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THESIS

OPTIMIZATION OF USMC HORNET INVENTORY

by

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OPTIMIZATION OF USMC HORNET INVENTORY

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The 2016 United States Marine Corps (USMC) Aviation Plan establishes the timeline to transition all F/A-18 Hornet squadrons to the F-35 Joint Strike Fighter. Ensuring Hornets can continue to support operational requirements during this transition is a challenge. In this thesis we address the management of the USMC Hornet inventory by developing, implementing, and testing an integer linear program called Hornet Assignment Sundown Model (HASM). HASM prescribes each individual Hornet's monthly squadron assignment, utilization, maintenance, storage, and retirement over its remaining service life while ensuring each squadron satisfies (to the extent possible) monthly flight hour requirements. To test HASM, this thesis develops forecasts of monthly squadron flight hour requirements and readiness rates from randomly and uniformly generated values using median performance with noise as inputs. Computational analysis using unclassified information on the USMC Hornet inventory demonstrate HASM's ability to illustrate the impact of management strategies on meeting future requirements. This thesis identifies future shortfalls and assesses requirement reductions to mitigate them so that resources can be applied to efficiently and effectively preserve the combat capability of the Marine Corps Air Ground Task Force.

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LIST OF ACRONYMS AND ABBREVIATIONS

ATARS	Advanced Tactical Airborne Reconnaissance System
AMSRR	Aviation Maintenance/Supply Readiness Report
CBR+	Center Barrel Replacement Plus
CNAF	Commander, Naval Air Forces
COMFRC	Commander, Fleet Readiness Centers
COSST	Carrier Optimal Strike-fighter Scheduling Tool
CVW	Carrier Airwing
DOD	Department of Defense
DON	Department of the Navy
FRC	Fleet Readiness Center
FRS	Fleet Replacement Squadron
FY	Fiscal Year
GAMS	Generalized Algebraic Modeling System
HASM	Hornet Assignment Sundown Model
HFH	High Flight Hour
HQMC	Headquarters Marine Corps
ILP	Integer Linear Program
IMC	Integrated Maintenance Concept
JSF	Joint Strike Fighter
MAG	Marine Air Group
MAGTF	Marine Air Ground Task Force
MCAS	Marine Corps Air Station
NAS	Naval Air Station
NAVAIR	Naval Air Systems Command
NAVMC	Navy Marine Corps
OPNAVINST	Office of the Chief of Naval Operations, Instruction
PHC	Planned Maintenance Interval + High Flight Hour
PMAI	Primary Mission Authorized Inventory
PMI	Planned Maintenance Interval
PSC	Planned Maintenance Interval + Service Life Extension

PTAI	Primary Training Authorized Inventory
RBA	Ready Basic Aircraft
SLE	Service Life Extension
SLEP	Service Life Extension Program
TACAIR	Tactical Air
TAT	Turnaround Time
T-2.0	Training and Readiness Level 2.0
USMC	United States Marine Corps
USN	United States Navy
VMFA(AW)	Marine Fighter Attack Squadron (All Weather)
VMFA	Marine Fighter Attack Squadron
VMFAT	Marine Fighter Attack Training Squadron

EXECUTIVE SUMMARY

The backbone of the tactical air component (TACAIR) of the Marine Air Ground Task Force (MAGTF) is the multi-role F/A-18 Hornet. This dynamic aircraft has played a major part in a variety of military actions over the last 30 years, and is now beyond its intended service life of 6,000 flight hours. Continuing to preserve the combat power of the MAGTF through proper management of the Hornet inventory is paramount while Hornet squadrons transition to the Joint Strike Fighter (JSF) over the next 14 years.

In this thesis, we address the management of the United States Marine Corps (USMC) Hornet inventory by developing, implementing, and testing an integer linear program called Hornet Assignment Sundown Model (HASM). HASM prescribes each individual Hornet's monthly squadron assignment, utilization, maintenance inductions, storage inductions, and retirement over its remaining service life while ensuring each squadron satisfies (to the extent possible) monthly flight hour requirements. To test HASM, this thesis develops forecasts of monthly squadron flight hour requirements and readiness rates using randomly and uniformly generated values from median performance with noise as inputs. HASM connects the monthly inventory management of USMC Hornets to the transition timeline and goals published in the 2016 Marine Aviation Plan. Specifically, it details a strategy to preserve (to the extent possible) the Hornet combat capability throughout the sundown phase while sustaining a minimum monthly capability based on Training and Readiness Level 2.0 (T-2.0) and excursions based on this requirement.

This research identifies a resource gap that emerges as the Hornet inventory reaches a tipping point of asset availability and requirement. Scheduled depot maintenance results in insufficient Hornets to sustain the demand of the remaining Hornet squadrons in 2023 and beyond.

To remedy this shortfall, HASM explores the impact of mitigations. HASM reduces the T-2.0 monthly flight hour requirement by 21% for each squadron. This reduction leads to a shorter period of insufficient Hornets that begins later in the planning

horizon. Separately, HASM also reduces the Primary Mission Authorized Inventory (PMAI) and Primary Training Authorized Inventory (PTAI) by 17%. This results in dropping the number of Hornets assigned from 12 down to 10 at each squadron and from 43 to 36 at the Fleet Replacement Squadron (FRS). Reducing the number of Hornets at each squadron places an increased utilization on those in the operational rotation and causes the Hornet deficit to begin two years earlier. However, because more aircraft are cycled through service life extensions, the impact is not as dramatic as in the previous scenarios. In both cases a resource gap still exists, but these insights provide inventory planners the ability to make informed risk-based decisions.

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I. INTRODUCTION

A. OVERVIEW

The United States Marine Corps (USMC) has the challenge of continuing to provide aviation support for a wide range of contingency operations while simultaneously modernizing its aviation inventory of aging legacy platforms. The enduring requirement of training and deploying combat equipped squadrons necessitates the use of legacy aircraft to bridge the gap until follow-on replacements are procured. In particular, the fighter-attack inventory of 274 legacy F/A-18 Hornets, shown in Figure 1, requires careful management to ensure that the USMC can preserve combat capability while the service phases out, or *sundowns*, these aircraft.

Over the last six years, the USMC Hornet inventory flew more than 240,000 flight hours for training and support (Aviation Maintenance/Supply Readiness Report [AMSRR], 2010–2015), despite the fact that the vast majority of these Hornets are beyond their originally designed service life. The 2016 Marine Aviation Plan (USMC 2016) outlines an overarching strategy to replace all of the legacy Hornet aircraft in its inventory beginning in 2016 by 2030. This thesis introduces Hornet Assignment Sundown Model (HASM), an integer linear program (ILP) that prescribes each Hornet’s monthly squadron assignment, flight hour utilization, maintenance inductions, storage inductions, and retirement for the entire Hornet inventory to best achieve flight hour requirements and transition timelines over a 14-year planning horizon.

HASM connects the monthly inventory management of USMC Hornets to the transition timeline and goals published in the 2016 Marine Aviation Plan. Specifically, it details the strategy to preserve, to the extent possible, the Hornet combat capability throughout the sundown phase while sustaining Training and Readiness Level 2.0 (T-2.0) or other levels.



Two USMC F/A-18C Hornets belonging to the “Red Devils” of Marine Fighter Attack Squadron 232.

Figure 1. USMC F/A-18 Hornet. Source: Seck (2015).

B. BACKGROUND

The life cycle of the F/A-18 Hornet follows the same path as any other Department of Defense (DOD) weapon system, with four major phases as outlined by Mislick and Nussbaum (2015) (Figure 2). First, the research and development phase of the Hornet began in the early 1970s when the DOD initiated the development of a new generation fighter attack aircraft to replace the aging Douglas A-4 Skyhawk, A-7 Corsair II, and McDonnell Douglas F-4 Phantom IIs. It was during this phase that initial testing and evaluation of the Hornet occurred. Once evaluators deemed a stable and mature Hornet aircraft prototype acceptable for the design criteria, the production and procurement phase began. In 1984, the DOD contracted with McDonnell Douglas for full rate production of the aircraft and introduced it into the service of both the United States Navy (USN) and USMC. The operating service life phase began once the new Hornets were integrated into the operating forces. The Hornet was first deployed to combat against Libyan air defenses during Operation Prairie Fire in 1986. As technology changed

during the following decades, capital investment occurred to modernize and upgrade the Hornet (Jenkins 2000).

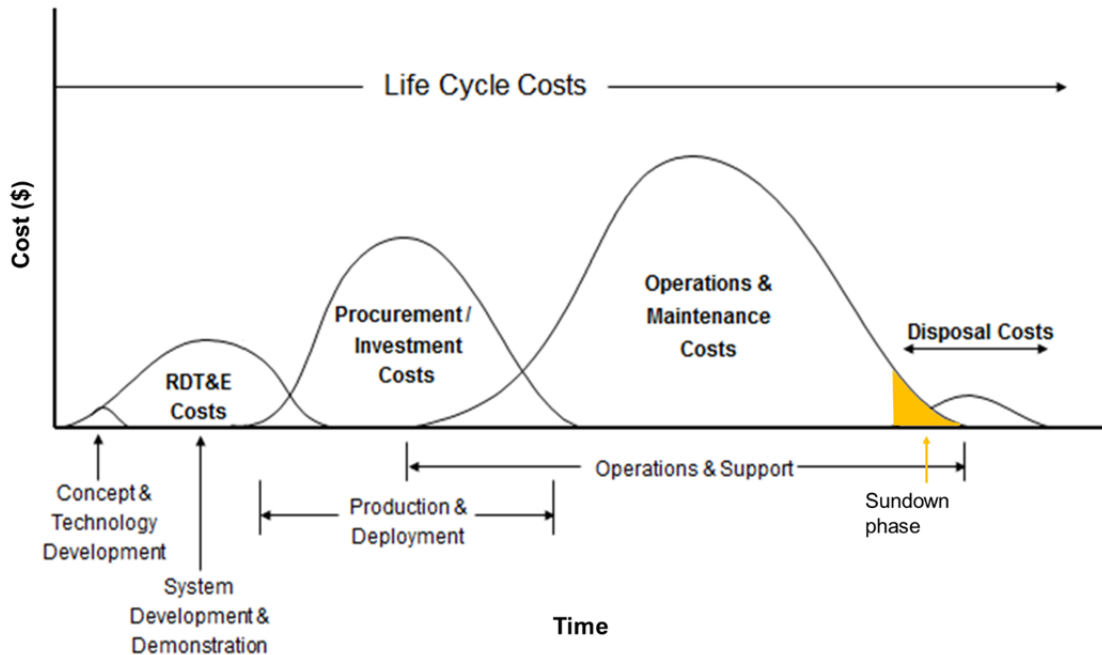


Figure 2. Complete Life Cycle of DOD Weapon System. Adapted from Mislick and Nussbaum (2015).

The Hornet continued to be a workhorse for both the USN and the USMC into the early 2000s when the first aircraft reached the end of their operating lives. The sundown phase began as these older Hornets in the USN inventory were retired. As the USN discussed the future of their Hornet inventory three distinct alternatives emerged: procure new legacy F/A-18 Hornets, purchase the F/A-18 Super Hornet, or wait to procure the new Joint Strike Fighter (JSF). They elected to purchase F/A-18 Super Hornets as a replacement for the legacy F/A-18 Hornet. However, the USMC elected to continue to fly its legacy Hornets and wait to procure the new JSF. Several factors led the USMC to make this decision. First, the procurement cost of a Super Hornet was at the time estimated at 75% of a new JSF. Also, the planned procurement schedule and fielding of the JSF made service extensions and new Hornet procurement seem unnecessary. The promised capability increases of a fifth generation fighter coupled with the low initial

cost estimates per aircraft proved pivotal in this decision. The USMC decided to extend the service life of its Hornet fleet during the sundown phase instead of retiring and disposing of them. This decision resulted in the USMC spending several million dollars per legacy Hornet to repair, refurbish, and, modernize the inventory in order to continue operating them instead of procuring new F/A-18 Super Hornets (Cooper 2011).

Since its introduction in the USMC aviation fleet in the early 1980s, the F/A-18 Hornet delivered exceptional performance as a multi-role fighter and attack aircraft for both expeditionary and carrier-based squadrons (Jenkins 2000). As a fighter aircraft, the Hornet provides fighter escort and intercept capabilities. As an attack aircraft, the Hornet gives the USMC the ability to project force through close air support and deep strike capability.

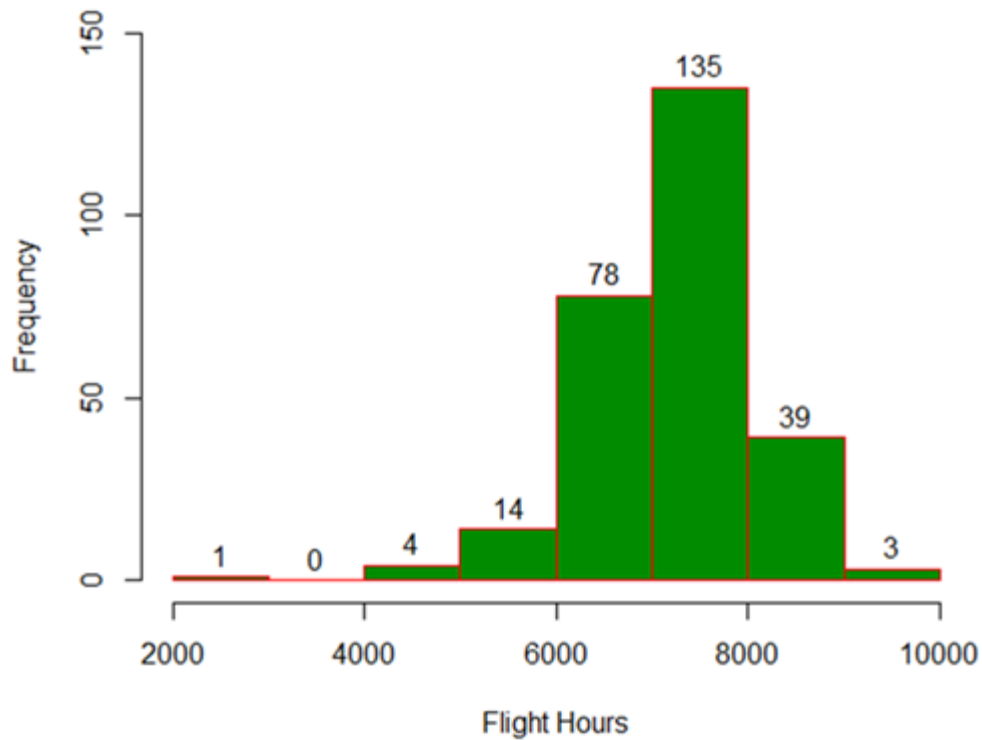
The USMC Hornet inventory contains all four variants of the F/A-18 Hornet, with each type of aircraft fulfilling a different role within the fleet. The F/A-18A and F/A-18C Hornets are single seat variants that replaced the McDonnell Douglas F-4 Phantom II aircraft used by Marine Fighter Attack (VMFA) Squadrons from 1962 until 1992, when the last squadron transitioned. The F/A-18D Hornets replaced the Grumman A-6 Intruders used by Marine Fighter Attack (All Weather) (VMFA(AW)) Squadrons and provide attack, tactical air control, forward air control, and reconnaissance capability. The F/A-18B is a dual seat training aircraft used exclusively by the Sharpshooters of Marine Fighter Attack Training Squadron 101 (VMFAT-101), to train replacement aircrew for the other operational squadrons. The USMC prefers to equip a squadron with all of the same type of Hornets, for maintenance and tactical reasons (Jenkins 2000). Table 1 lists the squadron names and types of Hornet employed.

Table 1. Name and Type of Each Squadron. Adapted from USMC (2016).

Squadron Designation	Squadron Name	Hornet Type
VMFA-112	<i>Cowboys</i>	F/A-18A
VMFA-115	<i>Silver Eagles</i>	F/A-18A
VMFA-122	<i>Werewolves</i>	F/A-18C
VMFA-232	<i>Red Devils</i>	F/A-18C
VMFA-251	<i>Thunderbolts</i>	F/A-18C
VMFA-312	<i>Checkerboard</i>	F/A-18C
VMFA-314	<i>Black Knights</i>	F/A-18A
VMFA-323	<i>Death Rattlers</i>	F/A-18C
VMFA(AW)-224	<i>Bengals</i>	F/A-18D
VMFA(AW)-225	<i>Vikings</i>	F/A-18D
VMFA(AW)-242	<i>Bats</i>	F/A-18D
VMFA(AW)-533	<i>Hawks</i>	F/A-18D
VMFAT-101	<i>Sharpshooters</i>	F/A-18 A-D

C. USMC HORNET INVENTORY

The USMC currently has 274 legacy F/A-18 Hornet aircraft of four distinct model types that comprise the backbone of the tactical air (TACAIR) component of the Marine Air Ground Task Force (MAGTF). After more than 30 years of continued service, the vast majority of these legacy USMC Hornets (89%) have flown beyond their original designed service life limitation of 6,000 flight hours per aircraft (NAVAIR 2016a). Figure 3 highlights the current service life picture of the inventory. A service life extension program (SLEP) can add up to 4,000 additional flight hours for some of these Hornets. The 2016 Marine Aviation Plan incorporates the SLEP for the Hornet in its TACAIR Transition Plan as the USMC looks to continue to fly this legacy Hornet fleet until fiscal year (FY) 2030 when the last Hornet squadron completes the transition to the new F-35 JSF (USMC 2016).



Note that 245 of the 274 (89%) of the legacy USMC Hornets are beyond the originally designed service life of 6,000 flight hours.

Figure 3. Histogram of Flight Hours per Hornet Aircraft. Adapted from NAVAIR (2016a).

