



**Extending Service Life of Aircraft Through Fleet Management: A Study in C-17
Base and Aircraft Assignments**

GRADUATE RESEARCH PAPER

Charles L. Eichner, Major, USAF

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**DEPARTMENT OF THE AIR FORCE
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Abstract

Modern aircraft leverage tremendous advances in technology, engineering, and manufacturing, resulting in synergistic systems, multirole platforms, networked fleets, and asymmetric advantages. However, leaps in technology generally suffer from long and uncertain acquisition programs leading to production delays and escalating costs, especially in military specific airframes. Initial C-17 proposals specified an aircraft service lifetime of 30 years and 30,000 flight hours (Gries, 2015). Since no suitable replacement exists in the near future, this research investigates operational decisions that may slow aircraft aging and extend the effective service life of the aircraft fleet. The research indicates that if aircraft basing assignments are changed as the aircraft return to active flying after their five year depot level heavy maintenance, the service life of the entire fleet can be extended by over fifteen years. Additionally, the schedule tracks and limits each aircraft's exposure to severe corrosion environments by regularly changing aircraft base assignments between high and low corrosive environments.

*“If your actions inspire others to dream more, learn more, do more and become more,
you are a leader.”*

-- John Quincy Adams, 6th President of the United States

“Then you will understand what is right and just and fair – every good path.”

-- Proverbs 2:9

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Charles L. Eichner

Table of Contents

	Page
Abstract.....	iv
Acknowledgments.....	vi
Table of Contents	vii
List of Figures.....	ix
List of Tables	x
I. Introduction	1
General Issue.....	1
Problem Statement	3
Research Objectives/Questions.....	3
Research Hypothesis	4
Research Focus.....	4
Methodology	5
Assumptions/Limitations	11
Implications.....	13
II. Literature Review	15
Chapter Overview	15
Theory	15
Strategic Environment.....	18
Overview of Current Organization	19
Existing Processes.....	20
Fatigue and Corrosion Research	24
Total Cost of Ownership, Beyond Intended Service Life	26
Other Strategic Fleet Rotations	27
Summary	28
III. Methodology	29
Chapter Overview	29
Boeing Data and Averages.....	29
GRASP – Greedy Randomized Adaptive Search Procedure	31
Summary	34
IV. Analysis and Results.....	36
Chapter Overview	36

Results of GRASP Scenarios	37
Summary	41
V. Conclusions and Recommendations	43
Chapter Overview	43
Discussion	43
Implications and Recommendations for Practice.....	44
Implications for Research	45
Summary	48
Appendix A: Statistical Analysis Outputs	49
Appendix B: GRASP Results	54
Appendix C: Quad Chart	55
Bibliography	56

List of Figures

	Page
Figure 1. Snapshot of C-17 Actual Flight Hours and Estimated Service Life.....	2
Figure 2. EFH compared to AFH.....	7
Figure 3. Accumulation of Corrosion Exposure	26

List of Tables

	Page
Table 1. Average Annual EFH Accumulation.....	8
Table 2. Variables	31
Table 3. GRASP Inputs.....	33
Table 4. GRASP Results.....	37

Extending Service Life of Aircraft Through Fleet Management: A Study in C-17 Base and Aircraft Assignments

I. Introduction

General Issue

The C-17 enables direct delivery into austere environments, global reach through air refueling air bridge operations, and insertion of troops and equipment through assault landing and air drop capabilities in day/night/all-weather environments (C-17 Globemaster III, 2015; C-17 Globemaster III Fact Sheet, 2015). In short, the C-17 enables the United States to rapidly mobilize in response to any crisis around the world.

From 1996 through 2014, the C-17 overflowed its estimated annual flying hours leading to concerns that it may need recapitalization earlier than expected (Figure 1) (Gries, 2015). Due to fiscal constraints, the U.S. Air Force (USAF) struggles to recapitalize its aging aircraft, operating many airframes longer than originally anticipated. At a cost of roughly \$202 million per aircraft, the Air Force cannot afford to replace the C-17 fleet any time soon, especially considering that the tanker recapitalization effort is projected to continue until 2040 or beyond (Sullivan, 2015). As a result many leaders in the Air Force, as well as civilians providing military oversight, intensely debate the best course of action to reduce costs while maintaining effectiveness. To be effective, the USAF must make changes early enough to affect overall fleet health and aircraft utilization leading to increased long-term effectiveness and efficiency as a fighting force. Specifically the C-17, or a suitable alternative, must remain a mission capable part of the Air Force's fleet. The goal of this research project is to provide plausible options to

control the accumulation of flight hour fatigue and corrosion to extend the C-17 fleet service life as far as possible, delaying the need to acquire a new airlift airframe. The research applies aspects of research orchestration theory to USAF aircraft lifecycle planning.

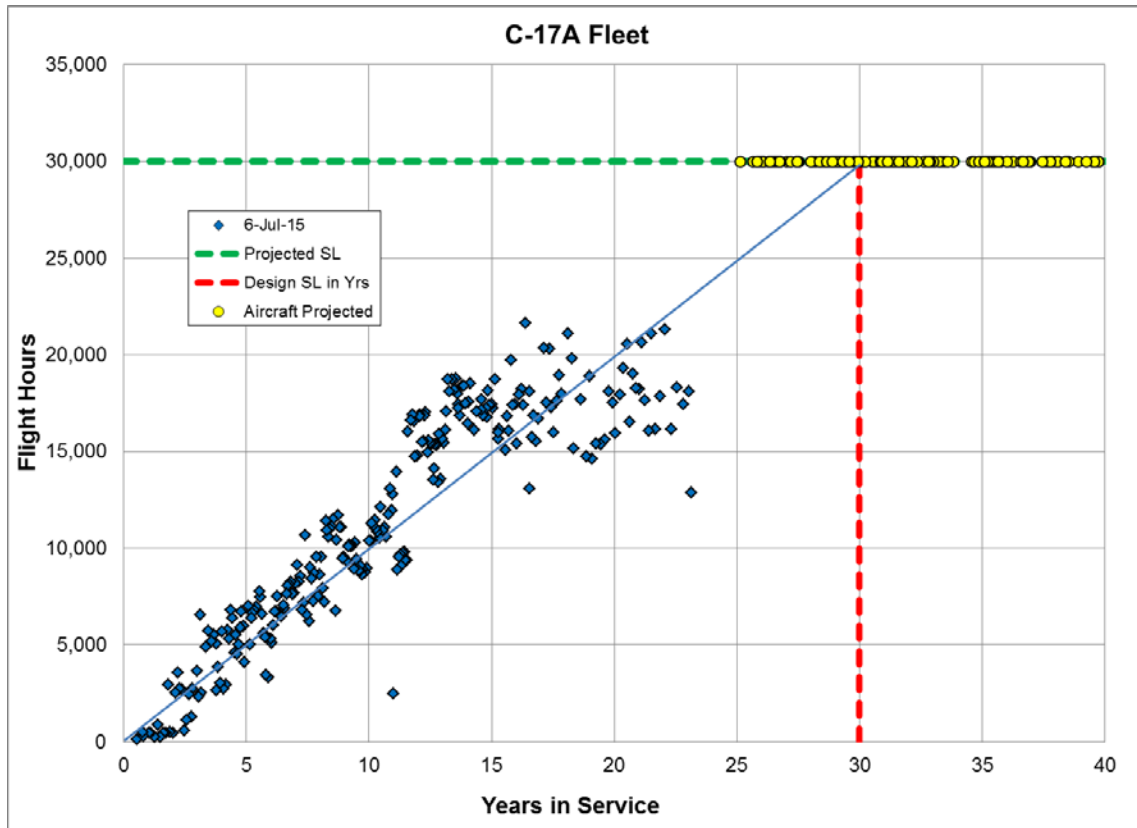


Figure 1. Snapshot of C-17 Actual Flight Hours and Estimated Service Life

Figure 1 depicts the original designed service life of the C-17 as the dashed red and green lines at 30 years and 30,000 flight hours. Each point represents one aircraft, and the blue line represents originally planned usage. This figure shows that approximately three-fourths of all C-17's are above their planned flight hour

accumulation. The yellow points at the top represent an estimate of when the aircraft will reach their designed hour limit. As shown by the yellow points beyond the red years of service design limit line, average usage is projected to decrease. As a result, two-thirds of the aircraft should not reach their 30,000 hour limit until after the expected 30-years of service point. In fact, according to Boeing estimates, as displayed by the farthest right yellow points, may not reach 30,000 flight hours until 40-years of service (Gries, 2015). To strike a balance between aircraft utilization and extending the service life of the C-17 fleet, the data suggests that a different fleet management approach could extend the maximum fleet life while simultaneously not requiring reduced annual utilization rates.

Problem Statement

This research aims to quantify the number of years an aircraft fleet could be extended by swapping aircraft basing assignments from units/routes/areas that incur more airframe fatigue and corrosion with units/routes/areas that incur relatively less fatigue and corrosion. The research accounts for airframe fatigue through the use of equivalent flight hour forecasting and corrosion damage through years of service in severe corrosion environments.

Research Objectives/Questions

The research objectives include balancing fleet-wide utilization, thereby delaying the need for airlift recapitalization, as well as ensuring the smooth and orderly retirement of aircraft as they fatigue beyond their service life. Additionally, the research accounts for corrosion, a major contributing factor to aircraft structural failure (Hoeppner &

Arriscorreta, 2012), in the modeling and forecasting of tail number/base assignment recommendations.

The Research Questions are:

1. Can the service life of aircraft be appreciably affected by basing/hub decisions?
2. If properly managed, can changing base assignments equalize the corrosion susceptibility and airframe fatigue accumulation, allowing aircraft utilization beyond the originally advertised service life?
3. In consideration of fatigue and corrosion, how many years can a specific aircraft fleet service life be extended by rotating aircraft base assignments?
4. What is the difference between the proposed scheduling assignments and the base case if no basing changes are made?

Research Hypothesis

Usage rate and airframe aging can be tempered by swapping aircraft between high use units and low use units to extend the total service life of the fleet while simultaneously limiting the amount of time each aircraft is assigned to highly corrosive environmental locations.

Research Focus

To analyze the effects of operating location decisions, this research must capture data from sources that had similar airframes with relatively large diversity in corrosion environments and airframe fatigue profiles. Additionally, the locations had to remain constant for the data to be useful in developing a reliable forecasting model. For research

application, the current USAF C-17 fleet provides the ideal scenario to study. The airframes are all similar, with very few aerodynamic or weight differences. Additionally, the types of flying missions executed at the bases are similar, but different enough to cause diversity of flight profiles and annual equivalent flight hour accumulations, leading to differences in actual airframe fatigue. This research will investigate how executing scheduled changes to base assigned aircraft might result in lifetime fatigue and corrosion benefits. The research also examines the value of moving higher aircraft stress training to simulators and minimizing stressful airframe flight training. This analysis provides insight into any high value fleet that operates and bases at locations with varying environmental and flight profile factors.

Methodology

Rooted in resource orchestration theory, (Sirmon, Hitt, Ireland, and Gilbert, 2011), this research examines USAF aircraft lifecycle management using onboard sensor data to determine EFH and create an optimized aircraft basing schedule based on predictive analytics for each basing location.

