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Fleet Management Decision Making With Individual Aircraft Tracking Data

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Abstract: Individual aircraft tracking data can be used by aircraft fleet managers to detect patterns in historical usage as a means to aid aging aircraft decision-making. This work tackles two aspects of applying these tracking data: investigating retirement patterns and assessing how base assignment can impact usage. The A-10, C-17 and F-35 acquisition schedules were analyzed to set the expectation for retirement forecasting. Then three types of retirement patterns were assessed - the Cliff, Multi-Step and Ramp - and the merits of each are presented. Equivalent flight hours were used as an approximation for fatigue life expended in the analysis of retirement patterns in tracking data. A candidate set of tracking data was investigated to uncover base usage variations across a network. The dissimilar mission type requirements at each base led to unique loading profiles for aircraft at each of the bases in the network. These findings lead to the natural conclusion that base assignment can be used as a way to modify the loading accumulation on individual tail numbers and across a fleet.

INTRODUCTION

Within the United States Air Force (USAF), each major weapon system's fleet planning is managed by an Aerospace Vehicle Distribution Officer (AVDO). These persons are instrumental in deciding which aircraft are rotated between bases and which aircraft are slated for retirement in accordance with the mandates set forth by the Future Years Defense Program. When deciding on fleet planning, AVDOs face a very complex problem involving multiple stakeholders including: Major Commands, the spare parts supply system, base commanders, System Program Offices and more. This work seeks to provide quantitative analysis to support AVDO decision-making. The motivation for this study was a program started in 2013 by the C-17 Globemaster III AVDO that instituted rotations of some high-time C-17s away from Altus Air Force Base, the fleet's training base. This program's goal was to ensure no C-17 would overfly a center-wing fatigue-critical structure's certified service life. Data analysis showed the C-17 AVDO that the rate of fatigue-loading at Altus was much higher than at the other bases, hence began the process of rotating high-time C-17s away from Altus. This methodology of fatigue failure prevention through active inventory management assumed the fleet manager opposed having some serial numbers reach their center-wing structural limit ahead of other aircraft. This simple fleet rotation scheme raised many questions and served as the impetus for this study.

Individual aircraft tracking (IAT) has led to known utilization histories for aircraft within some military fleets. These utilization histories have been mapped to fatigue life expended as well as mission severity, allowing for a direct comparison of sorties flown to lifetime prognostics [1] . These data span decades for some aircraft types, giving fleet managers the opportunity to investigate fleet management options. Fleet managers and AVDOs require more strategies and quantitative techniques to bridge the divide between massive amounts of fatigue data and practical, managerial decisions [2]. It is sensible to recognize that unused, unstudied IAT is a lost opportunity to make positive fleet decisions.

IAT data can include raw bus data, specialized sensor data and even hand-recorded data. The value of these data cannot be overemphasized but the staggering quantity of IAT data paralyzes some organizations' ability to use the data. IAT data can include aircraft locations which are easily mapped to environmental conditions. This can lead to improved aircraft wash programs for corrosion-inhibition. Mission identifiers can be mapped to structural degradation through the use of loads measurements. Even management changes and operational demands can be detected in IAT data. Understanding the demands of wartime and peacetime usage can become instrumental for future fleet planning.

The remainder of this paper is divided into four sections. The Literature Review highlights the relevant work on this subject matter, followed by the Methodology section which describes the authors' approach to using IAT data for analysis. In Results and Discussion, IAT data are presented, three retirement philosophies are discussed and base-to-base mission usage variations are shown. Lastly, the Conclusion summarizes the work and makes suggestions for future work.

LITERATURE REVIEW

The AVDO is responsible for planning fleet retirements and positioning individual serial numbers across a network of bases [3]. AVDOs are aware of future year requirements and use recommendations from the Aircraft Structural Integrity Program manager to best posture their fleet [4], [5]. This is a precarious activity given the usage differences among operational units found by Wallace and Spiekhout [6], [7]. These differences originate from training and operational requirements assigned to each base. Beaujon's work on demand uncertainty in a fleet dictates that there exists both a stochastic element and a deterministic element to usage differences [8]. Even though an AVDO may know the demands placed on a military aircraft fleet in the past year, the future prediction still requires a stochastic element. Therefore, there is also some uncertainty inherent to retirement forecasting.

