Validation of the SmartBasing Aircraft Rotation and Retirement Strategy

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ABSTRACT

SmartBasing provides fleet managers tools with which to manage their end-of-life aircraft fleets. The principles of SmartBasing include reassigning aircraft to different bases and assigning aircraft to a new mix of mission types to actively manage the remaining useful lifetime of each aircraft in a fleet. This paper employs a single case study aircraft to validate the SmartBasing approach for a dynamic strategy for aircraft retirement. The United States Air Force's A-10 Thunderbolt II was used for validation because it is an ageing fleet that experienced a partial fleet retirement in 2013. The efficacy of the SmartBasing principles was tested using the aircraft retired in 2013 by altering usage patterns and basing locations in the years leading to the 2013 retirement. It was shown that SmartBasing would have been a valid technique for managing the A-10 fleet prior to its partial retirement. Better aircraft utilisation planning could have expended more residual aircraft lifetime prior to retirement, resulting in savings of more than 1.88 full aircraft lifetimes or over 83 million USD.

KEYWORDS: *military aircraft, aircraft rotations, military retirements, SmartBasing*

1 INTRODUCTION

SmartBasing is the concept of dynamically utilising a fleet of capital assets distributed in a network architecture toward some goal. SmartBasing can be used to selectively utilise some aircraft more than others, for example. For this research, military aircraft represent the capital assets and the network is the set of military bases at which the aircraft operate. Military aircraft expend useful lifetime at varying rates depending on the base of assignment and depending on the missions assigned [1]. Therefore, SmartBasing works by reassigning aircraft to different bases and mission types to influence the expenditure of useful lifetime. In this way, a fleet manager can alter the profile of a fleet's remaining useful lifetime to any shape desired. A fleet manager can also strategically manage a subset of an aircraft fleet to have each aircraft reach retirement at approximately the same time. This application of SmartBasing can ensure a fleet manager retires a subset of aircraft that has very little remaining useful life, thereby increasing the return on investment from a fleet's acquisition cost. A fleet manager desiring to extract as much residual value from a fleet of aircraft could feasibly apply SmartBasing to a fleet if the number of aircraft and future retirement date for those aircraft was available.
Valuable fleet management information is contained in the Quadrennial Defense Review (QDR), which resulted from the National Defense Authorization Act of 1997 [2]. Since its inception, five QDRs (1997, 2001, 2006, 2010, 2014) have given strategic direction to the United States Air Force (USAF) [3-7]. The document outlines strategic objectives, force structuring and force resources, which makes it the guiding document that translates the National Security Strategy into defence strategy [8]. The QDR can be viewed as the best forecasting model available to USAF strategists when building fleet

management plans. Main force structure element listings in a QDR may or may not identify weapon systems by type like A-10 Thunderbolt II or F-35 Joint Strike Fighter, leaving the USAF some flexibility in meeting end-strength requirements [9]. This research assumed that a QDR or Headquarters USAF would specify the number of aircraft desired for retirement alongside a desired retirement year [10]. Thus, a QDR may be the impetus for a retirement forecast and a reason to implement SmartBasing.
The USAF may have four fiscal years or more to implement a QDR force restructuring. This informs a fleet manager about potential retirements well in advance of the actual date, giving the manager the opportunity to implement the core principles of SmartBasing. Expending more of an aircraft's residual life prior to its retirement effectively delays the need for future weapon system acquisition, potentially saving fleet costs. While fleet costs rise as a weapon system ages, it is still advantageous to consume near-retirement aircrafts' useful lifetime [11-12]. Upon retirement, the likelihood of recoupment of that lifetime through regeneration and removal from an aircraft boneyard is very unlikely [13].
This paper encapsulates the effort to validate the usefulness of SmartBasing for a military aircraft fleet. The USAF's A-10 Thunderbolt II fleet was chosen as the vehicle for validation because it is a weapon system nearing the end of its lifecycle [14]. Furthermore, a subset of the A-10 population encompassing 41 aircraft was retired in 2013. This recent retirement wave occurred after the inception of QDRs but recently enough for the existence of high-fidelity aircraft utilisation data in the years preceding the retirement wave. This paper determines whether the SmartBasing approach to utilising a subset of A-10s after the 2006 QDR would have extracted additional useful lifetime from the aircraft which were retired in 2013. Remaining flight hours was used as the metric to determine if SmartBasing resulted in lifecycle savings.
The remainder of this paper is split into four sections. First, the Literature Review puts SmartBasing's validation in context using the fields of study of engineering, economics and management science. Then, the Methodology section describes the process of using historical aircraft data to simulate whether SmartBasing would have positively impacted a real, historical retirement scenario. The Results and Discussion section outlines the results and intricacies of the simulation. Finally, the Conclusions section succinctly reviews the takeaways from this study and offers suggestions for future research.