There are currently 11 tactical active duty squadrons, one reserve squadron, and one fleet replacement squadron (FRS) within the USMC that employ the legacy F/A-18 Hornet aircraft (USMC 2016). These squadrons are located on both coasts of the United States, and there is also a forward deployed squadron based in Japan (Figure 4). Squadrons that are collocated at a Marine Corps Air Station (MCAS) comprise Marine Air Groups (MAGs). Over the next 14 years, these squadrons will either transition to the F-35 Lightning II JSF or be decommissioned as a part of force structure realignment based on the 2016 Marine Aviation Plan.

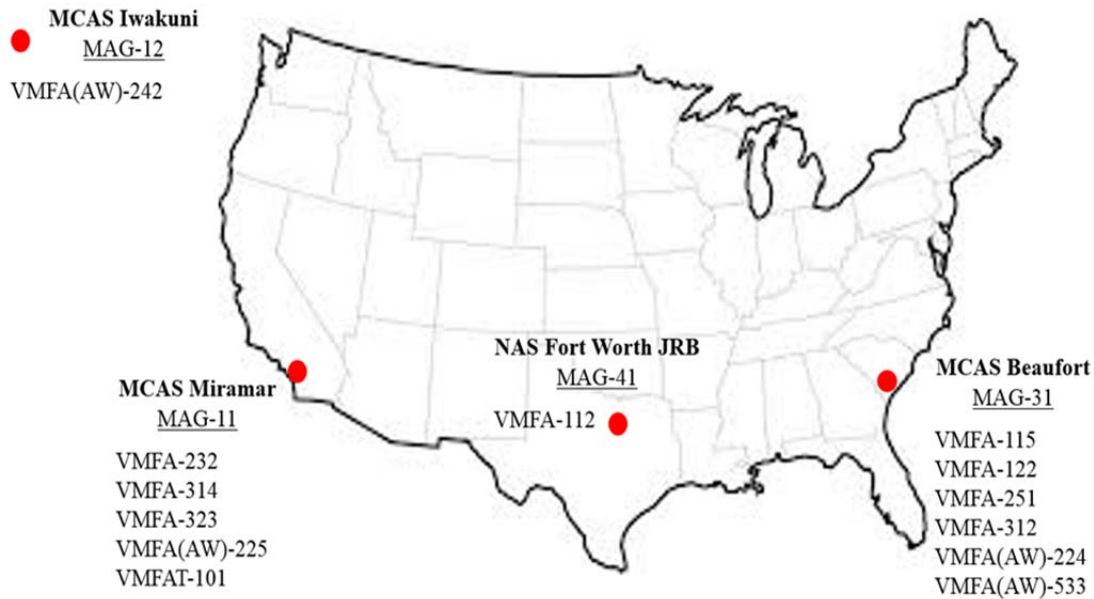
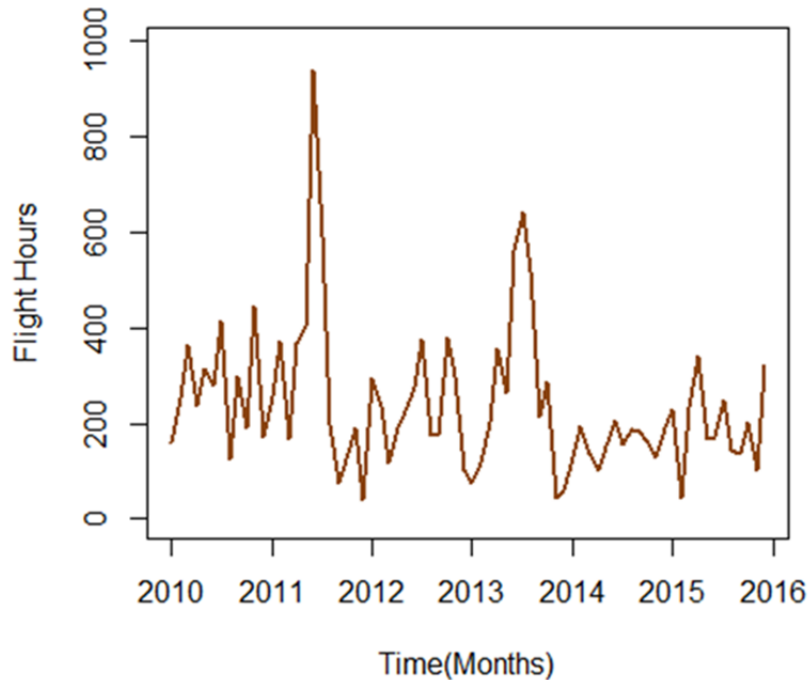


Figure 4. Location of All USMC Hornet Squadrons and MAGs. Adapted from Clipartbest (2016).

D. FLIGHT HOUR UTILIZATION AND READINESS RATES

Typically, a MAG rotates individual squadrons through a workup cycle, an operation deployment onboard an aircraft carrier, part of the Unit Deployment Program, or an expeditionary deployment, and then a sustainment period. Each Hornet squadron decides the level of utilization of each of its aircraft in order to satisfy its total monthly flight hour requirement. This requirement encompasses both training sorties and sorties in support of combat operations. To illustrate the flight hour demand, the chart in Figure 5 shows the total flight hours of the “Death Rattlers” of VMFA-323 from January 1, 2010, through December 31, 2015. The total flight hours over this six year span for the Death Rattlers was 17,443 hours with a monthly minimum of 39 hours and a maximum of 938 hours (AMSRR 2010–2015).



This plot shows the total monthly flight hours for F/A-18C Hornets assigned to VMFA-323. The average total flight hours over this six year span was 242 hours with a minimum of 39 hours and a maximum of 938 hours.

Figure 5. Monthly Total Flight Hours for VMFA-323. Adapted from AMSRR (2010–2015).

In order to properly execute flight hours each Hornet squadron must conduct organizational level maintenance, which includes scheduled and unscheduled activities on the aircraft assigned. These activities range from daily corrosion prevention to major engine overhaul or replacement. It is nearly impossible to keep all of the aircraft assigned to a squadron in peak operating condition continuously (CNAF 2009).

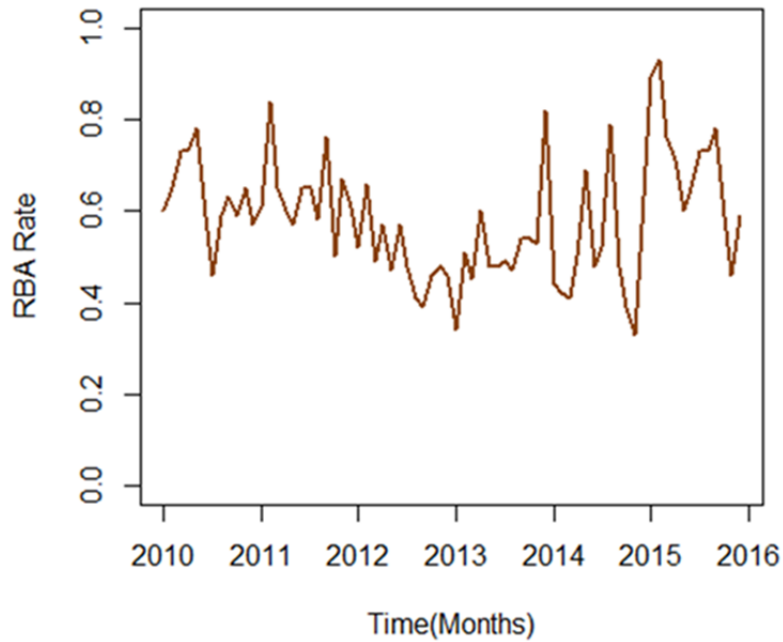
Based on anticipated scheduled and unscheduled maintenance, the USMC targets a specific level of readiness across each Hornet type in its inventory. Table 2 illustrates these goals as a percentage of the inventory (CNAF 2009).

Table 2. USMC Hornet Readiness Goals. Adapted from CNAF (2009).

USMC Hornet Type	Mission Capable Goals
F/A-18A	75%
F/A-18B	60%
F/A-18C	75%
F/A-18D	75%

As a result, only a certain percentage of the aircraft assigned to an operational squadron may be in the minimum state of materiel readiness and configuration required to fly a training or operational sortie at any given time. The DOD refers to this percentage as ready basic aircraft (RBA) rate. A squadron's monthly RBA rate indicates the materiel health of the inventory of its aircraft and provides a metric for assessing the effectiveness of that squadron's maintenance department to properly maintain their Hornets.

For example, the monthly average RBA rates for the Death Rattlers of VMFA-323 from January 1, 2010, through December 31, 2015, is shown in Figure 6. The monthly average RBA over this six-year span for the Death Rattlers was 57% with a minimum of 33% and a maximum of 93% (AMSRR 2010–2015). Figure 7 shows Sailors and Marines conducting preflight inspections to ensure that the aircraft are ready for the morning flight schedule.



This plot shows the average monthly RBA for F/A-18C Hornets assigned to VMFA-323. The average RBA rate over this six year span was 57% with a minimum of 33% and a maximum of 93%.

Figure 6. Average Monthly RBA for VMFA-323. Adapted from AMSRR (2010–2015).



The Marines and Sailors of VMFAT-101 prepare 12 F/A-18 Hornets for launch in support of training missions while on detachment at MCAS Yuma in January 2014.

Figure 7. VMFAT-101 Sharpshooters Morning Flightline.

In addition to performing all the other maintenance functions required for continuing flight operations, aircraft are sometimes transferred from one squadron to another. Transferring and accepting an aircraft from one squadron to another requires additional maintenance actions and functional check flights by maintainers of both the transferring and accepting squadrons. This process places an additional burden on both the transferring and accepting units' maintenance departments by requiring the investment of hundreds of man-hours to complete the transfer and acceptance. The total time to complete all required tasks can exceed four working days, although some portions can be waived or compressed, especially if both the accepting and transferring squadrons are collocated and conduct a joint acceptance transfer. However, the process can take significantly longer if the inspections uncover problems that require unscheduled maintenance to be performed. For these reasons, inventory planners seek to minimize the number of transfers between Hornet squadrons.

E. DEPOT MAINTENANCE

As a consequence of the high demands for Hornet flight hours, The USMC Hornet inventory requires a steady flow of in-depth depot level service repairs and modifications. The scheduled depot events fall into four broad categories: planned maintenance interval (PMI), initial service life extension (SLE), high flight hour (HFH) extension, or a combination of PMI with either SLE (PSC) or HFH (PHC). These depot events take place at one of the two major Fleet Readiness Centers (FRCs) located at either Naval Air Station (NAS) North Island, California, or Cecil Field, Florida. These events vary in length depending on the materiel condition of the aircraft, the availability of replacement parts and engineering depositions. Part of the depot rework facility at FRC Southwest located at NAS North Island is shown in Figure 8.



Naval Air Systems Command engineers and artisans are working on depot modifications for SLE on legacy F/A-18 Hornets at FRC Southwest at NAS North Island.

Figure 8. F/A-18 Depot Maintenance at NAS North Island.
Source: Myers (2015).

The Integrated Maintenance Concept (IMC) includes a unique set of depot level service repairs for each type of aircraft. Each IMC event includes paint and corrosion evaluation, limited life component replacement and technical directive modifications and upgrades that depot artisans perform. The F/A-18 IMC has two separate calendar driven inspections or PMI events. PMI 1 is performed at an FRC while PMI 2 can be performed at the FRC or with depot artisans at a satellite repair facility. These PMI events occur consecutively at four year intervals for F/A-18 aircraft that deploy aboard aircraft carriers and at six year intervals for aircraft that deploy as expeditionary based. This means that a complete cycle, which includes IMC of both PMI 1 and PMI 2, should occur every eight calendar years for sea-based Hornets and every 12 calendar years for land based Hornets (OPNAVINST 3110.11U 2013).

In addition to the lost availability in the operational rotation, the cost of inducting Hornets for PMI events is not trivial. It costs approximately \$1.1 million to complete a

PMI event on a legacy F/A-18 Hornet.¹ These costs increase if depot artisans note additional maintenance discrepancies during inspection (NAVAIR 2016b).

Independent of the Hornet PMI events, other scheduled depot events comprise the Hornet SLE. These events allow Hornets to continue flying beyond their original maximum service life of 6,000 flight hours. SLE requires several major airframe components and sections must be inspected and either replaced or modified. The Center Barrel Replacement Plus (CBR+) program replaces the critical center section of the Hornet's fuselage that bears the stress of supporting the wing structures and the landing gear. In addition to CBR+, another series of inspections that focus on both inner and outer wing structures must also be completed to ensure that an aircraft can fly up to 8,000 flight hours. Yet another round of engineering change proposals, airframe inspections, and modifications can further extend a Hornet's service life up to 10,000 flight hours (USMC 2016).

F. MARINE CORPS AVIATION PLAN

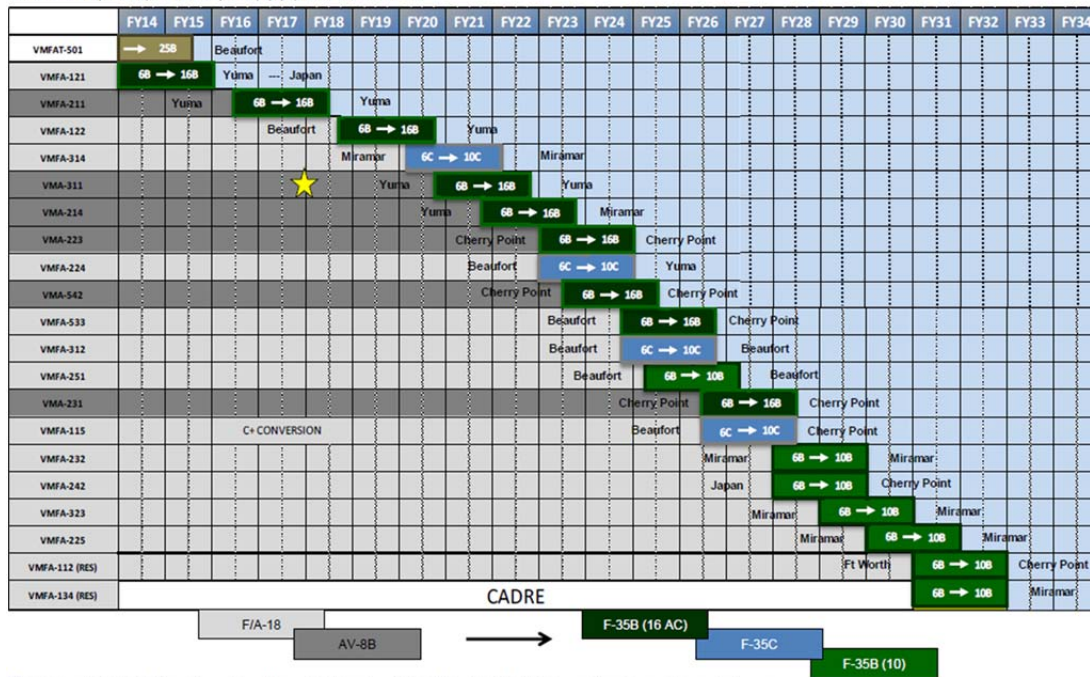
The 2016 Marine Aviation Plan (USMC 2016) outlines the strategic guidance for the air component of the USMC, in order to ensure the unique capabilities that are essential for the MAGTF to continue to fulfill its role in the Department of the Navy (DON). Included in this guidance is TACAIR 2030, which details the latest plan for the USMC's TACAIR transition from AV-8B Harriers and F/A-18 Hornets to the JSF. In particular, this plan establishes the phasing out of seven Harrier squadrons by FY 2025 and all 13 Hornet squadrons by FY 2030. This plan incorporates a procurement of 353 F-35Bs and 67 F-35Cs for a total compliment of 420 JSF aircraft to replace all of the legacy aircraft in the TACAIR inventory by 2030 (USMC 2016). This transition plan, shown in Figure 9 and the Hornet requirement shown in Figure 10, highlight the USMC's need to continue to utilize the legacy Hornet.

¹ FRC Southwest PMI 1: (9,907 hours * \$77 estimated labor cost + \$323,045 materiel cost)

CURRENT FORCE PAA:
 7 AC VMFA SQDN x 12 F/A-18 a++/C
 4 AC VMFA(AW) SQDN x 12 F/A-18D
 1 AC VMFA SQDN x 16 F-35B
 1 RC VMFA SQDN x 12 F/A-18A++
 6 AC VMFA SQDN x 14 AV-8B

1 FRS x 26 AV-8B/TAV-8B, 1 FRS x 36 F/A-18A/B/C/D, 1 FRS SQDN x 16 F-35B

FORCE GOAL PAA:
 9 AC VMFA SQDN x 16 F-35B
 5 AC VMFA SQDN x 10 F-35B
 4 AC VMFA SQDN x 10 F-35C
 2 RC VMFA SQDN x 10 F-35B
 2 FRS SQDN x 25 F-35B

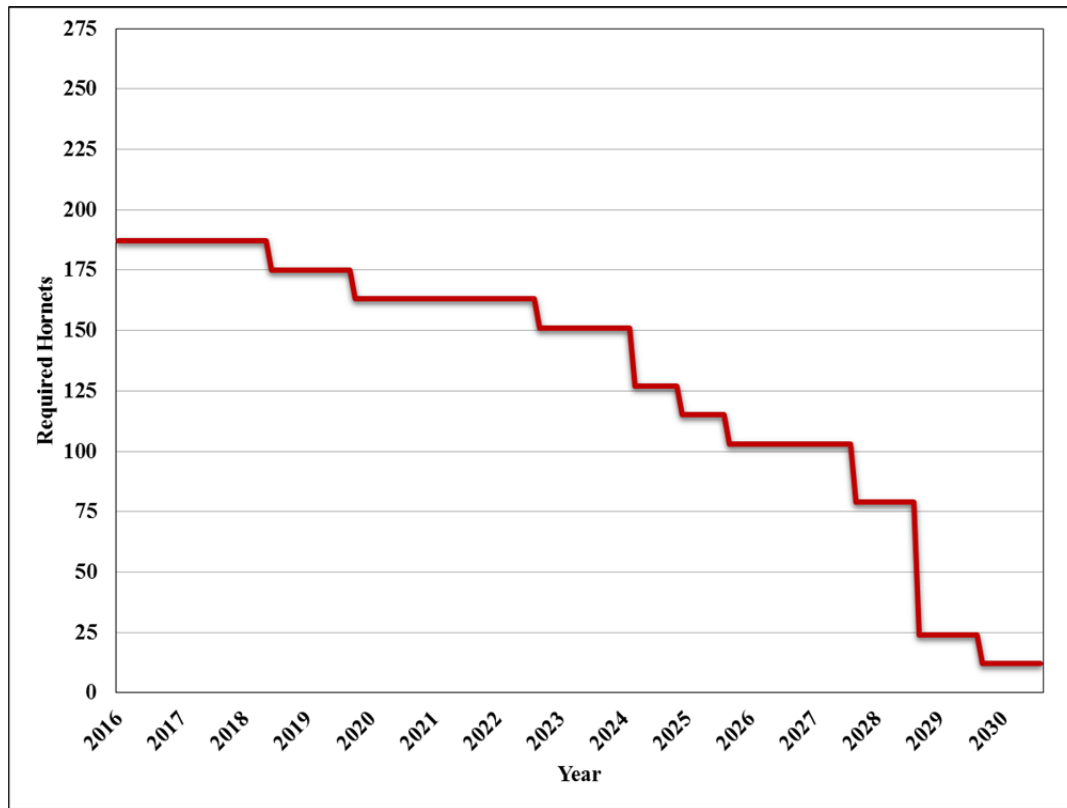


★ Decision Point: TACAIR transition order will be updated based on F/A-18 A-D and AV-8B flight-line readiness to maximize combat power

This figure shows the current transition plan to replace the legacy Hornets and AV-B Harriers with F-35 JSFs. The next Hornet squadron slated for conversion to the JSF is VMFA-122, which will transition in the second half of FY 18.

