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Time to retire: indicators for aircraft fleets

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

Keywords: aircraft retirement; available aircraft; fleet viability; retirement indicators; aging process.

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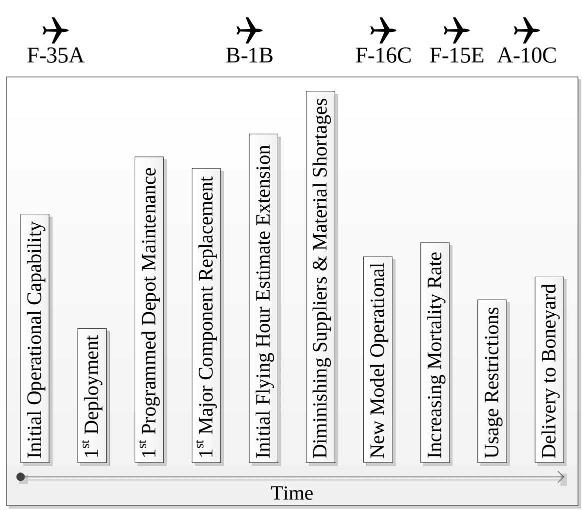
1 Introduction

The operations and sustainment phase of a system's lifecycle can span several decades (Gebman, 2009). Within that span, an aircraft fleet can undergo multiple management changes. Historical and corporate knowledge of the airframe can be lost, leading to the necessity for developing and managing a plan for an aging fleet's extended care.

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

Figure 1 Notional aging aircraft fleet milestones



Objective measures are required to benchmark a fleet's aging process. A fleet's average age, despite accumulation of EFH, indicates the onset of particular milestones. Milestones occur even though the fleet's relevance and ability to meet mission requirements may remain strong. Figure 1 proposes a notional timeline from initial operating capability through retirement and delivery to an aircraft boneyard. Several example aircraft fleets are shown at approximate positions on Figure 1 to illustrate the span of a typical aircraft's system lifecycle. These fleets, each known as a mission design series (MDS) do not experience every milestone pictured and the milestones may not occur in the order presented, but the events bound the position of a fleet on the aging aircraft timeline. Fleet managers must be continually cognisant of these indicators because proper planning and forecasting can mitigate aircraft safety risks and decrease lifecycle costs.

Each of the events in Figure 1 taken alone does not draw a pattern for an aging aircraft fleet. However, when viewed consecutively these events are seen as steps during aging. A major component replacement like a new wing or engine is an isolated event whose meaning enhances when shown next to a service life extension or supply chain disruptions. Similarly, airworthiness concerns manifest in multiple milestones such as increasing mortality rate and usage restrictions. It is incomplete to view any milestone in a vacuum. Each event may be separated by years and could be handled by a new fleet manager, so it is important to view the aging timeline at the appropriate level of fidelity.

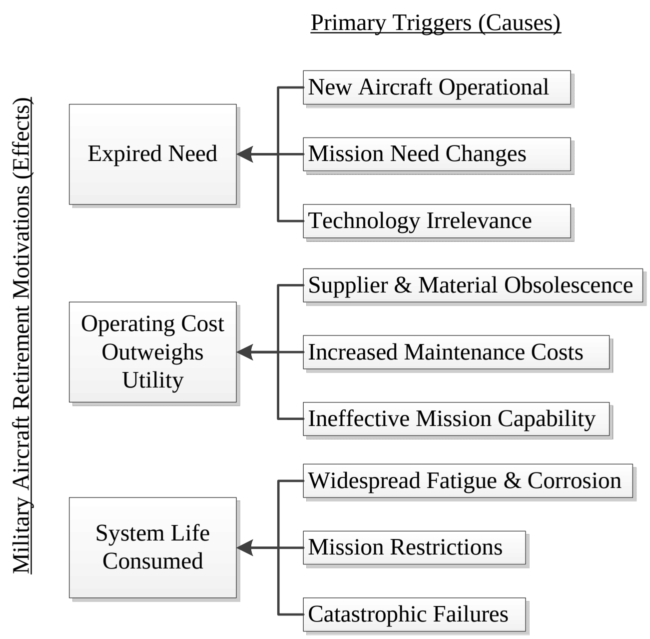
The USAF's organisation tasked with evaluating the fleet milestones on the Figure 1 timeline was the fleet viability board (FVB), which operated from 2003 until its deactivation in 2012. At its largest, the board employed 60 contractors and civilians who were divided between four assessment teams responsible for reporting on the future options for an MDS (Bullard, 2012). The board completed 15 fleet assessments before closing after a robust and impactful eight years. While the board's goal was to determine the future viability of each fleet, the FVB also developed concepts germane to aircraft retirement philosophy. For example, the FVB presented decision makers with a range of options, suggesting that given enough funding some aging aircraft could maintain relevancy and airworthiness regardless of physical age (Crowley, 2016). Unfortunately, no equivalent to the FVB currently exists in the USAF. Its functions are now conducted by disparate organisations.

