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A Case for End-of-Life Fleet Optimization**

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Aging Military Aircraft Landscape – A Case for End-of-Life Fleet Optimization

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Abstract

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

1. INTRODUCTION

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

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

The term 'aging aircraft' is new to the aircraft lexicon so operators and maintainers are continually adapting to the needs of these aircraft [7]. The USAF Scientific Advisory Board (SAB) defined aging aircraft as those aircraft whose age exceeds 20-25 years or those aircraft that have exceeded 75% of their certified service life, whichever is less [3]. The Australian Civil Aviation Safety Authority chose to

declare all aircraft ‘aging aircraft’ commencing at their date of manufacture, further suggesting that the rate of aging is the more dominant descriptor [8]. The sector of aircraft that comprise the category of aging aircraft in the USAF will continue to grow in size over the coming decades because aircraft retirement rates in the USAF are low. Since there is so much opportunity for value extraction from aging aircraft, techniques for managing these aircraft must be developed. Unfortunately, as Ribeiro and Gomes found, end-of-life aircraft research is young and there is a lack of “quantitative, transparent models about handling aircraft at the end of their lives” [9]. End-of-life strategies are worth capital investment and investigation. Fleet makeup must be optimized, economical basing strategies should be developed, fatigue and maintenance costs can be better forecast and smarter decisions about when to retire aircraft and fleets are needed.

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

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

2. BACKGROUND

Aging aircraft issues have increased in importance over the past decades, due in part to several high-visibility accidents. For the USAF, it was the 1950s in-flight structural failure of a B-47 wing that triggered the beginning stages of the Aircraft Structural Integrity Program (ASIP) [11]. The Department of Defense (DoD) wrote MIL-HDBK-1530A in 1972 to address structural concerns and the USAF wrote Policy Directive 63-10 [12], [13]. A detailed and relevant history of the ASIP and structural health monitoring is found in the work of Kudva, et al [14]. The five objectives of the ASIP are included in Table 1 [12]. The application of these objectives using structural health monitoring is summarized by Molent and Aktepe’s comprehensive review of the field [15].

Table 1: ASIP objectives.

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

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

There are a variety of structural health monitoring techniques spanning from very basic to very complex. Molent and Aktepe's summary, shown as Figure 1, clearly describes the four most common techniques [19]. Simple flight hour counting has been accomplished since the beginning of flight. Counting hours merely quantifies airframe use but says nothing about utilization. Fatigue meters are simple electrical or mechanical devices that increment counts each time a specified load factor is crossed. Most fatigue meter systems are mounted at the aircraft center of gravity and therefore only record the load factor at one location, limiting their usefulness. Also, most fatigue meters do not record a time history of loading so the data show how many times a load factor was reached and not how long a load factor was sustained. Further, aircraft weight is crucial to understanding the impact of a load factor but fatigue meter systems are not capable of monitoring aircraft weight. Flight parameter monitoring became more popular with the advent of aircraft data buses. Parameters from the bus, sometimes numbering in the thousands, are recorded. This monitoring type can leave a fleet logistician with an overwhelming volume of data that can be hard to interpret. Strain gauges provide the best loading information but can be expensive to install, calibrate and interpret.

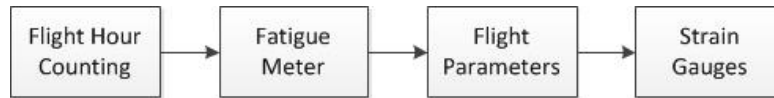


Figure 1: Structural health monitoring types [19].

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

3. THE CASE FOR END-OF-LIFE OPTIMIZATION

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

3.1. The Aging Aircraft Problem is Widespread

Air forces, navies and armies worldwide experience aging aircraft issues. Commercial airlines, private aircraft owners, tourism operators and airline brokers also face these problems. Structural fatigue and corrosion are widely studied but end-of-life fleet optimization sees much less academic and corporate investment. For example, Ribeiro and Gomes found the literature sparse on end-of-life alternatives [9]. Table 2 shows reasons why various entities do not focus their efforts on studying and publishing their findings.

Table 2: Reasons for sparse end-of-life literature.

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

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

The aging aircraft problem transcends borders and services. Kurdelski et al discuss the application of structural load monitoring systems in the Polish Armed Forces with some comparisons to the German Air Force [29]. The North Atlantic Treaty Organization is concerned about the aging aircraft problem, as is the United States Coast Guard [30], [31]. Garcia wrote about the United States Navy’s retirement planning and a novel method for optimizing fleet makeup [32]. Lincoln even posited that aging aircraft problems faced by military aircraft often have corollaries in the commercial sector – and management of both can be enigmatic [33].