The research started with close coordination between aircraft engineers and analysts to determine the limiting structural component of the aircraft. While all aircraft structures fatigue, some are stressed more than others (Gries, 2015). Additionally, there are differing factors of safety built into each part (Gries, 2015). When the C-17 was built, it had sensors built into it, which Boeing engineers monitor (Gries, 2015). Additionally, there were numerous flight tests with additional sensors and other sectional structural certification testing proving the airframe would meet or exceed the originally

designated service life of 30 years and 30,000 hours (Gries, 2015). After certification testing, the structurally limiting part was determined to be the wing upper skin (Gries, 2015). When the limiting structure reaches the end of its service life, fixing or replacing the damage would be a strategic decision point to accept additional risk, refurbish the airframe, or replace the airframe through recapitalization (Gries, 2015). Additionally, the aircraft engineers determined the types of flying that contribute the most fatigue to the limiting part (Gries, 2015). The engineers translated the amount of high stress flying proportionally into a normalized unit labeled “Equivalent Flight Hours” (EFH) to compare each aircraft to their standardized planned service life and readily compare expected fleet utilization to current fleet health (Figure 2) (Gries, 2015). The EFH for the C-17 wing upper skin (limiting part) is limited to 42,500 equivalent flight hours due to the testing and subsequent certification limit (Gries, 2015).

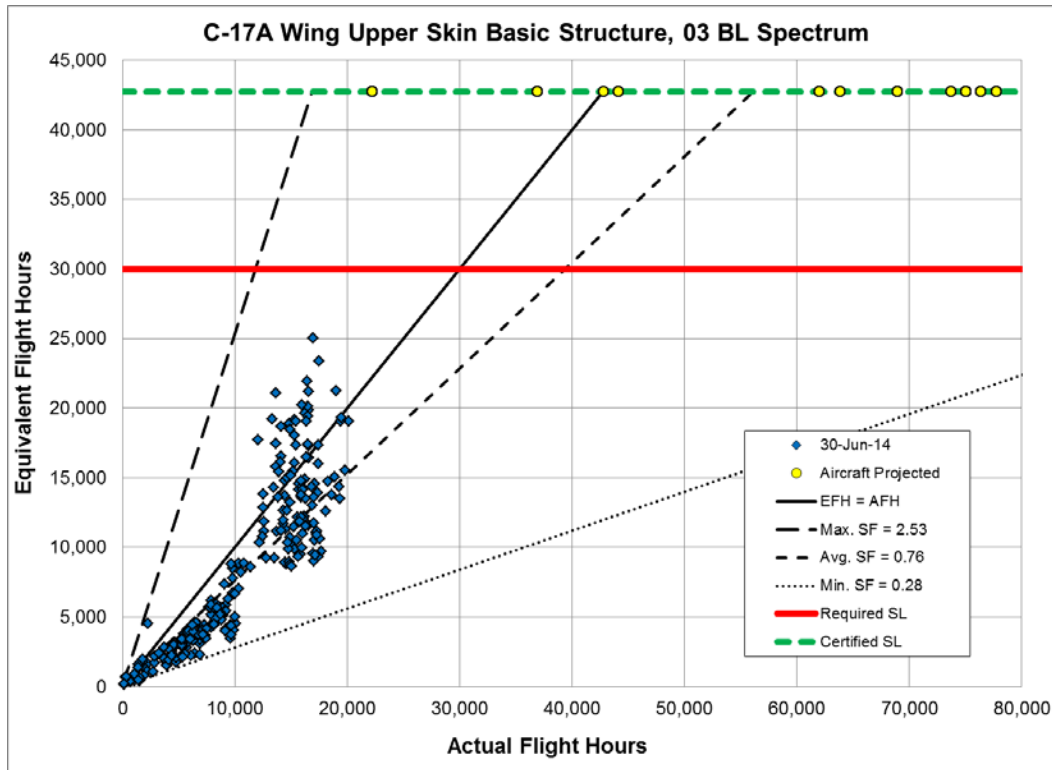


Figure 2. EFH compared to AFH

Data derived from engineering analysis of the current C-17 fleet determined the highest, lowest, and average EFH. As displayed in Figure 2, the severity factor (SF) lines correspond to EFH; SF is the ratio of EFH to actual flight hours (AFH); a number above 1 means that the airframe has more EFH than AFH, a number less than 1 means the aircraft's EFH is less than AFH. This research forecasts EFH by extrapolating average EFH accumulation by base. The averages were calculated for four time periods, lifetime of C-17 flight at that base, the last ten years, the last five years, and the last two years (Table 1). This information was then compared to the average EFH accumulation by base provided by Boeing engineers. Boeing's engineers calculated average EFH by base

over the last two years. The research data and Boeing data matched very closely as shown in Table 1. Notable exceptions are for locations that did not have long C-17 flight histories.

Table 1. Average Annual EFH Accumulation

Base	Lifetime Average	5-Year Average	2-Year Average	Standard Dev	Boeing Data
Altus	1390.52	1171.95	1047.32	537.41	1063.43
Charleston	895.59	689.46	560.38	304.74	544.35
Dover	596.12	546.19	451.93	192.43	440.20
Elmendorf	516.72	489.06	403.75	226.18	434.40
Hickam	583.24	455.26	357.05	132.83	337.48
Jackson	480.69	304.79	211.86	91.86	198.03
March	627.53	495.04	422.04	193.27	439.60
Martinsburg	224.93	224.93	224.93	204.13	500.00
McChord	837.10	551.53	487.51	330.84	479.12
McGuire	756.31	463.10	395.48	192.70	370.66
Memphis	277.76	277.76	277.76	145.83	227.70
Stewart	313.03	313.03	313.45	164.49	332.58
Travis	527.01	452.24	409.78	237.00	380.52
Wright-Patterson	651.74	651.74	657.29	348.70	685.56

Of note is that almost all bases, and more so, locations with long histories of flying C-17s displayed decreasing averages in annual EFH accumulation in the most recent two to five year periods compared to the lifetime and ten year averages.

According to Mr. Gries, C-17 Aircraft Structural Integrity Program (ASIP) Manager, this decrease can be attributed to two factors (Gries, 2015). First, the amount of flying has decreased as the United States involvement in Afghanistan (a land locked country) has decreased (Gries, 2015). Second, the focus of preserving the C-17 fleet has already resulted in changes in training by doing more highly stressful maneuvering in the simulator and decreasing the overall requirements for those maneuvers in general (Gries, 2015).

Based on historical usage, a Greedy Randomized Adaptive Search Procedure (GRASP) was employed. The procedure randomized the base schedule order, but prioritized the rank order of aircraft that would be assigned. Each aircraft remained at locations for six years, corresponding to five flight years and one year of depot level maintenance. Depot level maintenance on C-17s currently takes an average of six months to complete, depending on the amount and difficulty of repair work required (Gries, 2015). Since the model stations aircraft at each base for six full years it does not account for half a year of zero EFH accumulation while the aircraft is in depot level maintenance. Additionally, the intent is to coordinate for the base transition after depot level maintenance, this would put each aircraft at approximately five and a half years then transitioning to the next location. For the model to run smoothly and the tail swaps to work, the transition had to be forced into a whole number year. Thus, the model uses six year cycles instead of five year cycles. The result is that each location adds approximately half a year of flight time when the aircraft would otherwise be in maintenance accumulating zero flight hours, resulting in a maximum of one-twelfth (8.3%) too great an estimation of EFH within this model. Finally, in discussions with the C-17 ASIP manager, he concurred that this was an acceptable compromise since the depot schedule is flexible and coordinated fleet wide to ensure the depot repair facilities are not overwhelmed and each base does not have too many aircraft in heavy maintenance at the same time. Thus, a five and a half year flying schedule with six months in maintenance, creating a six year tail swap schedule is practically feasible. For the scope of this research project, six full flying years, thereby overestimating EFH by

whatever time was missed in depot level maintenance was determined to be an acceptable estimation.

The model cycled for 10,000 schedules, each schedule utilizing a different random order of bases and the same preference for rank ordering aircraft. Four separate runs of 10,000 schedules were accomplished with different orders of preference. First, the aircraft were rank-ordered based on highest EFH aircraft being assigned a new base first and EFH were accumulated at the rate given by Boeing engineers. Second, the aircraft were ordered based on highest total number of years stationed in highly corrosive environments and EFH were accumulated at the Boeing rate. Third, aircraft were ordered by EFH and EFH accumulation was added based on the base's C-17 lifetime EFH averages, which usually represented the most severe case. Finally, aircraft were ordered based on highest total years stationed in highly corrosive environments and EFH were added by base lifetime C-17 EFH averages. The model allows airframes to retire as they reach the 42,500 hour EFH point. Any remaining flight life at the end of the schedule could be flown off at the base it ends at because the model will not fly an aircraft if the annual EFH will result in greater than 42,500 hours. Additionally, the model does not prioritize bases as aircraft start to retire, so additional scheduling input would be required if, for example, it was desirable to have fleets fully resourced at critical bases.

The GRASP model can be updated based on initial starting conditions (current July 2015 data was utilized in this research) and for updates to forecasted EFH accumulation, which is a ratio of the annual flying hour program based on the base's 2 year historical average ratio. Additionally, if further flight testing, certification, and/or

waivers extend the limit to greater than 42,500 hours, then the model can be updated to retire the aircraft at the new limit.

While GRASP is not an optimization program, it is an accepted heuristic that demonstrates the results of feasible schedules (Festa P. , 2002). It cannot definitively say that one schedule is the best, but it can give an option that is better than 39,999 other options. Additionally, as circumstances change, the program can find solutions relatively quickly. Each run of 10,000 schedules only takes approximately three hours.

By analyzing the forecasted rate of EFH accumulation by base, this study recommends scheduling tail base assignment changes coincidental with the established five year depot level heavy maintenance. Some aircraft may remain at a location for more than one six year period (five flight years, plus one maintenance year). Changing base/hub assignments lowers EFH per airframe and decreases exposure per aircraft to highly corrosive environments. This “tail swap” moderates total fleet wear, and controls the rate at which aircraft reach the end of their service lives, resulting in an orderly, staggered retirement profile. The model changes aircraft basing assignments at the currently established maintenance scheduling interval providing predictability for base maintenance and making changes relatively seamless to operators because the aircraft will return completely refurbished from depot maintenance. When followed, the plan maximizes the overall fleet service life and controls the rate at which aircraft need to be retired and recapitalized.

Assumptions/Limitations

The research assumes:

1. The supply of replacement parts, knowledgeable maintainers, and overall logistical support for the C-17 remains viable well after the originally advertised retirement date. Assuming maintainers remain knowledgeable and current on C-17 structures and systems, as well as sufficient manufacturer participation ensuring parts availability through the supply chain means maintaining old C-17's costs less than purchasing a new airlift replacement.
2. All United States C-17 units approve of swapping aircraft at the optimal time for the greater good of the fleet and to extend the overall service life of a highly valuable national asset.
3. Future flight profile averages by base and unit remain relatively static over the cumulative of flight years remaining.
4. A maximum of 100 years of scheduling from the initiation of the model.
5. Six year assignment cycles for aircraft.
6. Flat rate EFH accumulation for the six years the aircraft is assigned to the base.
7. The upper wing skin and resultant EFH accumulation calculations remain the driving force in the C-17 service life extension/replacement decision.

Limitations include:

1. Limiting the study to Air Force C-17s ensures realism because no foreign C-17s will change country ownership.
2. Limiting the study to C-17s enables the correct scope for the time and resources allowed.