This look at aging aircraft indicators is necessary for the fleet management community. The purpose of this work is to continue the development of retirement planning best practices because divestment decisions are inherently imperfect and uncoordinated (Oakley-Bogdewic and Osman, 2015). The work is novel because it develops the utility to cost ratio metric, a quantitative measure that can be used to position an aircraft fleet on the aging aircraft timeline. The remainder of this paper is organised into three sections: Aspects of fleet retirement, results and discussion and conclusions. In the aspects of fleet retirement section, the motivations for retiring a fleet and the associated causes will be presented. Then, a utility per cost metric will be developed to quantitatively identify the relative goodness of a fleet. In the results and discussion section, the utility per cost metric is validated using historical data from six USAF aircraft fleets. Asset retirement planning is also addressed. Lastly, the conclusions section highlights the major findings from this research, lists the limitations of the work and then suggests areas for future work.

2 Aspects of fleet retirement

One of the most basic questions about aircraft retirement is simply, 'When should we retire the fleet?' Understanding when an MDS should be retired is a question whose answer hinges on a range of factors within and outside of a fleet manager's control. The most practical place to start is with the motivation for the retirement. Figure 2 shows three retirement motivations (effects) in the left column and associated triggers (causes) for each in the boxes on the right side. These causes and effects were derived from literature, subject matter experts and operational experience (Hartley, 2010; Robbert, 2013; Unger, 2007; Lincoln, 2001; Jin and Kite-Powell, 2000; Crowley, 2016). An example using Figure 2 might be an MDS that is considered for retirement when its system life has been consumed. The causes suggest reasons why the fleet manager may have come to the conclusion that the system life is consumed. In this example, perhaps the MDS has experienced widespread fatigue damage or major corrosion, has mission restrictions due to airworthiness concerns or has experienced catastrophic failures. It is the causes that must be addressed to prolong the efficacy of a fleet.

Figure 2 Retirement motivations and their associated triggers



In practice, aircraft retirement planning is far more complex than represented in Figure 1 and Figure 2, especially in the absence of the FVB. To understand the complexity, the A-10 Thunderbolt II will serve as an example. This aging aircraft, produced by the Fairchild Republic Company during the years 1975–1984, has undergone multiple upgrades and extensions to maintain an effective fleet (NRC, 1997; Jones and Zsidisin, 2008). Several small batch retirements have occurred during the lifecycle of the A-10 and the fleet-wide retirement plan has been proposed, delayed and cancelled several times

(Pendleton et al., 2015). Divesting the A-10 was proposed for fiscal reasons, but opponents have questioned the capability-gap that would be left in the close air support of ground personnel mission area (Pendleton, 2016). There are two elements of interest from this example. Picking an end-date for an aircraft fleet hinges on the capability need as well as the funding accessibility. The Air Force's close air support needs can be satisfied by other weapon systems (F-16, F-15), but transitioning aircrew and tactics requires time and funding. Waiting for the build-up of F-35 Joint Strike Fighter operating locations and the transfer of the close air support role also has complicated timing. Meanwhile, the budget appropriations for the A-10 are threatened each year and are uncertain in future years. This uncertainty can negatively impact maintenance operations and much needed upgrade programs.