There exist challenges with divestment decisions and spare parts cannibalizations toward the end of an aircraft's useful life [9]. This decision process can be simplified for the AVDOs using IAT but also by limiting the scope of the decision, which is what most often occurs. AVDOs faced with a multi-objective optimization problem for fleet planning focus more narrowly on which aircraft need to be divested next whereas a further-years focus would yield greater dividends. Zak's work with road freight transportation emphasizes the need for proper fleet management to solve such problems [10]. He advises the combination of human expertise with mathematical tools to solve divestment problems.

The RAND Corporation's Project Air Force investigated the costs of flying units in the USAF active duty inventory and those in the Air Reserve Component (Air Force Reserve and Air National Guard) [11]. RAND found dramatic differences in annual costs, showing a savings of one-third to one-half for those aircraft assigned to the Air Reserve Component. The reasons include a more experienced workforce and fewer expensive base facilities. However, despite these savings, RAND found that the active units fly a larger percentage of operational flight hours. These differences laid the foundation for this study, using IAT data to make informed fleet management decisions.

METHODOLOGY

To understand the relationship of IAT data to retirement decisions, the IAT data must be evaluated and baselines must be established. Military aircraft fleets employ a variety of IAT data collection techniques. Some fleets use a representative subset of aircraft for IAT collection while other fleets may use multiple IAT techniques. Regardless of technique, all IAT programs are designed to extract useful aircraft data with a minimal amount of effort. Thus by principle, IAT data can be utilized for future fleet management decisions.

Correlating IAT data directly to fatigue tracking was not the aim of this work. Instead, the goal was to use IAT data as a basis for understanding the lifespan of an aircraft or fleet. IAT data can show aggregated fleet patterns not visible at the individual serial number level. The investigation of IAT data led to two questions: *Can IAT data indicate retirement patterns?* and *How can base assignment impact usage?* These two questions were evaluated in this work using aircraft fleet data provided by the USAF's Aircraft Data Acquisition and Distribution System (ADADS). These data spanned the fiscal years 2003-2015 and included a representative set of aircraft types: attack, cargo and fighter.

ADADS data and data provided by USAF System Program Offices were used to correlate flight hours to equivalent flight hours (EFH). EFH is a measure calculated by applying a severity factor to each flight hour, based on loading conditions experienced during a flight. Depending on the operational profiles flown by an aircraft, its EFH may be greater than or less than its actual flight hours. EFH is a helpful way to monitor the condition of an airframe and can be used to gauge retirement potential.

Using EFH data, cumulative distribution functions (CDF) were built to show the relative (usage) age of each invidual serial number in a fleet. This method revealed two sets of outliers; those with very high EFH compared to the fleet's mean and those with very low EFH. Through serial number analysis, these aircraft were found to be special cases such as demonstration aircraft or Air Reserve Component aircraft. These same CDF profiles were used to develop retirement objectives.

Next, EFH data were used to show differences in utilization between bases. Knowing the EFH and the mission type for each flight at each base led to the development of typical base profile models. While these models were aggregations of volumes of data and fail to elucidate micro mechanisms, these models excelled at showing overall fleet health, which is valuable to fleet managers.

RESULTS AND DISCUSSION

Trends in IAT Data

Aircraft fleet recapitalization requires a complex and lengthy acquisition program as well as a detailed divestment plan. The economically ideal aircraft recapitalization is one that occurs instantaneously – a complete changeover of all completely used up old assets with new, challenger assets. Ideally there would be no residual value in the divested aircraft and full capability could be instantaneously achieved with the challenger assets. Production rates and pilot and maintenance spin-up are just several reasons why this ideal solution is not practical. Instead, challenger aircraft are built to replace an aging aircraft fleet over time. Figure 1 shows the acquisition rates for three candidate aircraft, the A-10 Thunderbolt II attack aircraft, the C-17 Globemaster III cargo aircraft and the F-35 Lighting II fighter aircraft. The F-35 data show the forecast acquisition numbers since its acquisition is ongoing. Both the quantity and timeline were normalized since shape is the valuable attribute for this discussion. Table I shows the three aircraft types and illustrates their representative breadth in fleet size and age.