Figure 9. TACAIR Legacy to JSF Transition Plan.
 Source: USMC (2016, p. 38).

In Figure 10, a more detailed breakdown shows the number of Hornets required in the operational rotation to meet the requirements of the Primary Mission Aircraft Inventory (PMAI) and the Primary Training Aircraft Inventory (PTAI). PMAI calls for 12 Hornets for each of the operational squadrons. PTAI requires 43 Hornets for the FRS to train replacement aircrew. In 2016, this requirement totals 187 Hornets [(12*12) + 43]. In 2018, this requirement drops to 175 Hornets when VMFA-122 transitions to the JSF. It is important to note that these numbers do not include aircraft that are out of the operational rotation, such as those at depot level maintenance (USMC 2016).



This figure illustrates the required number of Hornets in the operational rotation per the transition plan in Figure 9.

Figure 10. Number of Hornets Required in the Operational Rotation.
Source: USMC (2016).

G. CURRENT STATUS OF THE USMC F/A-18 INVENTORY

Currently, the USMC is facing a shortfall of more than 40 F/A-18 Hornet aircraft for the operational rotations of its 13 Hornet squadrons. Largely, this shortfall is due to fleet wide issues of depot level maintenance, both scheduled and unscheduled (USMC 2016). Figure 11 shows the current disposition of the 274 legacy F/A-18 Hornets (NAVAIR 2016a), with more than 54% of the Hornet fleet inducted or awaiting depot-level maintenance. These aircraft are not currently available in the operational rotation for training or deployment by USMC Hornet squadrons. This backlog of aircraft represents a very serious threat to ensuring that Hornet squadrons can sustain the current levels of training and deployment necessary for contingency operations. USMC Hornet squadrons have 67% of the authorized number of aircraft assigned to them (USMC 2016).

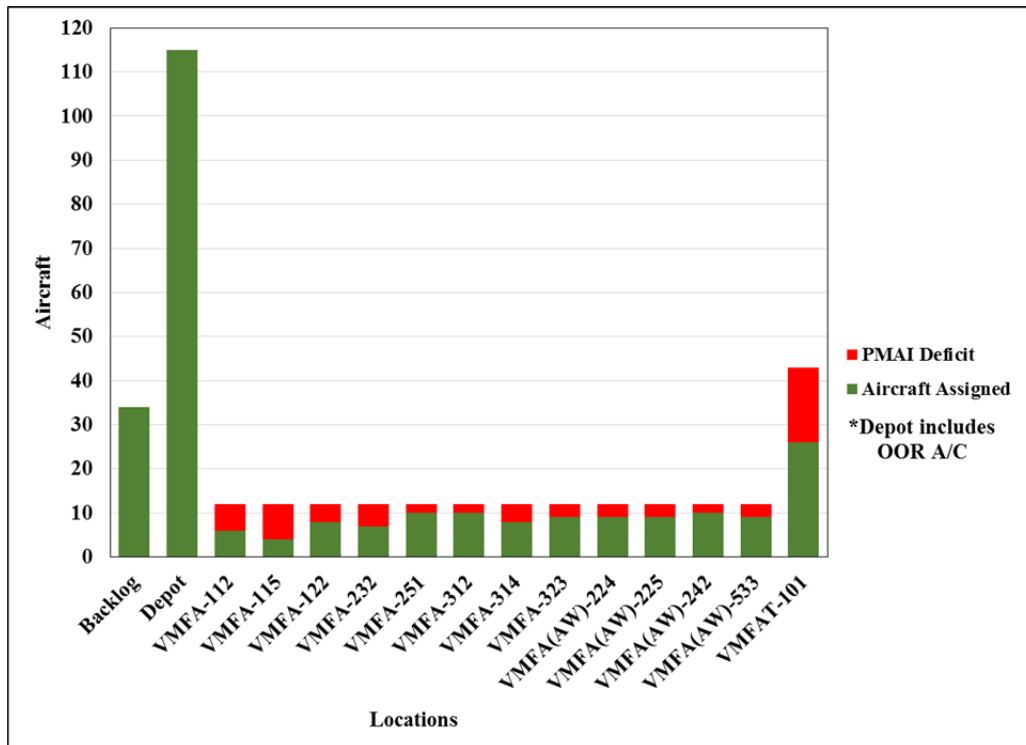


Figure 11. Legacy F/A-18 Hornet Fleet by Locations.
Adapted from NAVAIR (2016a).

Further compounding this shortfall in the operational rotation is the alarming downward trend in RBA rate of aircraft in the fleet. The aging airframe falls victim to unscheduled organizational level maintenance at increasing rates. Figure 12 shows the downward trend of readiness for each type of Hornet. USMC Hornet squadrons' maintenance departments struggle to keep pace with the increased demands on fewer and less healthy Hornets. The lack of readily available spare parts forces the cannibalizations of some Hornets to continue to fly others exaggerating this problem. The yearly averages do not tell the entire story, as the daily struggle to maintain flyable aircraft at the squadron level swings from day to day with a high level of variability. For example, on April 20, 2016, only 30% of the entire USMC inventory was RBA (Schogol 2016). As operational squadrons cope with fewer Hornets in worse materiel condition, minimizing the lost time Hornets are out of the operational rotation for scheduled maintenance becomes vital.

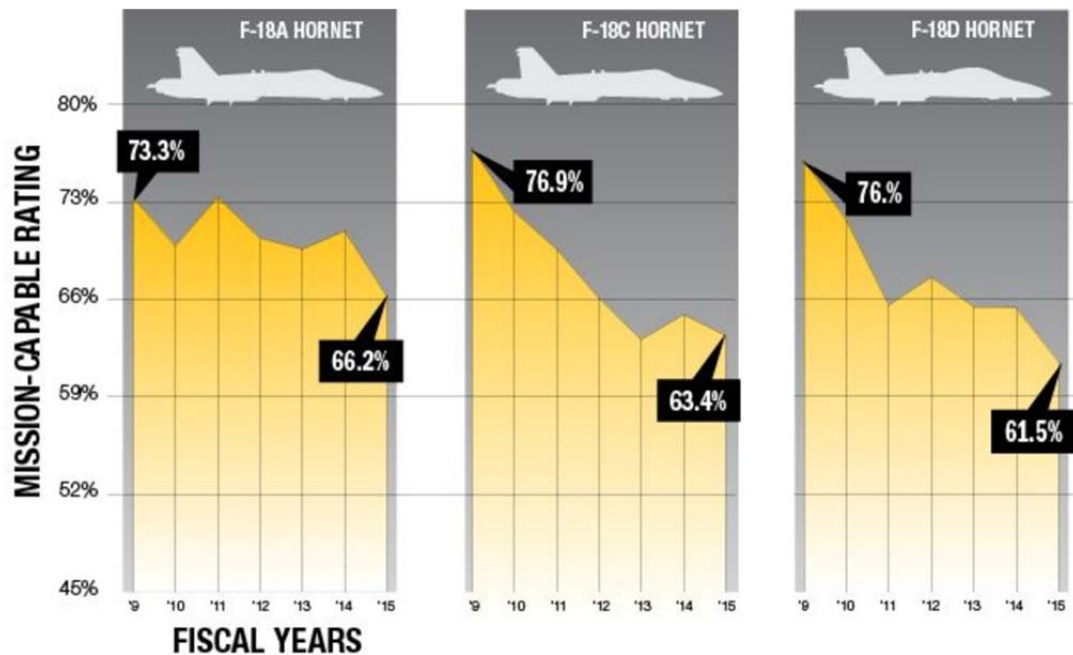


Figure 12. Average Mission Capability Rating by USMC F/A-18 Hornet Type.
Adapted from Schogol (2016).

H. REASONS FOR THIS STUDY

Based on the required number of flight hours and the current number of available flight hours, there is a need for almost all of the Hornets currently in the operational rotation to undergo a service life extension to 10,000 flight hours. Assuming that every Hornet squadron flies the minimum number of flight hours required to maintain pilot proficiency through the transition prescribed in the 2016 Marine Aviation Plan, this requires 454,860 flight hours (Commandant of the Marine Corps, 2009)². If every Hornet currently in the operational rotation, not including those undergoing depot events at a FRC, receives a service life extension to 10,000 flight hours, the total flight hours remaining on all aircraft would be 489,665 flight hours. The minimum number of hours to maintain proficiency requires flying 97% (454,860/489,665) of the available hours created by the 10,000 hour extended service life limit.

² This assumption comes from the standard Table of Organization of F/A-18 pilots in squadrons flying the minimum number of monthly flight hours per the *F/A-18 Training and Readiness Manual* and continued average pilot production at VMFAT-101.

Depot events take significant time to complete, so they must be well planned to avoid inventory shortfalls. For example, Hornets inducted for stand-alone HFH are out of the rotation for 24 months or more. A high workload and competition for shared resources can result in additional delays in turnaround time (TAT) from FRCs. Based on historical data, the median TAT is 511 days from induction to completion of the HFH series of inspections to extend a Hornet's service life beyond 8,000 flight hours (COMFRC 2016).³ Completing the necessary extensions to prolong the service life of all the Hornets in the current operational rotation requires removing these Hornets from the operational squadrons for a cumulating total of 137 aircraft years of lost Hornet availability (NAVAIR 2016a).

I. THESIS SCOPE AND ORGANIZATION

Our optimization model, HASM, prescribes each individual Hornet's monthly squadron assignment, utilization, maintenance, storage, and retirement over its remaining service life while ensuring each squadron satisfies, to the extent possible, monthly flight hour requirements. HASM allows inventory management strategies to be evaluated and compared in the context of penalties for failing to meet required flight hours and maintenance windows. In particular, HASM provides an analytic framework to inform decision makers on the impact of changes to any aircraft assignment and maintenance. Scenario analysis with HASM provides inventory managers greater resolution to see what effects changes in inputs have on a particular strategy, such as the 2016 Marine Aviation Plan.

This thesis consists of five chapters. Chapter I contains an introduction to the problem and the motivation for addressing it. Chapter II provides background information and a literature review of related research. Chapter III describes the assumptions that represent the foundation of the ILP and presents the HASM formulation. Chapter IV discusses several analyses made with the model. Finally, Chapter V offers conclusions and recommendations for follow-on research related to this work.

³ 511 days is the median turnaround time based on an inventory report pulled by Commander, Fleet Readiness Centers (COMFRC) of the Naval Air Systems Command, Aviation Maintenance and Material Department (N42) on February 25, 2016.

II. LITERATURE REVIEW

Although there exists a rich body of operations research literature that relates to HASM, there are no previous works that incorporate all of the same aspects as this research. Most related research falls into the broad categories of equipment replacement, procurement and retirement, or military aircraft scheduling. In addition to these broad categories, one specific work contains a blending of many of the key concepts into a single “Tail Assignment” problem that is similar to the Hornet sundown assignment problem.

A. PREVIOUS WORK IN EQUIPMENT REPLACEMENT

Research in equipment replacement often aims at identifying the optimal time to replace or phase out an obsolete piece of equipment. Solutions to equipment replacement problems typically look at modeling the overall life cycle of equipment replacement from procurement to retirement, or what is commonly called “cradle to grave.”

In 1955, R. E. Bellman discussed an analytical solution for equipment replacement through a replacement-decision policy. In particular, Bellman (1955) showed that the best age at which an old piece of equipment should be replaced can be determined analytically. His solution incorporated a discount factor that ensured the costs associated with future decisions were scaled appropriately. This prevented infinite returns and costs and allowed the problem to be solved in closed form. This work provides the foundation for determining which time period is best to replace an aging or obsolete piece of equipment. Knowing at what point to replace a piece of equipment in its life cycle answers an important capital management question. In his research, Bellman looked at the entire life cycle of a piece of arbitrary equipment; by contrast this thesis focuses on the management of assets during the critical sundown period, where the time of replacement has already been established. The entire life cycle, from “cradle to grave,” of a DOD acquisition process of a weapon system, such as the F/A-18 Hornet, is broken up into major phases, as shown in Figure 2. Bellman’s work looks at the entire life cycle; in this work, the area of consideration is the ending of the F/A-18 Hornet’s operating life.

Sheler and Cooper (1971) built on Bellman's work and used statistical analysis to determine optimal repair and retirement policies for naval aircraft, focusing on the F-4 Phantom II. Specifically, they were interested in identifying solutions for the age at which the F-4A should be replaced by the F-4J. Also, which maintenance schedule best facilitated this transition. The objective of their work was minimizing the costs of aircraft operations over a finite planning horizon. They concluded that older naval aircraft require more (in terms of man-hours and funding) to maintain, are not as frequently mission capable while assigned in the fleet, and require additional depot level repairs more often than aircraft with fewer flight hours. In addition, they advocate against a fixed tour length for aircraft in deploying squadrons and instead suggest that aircraft should be individually managed for rotation in the fleet and sent to retirement based on specific criteria. While their research used a slightly different approach than Bellman, both works provided optimal times to replacement. The research presented in this thesis prescribes based on the individual management of each Hornet in the fleet when the decision to replace has already been made. This work also incorporates a statistical approach to forecasting requirements and readiness in future time periods in the planning horizon and uses this information to individually prescribe rotations for each Hornet.

B. PREVIOUS WORK IN PROCUREMENT AND RETIREMENT

Another area of research focused on capital investment and determining whether a service life extension is more advantageous than retirement and procurement of a replacement. The "Phoenix" model (Brown, Clemence, Teufert, and Wood 1991) assessed options for scheduling the procurement and retirement of helicopters for the United States Army. Across the 25 year time horizon of the model, they looked at different types of helicopters and focused on decisions relating to the retirement, modernization, or SLEP before each type reached its maximum useful service life. In their model, they assumed helicopter usage was a function of age and prescribed a regular annual number of flight hours to each airframe. Their work allowed the Army to evaluate dozens of possible helicopter force-planning scenarios without spending significant amounts of time manually calculating solutions. Examining the ability to extend the service life of aircraft is an important concept that is incorporated in this work. However,

in this case, the decision has already been made to extend the service life of the Hornet fleet, and the ILP specifically prescribes which Hornets will receive additional extensions.

Zabinski (2015) built on the framework of Garcia (2001) and Field (1999) by adding further refinements onto a force structure U.S. Navy capital investment planning aid which assist planners in making procurement and modernization decisions for aircraft on a yearly basis to meet established mission criteria within budgetary constraints. Much like the “Phoenix” model, an ILP approach is utilized to create yearly procurement, modernization, and retirement decisions over a time horizon while minimizing the penalties associated with violations of specified constraints. This thesis also recommends a schedule of asset management utilizing an ILP approach to generate prescriptions each month for assignment, SLEP, and retirement of individual Hornet aircraft confined by the decisions previously made in earlier phases of that Hornet’s life cycle.

C. PREVIOUS WORK IN OPTIMIZING MILITARY AIRCRAFT SCHEDULING

Optimizing the scheduling of maintenance activities is a topic of particular importance to military aviation planners as they grapple with maintaining the necessary aircraft in the operating forces for deployments and training while ensuring that inventories are cycled through required maintenance inductions. Avoiding the bottleneck of maintenance backlogs is a primary concern. Pippin (1998) modeled monthly flight hour allocations for Army helicopter battalions consisting of UH-60 Blackhawks in an effort to effectively manage readiness and deployability of helicopter battalions. He used actual flight data from a Blackhawk battalion, including both normal flight operations and those in support of contingency operations. His models showed that a steady-state sequencing of helicopters into maintenance periods eliminated maintenance backlogs and generated a fixed number of aircraft that were constantly available for operations.

In work related to Pippin’s research of United States Army helicopter maintenance, Baker (2000) tackled the issue of scheduling EA-6B Prowler aircraft for depot maintenance activities while adhering to the required number of aircraft for

operational use. He introduced an optimization based on an ILP decision support tool to provide a monthly schedule for depot events. This schedule ultimately minimizes the time that aircraft are out of the operating forces and reduces the backlog at depot facilities. Similarly, this research takes into account the sequencing of aircraft into scheduled depot maintenance events and maintain a constant pool of Hornets available to the operating forces for both training and deployment, while mitigating the cascading effects of depot maintenance backlogs.