2 LITERATURE REVIEW

While there is little precedence in literature for the novel idea of SmartBasing, there has been a great deal of research on assigning capital assets to particular tasks. The two main areas concern commercial aircraft operator assignment problems and military aircraft assignment for air wars [15-16]. Within the field of assignment problems, two principal types of constraints relate to this SmartBasing validation study. First, cover constraints ensure that each mission type is assigned to an asset that can perform that mission. Second, the aircraft availability constraint ensures there are enough aircraft at each base location able to meet the demand at that location. These constraints are necessary in the formulation of the problem addressed by this research.
Beaujon et al extended the assignment problem by addressing the vehicle redistribution strategy. Therein they were able to optimise vehicle utilisation to ensure the fleet was sized correctly in accordance with the demand placed on the fleet [17]. An efficient redistribution mandates that there are enough assets at each location to meet the demand.
The work of Jones et al discussed parallel machine replacement, which is analogous to aircraft retirement planning [18]. Their work used an optimisation approach to prove two theorems. First, like-aged assets are best clustered together in usage scenarios. Second, it is optimal to retire older clusters prior to younger clusters. Applying these ideas to military aircraft fleets can inform fleet managers on how to manage their ageing fleets. Clustering similarly utilised aircraft may present operations and maintenance savings and generally, it is advisable to retire the aircraft clusters with the most usage first. The work of Karabakal et al adds the complexity of capital rationing to the discussion about retiring assets [19]. The QDR is in effect capital rationing guidance that is applied to the force structure through acquisitions and retirements. Such guidance must be combined with objective analysis to yield an effective management strategy [20-21].
Sherali and Maguire's work on rail car fleet sizing found that rail shipment companies had historically demanded one-hundred percent rail car availability at all times [22]. This resulted in poor utilisation of those assets. Similarly, the USAF's high readiness standards negatively impact the ability to optimise a fleet's assignment to bases and missions. A military fleet must meet mission demands

before cost or other factors are considered. Another complicating factor in working with military fleets is that the utilisation is never a predictable pattern like that seen in commercial airline operations [23]. These factors were addressed in the methodological formulation of this validation. Namely, inputs from fleet managers, exact historical utilisation and the necessity for complete coverage were part of the validation effort. Once all constraints were met, cost became an important factor. As Narisetty et al showed in their freight car assignment optimisation model, once demand is met by the available supply, cost must be minimized [24]. For the A-10 SmartBasing validation the number of aircraft relocations was the principal cost factor for comparison with the present equivalent cost of the alternative (no SmartBasing) [25]. If deciding between SmartBasing and the status quo on an iterative basis, annual equivalent evaluation would be applied.

3 METHODOLOGY

To validate the SmartBasing aircraft rotation strategy, this project looked to the past to determine whether rotating aircraft between bases could reduce the variation in remaining flight hours for aircraft pending retirement. The A-10 Thunderbolt II underwent a partial retirement in 2013, making it an ideal fleet to consider for validating the efficacy of SmartBasing.
The retirement wave of 41 A-10s arrived at the 309th Aerospace Maintenance and Regeneration Group (AMARG) boneyard in Tucson, Arizona throughout 2013 [26]. The first two arrivals were 8 April 2013 while the last two aircraft arrived on 11 December 2013. Several aircraft arrived in 2014, but those aircraft were not considered part of the retirement cluster and were not included in this study. Though the A-10 fleet was produced by the Fairchild Republic Company from 1972 to 1984, the serial numbers in the 2013 retirement spanned from the 1979 series through the 1982 series. The serial numbers were removed for this study and replaced with the identifiers *A* through *AO* for simplicity. Each aircraft was outfitted with an individual aircraft tracking data system that collected flight and loads data during the lifetime of the aircraft [27]. Figure 1 shows the cumulative distribution function for the remaining useful lifetime flight hours at retirement in 2013 for the 41 A-10s studied. Five aircraft had overflown the aircraft's certified service life of 12,000 flight hours, so they are represented as having zero remaining flight hours [28].