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

3.2. Aircraft are Continuing to Age With Little Remediation

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

Relevant studies that recommend recapitalization of fleets increased in the 1990s through the 2010s because large data sets from digital recording means became available. Unfortunately, Hall found that most aircraft programs focus more on collecting aging data than they do on using those data to make management decisions [40]. The current organizational climate suggests that fleet managers desire to recapitalize their fleets but do not do so because of high up-front development and replacement costs or because they are not trained to understand the available data. DoD data from fiscal years 2016 until 2025 show a negative trend in fleet size, as shown in Figure 2 [41]. These data include all planned retirements as well as all planned purchases of aircraft over the next ten years. The net loss of aircraft over the forecast period is 962 aircraft, or 7% of the force’s 2016 end-strength.

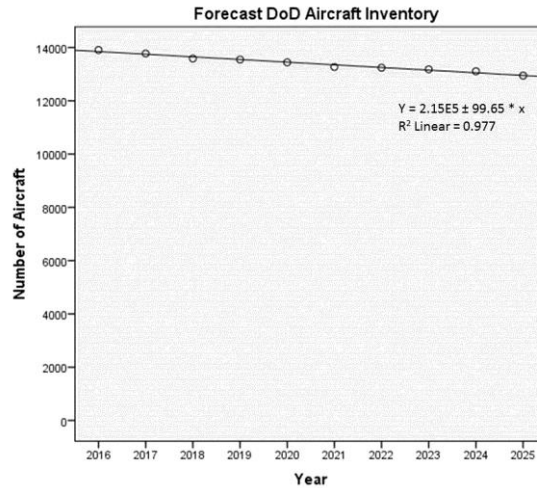


Figure 2: U.S. DoD aircraft inventory forecast for FY 2016-2025.

3.3. Aging Aircraft Cost More to Maintain

Some analysts anecdotally describe the cost trend over time for aircraft as a bathtub-shaped curve like the one shown in Figure 3. Evidence exists to support the high operations and maintenance costs early in the system lifecycle but the CBO found no studies that illustrate the rapidly rising cost curve indicative of wear-out at the end of an aircraft's lifecycle [1].

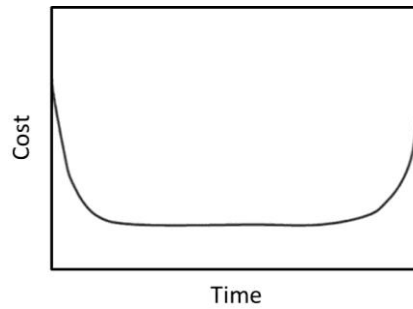


Figure 3: Notional bathtub curve.

There is evidence, though, that after the initially high costs for maintenance there is an increase in annual operating costs between 1% and 3% per year for military services like the Air Force and Navy [24], [32]. This is due in part to decreased scheduled inspection intervals. According to Bond et al's two case studies, these inspections alone without aircraft loading pattern knowledge add risk to the understanding of aircraft health [42]. Grimsley's comprehensive review of the USAF aging aircraft strategy showed that unintended problems arise with aging aircraft during inspections, further increasing maintenance costs [43]. Greenfield used stochastic and deterministic modeling to show this positive relationship between aircraft age and sustainment cost [44]. He also found that operating organizations are unable to accurately predict when to begin a new aircraft acquisition program because development cycles vary greatly in length. This makes it difficult to know how to manage an aging fleet economically. Dixon's work summarized previous studies and showed that all but Kamins found a positive age effect, which is the increase in maintenance cost as an aircraft ages [10]. Dixon's summary is included as Table 3. His log-linear regression analyses used Department of Transportation Form 41 data from U.S. airlines divided into three age groups (0-6 years, 6-12 years, 12+ years). The results showed a positive age effect for the first two age groups and a non-statistically significant positive age effect for the aging aircraft in the third group [10]. Dixon's study is added as the last row in Table 3. Note that Dixon's endogenous

divisions for aircraft ages do not suggest an alternative definition contradictory to that shown in this paper's introduction.

Table 3: Aging aircraft age effect [10].

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

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

3.4. Aircraft Utilization Directly Correlates to Aircraft Lifetime

Military aircraft fleets are disposed of when they become too costly to maintain at a desired level of availability. For most platforms, flight hours, effective flight hours or cycles are used as the independent variable for this decision with the dependent variable being maintenance costs. Flight hours are calculated from liftoff to touchdown in most flight organizations. Some organizations add a token amount of time for taxiing operations (USAF standard is 0.3 hours), which may skew loading estimations for those aircraft flying short-duration missions. Effective flight hours is an algorithm-based number typically derived from flight condition severity factors. Cycles are an important metric for life-limited components and for fatigue concerns. Original Equipment Manufacturers (OEM) test aircraft to these metrics and make recommendations to aircraft operators based on test results. Therefore, if a flying organization reaches the recommended aircraft lifetime in flight hours, effective flight hours or cycles, aircraft disposal or overhaul must be discussed.

