer at the F-35 Integrated Test Force, Edwards Air Force Base, California. His responsibilities included the full spectrum of test execution for the first low rate initial production jet produced in the F-35 program. Major Newcamp conducted the first F-35A aerial refueling testing, night flight, simulated weapons release and other firsts.

After his work in flight test, Major Newcamp served as an Assistant Professor of Aeronautics at the United States Air Force Academy in Colorado Springs, Colorado. There he was a course director, taught senior design courses and focused his research efforts on airborne birdstrike countermeasures.

Major Newcamp is a graduate of the United States Air Force's Air and Space Basic Course, a graduate of the Aircraft Mishap Investigation Course, a Distinguished Graduate of

Squadron Officer School and a graduate of Air Command and Staff College's Master's degree program.

Major Newcamp is married to Elizabeth Diehl Newcamp and the two have three boys: Henry, Oliver and Teddy. Major Newcamp enjoys traveling with his family, running, hiking and cooking.

## List of Publications

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