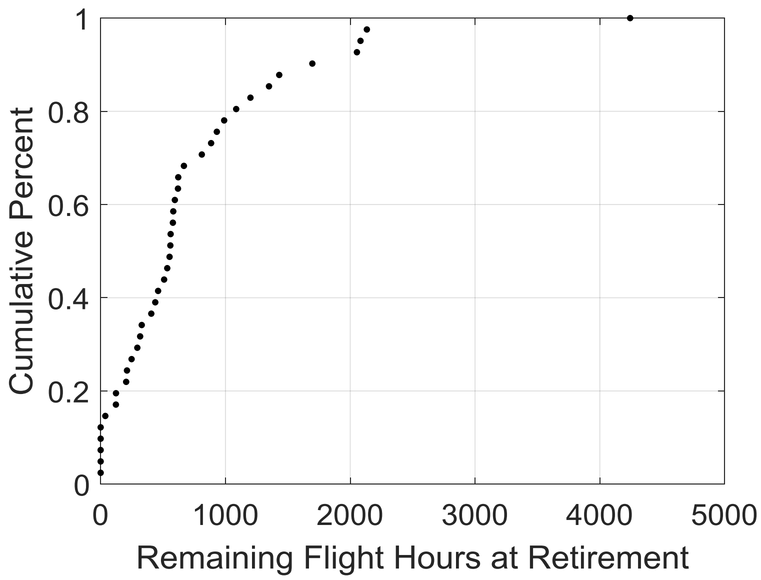

Figure 1: CDF of remaining flight hours for A-10 retirement wave

Figure 1 shows that most of the A-10s were retired with remaining flight hours, including three aircraft that possessed over 2000 remaining, unused flight hours. The residual lifetime remaining in the retirement wave averaged 742 flight hours per tail number, or 30,456 flight hours for the retirement cluster. The current certified service life was 12,000 flight hours, meaning the residual lifetime represented over 2.5 full aircraft. The unit cost of the A-10 was 18.8 million USD when built [29]. Adjusted for inflation to the time of retirement in 2013, the unit cost was 44.6 million USD. Losing useful lifetime for aircraft, at an average of 742 flight hours per retired aircraft is a significant

problem when viewed in aggregate. In this simplified example, over 100 million USD of useful aircraft lifetime was summarily disposed in 2013.
The status of the entire A-10 fleet in the years leading up to 2013 was provided by the USAF. The data included mission types, flights and base locations for each aircraft for each day. The 41 aircraft that were retired in 2013 were segregated from the population starting in 2006. This work assumed that the 2006 QDR would have been the impetus for the 2013 retirement wave, thus the A-10 fleet manager could feasibly have eight yearly cycles with which to implement SmartBasing. If the 2010 QDR inspired the 2013 retirement, the method is the same but there would have been less time for SmartBasing implementation.
The mission activity conducted by the 41 aircraft subgroup from 2006-2013 was catalogued as were the bases of assignment for those aircraft in those years. Then the question was asked, "Can these aircraft fly the same mission demands using SmartBasing but have a more uniform distribution of the remaining useful lifetime in 2013?" To answer this question, simulations were conducted within the constraints of the problem.
The simulation network must mimic the actual network. Each of the eight A-10 bases had minimum numbers of assigned aircraft as shown in Table 1. The total number of aircraft-to-base assignments must not be greater than 41. While SmartBasing advocates moving aircraft and changing their mission assignments, it is imperative to respect that a base possesses a minimum number of aircraft for training, deterrence and other reasons. The results of SmartBasing would be more pronounced if the network architecture allowed for more flexibility.