Because of the A-10's age, it is a useful aircraft to map to the milestones identified in Figure 1. Initial operational capability occurred in 1977, aircraft were first deployed in 1978, depot maintenance has occurred periodically and most notably the main wing has been changed. The initial design life was 6,000 flight hours but the fleet average has eclipsed 10,000 hours per aircraft (2015) (NRC 1997). The CSL is 12,000 EFH and the ESL is 16,000 EFH, both fast approaching. The original equipment manufacturer as known in 1977 has disappeared, the supply base has contracted, the newer model A-10C reached initial operational capability in 2007 and other aircraft can perform the A-10's mission. Lastly, hundreds of A-10s (309 A-10A models and 49 A-10C models) have been delivered to the USAF's aircraft boneyard (USAF, 2015). Usage restrictions for the remaining active fleet have been avoided primarily through extensive modifications.

Despite being at the far right end of Figure 1, the A-10 remains actively flying at nine permanent operating locations. This is because the A-10 has not met any of the retirement motivations shown in Figure 2. There is great need for a close air support aircraft in today's threat environment. The aircraft has been able to adapt to changing needs through system upgrades, including global positioning system capabilities, targeting pod integration, joint direct attack munitions and cockpit upgrades. The operating costs are lower than replacement aircraft (ESL not yet reached) and commanders maintain that the A-10 is their most useful air asset during engagements with enemy ground forces (Jones and Zsidisin, 2008). Despite rising maintenance costs, the A-10 is still operationally useful. Lastly, the system life or CSL of the A-10 has been largely consumed, but timely modifications and repairs have ensured airworthiness, preventing catastrophic failures or mission restrictions. Until one of the triggers (causes) drives greater attention to the retirement motivations, the A-10 will continue to operate unless budgetary or political conditions force fleet retirement.

Choosing when to retire a fleet will have a different answer depending on whom you ask. The USAF's status quo decision making for retirements starts with Headquarters Air Force, which tasks the Major Commands with force structure planning. With the many weapon systems across the military services, constantly changing global threats and political implications, picking the right time to retire assets is difficult and it is questionable whether an optimal solution exists (Keating and Dixon, 2004).

Making several assumptions can reduce the complexity of the problem but still yield beneficial results. Assume that an aircraft type is single-role and that it is replaced by a like, single-role aircraft. Replacing an aging aircraft type with a multi-role aircraft type requires cost and performance trade-offs that entangle the decision process. Further, assuming that an aging aircraft fleet is replaced by a new but similar fleet allows for a less complicated amortisation of procurement cost. To quantify the retirement planning problem, we must develop equations that allow comparisons within a fleet and between fleets. The place to start is with the premise that assets should be replaced when the operating cost grows beyond the replacement cost (Evans, 1989; Malcomson, 1979).

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

Measuring cost independently does not fairly address the value of an MDS. For example, if $C_{F16} < C_{F35}$ that does not imply that the F-16 is a more desirable aircraft in all scenarios. Another factor, like utility, must balance what could otherwise be an overreliance on cost metrics (O'Malley, 1983). Utility here is any suitable metric for an aircraft's usefulness to the fleet manager. Therefore, focusing on utility per cost leads to equation (1).

$$\frac{U(t_p)}{C(t_p)} = \frac{\textit{Utility During Lifecycle}}{\textit{Cost During Lifecycle}} \tag{1}$$

where t_p, the replacement interval, is assumed to be the aircraft's useful lifetime. Utility represents an amalgamation of availability and capability. It is an objective measure unique to each fleet; therefore it may be calculated from metrics. For most aircraft types, utility is commonly represented by available aircraft. This metric is the product of each aircraft's mission capable rate and each aircraft's field possessed rate, summed across the fleet. Equation (2) shows instantaneous available aircraft for a fleet of size, N.

$$U \equiv AA = \sum_{i=1}^{N} MC \times FP \tag{2}$$

Where FP is the field possessed rate and MC is the mission capable rate. The field possessed rate is the fraction of time an aircraft is available at home station. The field possessed rate excludes time when the aircraft is at a repair depot or in modification status. Mission capable rate is defined as the percentage of possessed hours that an aircraft can perform at least one of its assigned missions (Rainey et al., 2001). Available aircraft can be viewed relative to cost, as shown in equation (3).