Marlow and Dell (2015) present an ILP for managing a fleet of naval helicopters where the fleet must meet minimum monthly and annual flight hour requirements for squadrons that are both embarked aboard naval ships and ashore. This ILP plans both phase maintenance and depot-level maintenance much like Pippin (1998). They enforce a balance of flying hours across the fleet to ensure a sequence of maintenance inductions. Dell and Marlow (2015) present a similar ILP for the daily management of both helicopter flight and maintenance hours. Similarly, the research in this thesis prescribes monthly flight utilization, squadron assignments, calendar and flight hour based depot maintenance inductions, storage inductions, and retirements.

Meeks (1999) focused specifically on the scheduling of two major types of depot activities for the EA-6AB Prowler. He created an ILP to prescribe when individual aircraft should be inducted for standard depot level maintenance, wing center section replacements, or a combination of both events. The motivation to combine events is to maximize the amount of depot work that can be done in a single induction and take advantage of the fact that performing both events together requires less time (both elapsed time and maintenance man-hours) than performing each event individually. Meeks' model creates prescriptions that completed 378 depot events in only 216 inductions; this resulted in a decrease of nearly 50% of non-availability due to depot level maintenance. A key aspect of this work is to allow for the bundling of depot events in an effort to reduce the number of transfers and ultimately the amount of time each Hornet spends out of the operational rotation.

Gokcen (2006) analyzed building robust operational schedules for Air Force fighter squadrons. In particular, he focused on how to mitigate the effects of absenteeism

in pilots through creating schedules with fewer changes given various disruptions. He explored the tradeoffs of having redundant aircraft and pilots scheduled for a few events compared to multiple hard scheduled events. Ultimately, he developed an objective function to ensure that pilot tasking was at a minimum level across different groups within the squadron; which allowed for redundant scheduling, resulting in daily flight schedules less sensitive to perturbations. Likewise, the research presented in this thesis is interested in looking at the tradeoff of redundant Hornets in the fleet (which are taking additional resources to maintain and could be placed in storage or retired) and having enough Hornets to maintain the planning assumptions such as readiness rates, utilization, depot turnaround, and transition dates of the squadrons.

The scheduling of squadrons for deployment presents unique challenges in balancing training requirements, personnel and equipment dwell times, and maintenance cycles with operational demands. Madison (2010) proposed an ILP to optimally assign U.S. Navy F/A-18 strike-fighter squadrons to fill deployment requirements. Her objective was to develop assignments that minimize the number of moves that individual strike-fighter squadrons have to make between different carrier airwings (CVWs), while ensuring the required dwell time between deployment cycles through a decision support tool called Carrier Optimal Strike-fighter Scheduling Tool (COSST). COSST generates the 10 years' worth of assignments of strike-fighter squadrons to scheduled CVW deployments. It provides a valuable capability in its ability to analyze the effects of disruptions in scenarios such as force reduction or maintenance cycles. Related to the slating of squadrons for deployment, one of the objectives of this thesis is to minimize the number of moves that an individual Hornet undergoes during the remainder of its sundown.

D. TAIL ASSIGNMENT PROBLEM

In 2005, Grönkvist incorporated elements of equipment replacement, procurement and retirement, and maintenance scheduling in a holistic approach to an aircraft assignment model aimed at determining the optimal inventory management of a fleet of commercial airliners. He used the term “tail assignment” to refer to the complex problem

of managing individual aircraft in a fleet to satisfy operational requirements across the entire planning process. In dealing with tail assignment as an optimization problem instead of a feasibility problem, he was able to explore various robust solutions in order to mitigate compounding problems in the event of operational disruptions. Grönkvist's results showed that using a tail assignment approach provides reasonable solutions to real problems faced by commercial airlines.

The work in this thesis is related to the tail assignment problem, but focusses on the specific aspects of sundown management of a military aircraft vice operating life management of an airline's varied inventory across revenue routes. In this research a predetermined timeline exists for transitioning Hornet aircraft and the goal is to minimize the penalties associated with failing to meet operational requirements. This research focuses on the optimal prescriptions for each individual Hornet's monthly squadron assignment, scheduled maintenance inductions, storage inductions, and retirements to ensure that each squadron in the operational rotation has enough Hornets with sufficient service life to meet monthly flight hour requirements.

III. MODEL DEVELOPMENT

This chapter describes HASM, contains information on the assumptions and data used, and presents the integer linear program (ILP) formulation.

A. HORNET ASSIGNMENT SUNDOWN MODEL

HASM optimally assigns individual Hornet aircraft to USMC squadrons and prescribes monthly flight hours and depot inductions for scheduled maintenance over the planning horizon. The 2016 Marine Aviation Plan provides the transition timeline for each Hornet squadron as a HASM input. HASM prescribes decisions for each month of its planning horizon. Monthly resolution is convenient as the USMC collects and reports monthly metrics with many used as data inputs for HASM. Due to service life limitations and scheduled maintenance inductions, individual Hornets must move between different locations to satisfy operational requirements. Each PMI event must be accomplished at or before a prescribed month unless the Hornet has retired, is located in storage, or is in backlog awaiting maintenance.

In addition to individual Hornet prescriptions, HASM tracks and assigns a minimum number of Advanced Tactical Airborne Reconnaissance System (ATARS) equipped Hornets to the operational rotation for F/A-18D squadrons.

To model all of the F/A-18 Hornet aircraft movements and utilizations during their remaining service life, HASM must make simplifying assumptions with respect to depot maintenance, flight hour requirements, readiness, and utilization.

1. Assumptions

1. HASM assumes that monthly decisions provide sufficient resolution to inform the squadron assignments, maintenance inductions, storage inductions, and retirements across the planning horizon.
2. HASM limits each Hornet to no more than 40 flight hours per month.
3. HASM assumes that each individual Hornet squadron maintains its historic median performance with noise in both flight hour requirements and readiness rates.

4. HASM simplifies the suite of inspections and technical directives that make up the life extensions into two categories. SLE represents the initial set of inspections and modifications that extend an individual Hornet beyond its original service life of 6,000 flight hours to 8,000 flight hours. The HFH represents the additional depot level maintenance required to extend a Hornet from 8,000 flight hours to 10,000 flight hours.
5. Possible depot events in HASM include: PMI, HFH, SLE, PHC (bundled event of PMI and HFH), or PSC (bundled event of PMI and SLE). All other depot service repairs and modifications are not considered in this study.
6. HASM assumes each depot event requires a predetermined or fixed number of months.
7. HASM limits depot capacity by number of Hornets and the manpower available each month. HASM allows for additional man hours through the use of overtime. A maximum bound on overtime limits this additional capacity each month.
8. HASM aggregates all of the FRCs that service F/A-18 Hornets together to create a single depot maintenance activity. Costs and TAT for each are averaged to create aggregated values.
9. HASM assumes a Hornet currently in the inventory begins a PMI cycle based on its current squadron. The length of the PMI cycle is fixed per the OPNAVIST 3110.114 2013.
10. Individual Hornet aircraft of the same type are considered identical.
11. HASM assumes dissimilar aircraft types can be assigned to squadrons of a specific type, but some dissimilar assignments are penalized.
12. After the retirement of an individual Hornet, it cannot transfer back into the operational rotation.
13. HASM assumes squadron transitions occur at the end of each month and Hornets are available and arrive at their new location at the beginning of the next month.

2. Model Formulation

This section presents the indices, sets, parameters, decision variables, objective function, and constraints that comprise the mathematical formulation of HASM. Because of the size of the time horizon and the complicated bookkeeping to ensure each aircraft maintained its unique maintenance cycle, HASM requires 38 sets of constraints and an

additional 13 non-negative and binary restrictions. HASM only considers valid combinations of these sets. Many of the index sets defined in this formulation provide limitations on the summations in the constraints but for ease of presentation these are not shown.

a. Indexed Sets

A	The set of all F/A-18 Hornet aircraft: $a \in A = \{1 \dots N\}$
$AATARS$	The set of all F/A-18D equipped with ATARS $a \in AATARS$
$HFHC$	The set of initial aircraft that have received HFH: $a \in HFHC$
$SLEC$	The set of initial aircraft that have received SLE: $a \in SLEC$
L	The set of all locations: $l \in L$
S	The set of all F/A-18 Hornet squadrons: $s \in S = \{1 \dots M\}$
SD	The set of all F/A-18D Hornet squadrons: $s \in SD$
$Depot$	The set of all depot maintenance activities: $l \in Depot = \{PMI, SLE, HFH, PSC, PHC\}$
T	The set of all time periods [months]: $t \in T = \{1 \dots T^{max}\}$
TD_s	The set of all time periods when $s \in SD$ exist: $t \in TD_s$
$Prohibit_{a,l,t}$	Times when aircraft a cannot go to location l in time t : $a, l, t \in Prohibit_{a,l,t}$
$Trans$	The set of allowable transitions from l to l' in t : $(l, l', t) \in Trans$
$Allow$	The set of allowable locations at time t : $(l, t) \in Allow$
It	The set of a which begin HASM at $depot$: $(a, l) \in It$
B	The set of intervals for piecewise linear elastic constraints: $b \in B$

b. Data

1. Initial Conditions

$fT0_a$	The total flying hours for aircraft a at $t=1$. [flight hours]
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$xT0_{a,l}$	The initial starting condition for aircraft a at $t=1$. [indicator 0, or 1]
$jT0_a$	The time period that aircraft a must depart the depot if located at the depot at the beginning of model. [month]
$PMI0_a$	The next PMI for aircraft a must be completed on or before this month. [month]

2. Depot Data

cac	Capacity restriction on Hornets at depot locations. [Hornets]
q^{reg}	Number of regular depot maintenance hours. [man-hours]
q^{ot}	Number of overtime depot maintenance hours. [man-hours]
u^{reg}	Cost of an hour of regular depot level work for any event. [penalty units]
u_t^{ot}	Cost of an hour of overtime depot level work for any event. [penalty units]
$dmax_a$	The maximum number of months between PMI events for aircraft a . [months]
$dmin_a$	The minimum number of months between PMI events for aircraft a . [months]
$Lwin_1_a$	Lower limit for 1 st PMI event for aircraft a , similarly $Lwin_2_a, Lwin_3_a, Lwin_4_a$ are the lower limits for 2 nd , 3 rd , and 4 th PMI events.
$Uwin_1_a$	Upper limit for 1 st PMI event for aircraft a , similarly $Uwin_2_a, Uwin_3_a, Uwin_4_a$ are the upper limits for 2 nd , 3 rd , and 4 th PMI events.
$time_l$	Number of months to complete depot event at location l . [months]
$phours_t$	Number of hours of PMI maintenance in the t^{th} month of maintenance. [man hours]
$hhours_t$	Number of hours of HFH maintenance in the t^{th} month of maintenance. [man-hours]
$shours_t$	Number of hours of SLE maintenance in the t^{th} month of maintenance. [man-hours]

$phhours_t$	Number of hours of PHC maintenance in the t^{th} month of maintenance. [man-hours]
$pschours_t$	Number of hours of PSC maintenance in the t^{th} month of maintenance. [man-hours]

3. Flight Hour and Readiness

atr	Minimum number of ATARS equipped aircraft. [Hornets]
h_s^{sqdtot}	The required flying hours for squadron s over the time horizon. [flight hours]
$h_{s,t}^{min}$	Minimum flying hours for squadron s in month t . [flight hours]
h^{max}	Maximum flying hours for an aircraft in each month. [flight hours]
j	Minimum percentage of $h_{s,t}^{min}$ that must be completed by each aircraft assigned to s in t . [flight hours]
$r_{s,t}$	Ready Basic Aircraft (RBA) rate for squadron s at t . [fraction of RBA]

4. Aircraft Assignment

mov	Maximum number of transfers an aircraft can complete in a six month window.
$sqdmov$	Maximum number of squadron transfers an aircraft can complete in a six month window.
n_s^{max}	Maximum number of serviceable aircraft per squadron. [Hornets]
n_s^{min}	Minimum number of serviceable aircraft per squadron. [Hornets]
n^{floor}	Minimum number of aircraft assigned to any squadron. [Hornets]
end_s	End time period for squadron s

5. Penalties

w^{above}	Penalty for exceeding the required number of flight hours in a given month. [penalty units]
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w^{below}	Penalty for falling to achieve the minimum monthly hours at time t . [penalty units]
$w_{l,t}^{pen}$	Penalty per aircraft per month for non-squadron location. [penalty units]
$w_{a,l'}^{tms}$	Penalty for transferring not like type model series. [penalty units]
$w_{l,l'}^{xfr}$	Penalty per aircraft to transfer aircraft a from l to l' in time t . [penalty units]
$pens_{a,l'}$	Penalty multiplier for preference of transfer location. [penalty units]
$pe_{b,t}$	Segment penalties for number of aircraft below minimum assignment. [penalty units]
$pk_{b,t}$	Segment penalties for number of aircraft above minimum assignment. [penalty units]
$pa_{b,t}$	Segment penalties for number of flight hours below monthly minimum. [penalty units]
$pb_{b,t}$	Segment penalties for number of aircraft below the minimum. [penalty units]

c. Binary Variables

$H_{a,t} \in \{0,1\}$	Binary variable with value of one if aircraft a has completed HFH on or before time t , zero otherwise.
$SC_{a,t} \in \{0,1\}$	Binary variable with value of one if aircraft a has completed SLE on or before time t , zero otherwise.
$X_{a,l,t} \in \{0,1\}$	Binary variable with value of one if aircraft a is in location l at the start of month t , zero otherwise.
$Y_{a,l,l',t} \in \{0,1\}$	Binary variable with value of one if aircraft a transfers out of location l into location l' at the start of the month t , zero otherwise.

d. Nonnegative Variables

$E_{b,s,t}^{below}$	Number of flight hours achieved below the minimum requirement for squadron s in month t (piecewise linear penalty).
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E^{tot}	The total number of flight hours achieved below the minimum requirement of the model.
$F_{a,s,t}$	Number of flight hours assigned to aircraft a in squadron s during month t .
$F_{a,t}^{tot}$	Cumulative flight hours assigned to aircraft a up to and including month t .
$G_{b,s,t}^{above}$	Number of aircraft assigned to squadron s in month t above the maximum in piecewise segment b .
$G_{b,s,t}^{below}$	Number of aircraft assigned to squadron s in month t below the minimum in piecewise segment b .
K_s	The total flight hours below the goal for squadron s over the time horizon (piecewise linear penalty).
V_t^{ot}	Number overtime hours used at depot during month t .

e. Formulation

$$\begin{aligned}
Min_{H,SC,X,Y} \quad & \sum_{b,s,t} pe_{b,t} E_{b,s,t}^{below} + \sum_{b,s,t} pk_{b,t} K_s + \sum_a \left(\sum_{l,t \in Allow} w_{l,t}^{pen} X_{a,l,t} + \sum_{l,l',t \in Trans} w_{l,l'}^{xfr} w_{a,l'}^{tms} pens_{a,l'} Y_{a,l,l',t} \right) + \\
& \sum_{b,s,t} pa_{b,t} w^{max} G_{b,s,t}^{above} + \sum_{b,s,t} pb_{b,t} G_{b,s,t}^{below} + \sum_t u_t^{ot} V_t^{ot}
\end{aligned} \tag{0}$$

f. Constraints

$$\sum_a F_{a,s,t} \leq r_{s,t} h^{max} \sum_a X_{a,s,t} \quad \forall s \in S, 1 < t \leq end_s \tag{1}$$

$$F_{a,s,t} \leq h^{max} X_{a,s,t} \quad \forall a \in A, s \in S, t \leq end_s \tag{2}$$

$$F_{a,s,t} \geq j h_{s,t}^{min} X_{a,s,t} \quad \forall a \in A, s \in S, t \leq end_s \tag{3}$$

$$\sum_a F_{a,s,t} \geq h_{s,t}^{min} - \sum_b E_{b,s,t}^{below} \quad \forall s \in S, t \leq end_s \tag{4}$$

$$F_{a,t}^{tot} = \sum_s F_{a,s,t} + fT0_a \quad \forall a \in A, t = 1 \tag{5}$$

$$F_{a,t}^{tot} = \sum_s F_{a,s,t} + F_{a,t-1}^{tot} \quad \forall a, t > 1 \tag{6}$$

$$\begin{aligned}
F_{a,t}^{tot} &\leq 10000 & \forall a \in HFHC, t \in T & (7) \\
F_{a,t}^{tot} &\leq 8000 + 2000H_{a,t} & \forall a \in SLEC, t \in T & (8) \\
F_{a,t}^{tot} &\leq 6000 + 2000H_{a,t} + 2000SC_{a,t} & \forall a \notin SLEC \cup HFHC, & (9) \\
& & t \in T & \\
X_{a,l,t} &= xT0_{a,l} & \forall a \in A, l \in L, t = 1 & (10) \\
\sum_{l,t \mid (l,t) \in Allow} X_{a,l,t} &= 1 & \forall a \in A & (11) \\
X_{a,l,t} &= X_{a,l,t-1} + \sum_{l'} Y_{a,l',l,t-1} - \sum_{l'} Y_{a,l,l',t-1} & \forall a \in A, l \in L, t > 1 & (12) \\
\sum_{a \in AATARS} X_{a,s,t} &\geq atr & \forall s \in SD, t \in TD_s, & (13) \\
& & (s,t) \in Allow & \\
\sum_a X_{a,s,t} &\leq n_s^{max} + \sum_b G_{b,s,t}^{above} & \forall s \in S, t \leq end_s & (14) \\
\sum_a X_{a,s,t} &\geq n_s^{min} - \sum_b G_{b,s,t}^{below} & \forall s \in S, t \leq end_s & (15) \\
\sum_a X_{a,s,t} &\leq n^{floor} & \forall s \in S, t \leq end_s & (16) \\
\sum_{a,l \in DEPOT} X_{a,l,t} &\leq cac & \forall t \in T & (17) \\
\sum_{l'} Y_{a,l',l,t} &\leq X_{a,l,t'} & \forall a \in A, \forall l \in Depot, & (18) \\
& & t, t' \mid t < t' \leq t + time_l & \\
\sum_{l'} Y_{a,l,l',t} &\leq X_{a,l,t} & \forall a \in A, (l,t) \in Allow & (19) \\
\sum_{l'} Y_{a,l',l,t} &= \sum_{l'} Y_{a,l,l',t+time_l} & \forall a \in A, l \in Depot, & (20) \\
& & 1 < t \leq (T^{max} - time_l) & \\
\sum_{l'} Y_{a,l,l',t} &= 1 & \forall a \in A, l \in Depot, & (21) \\
& & (a,l) \in it_{a,l}, t = jT0_a & \\
\sum_{l,t' \mid t' \leq t} Y_{a,l,PMI,t'} + \sum_{l,t' \mid t' \leq t} Y_{a,l,PSC,t'} + \sum_{l,t' \mid t' \leq t} Y_{a,l,PHC,t'} + & & \forall a \in A, t \mid 1 < PMI0_a \leq t & (22) \\
X_{a,Store,t} + X_{a,Backlog,t} + X_{a,Retire,t} + X_{a,SLE,t} + X_{a,HFH,t} &\geq 1 & \\
\sum_{PMI \mid t - dmax_a < t' \leq t} X_{a,PMI,t'} + \sum_{PSC \mid t - dmax_a < t' \leq t} X_{a,PSC,t'} + & & \forall a \in A, t \geq dmax_a & (23) \\
\sum_{PHC \mid t - dmax_a < t' \leq t_a} X_{a,PHC,t'} + X_{a,Store,t} + X_{a,Retire,t} + & & \\
X_{a,SLE,t} + X_{a,HFH,t} + X_{a,Backlog,t} + & & \\
\sum_l Y_{a,l,PMI,t} + \sum_l Y_{a,l,PHC,t} + \sum_l Y_{a,l,PSC,t} &\geq 1 &
\end{aligned}$$