Table 1: Minimum number of aircraft at each base for each year

	2006	2007	2008	2009	2010	2011	2012	2013
Base 1	0	0	1	0	2	2	2	1
Base 2	24	25	27	28	28	26	30	33
Base 3	6	1	0	0	0	0	0	0
Base 4	0	0	2	3	4	5	2	2
Base 5	4	4	4	4	4	4	4	0
Base 6	2	2	2	2	3	3	3	3
Base 7	2	1	0	0	0	0	0	0
Base 8	3	5	5	3	0	0	0	0
Sum:	**41**	**38**	**41**	**40**	**41**	**40**	**41**	**39**

The simulation must conduct the same quantity of missions with the same mix of mission types at each base in each year. For example, if Base 2 flew 175 flight hours of *surface attack training* in 2006 then the simulation must assign aircraft to fly those same missions. This ensures that SmartBasing would have met all demands placed on the fleet. It is assumed that there is some inefficiency resulting in loss in the flight scheduling but SmartBasing makes no effort to improve that process. A necessary step involved ensuring the available aircraft for assignment to a base could meet the flight demands at that base. In Table 1 in the year 2006, note that Base 2 required 24 aircraft. That left a small pool of aircraft for assignment to the other bases requiring aircraft. This methodology ensured that the two aircraft at Base 7, for example, could meet the mission demands at Base 7.
SmartBasing's cost includes the additional management overhead as well as the cost of moving aircraft between bases. Increased management overhead is assumed to be negligible within the USAF enterprise. However, moving aircraft more frequently has a tangible cost that must be weighed. Relocation frequency is calculated by dividing the number of movements per aircraft by the number of years in the simulation. Doing this enables comparison between the costs of aircraft relocations that actually occurred in 2006-2013 with the SmartBasing recommendation for relocations. The reasons for the actual relocations were not evaluated. It was assumed that some base closures and force restructuring would occur in any population over time.
There were several limitations to this methodology. Artificiality was introduced to the validation because the whole fleet was not considered during the simulation window. Also, it was assumed that notification of a retirement would occur years before the retirement date. It is the case that some aircraft fleets are ordered into retirement with very short notice. In these circumstances, SmartBasing would be marginally effective.
The software tool used for this validation was ROTATE, the Retirement Optimization Tool for Aircraft Transfers and Employment [30]. It was developed in 2016 by the Air Transport and Operations

research group at the Delft University of Technology. ROTATE solved mixed-integer linear programming problems and was specifically tailored for determining how to optimally employ an aging aircraft fleet given a realistic base location network and flight demands for the aircraft. ROTATE employed IBM's ILOG CPLEX Optimization Studio software, version 12.6, to optimise the mission assignments for aircraft in a fleet for each iteration period [31]. Outputs of the software included base assignments for each aircraft, mission assignments and hours flown of each mission. For each iteration, the relocation frequency and remaining useful lifetime were calculated.

4 RESULTS AND DISCUSSION

SmartBasing provides fleet managers a methodology for achieving a fleet of retiring aircraft that possess similar remaining useful lifetime. The ROTATE software was used without modification with the settings displayed in Table 2. The number of bases, number of aircraft and number of mission types were all based on actual values for the fleet. The maximum and minimum number of flight hours were chosen from analysis of the subpopulation of the retiring aircrafts' actual flown flight hours.

Table 2: Simulation settings

Variable	Setting
Number of bases	8
Number of aircraft	41
Number of mission types	15
Max flight hours per aircraft per iteration	300
Min flight hours per aircraft per iteration	30
Min/Max aircraft at each base	Table 1/41
Permitted aircraft moves per iteration	1
Severity factors for mission types	Per Data*
*Large matrices were used but were not reproduced here.	

Determining whether SmartBasing could be effective required a direct comparison between what actually happened with the 41 A-10s leading up to their 2013 retirement and what would have happened having utilised SmartBasing. Figure 2 shows the difference between remaining flight hours at retirement for the historical (actual) case and the simulation using SmartBasing. The historical data were replicated from Figure 1. SmartBasing flew the aircraft with more remaining useful lifetime more frequently. This caused the spread of remaining flight hours to shrink between 2006 and 2013. Less variation gives a fleet manager the option to continue flying a subgroup closer to the expiry of useful lifetime. While the historical retirement left 30,456 flight hours remaining in the retired aircraft, the SmartBasing approach enabled the aircraft to be flown more iterations, effectively delaying the retirement by years. Assuming that the simulation continued until the first SmartBasing aircraft possessed zero remaining useful life, the resulting sum of remaining flight hours for the 41-aircraft group would have been 7,896 flight hours. Total fleet savings was therefore 22,560 flight hours or approximately 1.88 aircraft lifetimes. This translates in 2013 dollars to over 83 million USD.