Implications

This research is important because of the value and strategic importance of the C-17. Additionally, it is critical that senior leaders in the Air Force have confidence that the aircraft in their inventory are safe and reliable to accomplish critical mobility missions. In 1988, an Aloha Airlines aircraft experienced an explosive decompression (Wanhill, 2002). Approximately 17 feet of fuselage skin and supporting structure separated from the aircraft, which amazingly recovered safely (Wanhill, 2002). The investigation showed that the structural failure was the result of a combination of fatigue and environmental degradation of the bonded skin splice (Wanhill, 2002). The danger of fatigue and environmental damage can be partially mitigated through maintenance action, but this study seeks to also mitigate that risk through avoiding excessive exposure to fatigue and corrosion.

Overall, the data demonstrate the possibility of extending the airframe service life to 2080 and beyond, with the first projected retirement in 2048. While this study was constrained to one airframe for research time and resource limits, the methodology and modeling techniques used in this study may be followed by other airframes to maximize overall fleet health of any aircraft facing airframe age, fatigue, and corrosion challenges. The research methods apply most directly to other military airframes that are assigned to bases by tail numbers and experience significant divergence in airframe fatigue or corrosion between base locations. Additionally, the concept of EFH may be utilized by other fleet managers to balance and extend the serviceable lifetime of any high investment resource such as specialized manufacturing machinery, trains, and trucks. The key is analyzing the relative usages and factors involved in the repair/replace

decision. Once these factors are determined, the fleet can be balanced based on actual usage.

The broader implications directly impact other industries, but possibly most specifically the regional and commuter airlines. These fleets often operate out of more static locations and rely on older aircraft relative to larger airline operations. Such was the case in the 1988 Aloha Airlines incident (Wanhill, 2002). The regional airlines aircraft may be susceptible to the same environmental and route or base specific EFH concerns that the USAF is facing with the C-17.

Currently, trains are also utilizing onboard sensor technology and predictive analytics to explore maintenance, reliability, and material fatigue (Fatigue Analysis of the Structure of Trains, 2016). Sensor equipment is fitted onto various components such as the train body, wheel bogie, and axles. The sensors measure strain, vibration, displacement, temperature, and pressure. The resultant data is analyzed using statistics, time-based, and frequency-based analytics to study material fatigue, structural fatigue, and structural welds (Fatigue Analysis of the Structure of Trains, 2016).

Finally, the trucking industry may also be able to apply this research. The propagation of technology allows sensor data and data analysis to become cheaper and more common. If the technology and cost of analyzing the data became cost effective to analyze trucking fleets, preventive maintenance could be accomplished at more accurate intervals and structures could be analyzed and classified as the limiting structure in much the same way as the C-17 upper wing skin.

II. Literature Review

Chapter Overview

The purpose of this chapter is to analyze other research that contributes to this research as well as show where this research adds to the extant body of knowledge. First, foundational theories that the research builds upon are reviewed. Then, the strategic environment is reviewed from the time of solicitation and acquisition of the C-17 in order to evaluate the implications of requiring a replacement transport aircraft. Next, this study summarizes several technical studies on fatigue and corrosion to provide details on the causes and effects of flight and environmental conditions on airframes. Then other studies provide perspectives on the total cost of ownership after a decision was made to extend an aircraft beyond its originally intended service life and illuminate possible consequences of extending the C-17 service life. Finally, the literature review concludes by sampling similar studies in which rotating a normally static fleet demonstrated measurable benefits. The background literature information provides the frame work to discuss fleet value, fleet replacement, methodology, the research conclusions, and the importance of early decisive action.

Theory

This research is grounded in the resource based view of the firm, which postulates that competitive advantage can come from resources that are valuable, rare, inimitable, and nonsubstitutable (Barney, 1991). Resource orchestration further specifies that it is not simply having the resources, but also how they are utilized that creates the competitive advantage (Sirmon, Hitt, Ireland, & Gilbert, 2011). Resource orchestration combines the resource management and asset orchestration streams of literature (Sirmon,

Hitt, Ireland, & Gilbert, 2011). Specifically, asset orchestration encompasses two activities, searching/selecting and configuring/deploying (Helfat, et al., 2007).

Searching/selecting involves acquiring the right inventory, in the right locations, and determining the optimal management policies governing that inventory (Helfat, et al., 2007). The locating of assets such as aircraft can impact the long-term competitive advantage, or in the case of the USAF, the effectiveness and capabilities required to support the national military strategy.

This research provides the ground work to coordinate resource orchestration across the USAF enterprise. Resource orchestration addresses three aspects of organizational asset management that contribute to competitive advantage; breadth, depth, and life cycle (Sirmon, Hitt, Ireland, & Gilbert, 2011). Breadth addresses the range of firm strategies including how the range of firm strategies affect the management of this asset and development of the optimal strategy regarding the capability which the asset enables (Sirmon, Hitt, Ireland, & Gilbert, 2011). Depth refers to synchronizing resource orchestration across the levels of the organization, or ensuring that each level in the organization compliments the overall strategy (Sirmon, Hitt, Ireland, & Gilbert, 2011). Finally, life cycle considers that resource orchestration strategies may vary greatly depending on the life cycle of the organization, in this case, the USAF could be considered a mature organization (Sirmon, Hitt, Ireland, & Gilbert, 2011).

Based on asset orchestration research, the USAF may be able to manage fleet aircraft to maximize their return on investment. The Air Force serves others through the use of its aircraft, which means the aircraft are the valuable commodities that provide the service's competitive advantage. If this is the case, careful coordination between Air

Force Material Command (AFMC), Combatant Commanders, air crews, and aircraft manufacturers may result in advantages for each organization. Aircraft could be utilized at sufficient rates to meet Combatant Commander demands, they could be rotated through inspection cycles and lower use bases to extend the service life for AFMC, aircrews would remain proficient, and aircraft manufacturers could provide long term engineering and manufacturing support. Overall, the research suggests that if the aircraft are carefully orchestrated, the organization can increase performance and service delivery to the customers of the USAF.

Through the theoretical lens of resource orchestration, this study seeks to contribute to the USAF strategy in managing the C-17 inventory and service life. To do that, the study attempted to apply “big data” and predictive analytics to optimize C-17 base scheduling. Big data refers to large data sets that grow rapidly and are often supplied by real-time or near real-time sensors (Segaran & Hammerbacher, 2009). In this research, data was acquired from sensors mounted throughout the C-17 airframe at the time of its manufacture. C-17 maintenance personnel download the data and submit it to Boeing engineers for analysis. The research acquired analyzed data that showed the resultant EFH based on the actual stresses and strains experienced by those sensors during actual operation of the aircraft.

Predictive analytics applies statistical techniques from historical data to make forecasts about future or unknown events (Waller & Fawcett, 2013). This study applied analytical computations to historical base flight records and actual aircraft EFH resulting from those flight records to predict future EFH accumulation. The predicted EFH accumulation affected the resultant C-17 service life as well as the optimal base rotation

schedule. This study demonstrates how predictive analytics can be used to inform fleet management and maintenance decisions. Ultimately, the study seeks to provide a foundation for senior Air Force leaders to enable them to make asset orchestration decisions that will maximize aircraft service life.

Strategic Environment

The strategic environment of the Air Force and the United States is not new. In the late 1990s, the United States was beginning to decrease military spending after the Cold War (Jones & Zsidsin, 2008). While the A-10 and C-141 were used to great effect in the 1991 defense of Kuwait and Saudi Arabia both aircraft were old and needed to be replaced (Jones & Zsidsin, 2008; Bolkcom, 2000). Subsequently, strategic decisions led the country to weigh risks and costs of various alternatives and the C-141 was replaced by the C-17, while the A-10 service life was extended (Jones & Zsidsin, 2008; Greer, 2010). Likewise, today, the Air Force is working to replace several aging aircraft nearly simultaneously. The KC-135, in operation since the early 1960s, is being replaced by the KC-46 (Sullivan, 2015). The F-35 is in production to cover multiple attack roles (Sullivan, 2013). Unmanned Aerial Systems are being developed and procured to provide enduring presence and advantages over manned systems (Tucker, 2015). There are proposals for a new long-range strike bomber (Seligman, Clevenger, & Mehta, 2015). Finally, the C-17, while one of the newer aircraft, is being used at a rapid rate and the oldest aircraft are over 20 years old, which is old by airline standards (Pawlowski, 2010). The result is that the C-17 service life needs to be carefully managed to ensure it remains a capable aircraft until a suitable replacement can be acquired. Overflying the C-17 in

response to various global crises means that airframe fatigue may become an issue earlier than expected (Gries, 2015). As discussed below, those two issues together lead to compounding problems.

Literature surrounding the strategic environment at the start of the C-17 acquisition process reveals multiple detailed cost versus benefit analyses were conducted (Greer, 2010). Each one had slightly different parameters, but listed at least a minimum C-17 purchase and then recommended utilizing commercial off the shelf options for increased bulk cargo and passenger requirements (Bolkcom, 2000; Holmes, 1986). Congress determined to build C-17s to enable long-range strategic airlift directly to the front lines. The C-17 has the capability to deliver outsized cargo directly from the origin, transcontinental, to an austere forward operating location where forces and equipment can be employed (C-17 Globemaster III, 2015; C-17 Globemaster III Fact Sheet, 2015).

Today's forces face very similar situations. The global environment is unstable and may require forces moving on short notice to any area of the globe. Additionally, the USAF is modernizing numerous aircraft while fighting terrorism throughout the world. Congress has recently reduced the AF's budget, creating a challenging fiscal environment. As a result, recapitalizing the C-17 would be difficult, cause other budgetary sacrifices, and would challenge the USAF's ability to rapidly and flexibly project forces throughout the world.

Overview of Current Organization

Currently, C-17s are stationed in 14 locations throughout the United States (Gries, 2015). The final aircraft delivery occurred in 2013 (Trobe, 2013). Aircraft were first

assigned to Charleston AFB, SC; McChord AFB, WA; and Altus AFB, OK. McChord and Charleston were the initial operational wings and Altus was the training unit. As more C-17s were purchased, more bases were selected, many of which are Total Force locations such as Joint Base Pearl Harbor-Hickam, HI; Joint Base McGuire-Dix-Lakehurst, NJ; and Dover AFB, DE. Those units share aircraft between AD and ANG or AFRC. Other bases, such as Jackson, MS; Martinsburg, WV; and Stewart, NY are AFRC or ANG only. The result is that some units have relatively old aircraft (delivered in 1996), others relatively new, some are stationed in high corrosive environments (Hickam), some are in high operational tempo units, and some in high training sortie units (Altus), and some in units that accumulate relatively fewer flight hours. Stationing aircraft in highly corrosive environments would mean the aircraft would require more frequent and more detailed inspections to combat potential corrosion. The inspection time would decrease flying availability as well as increase maintenance costs when compared to non-corrosive environments (Hoepfner & Arriscorreta, 2012). Figure 3 shows the current number of days each aircraft has spent in various environmental severity conditions, green representing a mild corrosion environment, yellow for a moderately corrosive environment, and red for a severe corrosion environment.