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

3.5. Aircraft Are Retired With Unrealized Residual Value

Monitoring the structural health of individual tail numbers and then predicting the risk of continued flight is difficult. Military fleet managers often make group retirements based on OEM recommendations. This methodology ensures that some aircraft possess residual life, which is helpful if a fleet is pulled from desert storage for continued use in the future but not helpful if a fleet manager is trying to maximize aircraft lifetime. The clusters in Figure 4 show evidence that aside from outliers (hard landings, over-g incidents and crashes), this particular DoD aircraft type has had parts of its fleet retired at planned intervals ($n = 246$). The ordinate shows normalized flight hours and the abscissa shows normalized arrival time at the Aerospace Maintenance and Regeneration Group (AMARG; desert storage). Both axes are normalized to unity to show representative data. In this case, the concentrated data points show three separate retirement events, all correlating to flight-hour threshold retirements instead of retirement decisions based on individual aircraft structural lifetime calculations.

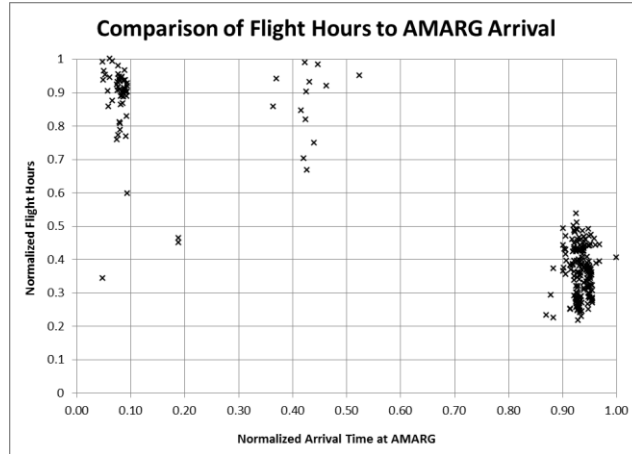


Figure 4: Normalized retirement schedule for USAF attack type aircraft.

What is seen in Figure 4 represents poor end-of-life planning and a loss of unrealized residual value. It shows a failure to utilize individual aircraft tracking for the benefit of fleet longevity. Greenfield showed that the USAF has great flexibility in choosing retirement windows, thus encouraging end-of-life fleet optimization [44]. This approach would result in more scatter on a retirement plot, retiring each tail number when appropriate.

3.6. Focusing on Aging Aircraft Optimization Can Realize Savings

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

Keating and Dixon used a parameter model to evaluate repair versus replacement decisions for two USAF aircraft, the C-21A distinguished visitor transport and the KC-135 aerial refueling tanker. They found that an aging system should be repaired "if and only if the availability-adjusted marginal cost of the existing aircraft is less than the replacement's average cost per available year" [24]. Understanding an aircraft fleet's real cost as it relates to availability can aid decision makers when evaluating retain versus retire discussions. Potential savings exist. Hsu et al conducted a related study about commercial aircraft and concluded that there exists a threshold for maintenance costs above which an airline should retire an aircraft [54]. The appropriate use of optimization in this trade space can allow fleet managers to find savings.

4. FLEET MANAGEMENT PARADIGM

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

Traditionally, the needs of the military service has determined how legacy aircraft fleets are managed. With the advent of fifth-generation aircraft possessing data recording capabilities, the ASIP manager has been able to advise fleet movements. This methodology is useful but does not take full advantage of endogenous engineering capabilities. The current state is reactive based on fatigue life and severity

factors, but future aircraft movements will be dynamic. Figure 5 proposes the author’s novel vision of future fleet management. The legacy block illustrates that assigning aircraft to bases and missions was conducted at a high level with little insight into specific aircraft detail. This method was binary in nature, meaning that an aircraft would move or not move. The fifth-generation block shows the current state, where ASIP managers use some fleet metrics to make informed decisions about the movements of aircraft. The future should hold a system where lifecycle managers are the ones who decide what is best for the aircraft’s mission assignment and basing. Predictive forecasting, instead of existing data, should inform fleet movements. This dynamic paradigm is more in line with modern analysis capabilities. The DoD may override the lifecycle manager’s recommendations to provide critical combat capability when needed. These deviations from the optimum solution are the reason for maintaining a flexible fleet optimization.