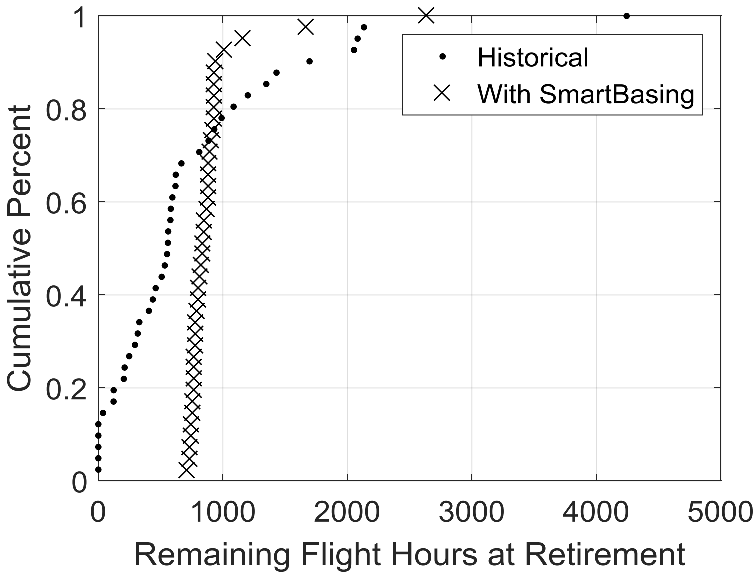

Figure 2: CDF of remaining flight hours with and without SmartBasing

Calculating the standard deviation of the remaining flight hours each year for the subgroup is key to understanding the utilisation dispersion. A decreasing standard deviation over time means that the aircrafts' remaining flight hours grow closer together while an increasing standard deviation means the flight hour dispersion becomes larger. A smaller standard deviation results in more aircraft being ready for retirement at one time. Figure 3 shows the standard deviation of the remaining flight hours for each year in the simulation for both the historical (actual) case and the simulation using SmartBasing. SmartBasing was built specifically to reduce the standard deviation among aircrafts' remaining flight hours, so a downward trend was expected. The historically flown data show that without an active management strategy, the standard deviation grows over time. This repeatable result occurs because of the many realities inherent to fleet management: deployments and major overhauls, for example.

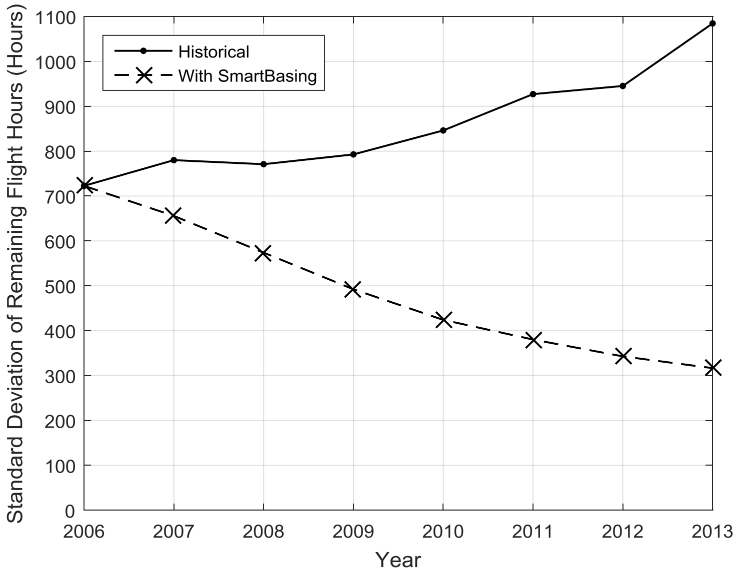

Figure 3: Standard deviation of remaining flight hours with and without SmartBasing