Existing Processes

Currently, the USAF manages its aircraft fleets through a series of inspections and preventive maintenance steps (Gries, 2015). While effective, this process alone will not control the rate at which these airframes are used up. As noted by Rousseau, when aircraft reach the end of their service life, they must be retired or recapitalized (Rousseau,

2005). The best scenario is to be proactive in managing potential solutions. In another study, it was noted that the Navy tracks usage and publishes the results frequently as a percentage of total airframe service life (Kim, Sheehy, & Lenhardt, 2005). As a result, the program managers are aware of updated information and the pending impacts of reaching 100% of the projected fatigue life before a suitable replacement is available. In general, this makes Navy system program managers more involved and proactive in managing the airframe service lives. Currently, the USAF stove pipes the airframe usage into a relatively low level Aircraft Structural Integrity Program (ASIP) manager, who reports the service life usage to the major command (MAJCOM) that owns/operates the aircraft. It is up to the ASIP program manager to direct inspection cycles and maintenance actions to keep the aircraft servicable (Kim, Sheehy, & Lenhardt, 2005). The MAJCOMs balance aging airframe maintenance costs with other competing priorities within the command. Often, this results in underfunding ASIP initiatives because the ASIP program is one of many competing priorities and the accountability chain is more concerned with accomplishing the current mission than system preservation (Kim, Sheehy, & Lenhardt, 2005). The AF uses “damage tolerance” methodology to manage their fleet in which structures are allowed to operate with slowly growing cracks until the crack reaches a critical length (Kim, Sheehy, & Lenhardt, 2005). This basically means there isn’t a hard limit to the service life of aircraft, but they are routinely inspected and complex models record current airframe fatigue and damage and project how much longer the airframe can safely be flown before a repair will be required (Kim, Sheehy, & Lenhardt, 2005).

The process the AF uses yields significant advantages such as longer total service lives of aircraft and relatively accurate and realistic models of structures. The system assumes that all units are utilized equally and the airframes will be retired due to technological advances before serious corrosion and fatigue problems become crippling. However, one negative aspect of the damage tolerance model is that the AF accepts risks of undiscovered damage. Clark and Jackson (2010) found a significant number of accidents result from undiscovered damage. When deeper inspections were conducted on the remaining aircraft, significant costs resulted from fleet wide inspections, damage, and subsequent fixes leading them to recommend research be conducted toward better proactive discovery methods (Clark & Jackson, 2010). The bottom line is that much of the damage tolerance model relies on the damage being discovered. The problem is that this is extremely difficult due to complex structures, accessibility, and human and equipment limitations. Extremely small cracks and imperfections can have disastrous consequences when exposed to the stresses of flying. New materials, connections, and layers of different kinds of materials makes detection of damage difficult. Aircraft structures are generally engineered to be efficient for flight, not for maintenance, thus simply accessing locations with personnel and equipment can be challenging.

Another study discovered the Navy could dramatically increase the service lives of their aircraft if they swap aircraft between carrier-based and land-base assignments (Meyerhoefer & Trost, 2006). The study found that to maximize the operational life of naval aircraft, they would need to reach the end of their projected “fatigue life expended” (similar to EFH) at the same time as their “arrested landings expended” (a measure of the number of carrier landings the structure was engineered to withstand) (Meyerhoefer &

Trost, 2006). The research showed that most carrier based aircraft had accumulated a higher percentage of arrested landings relative to fatigue (Meyerhoefer & Trost, 2006). In contrast, most of the land based units had accumulated more fatigue than arrested landings (Meyerhoefer & Trost, 2006). To balance the naval assets and maximize their operational life, Meyerhoefer and Trost recommended the Navy reassign aircraft between land to carrier assignments to balance the total fleet service life (2006). Perhaps this same concept could be applied to the USAF. Currently, the AF has strict basing assignments. Few aircraft are ever transferred between bases. Some C-17s were moved to new bases to begin C-17 operations at a new location (Gries, 2015). Subsequently, factory new aircraft were delivered to replace those aircraft at the losing bases, however, the final C-17 delivery was in 2013 and no new bases are projected to begin operating the C-17. (Gries, 2015). Now, the only current moves are between Air Mobility Command units and Altus AFB (an Air Education and Training base), which Boeing recommends accomplishing as Altus training aircraft reach five years time on station or 5,000 flight hours, rotating in any of the lowest 75% EFH aircraft (Gries, 2015). This helps with some of the fatigue accumulation problems that develop at those Altus AFB, but it stops short of the airline model that flows aircraft through all locations with no permanent base assigned. The result is that ANG and AFRC bases accumulate EFH much slower than AD based aircraft. Additionally, Hickam is a severe corrosion environment, so their aircraft experience greater costs to keep the seals and corrosion prevention coatings fresh to prevent corrosion, as well as increased inspection rates to detect corrosion as early as possible (Greer, 2015).

Fatigue and Corrosion Research

Fatigue is a well-documented problem with any structure, particularly in aviation. In 1988, Aloha Flight 243 experienced a fuselage failure in which the top of the fuselage, forward of the wings and aft of the cockpit bulkhead, departed mid-flight and was attributed to the compounding effects of fatigue, corrosion, and sealant failure (Wanhill, 2002). Aviation fatigue generally focuses around high-frequency, low amplitude stresses (for example buffeting and vibration) to various metal alloys such as aluminum, steel, and titanium (Schreiber, Cikalova, Hillmann, Meyendorf, & Hoffmann, 2013). Research shows that as metal is exposed to elastic deformation loads it gets brittle (Basov, Nesterenko, & Nesterenko, 2006). The more brittle the metal becomes, the more susceptible it is to fatigue cracking (Basov, Nesterenko, & Nesterenko, 2006). If cracks are detected, they can be tracked and growth can be forecasted based on the tracking data (Machniewicz, 2012). Additionally, the cracks can usually be fixed; however, the danger is in undetected cracks (Buynak, Blackshire, Lindgren, & Jata, 2008).

Corrosion is likewise a critical factor in assessing airworthiness. Corrosion is a result of environmental conditions and chemical processes (Shaw & Kelly, 2006). The composition of the alloys, the sealants, and the coatings used influence its susceptibility to corrosion because no metal or other material is completely free from corrosion (Shaw & Kelly, 2006). Additionally, environmental factors such as warmth, humidity, and air with high salt content increase rates of corrosion (Prevey & Cammett, 2004). Numerous studies show that corrosion deterioration negatively affects structural rigidity and durability of components (Hoepfner & Arriscorreta, 2012). Corrosion chemically dissolves metals, creating thinning, holes, delamination, pits, deformities, and defects in

various places that may not be visible (such as under panels, around interior joints, bolts, screws, and rivets) (Bond, 2014). Corrosion can be very difficult to detect because aircraft cannot be fully disassembled and inspected. Additionally, assembly irregularities, imperfections, or components not performing as expected may lead to corrosion years after the aircraft leaves the assembly line (Jaya, Tiong, & Clark, 2011). Another factor of corrosion is time of exposure, thus the age of an aircraft and time it spends in highly corrosive environments generally leads to higher levels of corrosion (Hoepfner & Arriscorreta, 2012).

When combined, in an older aircraft that has been exposed to corrosive environments and stressful flying, these two factors exhibit compounding effects (Hoepfner & Arriscorreta, 2012). Corrosion thins the metals and makes the metal brittle while high frequency vibrations create fatigue stress that makes the metals even more brittle and stresses the imperfections created by the corrosion (Hoepfner & Arriscorreta, 2012). Cracking is most likely to form originating from stress points that have been weakened by corrosion; it will also spread more quickly in areas that have been embrittled by corrosion and fatigue (Hoepfner & Arriscorreta, 2012). The results are often sudden and dramatic failure; often in areas that were not detectible or previously modeled to be problematic (Connor, James, Hollis, & Campbell, 2011; Clark & Jackson, 2010). Currently, there is one particular base in Hawaii that has demonstrated significantly higher rates of corrosion growth due to its environment (see Figure 3, tail numbers 55147 through 55152, which show significantly higher levels of severe corrosion exposure compared to moderate and mild exposure time (Figure 3).

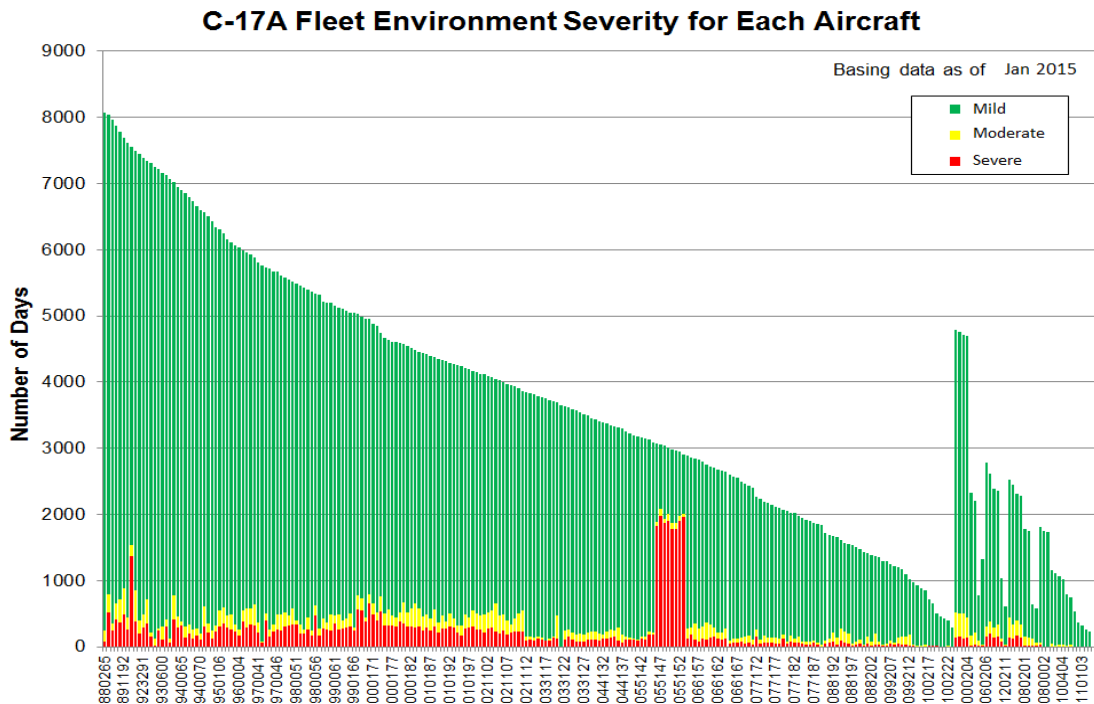


Figure 3. Accumulation of Corrosion Exposure

Total Cost of Ownership, Beyond Intended Service Life

The Air Force has faced similar problems in the past. For example, in the late 1980s and early 1990s, the Air Force decided to extend the life of the A-10 in lieu of replacing it (Jones & Zsidsin, 2008). As a result, the total cost of ownership since then has increased above the initial cost of replacement (Jones & Zsidsin, 2008). While there is never a perfect way to forecast the future outcome of current decisions, it is important to note that as the A-10 aged, the cost to maintain the airframe increased. Additionally, once the factory which produced the A-10 closed, the availability of replacement parts became a significant obstacle (Jones & Zsidsin, 2008). Modern 3-D printing, or additive

manufacturing, may help with certain structural components, but relatively few parts have been fully tested or certified for airworthiness (Sander, 2015). As a result, any aircraft that is flown beyond manufacture support capability will face substantial maintenance and logistics costs as structural components must be re-bid, tooling recreated, molds recast, and testing re-accomplished to verify the components meet or exceed the original design specifications (Clark & Jackson, 2010; Jones & Zsidsin, 2008).