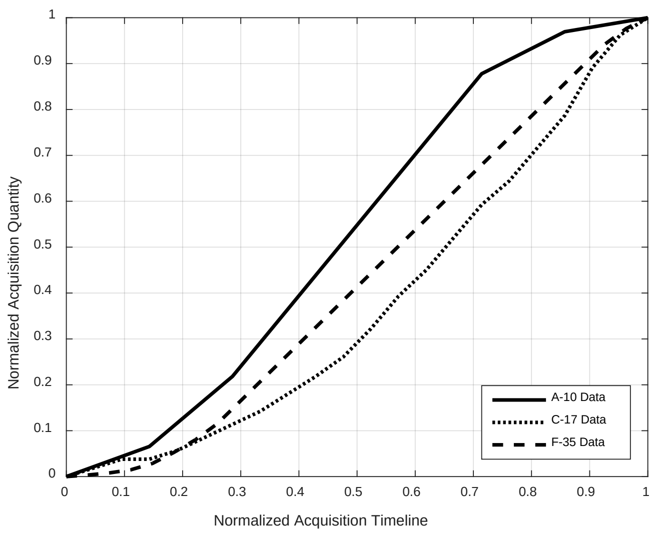

Figure 1. Comparison of acquisition quantity over time for military aircraft.

Table I. Reasons for choosing each aircraft type for evaluation.

	Introduced	Type	# In Service (USAF)
A-10	1977	Attack	291
C-17	1995	Cargo	222
F-35A	2016	Fighter	71 (1763 Planned)

Using the data in Figure 1, one can calculate linear fits for each aircraft’s acquisition rate. Table II shows the overall line fit and a fit of just the linear portion of each curve. The high coefficients of determination indicate that this modeling approach is reasonable.

Table II. Slope for acquisition rate curves.

MDS	Slope	Intercept	R^2	Slope (Linear Region)	Intercept (Linear Region)	R^2 (Linear Region)
A-10	1.143	-0.04313	0.9710	1.5389	-0.2214	0.9999
C-17	1.047	-0.1401	0.9508	1.3676	-0.3918	0.9999
F-35	1.114	-0.1211	0.9865	1.3907	-0.4079	0.9984

There exist data showing actual acquisition rates and expert opinions citing the desire to match retirement rates to procurement rates. Assuming the procurement fleet size is equivalent to the current aging fleet size, the desired retirement rates can be determined. If the fleet size is normalized to unity, then the assumption of matching fleet sizes can be eliminated. An S-curve (sigmoid curve) can be used. This Logistic function is represented by the equation:

$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}} \tag{1}$$

where L is the curve's maximum value, k is the steepness of the curve and x_0 is the x-value of the sigmoid's midpoint.

A candidate divestment curve (inverted acquisition curve) could be fitted with a high coefficient of determination using the logistic function equation. MatLab's Curve Fitting Tool produced the results shown in Table III. These coefficients were for actual data prior to normalization. The high coefficients of determination show that using the logistic function to model procurement or divestment rates is reasonable.

Table III. Logistic function fits for aircraft divestment forecast.

MDS	L	x_0	k (95% CI)	R^2
A-10	707	1979	-0.9456 (-1.056. -0.8351)	0.9963
C-17	213	1996	-0.3001 (-0.3298, -0.2703)	0.9869
F-35	1743	2022	-0.2332 (-0.2505, -0.2158)	0.9906

It is interesting to normalize the procurement number and timeline, *[0, 1]* of the fleets shown in Table III. The result is a logistic function independent of fleet size and acquisition production length. Table IV shows normalized data for the three aircraft types in this study. In each, the curve's maximum value, L, is unity since that is the normalized fleet size. The sigmoid's midpoint and steepness of the curve were both unconstrained variables in the curve fitting.

Table IV. Normalized logistic function fits for aircraft divestment forecast.