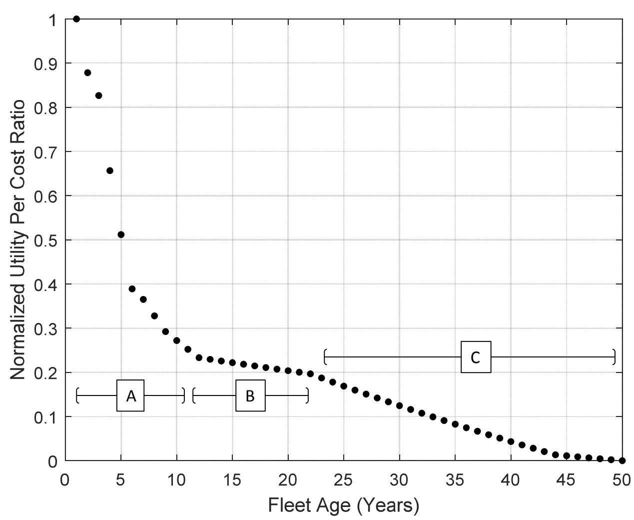
$$C_{AA} = \frac{C(t_p)}{AA(t_p)} \tag{3}$$

where C_{AA} is the cost per available aircraft. This was the principal metric used by the FVB because it included cost and available aircraft (Wright, 2011). For this analysis, equation (1) will be discussed because of its wider applicability to fleet managers.

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

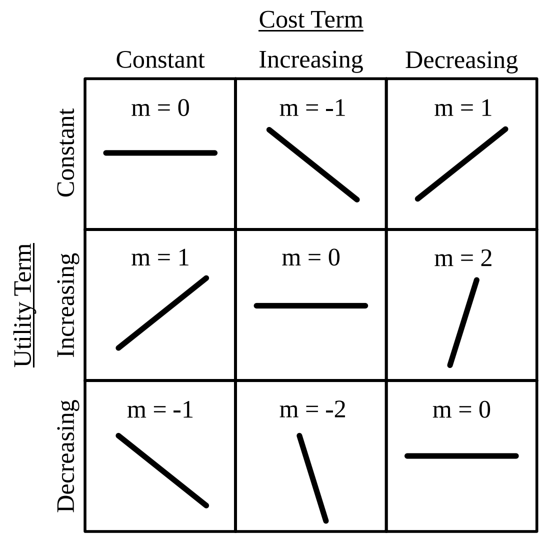
Implementing equations (1) and (2), utility per cost during a military fleet's lifecycle can be generically represented as Figure 3 where the data show a fleet's instantaneous, discretised utility per cost ratio. Cost data for this figure were derived from Dixon's (2006) RAND Corporation study while the utility data were derived from a 1997 Congressional Budget Office study (2006), (Belasco, 1997). The ordinate has been normalised to one while the abscissa represents a 50-year operational phase. Integrating these results from fleet inception until a defined point in the operations and sustainment phase of the system lifecycle results in an objective measure of utility per cost that can be used for comparisons. This approach, while objective and simple, ignores some valuable intricacies of retirement planning. Utility per cost cannot tell you everything about a fleet but it can be used as a primary motivation to encourage fleet retirement.

Figure 3 Notional utility per cost ratio for 50-year outlook



The general shape of Figure 3 is impacted by the operational demands put on a military aircraft fleet, the effectiveness of the fleet's maintenance practices and total obligation authority (budget). Figure 3 has three labels, each drawing attention to a different region. Figure 4 shows how utility and cost act and the resultant slopes that are produced. While it is possible for there to be a positive slope locally, the utility and cost terms will produce various negative slopes from near aircraft infancy until aircraft retirement. Label A marks a zone of rapid utility per cost depreciation caused by rising cost during early operations. There is no evidence of an infancy effect in Dixon's RAND data but it is reasonable to assume other models may include one. Label B evidences a zone where cost increases have subsided and utility is at its peak. Lastly, label C shows the onset of a steady decline. This zone is caused by a rapid decrease in utility despite a reduced cost increase rate.

Figure 4 Resultant slope options for utility per cost ratio



Replacement asset acquisition cost, if amortised across a useful lifetime, would drive a fleet manager to accept a lower utility per cost ratio as a trade-off to absorbing the high cost of new asset acquisition. Therefore, a fleet manager could overlay a new fleet's projected utility per cost curve on Figure 3 to help determine the optimal replacement time. The zones, labelled as A, B and C are valuable markers for comparison between old and new fleets.