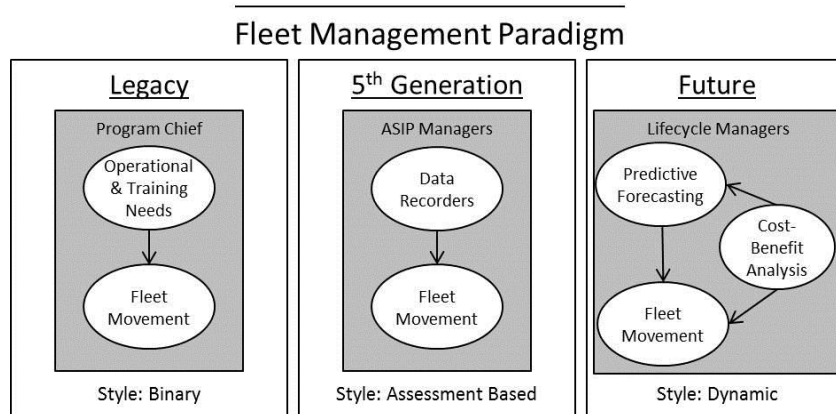


Figure 5: Fleet management paradigm from legacy to future.

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

Figure 6 shows the organizational trade-space for the future fleet management paradigm. Within the framework of aging aircraft fleet optimization, the three possibilities for change include usage, basing and retirement. It is likely that all three are part of the optimum solution for an aging aircraft fleet, making this a very difficult problem to solve. Complicating this framework further are operational demands and political climate. Having some aircraft in use for wartime needs significantly impacts an optimization routine. It is difficult to predict the location of conflict, the intensity and the duration. Also, despite having a good solution, politicians may argue against efficiency changes based on economic concerns in base communities. Regardless of the challenges, there needs to be a strong focus on end-of-life optimization strategies. The opportunity is present and the timing is ideal.

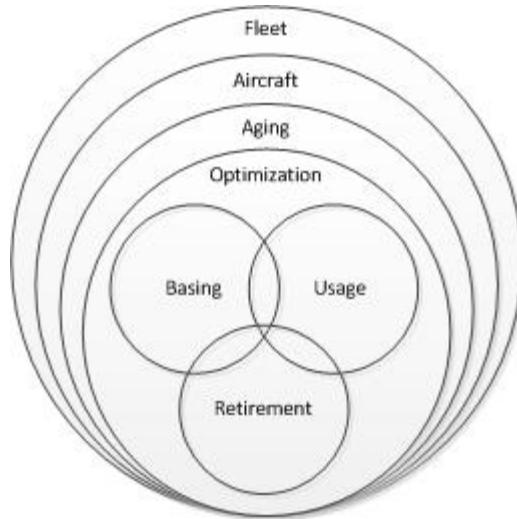


Figure 6: Visualization of how optimization fits into the fleet management perspective.

5. CONCLUSIONS

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

This paper has explored the case for end-of-life optimization through six tenets. First, this paper addressed how the aging aircraft problem is widespread. This tenet associates the problem well beyond the scope of military operations as a way to increase the number of stakeholders for the problems. An isolated military problem does not reach as many interested parties as a problem that plagues military and civilian aircraft would. Next, this paper used DoD data to show that the aging problem is not improving with time. While it was a 10-year snapshot in time representing today's paradigm of world conflict dangers, it showed that replacement programs are not a strong focus. Investment is focused less on aircraft replacement and more on other areas of the defense budget. With the help of Dixon's study, a positive correlation between aircraft age and maintenance costs was shown. This is the critical argument for aging aircraft replacement. At a point in time, the cost increases of an aging aircraft will outgrow the replacement cost and that point is the time to retire an aircraft. The actual observed retirement point may be scheduled earlier or later, but both incur a lost opportunity cost. The fourth tenet related aircraft utilization to aircraft lifetime. This common-sense tenet underscores that the primary degradation component for aircraft is usage. The more an aircraft is used, the less lifetime it possesses. Aircraft are retired with residual value. For most organizations, the cost of predicting exact lifetime and the risk of getting the prediction wrong is too great for individual aircraft retirement forecasting. Tighter controls and optimization in basing and usage can lead to a more focused retirement plan. The paradigm must shift so that aircraft residual value is less at retirement across tail-numbers. Lastly, this paper underscored the importance of focusing on aging aircraft. Fleet optimization techniques will remain a topic of the future until they become commonplace. Predictive forecasting can inform fleet movements, which will yield a more well understood aircraft history. This information can then be used to affect smart retirements.

This work looked at the existing aging aircraft literature as a way to provide direction to future end-of-life optimization research. The body of knowledge for traditional maintenance and aging studies is vast but the specific application of structural health monitoring data to fleet extension is quite lacking. Future research must be done in this area. Similar fields of study can inform this topic. Basing, usage and

retirement optimization also relate to railroad cars, shipping containers, ferries and many other industrial applications. Aging aircraft are unique from the aspects of increased risk to the user with age and necessity for combat needs, but are otherwise task-built vehicles. Specific future research should address the real costs of moving aircraft between bases, the effects of combat on a usage optimization algorithm and the sensitivity of retirement dates to mission utilization. It is in these areas that advancements could drive the future of aging aircraft optimization.

DISCLAIMER

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government.

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