MDS	L	x_0 (95% CI)	k (95% CI)	R^2
A-10	1	0.5325 (0.5141, 0.5509)	-7.641 (-8.594, -6.689)	0.9974
C-17	1	0.3600 (0.345, 0.375)	-6.474 (-7.047, -5.901)	0.9901
F-35	1	0.4303 (0.4184, 0.4423)	-6.306 (-6.746, -5.865)	0.9918

Two findings are evident from Table IV. First, x_0, the sigmoid's midpoint, shows the normalized time when the divestment rate slows. Because the divestment curve is generated from the acquisition curve, the sigmoid's midpoint is also indicative of the production rate increase. The sigmoid's midpoint is valuable for planning expected retirement rates. If a manager intends to retire at the rate of production, knowing the sigmoid's midpoint will tell the manager when his retirement rate will begin to slow. The second finding is that k, the steepness of the curve, is similar for the military aircraft in this study with the highest similarity being between the C-17 and F-35. When normalized, the steepness of the divestment curve for one aircraft type is similar to other types for those tested (attack/cargo/fighter). This implies that the rate of aircraft divestment is similar between weapon systems, as a percentage of fleet size when ignoring total program length. Since program length was ignored, this second finding's value is in describing the contribution of the serial numbers to the logistic function.

Figure 2 shows the A-10's normalized divestment function with logistic function prediction. The divestment function is the time-shifted inverse of the A-10's actual procurement schedule. This assumes that the procurement of the A-10's replacement mimics the procurement of the A-10. This type of plot can be used to illustrate the time-dependent retirement rate, which begins with a shallow negative slope, then becomes increasingly negative and completes by shallowing again. This is the curve that a divestment strategy must seek to optimize.

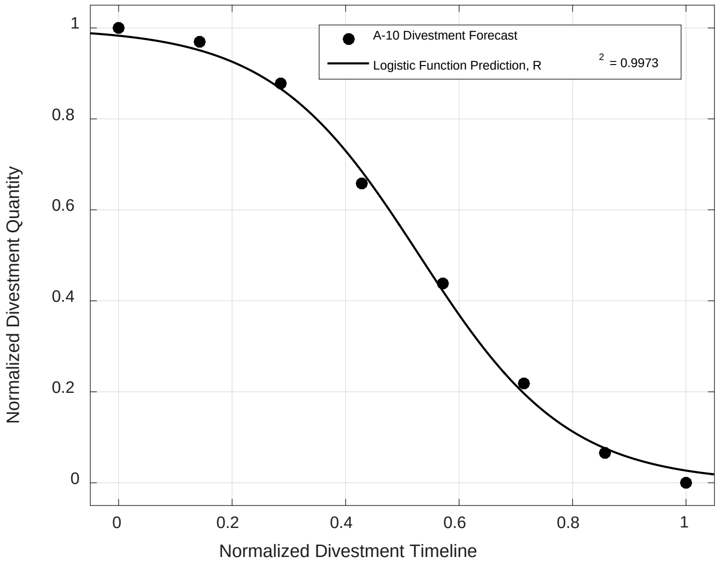

Figure 2. Normalized divestment timeline showing logistic function prediction for the A-10 fleet.

Figure 3 shows four representative EFH CDFs, including A-10 data for comparison to Figure 1. These curves are positive sloping lines for a reason; each aircraft fleet was acquired over multiple years, meaning that the usage of the assets will remain stratified unless active fleet management practices are employed. Therefore, each of the aircraft in a fleet will reach retirement at a different time. If that is not the desired retirement method, then a fleet manager must intervene. The C-130H data show a clear sigmoid – which is valuable if that is the fleet manager's desired divestment pattern.

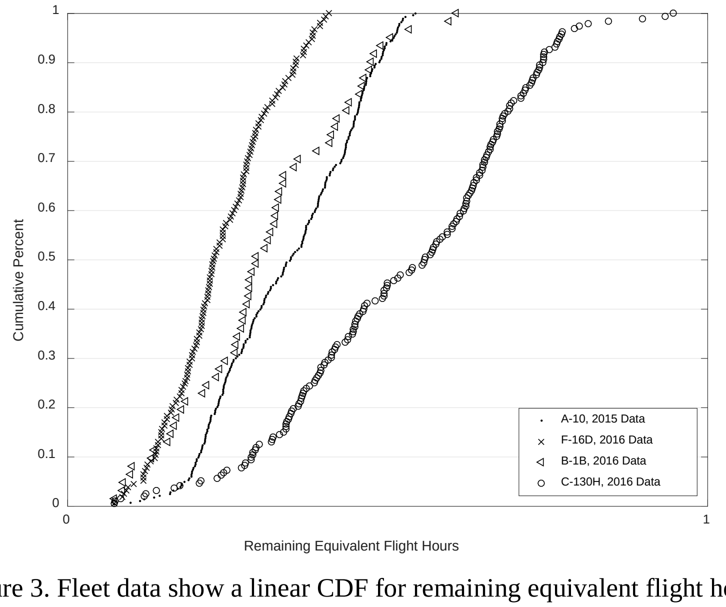

Figure 3. Fleet data show a linear CDF for remaining equivalent flight hours.