$$\sum_{l,t' | t-dmin_a < t' \leq t} Y_{a,l,PMI,t'} + \sum_{l,t' | t-dmin_a < t' \leq t} Y_{a,l,PSC,t'} + \quad \forall a \in A, t \geq dmin_a + PMI \quad (24)$$

$$\sum_{l,t' | t-dmin_a < t' \leq t} Y_{a,l,PHC,t'} \leq 1$$

$$\sum_{l,t | Uwin_{-1_a} \leq t \leq Lwin_{-1_a}} Y_{a,l,PMI,t} + \sum_{l,t | Uwin_{-1_a} \leq t \leq Lwin_{-1_a}} Y_{a,l,PSC,t} + \quad \forall a \in A \quad (25)$$

$$\sum_{l,t | Uwin_{-1_a} \leq t \leq Lwin_{-1_a}} Y_{a,l,PHC,t} \leq 1$$

$$\sum_{l,t | Uwin_{-2_a} \leq t \leq Lwin_{-2_a}} Y_{a,l,PMI,t} + \sum_{l,t | Uwin_{-2_a} \leq t \leq Lwin_{-2_a}} Y_{a,l,PSC,t} + \quad \forall a \in A \quad (26)$$

$$\sum_{l,t | Uwin_{-2_a} \leq t \leq Lwin_{-2_a}} Y_{a,l,PHC,t} \leq 1$$

$$\sum_{l,t | Uwin_{-3_a} \leq t \leq Lwin_{-3_a}} Y_{a,l,PMI,t} + \sum_{l,t | Uwin_{-3_a} \leq t \leq Lwin_{-3_a}} Y_{a,l,PSC,t} + \quad \forall a | Lwin_{-3_a} \leq T^{max} \quad (27)$$

$$\sum_{l,t | Uwin_{-3_a} \leq t \leq Lwin_{-3_a}} Y_{a,l,PHC,t} \leq 1$$

$$\sum_{l,t | Uwin_{-4_a} \leq t \leq Lwin_{-4_a}} Y_{a,l,PMI,t} + \sum_{l,t | Uwin_{-4_a} \leq t \leq Lwin_{-4_a}} Y_{a,l,PSC,t} + \quad \forall a | Lwin_{-4_a} \leq T^{max} \quad (28)$$

$$\sum_{l,t | Uwin_{-4_a} \leq t \leq Lwin_{-4_a}} Y_{a,l,PHC,t} \leq 1$$

$$\sum_{l,l',t' | t-6 < t' \leq t} Y_{a,l,l',t'} \leq mov \quad \forall a \in A, t \geq 6 \quad (29)$$

$$\sum_{l,s,t' | t-6 < t' \leq t} Y_{a,l,s,t'} \leq sqdmov \quad \forall a \in A, t \geq 6 \quad (30)$$

$$H_{a,t} \leq \sum_{l,t' | t' \leq t-time_{HFH}} Y_{a,l,HFH,t'} + \sum_{l,t' | t' \leq t-time_{PHC}} Y_{a,l,PHC,t'} \quad \forall a \notin HFHC, t \in T \quad (31)$$

$$\sum_{l,t} Y_{a,l,HFH,t} + \sum_{l,t} Y_{a,l,PHC,t} \leq 1 \quad \forall a \notin HFHC \quad (32)$$

$$\sum_t H_{a,t} \leq 1 \quad \forall a \notin HFHC \quad (33)$$

$$SC_{a,t} \leq \sum_{l,t' | t' \leq t-time_{SLE}} Y_{a,l,SLE,t'} + \sum_{l,t' | t' \leq t-time_{PSC}} Y_{a,l,PSC,t'} \quad \forall a \notin SLEC, t \in T \quad (34)$$

$$\sum_{l,t} Y_{a,l,SLE,t} + \sum_{l,t} Y_{a,l,PSC,t} \leq 1 \quad \forall a \in A \quad (35)$$

$$\sum_t SC_{a,t} \leq 1 \quad \forall a \in A \quad (36)$$

$$\sum_{a,l | t-time_{HFH}+1 \leq t'} hhours_{t-t'+1} Y_{a,l,HFH,t'} + \sum_{a,l | t-time_{PMI}+1 \leq t'} phours_{t-t'+1} Y_{a,l,PMI,t'} + \quad \forall t \in T \quad (37)$$

$$\sum_{a,l | t-time_{SLE}+1 \leq t'} shours_{t-t'+1} Y_{a,l,SLE,t'} + \sum_{a,l | t-time_{PHC}+1 \leq t'} phchours_{t-t'+1} Y_{a,l,PHC,t'} +$$

$$\sum_{a,l | t-time_{PSC}+1 \leq t'} pschours_{t-t'+1} Y_{a,l,PSC,t'} \leq q^{reg} + V_t^{ot}$$

$$V_t^{ot} \leq q^{ot} \quad \forall t \in T \quad (38)$$

$$F_{a,s,t} \geq 0 \quad \forall a \in A, s \in S, t \in T \quad (39)$$

$$F_{a,t}^{tot} \geq 0 \quad \forall a \in A, t \in T \quad (40)$$

$$F_{s,t}^{sqdtot}; E_{s,t}^{below} G_{s,t}^{above}; G_{s,t}^{below} \geq 0 \quad \forall s \in S, t \in T \quad (41-44)$$

$$E^{tot} \geq 0 \quad (45)$$

$$K_s \geq 0 \quad \forall s \in S \quad (46)$$

$$V_t^{ot} \geq 0 \quad \forall t \in T \quad (47)$$

$$H_{a,t}; SC_{a,t} \in \{0,1\} \quad \forall a \in A, t \in T \quad (48-49)$$

$$X_{a,l,t}; Y_{a,l,l',t} \in \{0,1\} \quad \forall a \in A, l \in L, t \in T \quad (50-51)$$

3. Explanation of Model Formulation

Equation (0) represents HASM's objective function. It has piecewise linear penalties for violating flight hour goals and aircraft assignment, and it also incorporates a discount factor. It has seven components:

$$(a) \sum_{b,s,t} pe_{b,t} E_{b,s,t}^{below}$$

$$(b) \sum_{b,s,t} pk_{b,t} K_s$$

$$(c) \sum_{a,(l,t) \in Allow} w_{l,t}^{pen} X_{a,l,t}$$

$$(d) \sum_{a,(l,l',t) \in Trans} w_{l,l'}^{xfr} w_{a,l'}^{tms} pens_{a,l'} Y_{a,l,l',t}$$

$$(e) \sum_{b,s,t} pa_{b,t} w^{max} G_{b,s,t}^{above}$$

$$f) \sum_{b,s,t} pb_{b,t} G_{b,s,t}^{below}$$

$$g) \sum_t u_t^{ot} V_t^{ot}$$

The first component of the objective function expresses the cost of deviating below the assigned number of flight hours, each month for each squadron. Component (b) addresses deviations below the total flight hour goal over the planning horizon. The next two components capture the penalties associated with moving aircraft, both in terms

of transferring them and keeping them out of the operational rotation. Components (e) and (f) add costs for not assigning the correct number of aircraft to each squadron, either below the minimum or above the maximum. The final component adds the depot overtime costs associated with the artisans and engineers completing depot level work on Hornets.

Constraint sets (1) through (9) provide the proper accounting for Hornet flight hours. The first three constraints ensure that flight hours assigned to all aircraft in a squadron do not exceed the maximum number of available hours. Constraint set (3) guarantees flight hours flown by an aircraft can only be credited to the squadron where the aircraft is assigned and every aircraft must fly at least a minimum percentage of the monthly flight hour goal in order to effectively distribute the workload. Constraint set (4) balances the total number of flight hours assigned to a squadron with the minimum required and deviations below that amount. Constraint sets (5) and (6) keep track of the cumulative flight hours accrued on each Hornet, starting with the initial number of hours that each Hornet begins the model with and then adds each subsequent time period. Constraint sets (7) through (9) define the different service life limitations on each Hornet based on whether it completed one or more of the depot events to extend its service life.

The next eight constraint sets keep track of an individual Hornet's assignments in HASM. Constraint sets (10), (11), and (12) establish the initial position of each aircraft at the start of the model, limit an aircraft to one unique location during any time period, and connect each aircraft's location to where it was in the previous time period. Constraint set (13) handles the assignment of ATARS equipped Hornets, ensuring that at least two are always assigned to each F/A-18D squadron. Constraint sets (14), (15), and (16) control the number of Hornets assigned to a squadron between a floor minimum number and an elastic maximum number with allowable deviations from an ideal quantity based on PMAI/PTAI. Facilitating depot capacity constraint (17) limits the number of Hornets that can occupy depot's floor space.

Monitoring the flow of Hornets into and out of depot maintenance events and preventing excessive aircraft transfers requires constraint sets (18) through (36). Constraint sets (18) and (19) balance the flow into each location and force aircraft to

remain at depot for consecutive time periods to complete a scheduled depot maintenance event. Constraint sets (20) and (21) ensure that aircraft are properly transferred into depot maintenance and must remain in a depot event until the event is completed. Constraint sets (22) through (28) require every aircraft to complete the first scheduled PMI event and every subsequent PMI event unless the aircraft is placed in storage or retired. Constraint sets (29) and (30) restrict the flow of aircraft transfers within a six month window to prevent repeated transfers of individual Hornets. Hornets receive credit for completing service life extension events and are prohibited from completing the same life extension again by constraint sets (31) through (36).

Establishing the capacity restrictions of depot's limited work force requires considering all regular and overtime hours used in HASM. Constraint set (37) accounts for all hours expended by depot artisans working on scheduled depot events for Hornets. Constraint set (38) bounds the maximum number of overtime hours to within a limit for each month.

Finally, constraint sets (39) through (47) indicate nonnegative variables and constraint sets (48) through (51) identify the binary decision variables.

IV. IMPLEMENTATION AND ANALYSIS

This chapter provides a description of the computer implementation of HASM, the data, and sample results.

A. COMPUTER IMPLEMENTATION

This research uses the commercially available optimization software package Generalized Algebraic Modeling System (GAMS), version 24.6.1 to generate HASM and CPLEX 12.0 to solve it (GAMS Development Corporation, 2016). All scenarios generated in HASM solve using a Dell computer with two 2.30GHz processors and 128 GB RAM. The base scenario considers all 274 F/A-18 Hornet aircraft in the USMC inventory on a 14 year planning horizon at monthly resolution with an aggressive discount rate of $(1 - 0.01)^t$, where t equals the time period. Implementing other discount rates did not significantly change HASM's results. Because of the size of the entire time horizon, HASM solves the entire planning horizon in smaller time epochs. Each epoch represents a six month time window with approximately 500,000 rows, 1.2 million columns, and 7 million non-zero elements. For each epoch, it typically requires 10–15 minutes to find a solution guaranteed to be within 2% of optimal. The entire planning horizon consists of 59 epochs with more than 28.8 million rows, 80 million columns (77 million discrete columns), and 388 million non-zero elements. To generate and solve all 59 epochs it takes approximately 7.5 hours. Because of memory requirements based on HASM's size, solving it on a computer with less than 96 GB RAM is not possible.

B. DATA IMPLEMENTATION

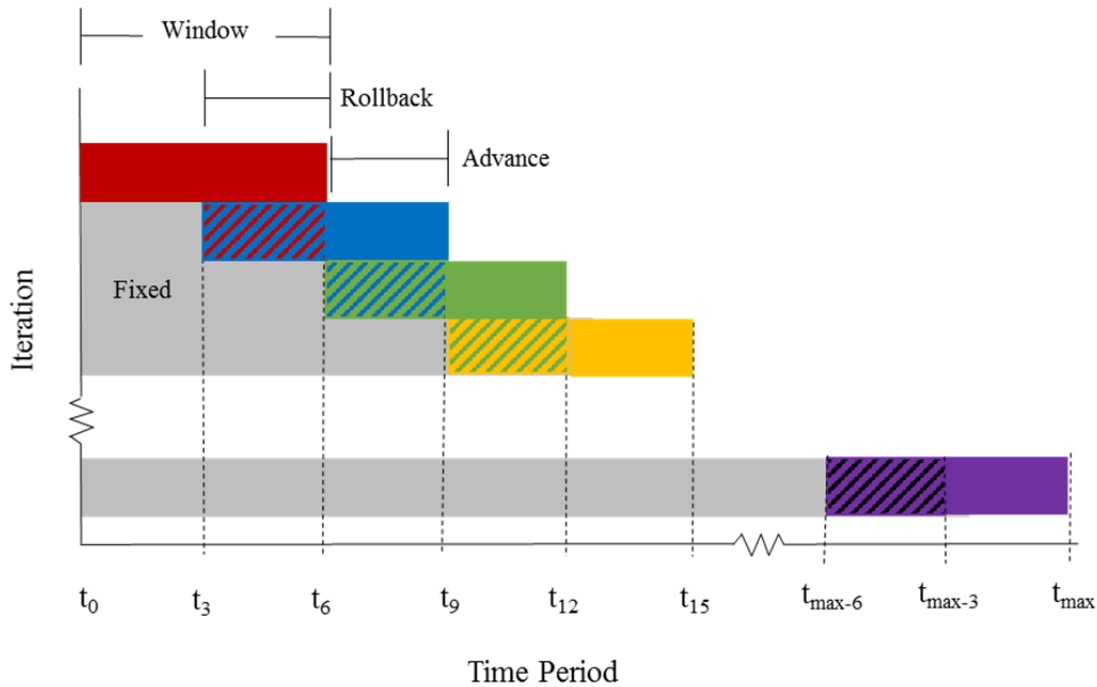
This research demonstrates HASM using inputs constructed from four main unclassified data sources: 2016 USMC Aviation Plan from Headquarters Marine Corps (HQMC) Aviation, February 2016 F/A-18A-F & EA-18G Flight Hour Inventory Report from NAVAIR, AMSRR Data from HQMC Aviation, and Depot Maintenance Data provided by NAVAIR. The overall framework for the 14 year time horizon with Hornet transition schedules and the modified T-2.0 came directly from information in the 2016

Marine Aviation Plan. Information regarding the current disposition of the USMC Hornet inventory is from the February 2016 F/A-18A-F & EA-18G Flight Hour Inventory Report. Flight hour requirements and readiness rates for each individual Hornet squadron comes from the six years' worth of historic AMSRR data. Depot Maintenance Data Report from Commander Fleet Readiness Centers (COMFRC) provides the necessary information to create depot turnaround times.

1. Time Cascade

Because of the size of the time horizon for this problem and the inherent structure where decisions in each time period affect those of every subsequent time period, it was necessary to implement an optimization based heuristic solution technique using a time cascade. In a time cascade, a solution results from sequentially considering smaller overlapping subsets of the entire planning horizon. Although this approach has no guarantee to yield a globally optimal solution over the entire time horizon, breaking it into smaller time segments and solving a moving window across the entire time horizon allows a more practical approach to solving a problem with similar structure and a long time horizon (Baker 1997).

HASM uses a time window of six months and progresses forward with an advance of three months. Figure 13 illustrates the outline of the time cascade used in HASM. The three month overlap of the window and the advance provided the best mitigation of end effects in each cascade and allowed sufficient foresight to ensure enough Hornets are available to meet the demand of future time periods. Implementing a longer window in HASM results in significantly longer solution time, and shorter windows do not provide enough foresight to prevent a compounding of myopic behavior toward the end of the time horizon. In order to mitigate these myopic behaviors as a result of the time window, certain controls prevent HASM from making early decisions that impact its ability to meet future demands. The monthly penalty associated with retiring a Hornet prevents HASM from retiring Hornets in order to avoid inducting them for their scheduled maintenance, is an example of such a control.



Time Cascade illustration showing the forward progression via sequentially solved subsets of the entire time horizon.

Figure 13. Time Cascade

2. Grounded Sets

The set of all Hornet aircraft A , represents only F/A-18 Hornets that are specifically part of the USMC inventory as listed in F/A-18A-F & EA-18G Flight Hour Inventory Report, February 2016. HASM excludes all Hornets that are in the DOD inventory, but not specifically assigned to a Marine Aircraft Wings. Both of the sets $HFHC$ and $SLEC$ contain Hornets which completed the appropriate depot activities and received additional service extensions as of February 1, 2016. The set of $AATARS$ contains F/A-18D Hornets listed as ATARS modified. The set L represents all the possible locations that a Hornet can occupy in HASM. This includes all 13 USMC Hornet squadrons (set S), the depot events (PMI , SLE , HFH , PSC , PHC), and also the remaining locations of *Store*, *Retire*, and *Backlog*.