Other Strategic Fleet Rotations

Research accomplished by Meyerhoefer and Trost (2006) showed the benefits of rotating fleets of naval aircraft between land-based and carrier-based units. The main problem in the Navy was structural fatigue of airframes became imbalanced due to disproportionate carrier launches and recoveries of sea based aircraft compared to the fatigue life expended by land based aircraft (Meyerhoefer & Trost, 2006). Naval aircraft have a very limited number of carrier takeoffs and landings that they are allowed to accomplish, after which, the aircraft is either retired or undergoes major structural refurbishing (Meyerhoefer & Trost, 2006). The research showed that major life cycle savings would be achieved by rotating aircraft between land and carrier based flying (Meyerhoefer & Trost, 2006). The current research seeks to apply a similar concept, using EFH, to USAF C-17s. By determining the approximate EFH usage per year by base, a schedule of aircraft basing assignment changes can be made that balances fleet service life of the C-17. Bases that fatigue aircraft at higher rates can swap for lower

EFH aircraft and bases that fatigue aircraft less can utilize high EFH aircraft. This concept mirrors the Meyerhoefer and Trost study to yield total life cycle savings (2006).

Summary

The research accomplished on aircraft fatigue, corrosion, and combined fatigue and corrosion is well documented. Inspections programs and methodologies attempt to mitigate the effects of corrosion and fatigue (Clark & Jackson, 2010). Research also shows that costs associated with maintaining older aircraft fleets tend to exceed replacement costs at some undetermined point in the future if a plan is not in place to manage logistics and maintenance supportability costs. However, looking at managing the aircraft service life through analysis of the physical and flight profile environment is relatively un-documented. Many airline companies avoid these issues by not permanently basing aircraft at locations and replacing aircraft with high flight hours much sooner than the military (Pawlowski, 2010). As shown by the study by Meyerhoefer and Trost (2006) on naval aircraft, there are benefits to managing the entire fleet over various critical factors.

III. Methodology

Chapter Overview

To determine a realistic schedule and forecast of fleet performance, it was critical to start with correct initial data. First, data from Boeing engineering teams were obtained from the USAF ASIP Manager. This data set the initial starting conditions such as EFH, location, and corrosion exposure, as well as enabled the creation of base average utilization. In consideration of EFH average annual accumulation by base and initial aircraft EFH accumulation was input into, a Greedy Randomized Adaptive Search Procedure (GRASP) program. Additionally, the last depot level maintenance date and current base assignment were used within the GRASP to generate aircraft basing schedules. Finally, the results were analyzed and the best alternative was selected as the recommended fleet basing schedule.

Boeing Data and Averages

Boeing provides flight history records for all C-17 aircraft in the USAF inventory to the ASIP Manager. The data include a current history of actual flight hours, the equivalent flight hours, and the current record of days spent in severe corrosion environments (see Table 2 for complete list of data provided). The data were analyzed to find any correlations that would help predict EFH and describe how changes in the annual flying hour program would affect the annual EFH accumulation at each C-17 base. Average flight hours and average EFH were calculated both by base and by tail number, by sorting the data by base and tail number and averaging over the reporting periods during which Boeing reported data to the USAF ASIP Manager. A few aircraft

have already shuffled locations due to ANG and AFRC bases acquiring C-17s. Additionally, Boeing and the ASIP Manager coordinated tail changes at Altus AFB, OK to mitigate structural fatigue. Altus based aircraft were accumulating EFH much more rapidly than any other location. Statistical regressions were performed by base to analyze factors affecting EFH. No statistical correlation existed between actual flight hours that could help forecast EFH by base for a given annual flight hour program (see Appendix A for statistical and mathematical analysis results). In coordination with the ASIP Manager and Boeing engineers, it was determined that the best predictor of future EFH is through a 2-year rolling EFH average for each base, regardless of the actual flight hours at the base (Gries, 2015). Part of the reason is that C-17 usage has significantly changed over the years. Initially, training was very intense and comprised a large portion of annual flight hours (Gries, 2015). As world events intensified and more crews were proficient in C-17 flight profiles, fewer hours were spent training and more hours were spent at cruise (Gries, 2015). In general, cruise contributes less to EFH than training. As a result, the average EFH per year by base decreased over the past ten years (as previously shown in Table 1). Boeing currently uses a rolling two year average to forecast future EFH (Gries, 2015). Analyzing the actual C-17 usage and training profiles by base showed this to be a valid assumption, but would have to be revisited if the fleet utilization changes significantly.

Table 2. Variables

Boeing Data:
Tail Numbers
Locations of Assigned Tails
Current Actual Flight Hours (AFH) by Tail
Current Equivalent Flight Hours (EFH) by Tail
Ratio of EFH per AFH (SF, 2-yr avg) by Base
Expected Future AFH per year by Base
Number of Days in Severe Environment by Tail
Tail Specific Breakout Data:
- Number of Landings
- Hours in Climb, Cruise, Descent
- Hours in Pattern training, Low Level, Air Drop
- Number of Assault Landings
- Hours in Air Refueling
- Average Takeoff and Landing Fuel
- Average Takeoff and Landing Gross Weight
- Average Cargo Weight
11 Sensor Position Readings for EFH
- Lower Wing
- Lower Wing Pylon Inboard Engine
- Lower Wing Pylon Outboard Engine
- Upper Wing
- Inboard Pylon Stub
- Center Fuselage
- Aft Fuselage/Vertical Stabilizer
-Aft Fuselage Bulkhead
-Wing/Fuselage Joint
- Vertical Stabilizer
-Horizontal Stabilizer

GRASP – Greedy Randomized Adaptive Search Procedure

Greedy Randomized Adaptive Search Procedures are a form of heuristics that rapidly generate a number of feasible solutions and then perform a local search, comparing each solution to determine which solution is best (Festa, Pardalos, Resende, & Ribeiro, 2002). The GRASP is best utilized in cases that involve many combinations and are difficult to solve with linear programming models (Festa P. , 2002). Heuristics find

good suboptimal solutions in reasonable computational time (Festa P. , 2002). GRASP programs use multi-start algorithms, iterations consist of two phases: a greedy adaptive randomized construction phase and a local search phase. The program requires an initial feasible solution, which is built during the construction phase, and then the local search explores other solutions until a local optimal solution is found. The best solution found overall the iterations is recorded as the optimal result (Festa P. , 2002). Greedy describes the way in which it favors certain criteria, whether to minimize cost or maximize profit. At the beginning of each construction sequence, the list of candidate elements is re-ordered by ranking all candidate based on a certain element (Festa P. , 2002).

In this research, the greedy part of the program was accomplished in two variations, each in independent program runs. One rank ordered aircraft from highest EFH to lowest EFH, allowing aircraft with the highest EFH to be assigned to open locations first. This tended to enable high EFH aircraft to be assigned to lower average EFH accumulating bases. The lowest EFH aircraft, at the bottom of the ranked list were forced into whatever open base was available. In the optimal solutions, these tended to be the higher average annual EFH locations. The other series of GRASP schedules rank ordered aircraft according to corrosion; the aircraft with the highest corrosion exposure time aircraft were assigned to bases first. In both cases, the order of bases was randomized except for the one in a severe corrosion environment, which was always ordered last. The GRASP ran four times, once rank ordering aircraft by EFH and accumulating EFH by a two-year rolling average, once rank ordering aircraft by corrosion with the two-year rolling average EFH, again rank ordering aircraft by EFH,

but accumulating EFH by the total historical average of each location, and finally rank ordering aircraft by corrosion and accumulating EFH by the total historical average of each location. The two-year rolling average EFH was provided by Boeing engineers for each C-17 base. The total historical average was calculated for each location by averaging the EFH accumulation from each sensor data download for aircraft assigned to that location for the entire history of C-17 operations at that location. The resulting 40,000 schedule options were compared to find optimal solutions. The GRASP inputs are summarized in Table 3.

Table 3. GRASP Inputs

Scenario 1		EFH Source	Priority
	Run 1*	Calculated	EFH
	Run 2*	Calculated	Corrosion
Scenario 2		EFH Source	Priority
	Run 3*	Boeing	EFH
	Run 4*	Boeing	Corrosion

*Note: Each run consisted of 10,000 schedules and resulted in two maximized solutions, one longest average service life and the other least average exposure to corrosion.

GRASP heuristics include an adaptive element because the benefits associated with each variable are updated at each iteration to reflect the changes brought on by the previous selection and probabilistic because components of a GRASP are randomly selected from a list, but the top candidate from the list is not necessarily selected first (Resende & Ribeiro, 2014). The randomized portion of this research was accomplished when the program created the base list order, which was used to match the rank ordered list of aircraft available to an open base. This research randomized the order of C-17

bases to assign aircraft at the beginning stage in creating each new full schedule. As the solution generator found an aircraft that should change locations, it looked at the list of bases for an open location. The first aircraft per rank order by EFH or corrosion was matched first, but the base list was randomly ordered except for Hickam and a retirement location, which were always the last two. The ordered list of bases was not reshuffled until an entire schedule was completed. 10,000 schedules were generated minimizing EFH and another 10,000 schedules were generated minimizing corrosion. Many GRASP studies limit the iterations to 1,000, but with modern computing power (Intel Core i5, 2.53 GHz, 6 GB RAM, in MS Excel 2010), 10,000 iterations of the schedule took approximately 3 hours, so the robustness was worth the computational time (De Leone, Festa, & Marchitto, 2011).

Summary

This research utilized data directly from sensor sources on operational aircraft to analyze actual aircraft usage compared to originally anticipated usage. The research compared current forecasts for service life, updated with current usage data, to original design specifications for service life. Additionally, the research took into consideration corrosion, which is a significant factor for aging aircraft fleets. This baseline data allowed an optimized schedule to be built that forecasts airframe usage and service life as functions of operating locations. The schedule of aircraft and locations is a complex many combination integer problem that is extremely difficult to solve with linear programming, but is ideally suited to the GRASP methodology (Feo & Resende, 1989). The schedules were generating using GRASP heuristics and optimized through

comparing thousands of iterations over various priorities such as EFH and corrosion (Hart & Shogan, 1987). The optimized schedule enables each factor to be balanced, enabling the entire fleet to share the stressful environments and contribute to a longer total service life than if no balancing was performed. It may not be the optimal schedule, but it is better than 39,999 others.

IV. Analysis and Results

Chapter Overview

The need to change basing assignments is clearly displayed by the difference between the current extrapolated schedule and the various modeled schedules (Table 4). The output from the GRASP models includes 4 optimized schedules. There is one minimized corrosion schedule and one maximized service life schedule for each scenario. One scenario includes 20,000 schedules in which EFH is accumulated by the total C-17 historical average at each location, giving the least conservative forecast and assuming higher annual utilization rates than are currently being experienced. The second scenario builds 20,000 schedules in which aircraft EFH is accumulated at a more realistic rate based on the two-year rolling average at each location. Within each 20,000 schedule scenario, 10,000 schedules are created by rank ordering aircraft by descending total EFH and 10,000 schedules are created in which aircraft are rank ordered by descending exposure to corrosion. As displayed in Table 4, the best schedule results from minimizing corrosion and then choosing the maximized service life option from that scenario. The various options and best compromise are discussed in this section. Full schedules from the GRASP model are available from the author upon request. Additionally, to assess the validity of the initial schedule solutions, a second run of each scenario was performed. The results of the second GRASP generated 40,000 schedules mirror the first 40,000 schedules and are included in Appendix B.