The results in Figure 2 and Figure 3 validate the SmartBasing approach. Though it is feasible, fleet managers must understand the additional cost of SmartBasing. The subgroup of 41 A-10s had a relocation frequency of only 0.0701 movements per aircraft per year in the years 2006-2013. SmartBasing required a movement frequency of 0.4390, which represents a significant increase in annual equivalent cost. It is incumbent upon a fleet manager to determine whether the savings of remaining useful lifetime outweighs the cost of relocations. Table 3 shows just 10 aircraft from the group of 41 for the duration of the study period. The values in the table, one through eight, represent

base locations. Each relocation is indicated by a shaded cell, so Table 3 illustrates that the actual aircraft in the study moved rather infrequently (0.1625 movements per aircraft per year).
Table 4 shows the same 10 aircraft but for the SmartBasing simulation. Visually, it is clear that there were more relocations requested by the SmartBasing software, ROTATE (0.4125 movements per aircraft per year). The aircraft chosen for Table 3 and Table 4 were the youngest aircraft in the retirement set, $\{AF{:}AO\}$, which happen to have been almost entirely from the active duty component of the USAF. Active duty aircraft relocate more frequently than their Air Reserve Component (Air Force Reserve, Air National Guard) counterparts, which is the reason that the results in Table 1 are more than double the 0.0701 movements per aircraft per year subgroup benchmark.

Table 3: Base assignments for a 10-aircraft sampling of historical data

		Year							
		2006	2007	2008	2009	2010	2011	2012	2013
Aircraft	AF	8	8	8	8	2	2	2	4
	AG	7	7	7	4	4	4	4	2
	AH	8	8	8	1	1	1	1	2
	AI	2	2	2	2	2	2	2	2
	AJ	3	2	2	2	2	2	2	2
	AK	5	5	5	5	5	5	5	2
	AL	8	8	8	8	2	2	2	2
	AM	2	2	2	2	2	2	2	6
	AN	8	8	8	8	2	2	2	2
	AO	7	7	4	4	6	6	6	6

Table 4: Base assignments for a 10-aircraft sampling using SmartBasing

		Year							
		2006	2007	2008	2009	2010	2011	2012	2013
Aircraft	AF	2	2	2	2	2	2	2	2
	AG	2	2	2	6	2	2	2	2
	AH	3	2	2	2	1	2	2	2
	AI	2	3	5	2	2	2	2	2
	AJ	5	2	2	8	2	2	2	2
	AK	8	2	2	5	2	2	2	2
	AL	3	2	2	4	2	2	2	4
	AM	2	2	2	2	2	2	2	2
	AN	2	8	2	2	5	2	1	4
	AO	3	2	2	2	2	2	2	2

During sensitivity analysis for this simulation, the minimum and maximum number of flight hours per aircraft per iteration were found to levy the greatest impact on simulation run time and solution status. ROTATE used a mixed-integer linear programming approach to the optimisation where base assignments were integer and flight hours were continuous variables. Greater ranges of acceptable flight hours (25-300 vice 50-150, for example) yielded faster solutions. For each aircraft, a matrix listing acceptable mission types and basing locations ensured that the aircraft possessed the correct mission equipment for the assignments requested. These mission and basing restrictions also increased the problem's run time but all problem run times were less than 60 seconds.

5 CONCLUSIONS

This work has shown that SmartBasing would have been a valid technique for managing the A-10 fleet prior to the retirement of 41 aircraft in 2013. SmartBasing is an active management technique that more closely manages the assignment of aircraft to bases and mission types. Using SmartBasing to more closely schedule aircraft utilisation could have expended more residual aircraft lifetime prior to retirement, resulting in savings of more than 1.88 full aircraft lifetimes or approximately 83 million USD for the 2013 A-10 retirement. The downsides to SmartBasing include the increased management costs and the increase in expenditures for relocating aircraft. SmartBasing moves aircraft multiples times more than the rate at which traditional fleets relocate aircraft.

This limited validation only evaluated one major aircraft fleet and only one retirement wave for that fleet. Future work in this field must test the efficacy of SmartBasing for fleets other than attack aircraft as well as extend these methods to a non-USAF fleet. The ideal SmartBasing validation would entail a multi-year study using a control group of aircraft and an experimental group in an active fleet. The experimental group would be employed in accordance with SmartBasing principles. The cost to operate each subgroup would be monitored, as would the utilisation over time.

The QDR does not specify which aircraft should be retired, leaving ample flexibility for fleet managers to cater their fleet's utilisation pattern to the strategic guidance. Ultimately, the role of an aircraft fleet in the overall defence strategy requires the fleet to be postured for wartime operations. That is the primary goal. However, providing combat capability for a longer lifecycle duration reduces the amortised lifecycle cost of fleet acquisition, despite an increase in relocation costs. SmartBasing is a technique worth serious consideration by fleet managers.

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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