3 Results and discussion

3.1 Validating utility per cost zones

Data obtained from the USAF's Logistics, Installations and Mission Support-Enterprise View database were used to validate the model shown in Figure 3. Mission capable rate was used as the metric for utility because it was the most consistently collected metric throughout a fleet's lifecycle. Total maintenance man hours were used as a proxy for cost, eliminating the need to correct for inflation. All data were averages for the fleet and were assessed discretely, for each fiscal year available in the database from database inception through fiscal year 2016. Monthly data were also evaluated and the results were similar. Six aircraft fleets were chosen for analysis: the C-130H cargo aircraft, the F-15E multi-role fighter, the T-6A turboprop trainer, the F-16C fighter, the MQ-9 and the MQ-1 unmanned aerial systems. These fleets were chosen because they represented a variety of aircraft roles and ages, which increased the robustness of the model validation.

The utility per cost ratio data for each aircraft fleet were normalised with respect to the model data. For example, the F-15E data available for years 3 to 28 were normalised according to the values in the model in years 3 to 28. Figure 5 shows the six validation aircraft fleets compared to the model.

Figure 5 Aircraft data comparison to the normalised utility per cost ratio model

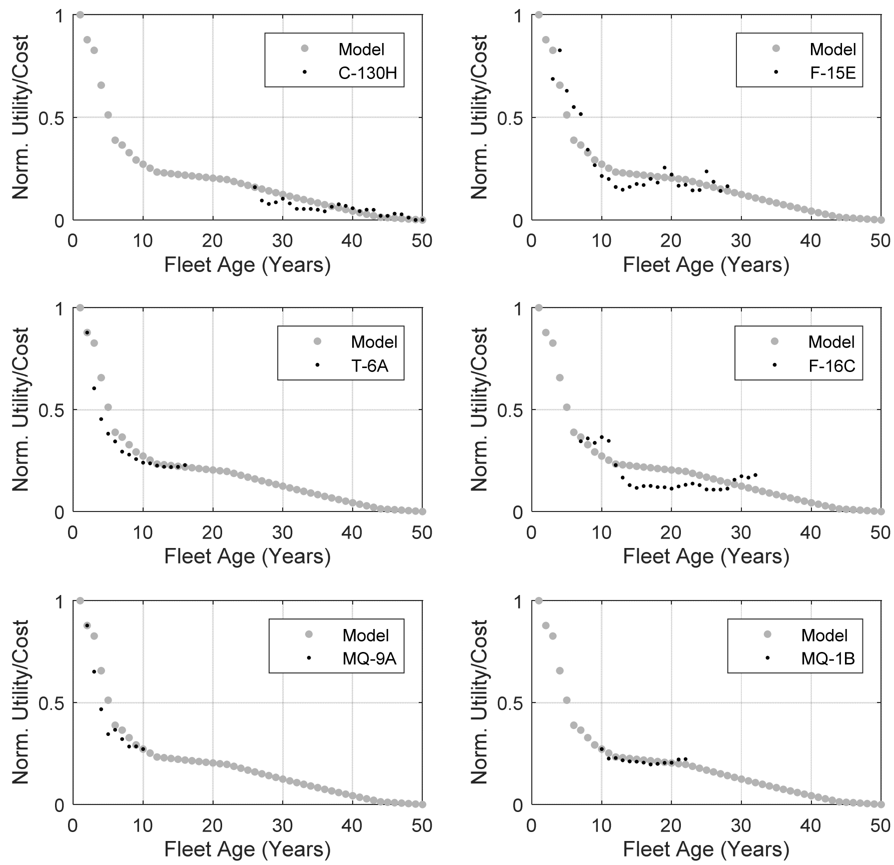


Figure 5 shows that some aircraft types match Dixon's model and experience zone changes. A closer look at the C-130H and T-6A fleets will help to illustrate the value of these results. The C-130H data span an average fleet age of 26 years through 50 years. These data fall entirely within Dixon's zone C and are valuable because they show no change within a zone. The T-6A data span an average fleet age of two years through sixteen years, crossing the boundary between zones A and B. A very clear slope change occurred. The F-15E data may show a transition from zone B to C but the research team was not confident of this assertion. Some fleets like the F-16C and others not shown do not follow the model. They show evidence of changing utility per cost over time, but do not fit the model with a high coefficient of determination. The reasons for this mismatch may include changes in maintenance, changes in operations or changes in data collection practices, among others.