3. Combination Sets

Because there are 274 aircraft and 176 months in the base scenario, the combinatorics of the HASM expand rapidly as the model scales up in time periods. For example, there are 36,960 [(21 possible locations choose 2)*176] combinations of transitions from 21 location l to 20 location l' across the entire time horizon. Adding each individual Hornet to this calculation, the number of possible combinations grows to more than 10.1 million (36,960*274). In order to prevent unwanted combinations, HASM filters out transitions and locations based on aircraft and time period. The set $(l, l', t) \in Trans$ is all the combinations where an aircraft can transfer from location l to l' in time period t . The set $(l, t) \in Allow$ is all the combinations where an aircraft is allowed to be located in location l in time period t . The use of these and other filters rules out locations or transitions that are not possible. Prohibiting the transfer of a Hornet to a squadron that already transitioned to the JSF in a previous time period is a simple example of such an exclusion.

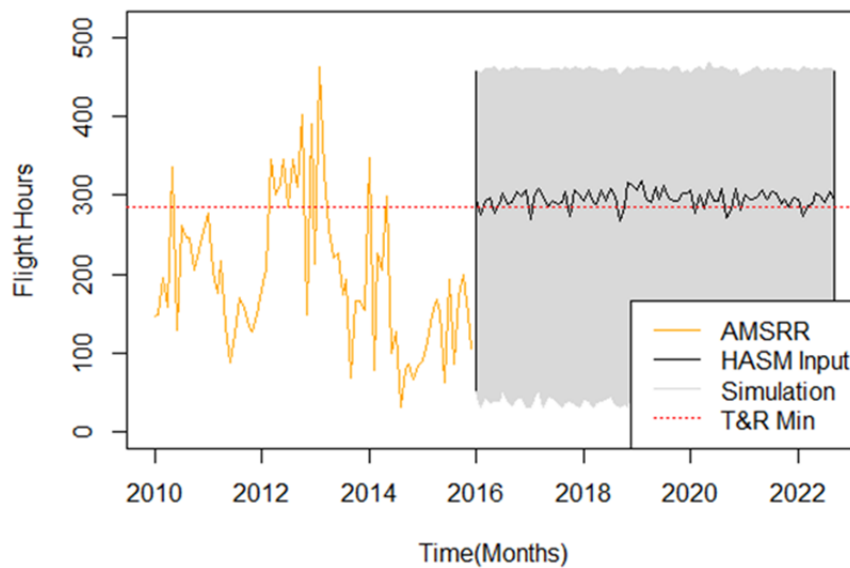
4. Flight Hour Requirements and Readiness Rates

HASM requires inputs of both the flight hour requirement by squadron and month ($h_{s,t}^{MIN}$) and the readiness factor ($r_{s,t}$). HASM uses historical information to estimate future flight hour requirements and readiness. Using a statistical analysis HASM captures the median performance with noise for each squadron.

HASM uses a data set containing six years of AMSRR information of all 13 Hornet squadrons as a starting point and replaces missing values with weighted averages or forecasted trend values, as appropriate. This data set provides enough depth to capture multiple cycles of pre-deployment workups, deployment, and post deployment sustainment periods. This allows the forecasted values to capture the cyclic trends inside of the broader trends of the data.

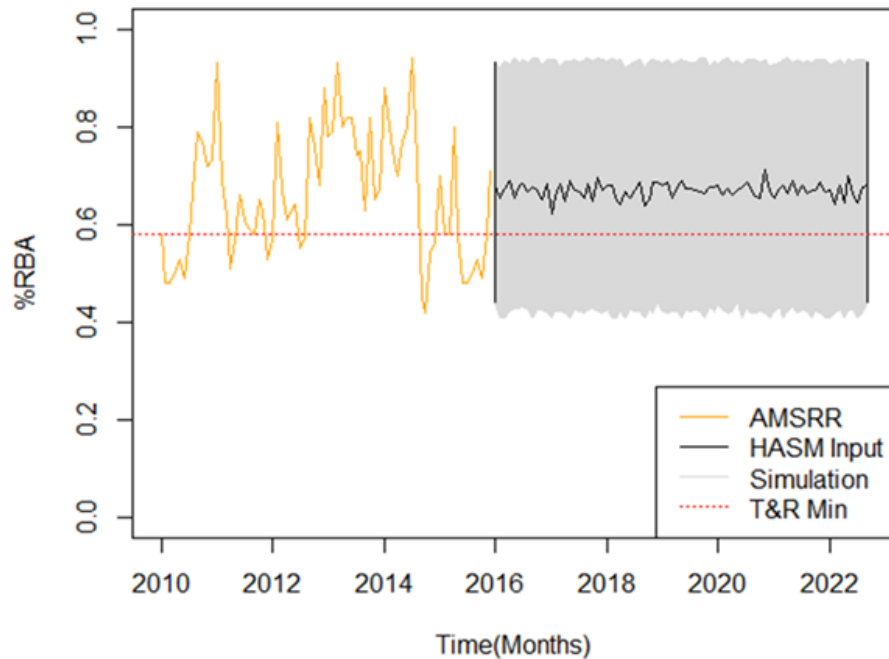
From this data set, HASM creates a time series for each Hornet squadron for both flight hour requirements and RBA rates for every month until the squadron transitions. The R package *surrogate* generates these vectors based on each squadron's AMSRR data.

In order to provide additional fidelity to the estimates, HASM generates 1,000 random realizations for each forecast. This provides 1,000 unique estimates of the flight hour requirements and readiness rates for every month. HASM uses the median for each month as the point estimate for each input to reduce the influence of outliers. Figure 14 and Figure 15 illustrate an example of these inputs. These figures show the six year historic data and the statistical simulation for the “Bengals” of VMFA(AW)-224. On the left, the orange plot represents the historic data from the AMSRR, the shaded region in gray represent the range of the 1,000 realizations for each month, the black line illustrates the median values for each month, and the red dotted line depicts the T-2.0 minimum value. The month to month variability represents the combination of factors that cannot be explicitly modeled.



Example of statistical simulation of monthly flight hour requirement for VMFA(AW)-224.

Figure 14. Monthly Flight Hours for VMFA(AW)-224.
Adapted from AMSRR 2010–2015.

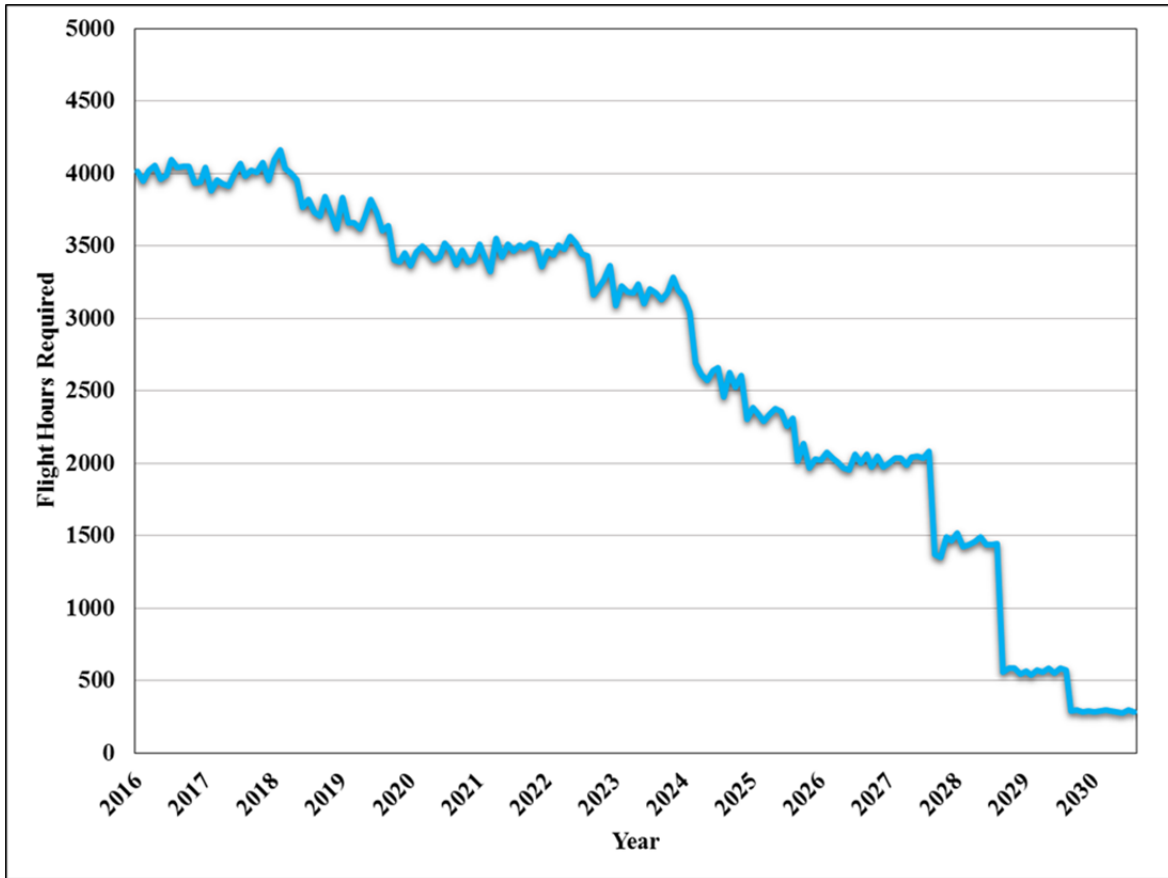


Example of statistical simulation of RBA rates for VMFA(AW)-224.

Figure 15. Monthly RBA Rates for VMFA(AW)-224.
Adapted from AMSRR 2010–2015.

5. Minimum Flight Hour Constraints

The monthly minimum flight hour requirement uses the T-2.0 basis from the 2016 Marine Aviation Plan. The requirement for 15 hours per aviator per month yields a total squadron requirement of 285 hours each month for each squadron except, VMFAT-101 which includes additional hours for both student flight time and instructor proficiency (USMC 2016, page 46). Each squadron's flight hour requirement varies slightly based on the median of the 1,000 realizations of each month; however, the total across the model is equal to the T-2.0 minimum multiplied by the number of months until the squadron transitions. Figure 16 plots the total number of flight hours across the time horizon.

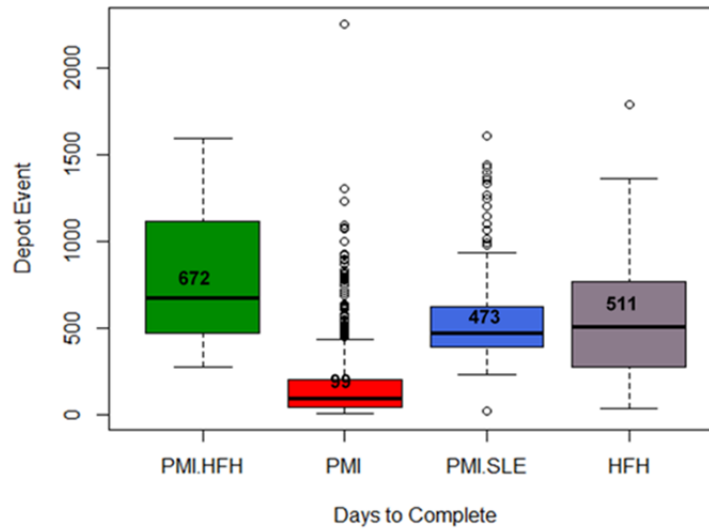


This figure plots the total monthly flight hour requirement of all Hornet squadrons.

Figure 16. HASM Total Monthly Flight Hour Requirements

6. Depot Turnaround Times

HASM assumes that each aircraft's repairs and modifications are the same and induction to completion for each event is a fixed number of time periods. A Depot Maintenance Report for all F/A-18A-D Hornets provides the length of these depot events. Figure 17 shows a boxplot of the turnaround time for events completed as of February 25, 2016. Because of the significant amount of variability in these events, as evidenced by the long tails of the boxplots in Figure 17, HASM uses the median values as the inputs for the parameter $time_l$.



This boxplot show the variability in depot events. Note the outliers for PMI events.

Figure 17. Boxplot of F/A-18A-D Depot Events 2002–2016.
Adapted from COMFRC 2016.

Table 3. HASM Depot TAT Input Values

Event	Value (months)	Parameter
PMI	4	$time_{PMI}$
HFH	17	$time_{HFH}$
SLE	12	$time_{SLE}$
PHC	23	$time_{PHC}$
PSC	16	$time_{PSC}$

7. Other Important Parameters

Table 4 lists other parameter inputs for HASM and a brief background on their values.

Table 4. Parameter Values of HASM

Parameter	Value	Background
c^{ac}	115	Derived from the number of aircraft in work at depot facilities
d_a	48 or 72	Set depending on aircraft's reporting custodian
$pcool_a$	42 or 66	Set depending on aircraft's reporting custodian
q^{reg}	138,797	Derived from number of hours needed for 115 aircraft in work
q^{ot}	34,699	Derived from 25% of q^{reg}
J	5%	Leveling criteria to ensure equal flying of assets
n^{floor}	4	Each squadron requires a division of Hornets
n_s^{max}	15, 54	125% of PMAI/PTAI
n_s^{min}	12, 36	Derived from PMAI/PTAI
$phours_t$	122	FY16 Workload Standard /Median TAT for event
$hhours_t$	1362	FY16 Workload Standard /Median TAT for event
$shours_t$	1337	FY16 Workload Standard /Median TAT for event
$phhours_t$	1324	FY16 Workload Standard /Median TAT for event
$pschours_t$	585	FY16 Workload Standard /Median TAT for event
u^{reg}	80	FY16 Cost per Man-Hour Depot Level Maintenance
u^{ot}	240	300% FY16 Cost per Man-Hour Depot Level Maintenance

8. Objective Function

HASM's objective function contains a combination of costs associated with reducing operational availability and failure to meet mission requirements. Through the use of elastic variables, which allow penalized violations to occur, HASM captures violations of minimum flight hour requirements and number of aircraft assigned to each squadron. HASM establishes a linkage between the cost of lost operational availability and the FY16 fully burdened cost of a USMC F/A-18 Hornet flight hour. Basing penalties on the lost opportunity to execute flight hours and the costs of depot activities from the FY16 Aircraft Workload Standards Revision 1 (NAVAIR 2016b), HASM links the time out of the operational rotation to a monetary cost of lost Hornet flight hours. This ensures the penalties in the objective function have a tangible basis.

9. Aircraft Assignment Constraints

HASM uses the FY16 PMAI and PTAI requirements for outfitting a squadron with its complete complement of Hornets and preventing a squadron's maintenance department from being overburdened with the organizational maintenance requirements of too many Hornets (USMC (2016)). HASM seeks to fill the PMAI and PTAI requirement first and then looks to assign the appropriate type of Hornet to each squadron. HASM uses a preference based on each Hornet's reporting custodian and then squadrons that employ the same Hornet type located as geographically close as possible. The parameter $pens_a$ contains this preference matrix for each individual Hornet and adds a penalty multiplier based on the degree of fit for the transfer of an aircraft to a squadron.

C. ANALYSIS

The analysis of HASM's output highlights deficits that occur in the inventory and potential shortfalls in operational capability if the current plan does not adjust to accommodate these problems. Several main scenarios present an opportunity to provide a comparison of different alternatives to preserve combat capability in the Hornet inventory. The base case, referred to as S1, represents the proposed timeline in the 2016 Aviation Plan with T-2.0 requirements for every squadron (19 pilots and a 12 Hornet goal per operational squadron). The next scenario, S2, relaxes the monthly flight hour requirement for each operational squadron from 285 flight hours per month down to 225. The third scenario, S3, relaxes S1 by reducing the goal of 12 Hornets per operational squadron and 43 at the FRS to 10 and 36 respectively. The fourth scenario, S4, combines both of the previous relaxations of S2 and S3 together.