Table 4. GRASP Results

Corrosion Rank Order 10,000 Schedules, Boeing EFH:

BEST SOLUTION: Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	41963.6	2.1	2087
Max	42498.0	6.4	2122
Min	31627.6	0.0	2048

Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	41577.4	1.8	2083
Max	42498.3	6.3	2122
Min	30898.4	0.0	2036

Corrosion Rank Ordered 10,000 Schedules, Calculated EFH:

Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	42195.8	1.6	2065
Max	42499.8	6.3	2117
Min	40390.6	0.0	2038

Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42020.1	1.4	2062
Max	42497.2	6.2	2122
Min	37702.6	0.0	2032

EFH Rank Order 10,000 Schedules, Boeing EFH:

Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	42288.4	2.6	2086
Max	42499.4	54.1	2122
Min	39201.3	0.0	2067

Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42217.2	1.6	2083
Max	42499.7	24.3	2122
Min	41449.1	0.0	2041

EFH Rank Order 10,000 Schedules, Calculated EFH:

Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	42312.6	2.1	2063
Max	42500.0	36.0	2115
Min	41854.4	0.0	2053

Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42099.3	1.3	2061
Max	42498.9	18.1	2084
Min	41118.3	0.0	2031

Base Case

If No Changes Are Made			
	EFH	Corrosion	Service Life
Avg	42256.8	5.0	2093
Max	42512.5	118.4	2208
Min	41440.0	0.0	2042

Results of GRASP Scenarios

In Table 4, the best solution is the solution that results in the most benefit over the base case. The table values are color coded for quick identification and relative comparison. Values in red are base case or worse, values in orange are less than eight years difference in service life or less than 100-year improvement in corrosion, and values in green are better than an eight year improvement in service life or 20-year improvement in corrosion. Only the realistic solutions with Boeing’s two-year rolling average EFH values are color coded. The worst case results using total historical EFH

averages are included for comparison reference, but are not considered realistic due to the difference in expected EFH accumulation for the remaining C-17 operational service life.

The best solution extends the average service life to the year 2087, accumulating a maximum of just over six years of corrosion on the most severe aircraft, and extending the time of the first C-17 retirement until the year 2048. This means the Air Force can extend the fleet service life for approximately another 70 years and accumulate a maximum of just over 6 years exposure to highly corrosive environments for the worst case aircraft. The results of changes already made in flight profiles have made significant improvements to the airframe fatigue as demonstrated in the greater than 15 year difference between the schedules using lifetime total average EFH accumulation compared to the Boeing EFH accumulation forecast (the right columns of Table 4 compared to the left columns respectively). This again highlights the value of simulator training and judiciously balancing required currency with aircraft stress.

The recommended solution extends the service life of all C-17s approximately 6 years longer than currently forecasted before the first retirement. The lower total average service life for the fleet is due to the fact that in the base case, some aircraft will be operating at such low EFH per year that they will hypothetically not reach the end of their EFH limit for over 100 years and are skewing the average. The recommended case allows more realistic utilization across the fleet. This solution was found by utilizing the GRASP to assign 10,000 schedules minimizing corrosion, then choosing the one schedule that resulted in the highest average service life. The values in Table 4 were derived from the GRASP results by summing the number of operational years for each aircraft and finding the average and minimum. The average number of years of aircraft

service life was added to the 2016 starting year, resulting in the year 2087. The minimum number of service years is the aircraft which would need to retire first. Adding this value to 2016 resulted in the first retirement being in 2048. Finally, the average number of years and maximum number of years each aircraft was stationed at a highly corrosive location was calculated. The average reveals total fleet exposure while the maximum shows the exposure to the most severe aircraft.

Utilizing the best schedule, the first C-17 would not need to be retired until 2048. Additionally, the total fleet life could be extended until approximately 2087 with a maximum of 6.4 years of total exposure to a severe corrosion environment for any single jet and a fleet-wide average of just two years. If followed, in 2087, 122 aircraft would have been retired. The first six would retire within 40 years, followed by approximately two per year for the next 10 years, and then accelerating to an average of three to four per year until 2087. The model continued to assign aircraft to open bases for an additional 35 years; however, the number of open aircraft positions at each base becomes so great that available aircraft favor the low EFH per year assignments when, in reality, the basing decisions at that time would depend on needs of the nation and may dictate fully equipped units at strategic locations above economically advantageous locations.

The same run placing priority on minimizing corrosion also produced a schedule that resulted in less corrosion by an average of 3 months, but only decreased the maximum exposure by 18 days while sacrificing the first retirement by 12 years.

Alternatively, the GRASP solution set that minimized EFH was analyzed. The schedule in that run which had the longest average service life extended the first

retirement by 25 years, but in doing so, allowed a maximum of 54 years of exposure to a severe corrosion environment.

Even the schedule with the least corrosion under that program set allowed one aircraft to be assigned to a severe corrosive environment for over 24 years and six others over 18 years, thereby increasing the risk of corrosion and significantly increasing the maintenance costs through inspections, sealants, and coatings. Additionally, this schedule only gains one year from the base case over the first C-17 retirement, although the average over the rest of the fleet utilization is much better than the base case and still doubles the average service life expected.

The research answered several significant questions. The research suggests that service life can be significantly affected for a fleet of aircraft by scheduling changes to aircraft and operating base assignments. However, that is predicated on the assumption that various operating locations experience significant differences in aircraft utilization, resulting in significantly diverse EFH accumulation rates. Aircraft scheduling can also manage risk and exposure to highly corrosive environments. If the number of locations which routinely expose aircraft to highly corrosive environments is small in relation to the total number of bases, then scheduling basing assignment changes can help manage exposure and potential risk due to corrosion. Additionally, savings may be realized in reduced maintenance inspections, sealants, and coatings costs if aircraft spend less time in highly corrosive environments. Low corrosive locations do not threaten the airframe or its seals and coatings as much as salt laden environments and have a less frequent and less rigorous inspection, paint, and sealant need. If nothing is done, there is a greater risk of early C-17s retirement and increased corrosion damage.

For fleets similar to military fleets in which aircraft are assigned to locations and rotate through maintenance depot on set schedules and there are significant differences between various locations based on airframe utilization or environmental considerations, there may be significant risk and costs associated with extending service life of aircraft without changing location assignments. The inspection, seals, and corrosion prevention coating costs rise significantly in high corrosive environments. Any aircraft flown beyond its intended service life and beyond factory and manufacturer support costs more to maintain due to unique part availability and decreasing airframe specific experiential knowledge (Jones & Zsidsin, 2008). Additionally, as airframes fatigue, they will crack, requiring more and more detailed inspections to remain airworthy (Clark & Jackson, 2010). Finally, the risk of undiscovered discrepancies, whether corrosion, cracking, or both, increases with airframe complexity, age, environment, and usage (Clark & Jackson, 2010). If nothing is done, costs will continue to rise and the fleet will need to be recapitalized early or contracted for a Service Life Extension Program to refurbish the airframes.

Summary

The bottom line is that any amount of tail and operating base assignment changes based on EFH and corrosion can improve the total fleet health. The more rapidly these changes are made, the greater the impact will be. Additionally, the more locations able to swap aircraft, the better the resulting fleet health. The maximum advantage is realized by targeting locations with the highest and lowest EFH accumulation and the one operating

location with a severe corrosion environment; however, any change will result in incremental improvements.

V. Conclusions and Recommendations

Chapter Overview

The C-17 brings critical capabilities to the United States. It enables rapid, global mobility, which in turn, enables the flexibility the United States needs to employ smaller forces more efficiently wherever they are needed. This section will briefly review the research conclusions, significance of the research, recommended actions, and possible recommendations for future research.

Discussion

The research indicates possible advantages to a new paradigm for fleet basing decisions. The airline model of not keeping aircraft stationed statically is not feasible in the military and some other sectors, such as corporate and private aircraft. However, if service life is a concern and the fleet has numerous operating locations with disparate usage and environmental conditions, then consideration should be given to rotating fleet basing assignments. The research supports the need to be able to dynamically change aircraft basing assignments as aircraft rotate through depot level maintenance. In the case of the C-17, the total fleet service life may be extended to 2048.

The risks of flexible basing include many qualitative factors. For example, each unit takes pride in its resources. If the units know that in a few years, that aircraft and all their hard work will be rotated to another base which may not appreciate the meticulous care, will they be as motivated to take care of the aircraft? Also, there may be the impression that high use locations get all the good aircraft and low use locations are not valued and receive all the old, broken aircraft. There is also a significant amount of

corporate knowledge, especially in ANG and AFRC units for each aircraft. Will the knowledge be available to the next maintainers who work on a particular aircraft? What processes need to be implemented to capture and convey corporate knowledge.

Additionally, risks to the airframe increase as age increases. As previously discussed, airframe complexity makes inspections difficult. The USAF relies on inspections to inform the ASIP manager of fleet health, who recommends future programs for service life extension and retirement. The ASIP manager also recommends inspection schedules based on fleet health and past inspection findings. As airframes age, the risks of undiscovered damage increases. Airframe aging may also lead to high maintenance costs if parts are no longer available and subsystems begin to break with higher frequency.

Implications and Recommendations for Practice

The C-17 gives the United States a significant and viable long term option for strategic and tactical delivery for joint and multinational operations. Extending the service life of the aircraft will result in a better return on investment for the significant design and manufacturing costs associated with the development of a specialized, unique airframe. The research is also only the second time that consideration has been given to managing fleet health through rotating aircraft and operating location assignments. Other research shows the advantages of rotating naval aircraft between land-based and carrier-based operations; however, this is the first truly large, complex scheduling problem applied to fleet service life management. The research accounts for actual airframe usage through equivalent flight hours (EFH) and mitigates exposure to highly corrosive

environments by tracking amount of time each aircraft is assigned to a severe corrosion location. With 222 aircraft and 14 locations, the multitude of options problem proved too complex and time consuming for linear programming, but Greedy Random Adaptive Search Procedure heuristics proved to be a perfect method for quickly exploring feasible solutions and finding an optimal choice.

Rapid implementation is critical to delay the initial retirement of critical national assets. Initial actions should focus on aircraft with the highest EFH and highest time in severe corrosive environments. Agreements between the active duty component of the U.S. Air Force and the Air Force Reserves and Air National Guard need to be coordinated rapidly to allow all aircraft to be treated like national assets and managed for the good of the fleet and the needs of the nation. By coordinating for the basing location changes as aircraft end their depot level maintenance, the aircraft should be fully refurbished and updated so whatever airframe is being assigned to a new base will arrive as virtually a new aircraft with new upholstery and avionics. This should mitigate the perspective that units are being forced to give up their nice aircraft for another unit's old, abused aircraft. The bottom line is that changes are based on structural fatigue and corrosion risks, with the goal of preserving vital national capabilities and being good stewards of the resources granted to the government by the taxpayers, not upholstery and avionics.

Implications for Research

This research indicates that if assets are orchestrated correctly, they may continue to provide service longer than previously estimated. This research used C-17 service life

to show that fatigue and corrosion could be managed and service life extended.

Numerous factors influence service life and for that reason, the breadth and depth aspects of asset orchestration particularly apply. The research shows that two overall competing strategies between commands in the USAF can both be met if the depth of the strategy in managing the C-17 is correctly implemented. For this scenario, Air Mobility Command wants maximum utilization of its aircraft to train pilots and meet the nation's mobility demands. AFMC desires to maximize the service life and minimize maintenance costs. These two goals are competing for the same resources in opposing manners. To meet both demands requires careful balance. This study indicates that if all organizations agree to a unified strategy regarding a specific airframe, the competing demands may be both met through careful optimization strategies such as scheduled aircraft and base reallocations in conjunction with depot level maintenance. Overall, the study seems to validate the theory of resource orchestration.