Acquisition and production timelines partially dictate a divestment strategy. While a Cliff retirement is ideal, a replacement fleet would not be in place. The remaining two options include the Multi-Step retirement and the Ramp retirement. All three retirement philosophies are shown in Figure 4 and are then discussed.

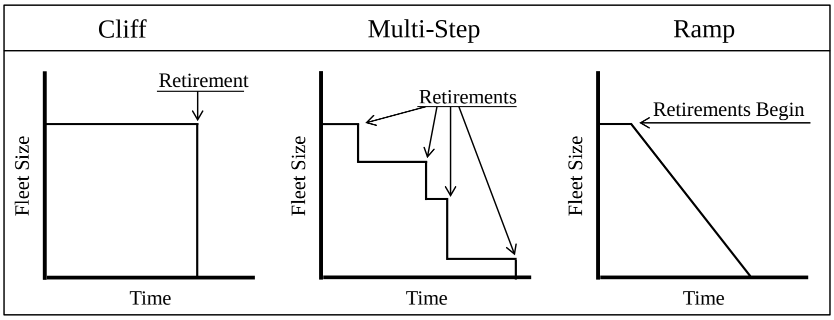

Figure 4. Three viable retirement philosophies, cliff, multi-step and ramp.

Cliff. The Cliff retirement philosophy most often occurs when an aging aircraft fleet encounters a catastrophic structural or safety of flight issue. When a problem is uncovered that is too costly to ameliorate fleet-wide, the decision to retire the entire fleet may occur at a singular point in time. Administrative and retirement planning costs can be avoided through this approach to retirement, but there are numerous disadvantages. Despite the current problem with the fleet, it is likely that there is ample residual life in the airframes. Further, it is difficult to replace a fleet's capability with a new asset quickly. To achieve a Cliff retirement, a fleet's CDF for its EFH must be close to a vertical line with minimum tails. To create a vertical EFH CDF, a fleet manager must selectively fly aircraft in such a way to equalize the EFH for all assets over time.

Multi-Step. The Multi-Step retirement philosophy is the closest approximation to current fleet management practices. For the USAF, a decrease in funding for a weapon system leads to the decision to divest assets. Groupings of aircraft are chosen for divestiture, which leads to the stair step shape. Since budgeting varies over the lifecycle of a weapon system, the time and size of the steps changes. The advantages to this approach include predictability and the efficiencies inherent to bulk retirements. The clear disadvantage is that groupings of aircraft will have various percentages of remaining useful life (residual EFH). Some losses in efficiency are caused by this method, although less losses than with the Cliff method. To create a fleet utilization to minimize losses, the EFH CDF must also have steps, or inflections. This indicates groupings of aircraft with different remaining lifetime. Selectively flying some groups of aircraft in more demanding roles at more demanding locations, or vice versa, will achieve the inflections necessary for a more efficient Multi-Step retirement philosophy.

Ramp. The Ramp retirement philosophy is a method that can help minimize gaps in operational capability. Low monthly aircraft production rates can drive a replacement philosophy where there is a one-to-one or squadron-to-squadron replacement program. This is especially true for low-density, high-demand assets. It may be necessary to retire one aircraft each time period (monthly, for example). Also, processing capacity at an aircraft boneyard might drive a Ramp retirement. The advantages are generally programmatic or capability-based but the disadvantages include administrative and operational inefficiencies. If a fleet is constantly losing aircraft or focused on losing aircraft, there can be problems. A Ramp retirement philosophy can maximize the use of residual aircraft life quite easily. The EFH CDF must take the shape of a linearly increasing function. The slope of the line dictates the retirement frequency. A larger slope means that aircraft retire more closely together while a smaller slope means that aircraft retirements can occur at greater spacing.