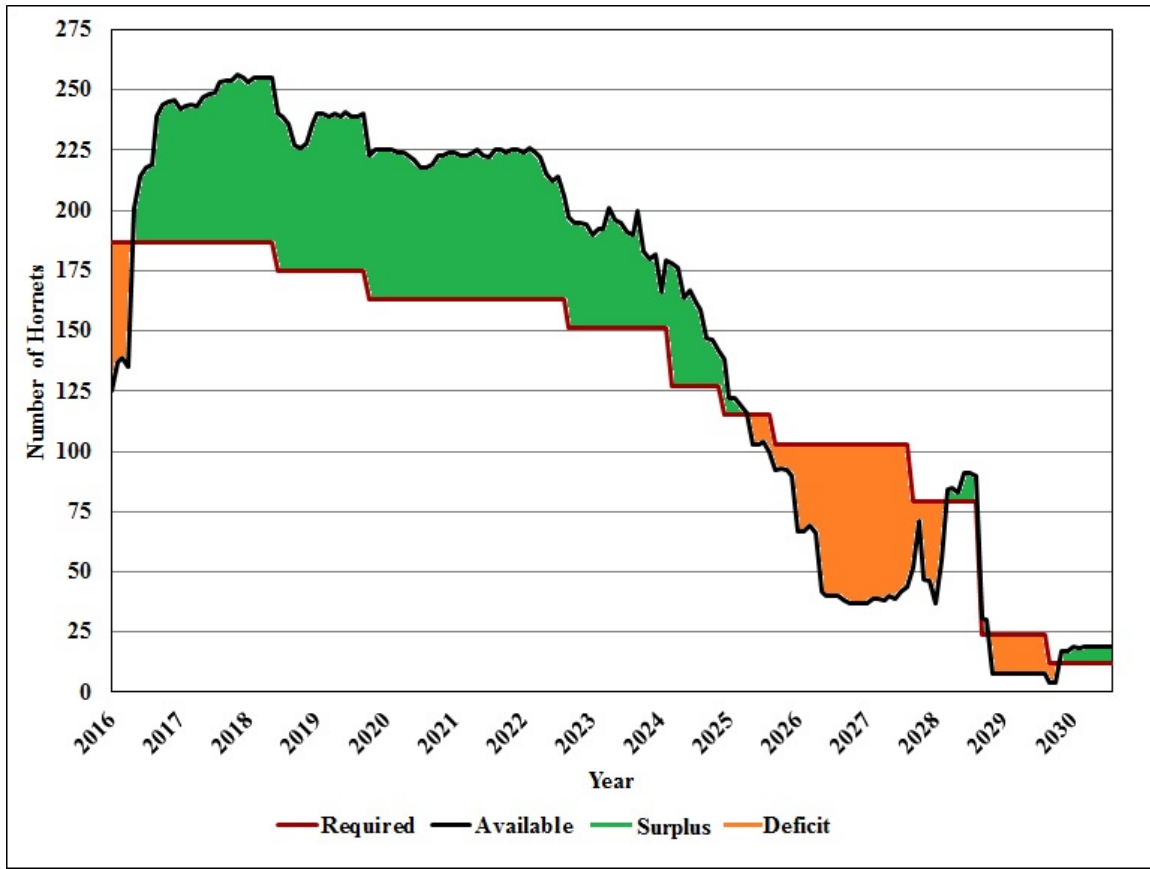
Because of the penalty structure of HASM, we provide an initial period to wash out the initial conditions. All scenarios allow for a grace period of the first five months to prevent massive penalties associated with Hornet shortfalls and missed flight hour goals which drive decisions that impact the ability of HASM to meet future requirements. HASM does not assess penalties for the assignment of Hornets below the minimum number or flight hours below the monthly minimum during the grace period.

1. S1: Base Case

The base case examines the planned transition timeline in the 2016 Aviation Plan with the assumptions of a full PMAI/PTAI number of Hornets and a complete Table of Organization number of aviators achieving an average of 15 flight hours per month. Figure 18 highlights an area of concern in S1 beginning in June of 2025 and extending until March 2028 when there are insufficient Hornets in the operational rotation to meet the demands of the remaining squadrons. During this 23 month deficit, the operational rotation averages 41 less Hornets available than required. This is 41% of the operational rotation's Hornet requirement during this time period.

In addition to a shortfall of Hornets for the squadrons of the operational rotation, a capability gap for ATARS equipped aircraft emerges during June 2026. All 18 ATARS equipped Hornets are not available for assignment in the operational rotation to the remaining F/A-18D squadrons. This shortfall affects VMFA(AW)-225 and VMFA(AW)-242.

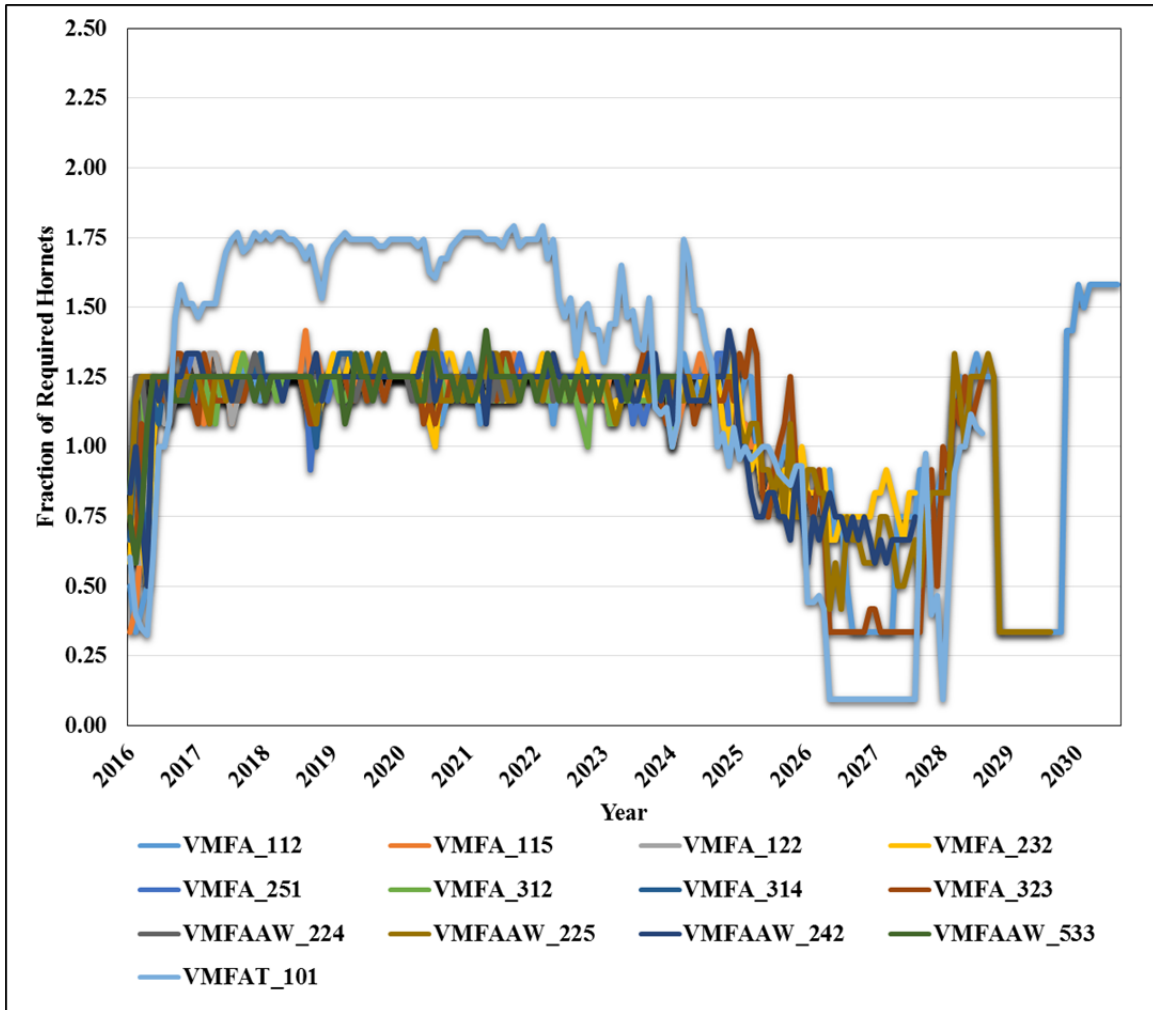
Figure 19 illustrates the fraction of the required number of Hornets assigned to each squadron across the entire time horizon. A value of 1.0 represents 12 Hornets assigned to an operational squadron or 43 Hornets assigned to the FRS. Once HASM exits the five month grace period, it maintains most squadrons above a rating of 1.0 until there are insufficient Hornets to meet the requirement. The excess inventory represents a buffer that prevents falling below the required number of aircraft given the transition restrictions imposed. HASM uses the FRS as a revolving pool to absorb Hornets from the depot and transfer them to operational squadrons when required.



This figure compares the required number of Hornets for the operational rotation with the number that HASM prescribes as available. Note the significant shortfall that begins May 2025 when the number of available Hornets plunges below the required number.

Figure 18. S1 Number of Required Hornets versus Number of Hornets Available for the Operational Rotation.

Figure 20 illustrates the number of Hornets in each type of scheduled depot activity during each time period. HASM uses the median TAT for each type of depot event and completes all of the aircraft that start in depot by November 2017. Based on the Hornets in the inventory and the timing of PMI events and the initial service life extension, HASM elects to complete only one PSC (PMI combined with SLE) event in the entire planning horizon. Figure 20 also shows the waves of PMI and HFH events that wash through the time horizon.



This plot shows the number of Hornets assigned to each squadron across the time horizon normalized to the PMAI/PTAI values.

Figure 19. S1 HASM Hornets Assigned per Squadron Plot.

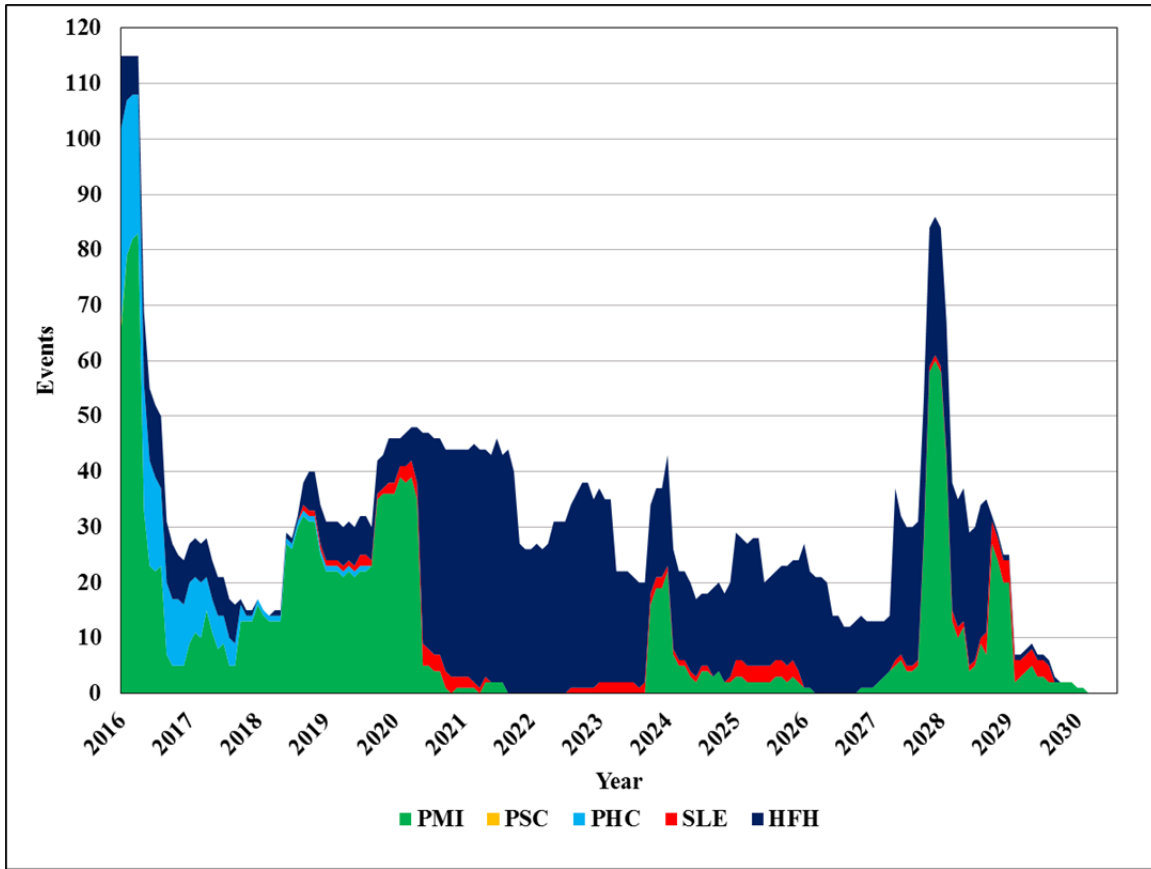


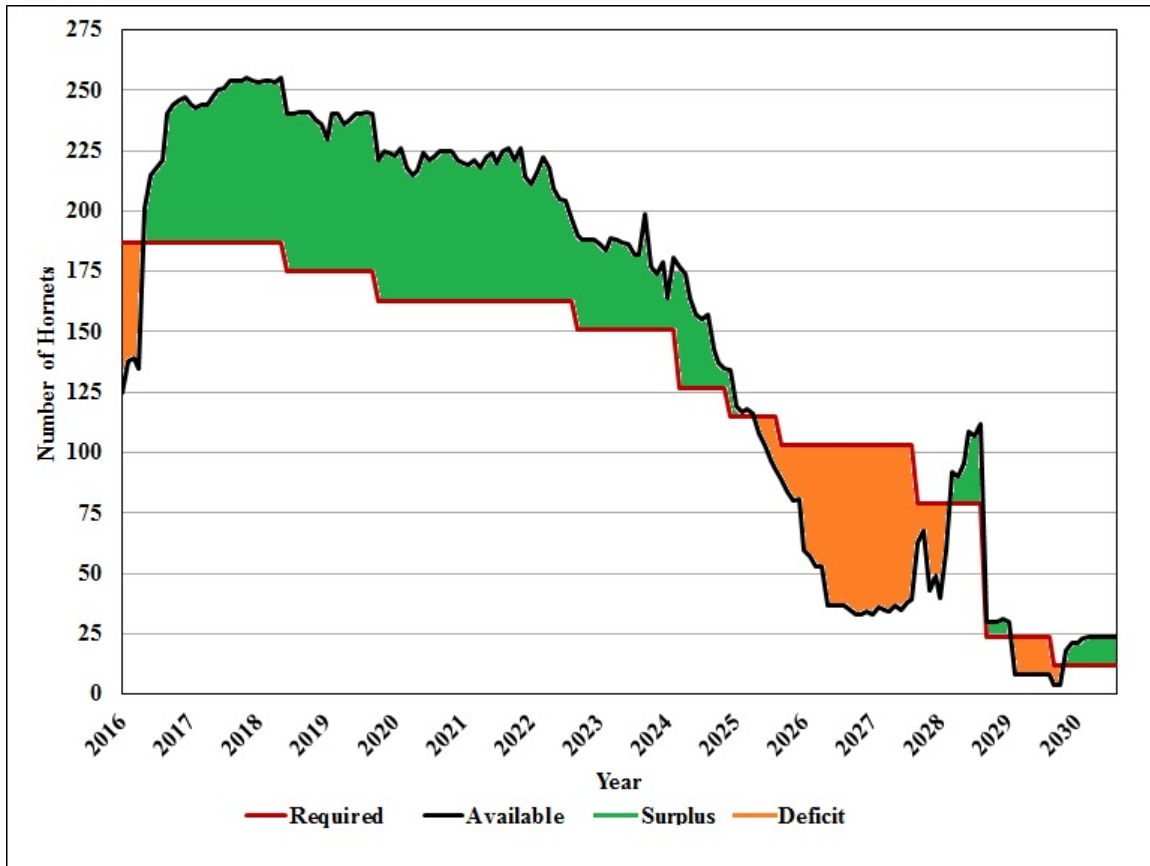
Figure 20. S1 HASM Hornets Inducted for Depot Events.

2. S2: Relaxation of Total Monthly Flight Hours

S2 relaxes the monthly flight hour requirement in S1 by 21%. This eases the burden on the Hornet inventory and allows greater flexibility to spend aircraft service life on flight hour demand in the future. HASM does not specify whether this reduction results from fewer than the standard 19 pilots per operation squadron or a decrease in the hours necessary for training. HASM seeks to allocate Hornets to achieve 225 monthly flight hours per operational squadron and 474 monthly flight hours to the FRS vice 285 and 600 respectively.

Figure 21 shows that a Hornet shortfall occurs in S2 nearly at the same time as in S1, occurring in 2025. This illustrates that reducing the requirement of monthly flight hours is insufficient to prevent a shortage of Hornets toward the end of the planning horizon. During this 23 month time window of Hornet shortfall, the operational rotation

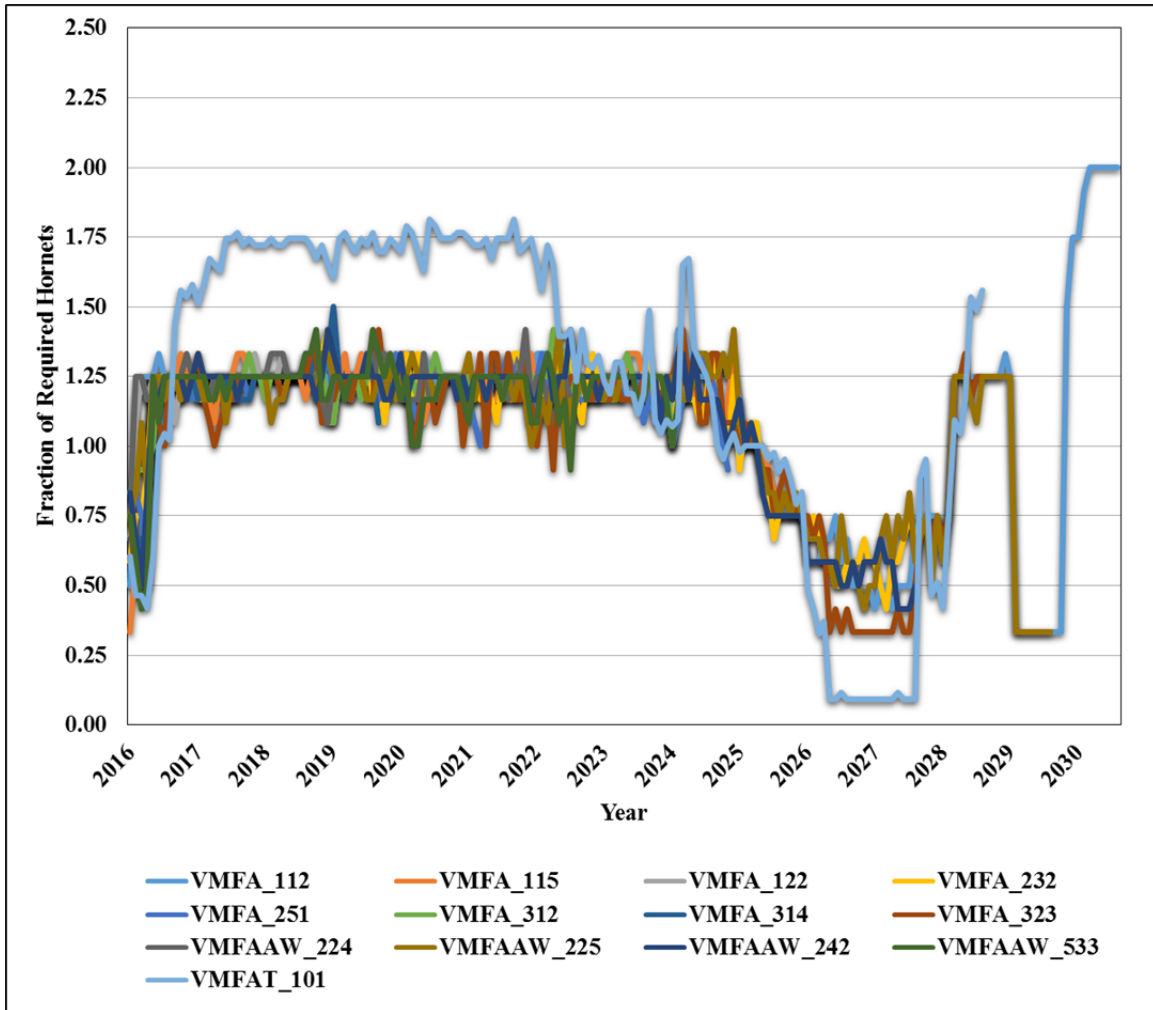
averages 45 less Hornets than the requirement. This is 45% of the operational rotation's Hornet requirement during this time period.