The research also sought to apply predictive analytics. However, until the schedule is implemented, not enough is known to determine if the EFH scheduling predictive analytics were accurate enough to provide valuable forecasts for decision makers. Additionally, the research did find that a certain amount of predictive analytics were already being applied. For example, Boeing is already recommending that some aircraft at Altus AFB be changed with low EFH aircraft from the rest of the fleet (Gries, 2015). Additionally, actual flight profiles, especially training flight profiles, have been modified to reduce airframe fatigue based on Boeing sensor data and resultant EFH accumulation (Gries, 2015).

Future research may include utilizing this methodology to promote military-wide fleet basing flexibility for any high value, limited service life asset, be it Air Force aircraft, naval aircraft, Army helicopters, or Army tanks. Additionally, research could explore partial schedules with more variations such as not all bases participating, forcing fully resourced squadrons at various locations, or minimum numbers of aircraft at certain locations.

Future research should also be accomplished in analyzing the long term total costs of ownership resulting from extending the service life of aircraft. The C-17 should be comparable to other aging aircraft such as civilian Boeing 737s and USAF B-52s that have been in service for more than 40 years. As the C-17 ages, will the amount of time it is mission ready decrease and will the amount of time it spends receiving required maintenance increase? Will the cost of those maintenance actions increase due to part availability? Will the time for repairs increase due to a decrease in knowledgeable specialists and time spend waiting for parts?

Additionally, as previously mentioned, future research can focus on programs intended to retain corporate knowledge and reduce institutional behavioral factors that may resist flexible basing. This may include studying the enroute maintenance structure, home base maintenance capabilities, and centralized maintenance location services. When compared to the airline model, can the USAF glean efficiencies in maintenance in addition to better aircraft service life management with a flexible basing model combined with more centralized maintenance? What can be done to increase the pride and accountability within units if the aircraft basing is changed frequently? Questions such as these may provide opportunities for more qualitative research supporting this topic.

Summary

The research used GRASP methodologies to analyze a complex scheduling problem with a high multiplicity of scheduling options. The research demonstrates how aircraft basing assignments affect total service life expectancies. The Air Force is seeking innovative ways to balance priorities of remaining a small, but capable force, with the right number of competent people, while still having resources to modernize critical capability-enabling weapons systems. This research gives commanders tools and options to analyze various fleets to maximize strategic capability, thereby saving and deferring maintenance and recapitalization costs. The nation depends on the Air Force to be ready when called upon and this research helps ensure the C-17 will be available to answer the call for years to come.

Appendix A: Statistical Analysis Outputs

Fleet EFH Regression by Flight Profile

SUMMARY OUTPUT								
<i>Regression Statistics</i>								
Multiple R	0.879289529							
R Square	0.773150075							
Adjusted R Square	0.772488448							
Standard Error	134.0340241							
Observations	5159							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	15	314899376.2	20993291.75	1168.558418	0			
Residual	5143	92394610.16	17965.11961					
Total	5158	407293986.4						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.606434883	10.97379587	0.055262089	0.955931811	-20.90687276	22.11974252	-20.90687276	22.11974252
Service Yrs	95.32425563	11.96586376	7.966349736	1.99668E-15	71.86607293	118.7824383	71.86607293	118.7824383
AHF	13.48787623	0.789089816	17.09295438	9.3872E-64	11.94092455	15.03482791	11.94092455	15.03482791
NLAND	0.367131088	0.016429711	22.34555957	1.233E-105	0.334921866	0.39934031	0.334921866	0.39934031
Climb (hrs)	-8.833820526	0.975080101	-9.059584459	1.82489E-19	-10.74539228	-6.922248775	-10.74539228	-6.922248775
Cruise (hrs)	-13.70591168	0.785822125	-17.44149373	3.11764E-66	-15.24645729	-12.16536606	-15.24645729	-12.16536606
Refuel (hrs)	-11.16470099	0.808924456	-13.80190809	1.4136E-42	-12.750537	-9.578864979	-12.750537	-9.578864979
Descent (hrs)	-13.29993879	0.868373554	-15.31591874	8.20932E-52	-15.00232032	-11.59755726	-15.00232032	-11.59755726
AD (hrs)	-10.53121389	1.123529698	-9.373329347	1.02711E-20	-12.73380999	-8.328617783	-12.73380999	-8.328617783
Low Level (hrs)	-12.27045448	0.820218414	-14.95998416	1.45948E-49	-13.87843146	-10.66247751	-13.87843146	-10.66247751
Pattern (hrs)	-0.071575029	0.119644857	-0.598229049	0.549713454	-0.306129841	0.162979783	-0.306129841	0.162979783
Avg T/O Fuel Wt	0.015276474	0.00281273	5.431190281	5.85535E-08	0.009762326	0.020790622	0.009762326	0.020790622
Avg Land Fuel Wt	-0.007977094	0.002813779	-2.835011365	0.004600287	-0.013493297	-0.002460891	-0.013493297	-0.002460891
Avg T/O Gross Wt.	-0.015167248	0.002797427	-5.421855936	6.16772E-08	-0.020651395	-0.0096831	-0.020651395	-0.0096831
Avg Land Gross Wt.	0.013604586	0.002797286	4.863495447	1.18768E-06	0.008120716	0.019088456	0.008120716	0.019088456
Avg Cargo Wt.	0.002038355	0.000337788	6.034419483	1.707E-09	0.001376147	0.002700563	0.001376147	0.002700563

Charleston EFH Regression by Flight Profile

SUMMARY OUTPUT									
<i>Regression Statistics</i>									
Multiple R	0.861382								
R Square	0.74198								
Adjusted R Square	0.739818								
Standard Error	132.7204								
Observations	1806								
ANOVA									
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>				
Regression	15	90670618	6044708	343.1626	0				
Residual	1790	31530320	17614.7						
Total	1805	1.22E+08							
	<i>Coefficients</i>	<i>Standard Err</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>	
Intercept	2.406903	15.52549	0.155029	0.876816	-28.0430845	32.85689	-28.0431	32.85689	
Service Yrs	77.64801	18.20095	4.266151	2.09E-05	41.95066374	113.3454	41.95066	113.3454	
AHF	15.83474	1.820167	8.699607	7.4E-18	12.26486046	19.40461	12.26486	19.40461	
NLAND	0.317987	0.030837	10.31178	2.93E-24	0.257505822	0.378467	0.257506	0.378467	
Climb (hrs)	-13.8116	1.944106	-7.10436	1.74E-12	-17.6245925	-9.99868	-17.6246	-9.99868	
Cruise (hrs)	-15.859	1.817228	-8.72703	5.87E-18	-19.4231047	-12.2949	-19.4231	-12.2949	
Refuel (hrs)	-12.7919	1.839395	-6.9544	4.95E-12	-16.3994646	-9.18429	-16.3995	-9.18429	
Descent (hrs)	-14.3016	2.11719	-6.75499	1.93E-11	-18.4540329	-10.1492	-18.454	-10.1492	
AD (hrs)	-13.1351	2.099947	-6.25495	4.96E-10	-17.2536802	-9.01647	-17.2537	-9.01647	
Low Level (hrs)	-18.0712	1.919361	-9.41524	1.4E-20	-21.8356703	-14.3068	-21.8357	-14.3068	
Pattern (hrs)	1.600978	0.25563	6.262862	4.72E-10	1.09961276	2.102344	1.099613	2.102344	
Avg T/O Fuel Wt	0.012535	0.003952	3.171523	0.001542	0.004783324	0.020287	0.004783	0.020287	
Avg Land Fuel Wt	-0.00599	0.003972	-1.50807	0.131712	-0.01378131	0.0018	-0.01378	0.0018	
Avg T/O Gross Wt.	-0.01245	0.003895	-3.19571	0.001419	-0.02008701	-0.00481	-0.02009	-0.00481	
Avg Land Gross Wt.	0.011134	0.0039	2.854667	0.004358	0.003484494	0.018784	0.003484	0.018784	
Avg Cargo Wt.	0.000897	0.000622	1.443208	0.149137	-0.00032214	0.002117	-0.00032	0.002117	

Tail 900532 EFH Regression by Flight Profile

SUMMARY OUTPUT								
<i>Regression Statistics</i>								
Multiple R	0.967931075							
R Square	0.936890566							
Adjusted R Square	0.901829769							
Standard Error	111.0888966							
Observations	43							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	15	4946518.657	329767.9105	26.7218847	2.40439E-12			
Residual	27	333200.0599	12340.74296					
Total	42	5279718.717						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.190969299	55.54433681	0.003438142	0.997282043	-113.776596	114.1585346	-113.776596	114.1585346
Service Yrs	148.7744771	119.1144571	1.249004367	0.222384204	-95.62820092	393.1771552	-95.62820092	393.1771552
AHF	11.93133945	23.70439299	0.503338746	0.618807981	-36.70605747	60.56873636	-36.70605747	60.56873636
NLAND	0.287909654	0.163555874	1.760313746	0.089680289	-0.04767928	0.623498587	-0.04767928	0.623498587
Climb (hrs)	-15.7874441	24.00738318	-0.65760787	0.516357778	-65.04652553	33.47163732	-65.04652553	33.47163732
Cruise (hrs)	-12.61742511	23.61124902	-0.534381942	0.597450545	-61.06370639	35.82885617	-61.06370639	35.82885617
Refuel (hrs)	-6.654577786	23.97815974	-0.277526627	0.783489723	-55.85369768	42.54454211	-55.85369768	42.54454211
Descent (hrs)	-1.394672958	27.41357066	-0.050875275	0.959799425	-57.6426738	54.85332789	-57.6426738	54.85332789
AD (hrs)	-0.829646772	27.29575534	-0.030394717	0.975975824	-56.83591055	55.17661701	-56.83591055	55.17661701
Low Level (hrs)	-17.64571653	22.70327965	-0.777232047	0.443778826	-64.22899855	28.93756549	-64.22899855	28.93756549
Pattern (hrs)	1.853840843	1.628864116	1.138118782	0.265069567	-1.488312257	5.195993943	-1.488312257	5.195993943
Avg T/O Fuel Wt	0.146290751	0.082672674	1.769517589	0.088102536	-0.023339565	0.315921066	-0.023339565	0.315921066
Avg Land Fuel Wt	-0.132111786	0.083258712	-1.586762302	0.124210071	-0.302944552	0.038720981	-0.302944552	0.038720981
Avg T/O Gross Wt.	-0.14112202	0.082210183	-1.716600233	0.097505417	-0.309803383	0.027559343	-0.309803383	0.027559343
Avg Land Gross Wt.	0.137759952	0.082331207	1.673241001	0.105828804	-0.031169732	0.306689635	-0.031169732	0.306689635
Avg Cargo Wt.	0.006352205	0.00436062	1.456720447	0.156725711	-0.002595049	0.015299459	-0.002595049	0.015299459