Base Assignment Impact on Usage

IAT data can give clues about variations across a network of operational locations (bases). Each base in an air force may accrue flight hours and fatigue loading on its aircraft at different rates because of variations in tactics or assigned missions. Data from the USAF's A-10 Warthog II ADADS were analyzed to verify the hypothesis that base assignment impacts loading accumulation. Previous work proved the correlation of mission type to loading [1]. This work's challenge was to show that network location impacted the loading accumulation. Six bases were selected for comparison. At those bases, five mission types were evaluated (BFM: Basic Fighter Maneuvers, CAS: Close Air Support, FCF: Functional Check Flight, NAV: Navigation and SAT: Surface Attack Tactics). The bases and missions were chosen for their representativeness of the full 20 bases and 18 mission types available in ADADS. Each mission flown at each base was assigned a severity factor based on available structural loading IAT data. The mission types were then aggregated at each base to show a mean severity factor for each mission type at each base.

Figure 5 shows the differences of the contribution of each mission type to the total severity factor at each base. All available data were included, fiscal years 2003-2015. While differences existed between the bases (between groups F-statistic: 2.078, significance: 0.042), optimizing aircraft base assignment given the small changes represented here would be difficult. It was suspected that a time-averaging phenomena was present due to tactics and assigned missions shifting over time. Standard military processes caused the time-averaging effect. As the worldwide threat posture has changed, bases have closed and base mission requirements have morphed. The mission severity standard deviation between bases shrank. This valuable finding demands a management strategy receptive to periodic updating. To remove this effect, single fiscal year time-slices were evaluated.

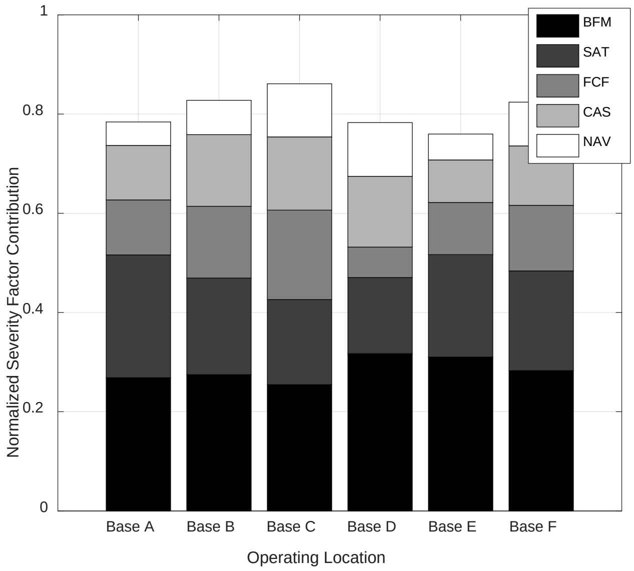

Figure 5. Severity factor network utilization, 13 year view.

Figure 6 shows data for one representative time-slice, fiscal year 2011. Others years were similar. Figure 6 shows that each base had a different severity profile for its aircraft. In this particular year the aircraft assigned to *Base B* accrued fatigue loading from BFM sorties at a rate 456% greater than the aircraft assigned to *Base E*. BFM is a particularly damaging mission profile for an aircraft because of the high load factors achieved during these simulated air-to-air combat missions. Similarly, *Base B* aircraft flew a disproportionately high share of all the FCF missions flown in the fleet in 2011. FCF missions examine the aircraft in all altitudes, airspeeds and loading conditions making them nearly as damaging as BFM missions. Seeing usage differences between bases was an expected result, but the wide disparity in utilization was unexpected. Aircraft at *Base B*, for example, accrued a total severity factor 265% greater than aircraft at *Base E*. These real differences indicate that base assignment impacts usage – and active management of base assignment can design the fatigue loading history for an aircraft.