Because this is a broad snapshot of the overall fleet's lifecycle using aggregated metrics, the data do not map seamlessly to the notional data presented in Figure 3, but there is evidence of zones. This method has shown mission capable rate and maintenance man hours, via equation (1) and equation (2) can be used to show zone transition. This is important because asset retirement planning hinges on understanding the position of a fleet in its system lifecycle.

3.2 Asset retirement planning

Retirement planning can be as important as acquisition planning and should be conducted simultaneously (Oakley-Bogdewic and Osman, 2015). Without an effective asset divestiture plan, potential savings from a fleet's retirement can be lost. Worse, maintaining a failing fleet whose utility per cost ratio is in continual decline can divert focus and funding away from a replacement fleet (White, 1989). Some reasons for poor divestiture planning are programmatic and budgetary while others reveal human nature. Divestiture planning exposes employees to questions about future employment stability but also forces employees to adapt their skills to a new fleet or new project. A fleet manager must recognise the human element to divestiture planning and assess the effects on the team (Smith, 1986).

Those responsible for retirement planning must also be aware of psychological biases that exist, such as escalating commitment. Managers may continue to invest in a failing system and ignore alternative options because of their previous commitments to the existing system (Duhaime and Schwenk, 1985). For example, an aircraft fleet that has recently undergone a modernisation program should not be immune from divestment discussions on the basis of renewed financial commitment. Also, retirement planning must not be fickle. Changes to planned fleet retirement dates are inherently inefficient and must be avoided through structured planning efforts.

While the optimal time for new asset acquisition depends on the specific factors for a particular fleet, two generalisable findings from this research are important. The first finding is that the divestment decision should be made using the utility per cost ratio because utility and cost are dependent factors. Either utility or cost can be artificially adjusted using the other factor. If a fleet experiences low utility, an influx of funding can increase utility. Similarly, budget decreases can be absorbed by allowing a fleet's utility to falter. The ratio of utility to cost tells stakeholders the exact usefulness of an aircraft fleet for the cost of that fleet. The second finding is that the optimal time to acquire a new aircraft fleet is dependent on the naturally occurring inflection points of the existing fleet's utility per cost ratio curve. The model derived from literature and proposed in Figure 3 is not representative of all aircraft types or all fleet management practices. However, the model is a starting point for comparisons. The relatively flat portion of the curve (Figure 3, B) is analogous to what has traditionally been termed the trough of the cost bathtub curve. This region reflects a low cost increase with age and a stable utility. New asset acquisition must begin after region B's slope becomes more negative (Figure 3, C). This will always be the case because a like challenger asset carries a cost amortisation penalty that an aging system does not have. Aircraft are complex capital assets and have a lengthy acquisition timeline. The length of this timeline can drive an acquisition decision years ahead of the need for those assets, forcing a fleet manager to make a prediction of when the utility per cost ratio decline will occur despite the manager having incomplete data. The model presented herein can be used as a guide for fleet managers attempting to predict the more rapid decline. However, caution must be exercised to avoid making premature decisions. Fleet-specific operations and maintenance practices may cause yearly fluctuations in aircraft metrics.

Looking at a fleet in aggregate and ignoring the infancy years, the utility decreases with time and the cost increases with time. The rates may change with asset type and overhauls can cause step functions in the values, but the gross patterns are set. Tracking utility and cost alongside the retirement milestones in Figure 1 can help identify or predict the triggers discussed in Figure 2. This work can indicate patterns in the fleet and prompt a more advanced look at the fleet retirement plan.

4 Conclusions

System program offices employ analysts who are experts on their fleets. Major Commands also employ analysts who assess fleet capability and costs at an aggregate level. However, the number of these positions is shrinking and additionally, the loss of the USAF FVB in 2012 means that there are fewer experts invested in the aircraft retirement puzzle. The complexity inherent to retirement decisions is itself evidence that logistical decisions can lead to savings. As shown herein, even the most basic question asking when a fleet should be retired is a difficult logistical query. Through the difficult aspects, simplifications can be made to show patterns and generalised retirement suggestions.

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

Future work could address specific case study fleets or could apply these ideas to other capital asset types such as locomotives or wind turbines. Also, researchers could investigate metrics relevant to the primary causes presented in Figure 2. While the method presented herein utilised maintenance metrics for recognising changes in the utility per cost metric, other metrics and methods could be applied to the other retirement causes.

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Disclaimer

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