900532 EFH Regression by 8 Flight Factors

SUMMARY OUTPUT								
<i>Regression Statistics</i>								
Multiple R	0.924016479							
R Square	0.853806453							
Adjusted R Square	0.819407972							
Standard Error	150.6711265							
Observations	43							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	8	4507857.912	563482.2391	24.82105066	4.64731E-12			
Residual	34	771860.8043	22701.78836					
Total	42	5279718.717						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.605383677	75.33531104	0.008035856	0.993635351	-152.4943885	153.7051559	-152.4943885	153.7051559
NLAND	0.47554027	0.145806342	3.261451205	0.00252425	0.179226132	0.771854409	0.179226132	0.771854409
Low Level (hrs)	-4.431577529	1.803388891	-2.457360999	0.019252459	-8.096504701	-0.766650356	-8.096504701	-0.766650356
Pattern (hrs)	6.363926814	1.381369597	4.60696893	5.52051E-05	3.556646035	9.171207594	3.556646035	9.171207594
Avg T/O Fuel Wt	0.024284048	0.088743562	0.273642923	0.786014576	-0.15606457	0.204632665	-0.15606457	0.204632665
Avg Land Fuel Wt	-0.010117878	0.089726366	-0.112763708	0.910881062	-0.192463793	0.172228037	-0.192463793	0.172228037
Avg T/O Gross Wt.	-0.018405038	0.088997116	-0.206804883	0.837395792	-0.199268939	0.162458862	-0.199268939	0.162458862
Avg Land Gross Wt.	0.015496004	0.08927501	0.173576053	0.86322797	-0.165932644	0.196924652	-0.165932644	0.196924652
Avg Cargo Wt.	0.002655359	0.004272853	0.621448667	0.538449179	-0.006028124	0.011338842	-0.006028124	0.011338842

900532 EFH Regression by 3 Flight Factors

SUMMARY OUTPUT								
<i>Regression Statistics</i>								
Multiple R	0.882696496							
R Square	0.779153104							
Adjusted R Square	0.762164882							
Standard Error	172.9094537							
Observations	43							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	3	4113709.229	1371236.41	45.86430944	7.31558E-13			
Residual	39	1166009.488	29897.67918					
Total	42	5279718.717						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	109.6067453	40.67832327	2.694475496	0.010345013	27.32707014	191.8864204	27.32707014	191.8864204
NLAND	0.589995598	0.131051194	4.502023824	5.9411E-05	0.324919538	0.855071659	0.324919538	0.855071659
Low Level (hrs)	-2.18863076	1.605592399	-1.363129747	0.180660145	-5.436247926	1.058986407	-5.436247926	1.058986407
Pattern (hrs)	5.09649623	1.145663517	4.448510539	7.00821E-05	2.779173036	7.413819423	2.779173036	7.413819423

900532 EFH Regression by Actual Flight Hrs Only

SUMMARY OUTPUT								
<i>Regression Statistics</i>								
Multiple R	0.393229092							
R Square	0.154629118							
Adjusted R Square	0.134010316							
Standard Error	329.9416233							
Observations	43							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	816398.2508	816398.2508	7.499423027	0.009090924			
Residual	41	4463320.466	108861.4748					
Total	42	5279718.717						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	279.2713425	86.21001877	3.239430249	0.002377609	105.1666776	453.3760075	105.1666776	453.3760075
AHF	0.490849844	0.179239916	2.738507445	0.009090924	0.12886749	0.852832197	0.12886749	0.852832197

Appendix B: GRASP Results

Complete Second Run of 40,000 Schedules Results

Run 2			
Corrosion Rank Order 10,000 Schedules, Boeing EFH			
Best Solution: Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	41939.77	2.056698	71.3063063
Max	42497.68	6.375266	106
Min	32066.46	0.037092	32
Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42246.19	1.777419	66.1441441
Max	42498.29	6.325562	104
Min	41634.09	0.033435	20
EFH Rank Order 10,000 Schedules, Boeing EFH			
Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	42282.58	2.615256	69.9369369
Max	42498.98	48.34856	106
Min	37134.92	0.002925	49
Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42058.17	1.39904	67.0225225
Max	42492	24.01941	88
Min	41452.1	0.002925	18

Corrosion Rank Order 10,000 Schedules, Calculated EFH			
Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	42180.82523	1.5657068	49.1576577
Max	42500	6.3236087	105
Min	39623.4	0.033435	21
Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42140.62072	1.3720131	47.0630631
Max	42497.3	6.2472501	101
Min	40357.8	0.033435	16
EFH Rank Order 10,000 Schedules, Boeing EFH			
Service Life Maximized Solution			
	EFH	Corrosion	Service Life
Avg	42359.15541	2.0747158	47.2747748
Max	42499.5	36.093066	94
Min	42019.5	0.0029248	36
Corrosion Minimized Solution			
	EFH	Corrosion	Service Life
Avg	42162.87072	1.3179591	45.1531532
Max	42499.3	18.093066	62
Min	41152.9	0.0029248	15



Extending Service Life Through Fleet Management: A C-17 Basing Study



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Abstract

Modern aircraft leverage tremendous advances in technology, engineering, and manufacturing, resulting in synergistic systems, multiple platforms, networked fleets, and asymmetric advantages. However, leaps in technology generally suffer from long and uncertain acquisition programs leading to production delays and escalating costs, especially in military specific airframes. Initial C-17 proposals specified an aircraft service lifetime of 30 years and 30,000 flight hours (Gates, 2015). Since no suitable replacement exists in the near future, this research investigates operational decisions that may slow aircraft aging and extend the effective service life of the aircraft fleet. The research indicates that if aircraft basing assignments are changed as the aircraft return to active flying after their five year depot level heavy maintenance, the service life of the entire fleet can be extended by over fifteen years. Additionally, the schedule tracks and limits each aircraft's exposure to severe corrosion environments by regularly changing aircraft base assignments between high and low corrosive environments.

Research Goals

The research objectives include balancing fleet-wide utilization, thereby delaying the need for airframe recapitalization, as well as ensuring the smooth and orderly retirement of aircraft as they fatigue beyond their service life. Additionally, the research accounts for corrosion, a major contributing factor to aircraft structural failure.

1. Can the service life of aircraft be appreciably affected by basing/hub decisions?
2. If properly managed, can changing base assignments equalize the corrosion susceptibility and airframe fatigue accumulation, allowing aircraft utilization beyond the originally advertised service life?
3. In consideration of fatigue and corrosion, how many years can a specific aircraft fleet service life be extended by rotating aircraft base assignments?
4. What is the difference between the proposed scheduling assignments and the base case if no basing changes are made?



Results & Analysis

Air Force leaders require a predictive tool to extend the service life of major weapon systems to delay recapitalization while mitigating the adverse impacts of high operations tempo and corrosive environments

Corrosion Rank Order 10,000 Schedules, Basing EHH			Corrosion Rank Ordered 10,000 Schedules, Calculated EHH		
BIST SOLUTION: Service Life Maximized Solution			Service Life Maximized Solution		
EHH	Corrosion	Service Life	EHH	Corrosion	Service Life
Avg	41963.66	2.0866978	42195.7991	1.86706799	2065
Max	42498.04	6.3752466	42499.8	6.301303158	2117
Min	31627.62	0.0370917	40390.6	0.03343996	2038
Corrosion Minimized Solution			Corrosion Minimized Solution		
EHH <td>Corrosion</td> <td>Service Life</td> <td>EHH <td>Corrosion</td> <td>Service Life</td> </td>	Corrosion	Service Life	EHH <td>Corrosion</td> <td>Service Life</td>	Corrosion	Service Life
Avg	41577.363	1.7303915	42020.08694	1.372013105	2062
Max	42498.3	6.335562	42497.2	6.247260051	2122
Min	30898.36	0.033435	37702.6	0.03343996	2032
EHH Rank Order 10,000 Schedules, Basing EHH			EHH Rank Order 10,000 Schedules, Calculated EHH		
Service Life Maximized Solution			Service Life Maximized Solution		
EHH <td>Corrosion</td> <td>Service Life</td> <td>EHH <td>Corrosion</td> <td>Service Life</td> </td>	Corrosion	Service Life	EHH <td>Corrosion</td> <td>Service Life</td>	Corrosion	Service Life
Avg	42288.398	2.6422834	4212.6333	2.128769862	2063
Max	42499.37	54.09507	42300	36.0194014	2115
Min	39201.3	0.0029248	41854.4	0.002924843	2053
Corrosion Minimized Solution			Corrosion Minimized Solution		
EHH <td>Corrosion</td> <td>Service Life</td> <td>EHH <td>Corrosion</td> <td>Service Life</td> </td>	Corrosion	Service Life	EHH <td>Corrosion</td> <td>Service Life</td>	Corrosion	Service Life
Avg	42217.186	1.6422834	42099.31396	1.317959051	2061
Max	42499.71	24.34856	42498.9	18.09306639	2084
Min	41449.05	0.0029248	41118.3	0.002924843	2031
Base Case			*EHH: Equivalent Flight Hours is the Actual Flight Hours adjusted for actual stress from various flight profiles. The stress is recorded by onboard sensors and analyzed by Boeing engineers and provided to the ASIP.		
If No Changes, Ave Made					
EHH <td>Corrosion</td> <td>Service Life</td> <td colspan="3"></td>	Corrosion	Service Life			
Avg	41985.245	2.0612023			
Max	42497.74	41.37987			
Min	41437.47	0			
		2033			



Rotating aircraft between locations can extend the first retirement 15 years and overall service life nearly 40 years, while minimizing exposure to corrosive environments



Methodology

To determine a realistic schedule and forecast of fleet performance, it was critical to start with correct initial data. First, data from Boeing engineering teams were obtained from the USAF ASIP Manager. This data set the initial starting conditions such as EHH, location, and corrosion exposure, as well as enabled the creation of base average utilization. The EHH average annual accumulation by base and initial aircraft EHH accumulation was input into a Greedy Randomized Adaptive Search Procedure (GRASP) program. Additionally, the last depot level maintenance date and current base assignment were used within the GRASP to generate aircraft basing schedules. Finally, the results were analyzed and the best alternative was selected as the recommended fleet basing schedule.

Implications

1. The research supports the need to be able to dynamically change aircraft basing assignments as aircraft rotate through depot level maintenance. In the case of the C-17, the total fleet service life may be extended to 2048.
2. The research accounts for actual airframe usage through equivalent flight hours (EHH) and mitigates exposure to highly corrosive environments by tracking amount of time each aircraft is assigned to a severe corrosion location.

Conclusions & Recommendations

1. Adopt a fleet rotation policy among AMC units and coordinate rotations with other commands, including AETC, PACAF, AFRC, and ANG for increased fleet benefits.
2. Rapid implementation is critical to delay the initial retirement.
3. Coordinate for the basing location changes as aircraft end their depot level maintenance; the aircraft should be fully refurbished and updated so whatever airframe is being assigned to a new base will arrive as virtually a new aircraft.

Collaboration

AMC/AO, AFMCC-17 ASIP, and the Boeing Co.

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14. ABSTRACT Modern aircraft leverage tremendous advances in technology, engineering, and manufacturing, resulting in synergistic systems, multirole platforms, networked fleets, and asymmetric advantages. However, leaps in technology generally suffer from long and uncertain acquisition programs leading to production delays and escalating costs, especially in military specific airframes. Initial C-17 proposals specified an aircraft service lifetime of 30 years and 30,000 flight hours. Since no suitable replacement exists in the near future, this research investigates operational decisions that may slow aircraft aging and extend the effective service life of the aircraft fleet. The research indicates that if aircraft basing assignments are changed as the aircraft return to active flying after their five year depot level heavy maintenance, the service life of the entire fleet can be extended by over fifteen years. Additionally, the schedule tracks and limits each aircraft's exposure to severe corrosion environments by regularly changing aircraft base assignments between high and low corrosive environments.					
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