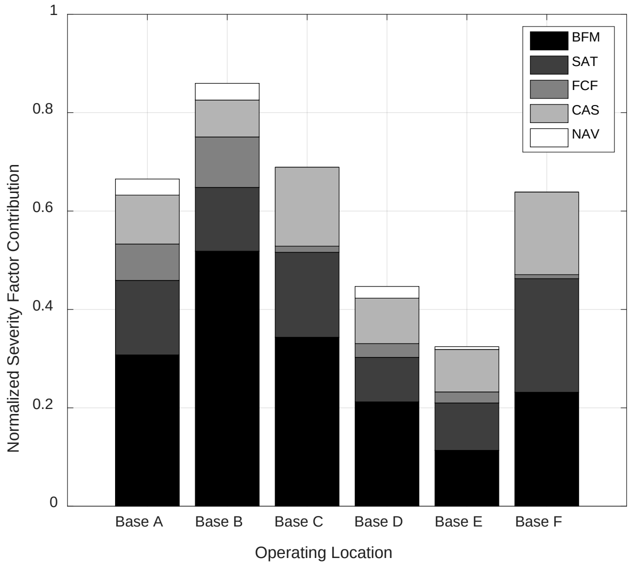

Figure 6. Severity factor network utilization, 2011.

Figure 7 follows just one mission type, BFM, for eight years at two bases to illustrate how frequently mission demands changed.

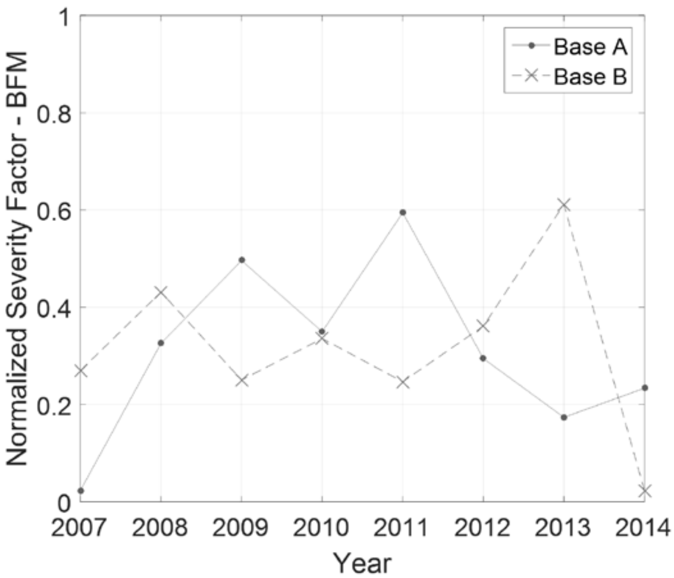

Figure 7. BFM's severity factor per year for two bases.

The full 2003-2015 dataset contained 359 aircraft. Of those, 224 moved locations at least once during the collection period, for a total of 558 aircraft movements. This resulted in a movement rate of one move per aircraft every 9.0 years. To actively manage fatigue loading history based on base assignment, aircraft would need to move more frequently than the 9-year average shown in this evaluation. However, increased fleet assignment mobility is likely to increase operations and support costs. The results in Figure 7 are useful to show the overall network usage model and underscore how that changes with time. Studying the loading accumulation on the fleet each year given changes in operational demands can inform decision makers of the impact of future operational demands. For example, the impact of wartime for an attack aircraft fleet might mean fewer high-loads training missions and more low-loads contingency missions. Or, the effects of the closure of one operating location can be modeled across the network.

CONCLUSION

This study answered two important questions: *Can IAT data indicate retirement patterns?* and *How can base assignment impact usage?* The results showed that IAT data give an indication of overall fleet lifespan. Using the EFH analysis methodology allows decision-makers to visualize the distribution of aircraft residual life. The three retirement philosophies, Cliff, Multi-Step and Ramp were each presented and their advantages and disadvantages were discussed. To answer the base assignment question, a fleet's network was analyzed using IAT data for six bases using five representative mission types. The data available showed that each base had a unique severity factor profile, meaning each base structurally aged aircraft at a different rate than other bases. For an air force, loading history can be tailored by base or by aircraft tail number. As part of this work, the historically accepted rate of aircraft relocations was found to be one move per aircraft every 9.0 years. While this study was based on one air force and one fleet within that air force, these results are valuable and stimulate a need for more linkage between IAT data and retirement analysis.

Future work in this area includes the application of fatigue data, loading profiles and base utilization to a base rotation optimization model. This extension could suggest to decision-makers how to extend useful lifetime of assets. It could also lead to an asset rotation model that designs a retirement profile for a fleet to mimic the Cliff, Multi-Step or Ramp philosophy. More aircraft types and air forces should be investigated using this methodology. Doing so could further validate the results presented herein.

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. This research was funded by the United States Air Force. The authors declare no conflict of interest.

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