This figure compares the required number of Hornets for the operational rotation with the number that HASM prescribes as available. Note the significant shortfall that begins June 2025 when the number of available Hornets plunges below the required number.

Figure 21. S2 Number of Required Hornets versus Number of Hornets Available for the Operational Rotation.

Figure 22 highlights the fraction of the required number of Hornets assigned to each squadron across the entire time horizon. Despite the reduction in monthly flight hours, HASM still carries a buffer of Hornets to prevent shortfalls in the number of assigned Hornets when aircraft are available. Also, Figure 23 shows that requiring fewer monthly flight hours does not significantly change the depot induction profile from S1. Ultimately, S2 shows that reducing the flight hour requirement by 21% does not drastically change the Hornet shortfall that still occurs at the end of the planning horizon.



This plot shows the number of Hornets assigned to each squadron across the time horizon normalized to the PMAI/PTAI values.

Figure 22. S2 HASM Hornets Assigned per Squadron Plot.

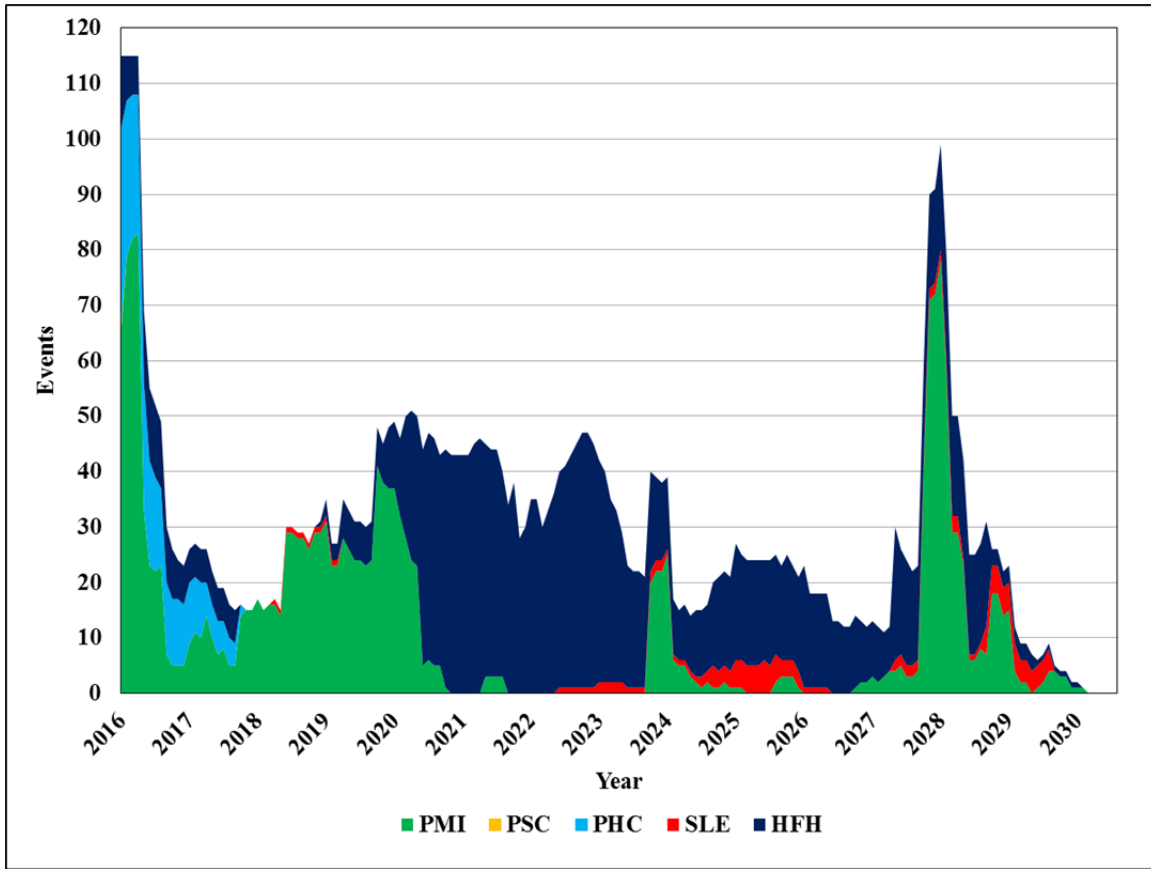
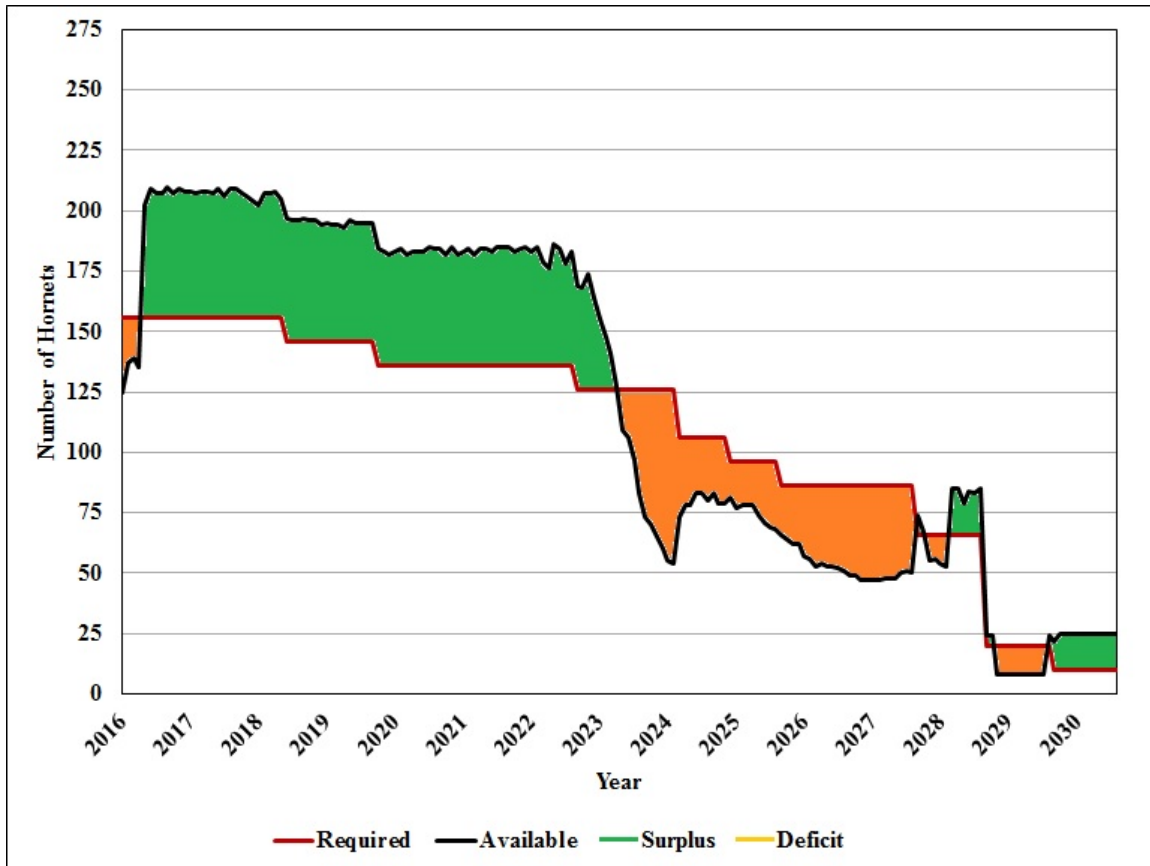


Figure 23. S2 HASM Hornets Inducted for Depot Events.

3. S3: Relaxation of the Number of Hornets Assigned to Each Squadron

S3 drops the monthly target of 12 Hornets assigned to each operational squadron and 43 Hornets to the FRS to 10 and 36 while still maintaining the T-2.0 flight hour goals of S1. This reduction eases the burden on HASM to allocate only 83% of PMAI/PTAI per month and the remaining Hornets are available for circulation in the operational rotation or depot induction. Unfortunately, this depletes the flight hours of the Hornets in the operational rotation much faster. The deficit appears earlier, but represents a lower deviation from the flight hour requirements than in S1 or S2. Figure 24 illustrates the resulting Hornet shortage begins more than two years earlier, compared to S1 and S2, beginning in 2023. The operational rotation faces an average deficit of 30 Hornets (compared to 41 in scenario S1), which is 37% of the operational rotation's Hornet

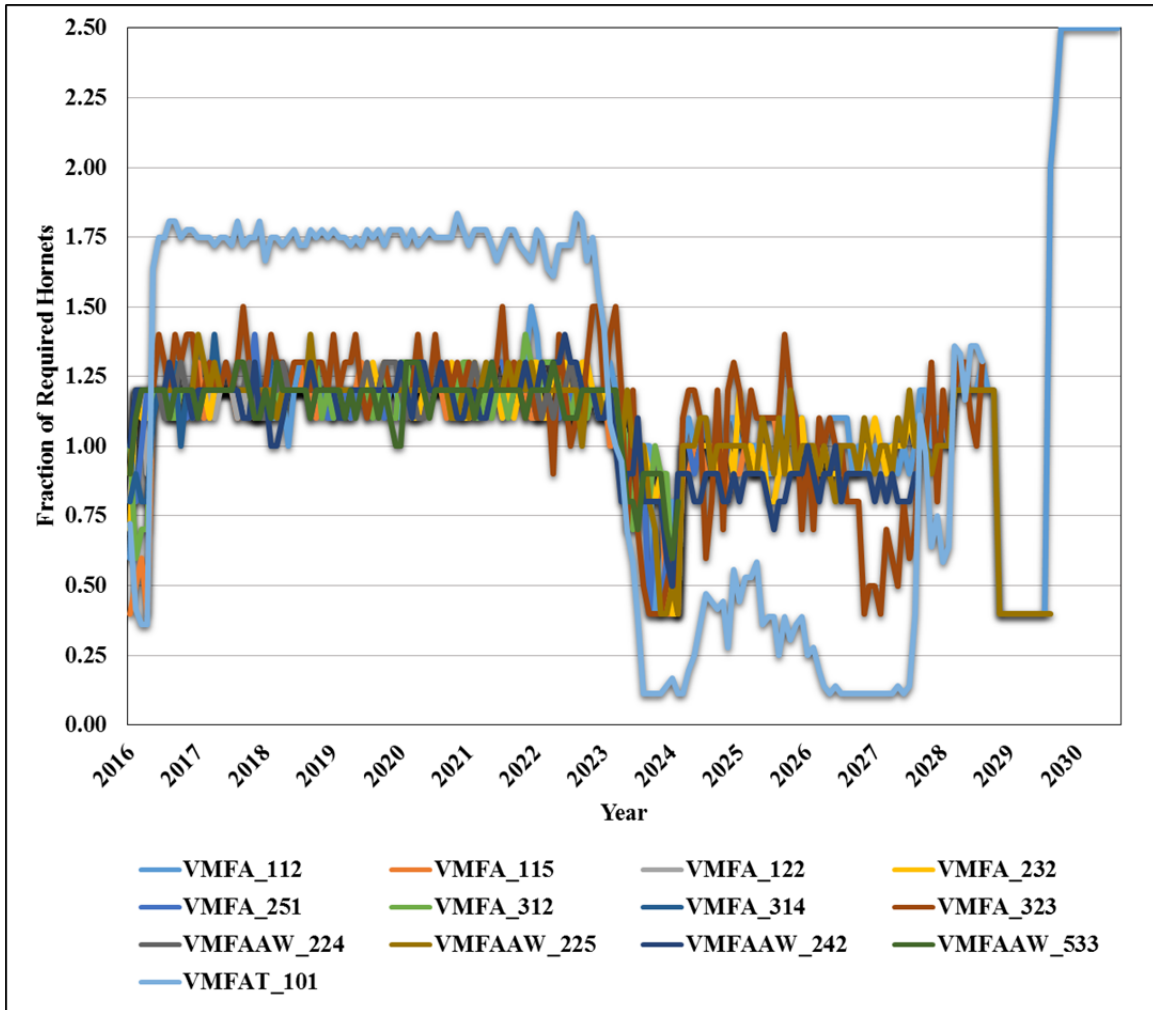
requirement during this 58 month window of shortages. The Hornet inventory still struggles to keep pace with the T-2.0 with fewer aircraft per squadron.



This figure compares the required number of Hornets for the operational rotation with the number that HASM prescribes as available. Note that despite the only requiring 83% of PMAI/PTAI to each squadron a shortfall begins May 2023.

Figure 24. S3 Number of Required Hornets versus Number of Hornets Available for the Operational Rotation.

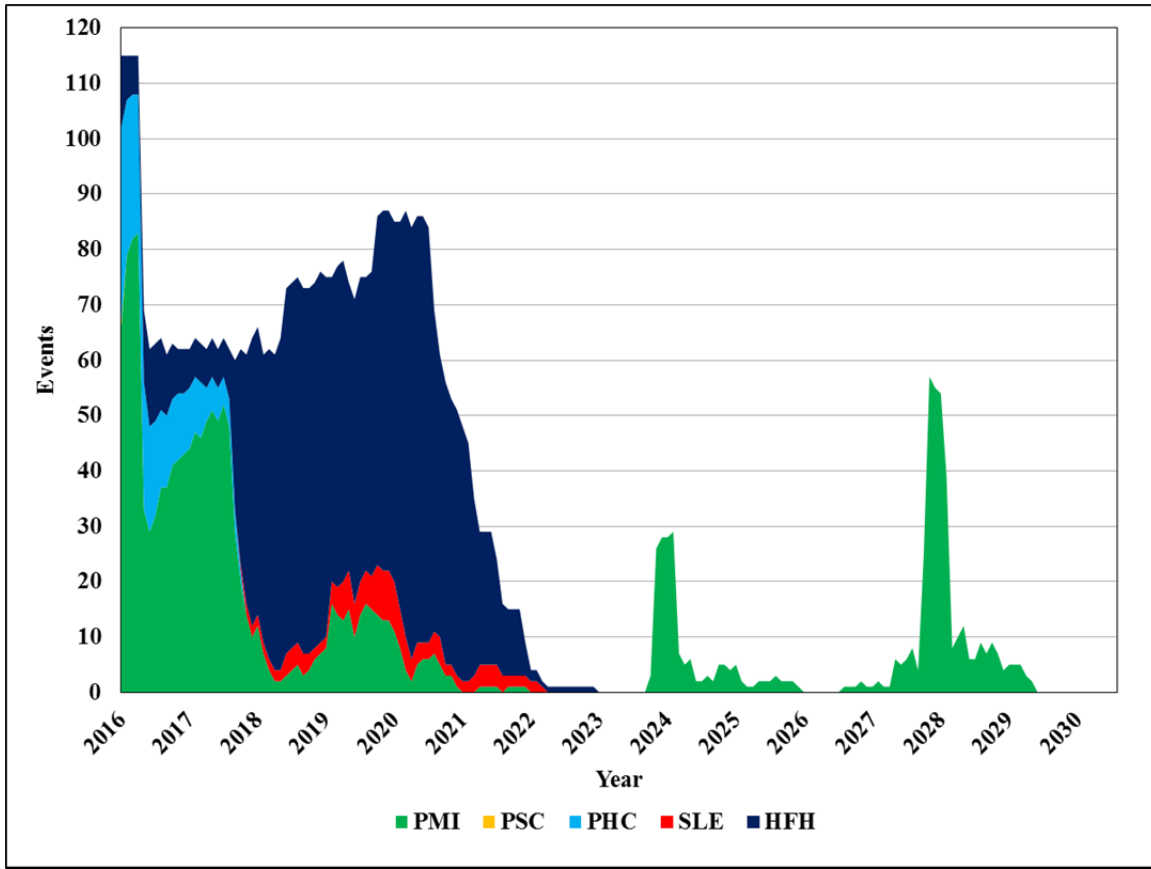
Figure 25 illustrates the fraction of the required number of Hornets assigned to each squadron across the entire time horizon. Reducing the required number of Hornets at each squadron gives HASM a greater degree of flexibility, but it uses up the remaining service life of the Hornets in the operational rotation much faster resulting in the shortfall beginning sooner.



This plot shows the number of Hornets assigned to each squadron across the time horizon normalized to 87% of the PMAI/PTAI values.

Figure 25. S3 HASM Hornets Assigned per Squadron Plot.

Figure 26 shows that HASM takes advantage of the lower number of Hornets required in operational rotation by front loading scheduled maintenance inductions. In particular, HASM accomplishes more HFH events compared to the previous scenarios. This helps to lessen the effects of the shortage of Hornets that occurs by having more Hornets available in the later time periods.



This figure shows that HASM front loads as much scheduled maintenance as possible.

Figure 26. S3 HASM Hornets Inducted for Depot Events.

4. S4: Relaxation of Both Flight Hours and Aircraft Assigned

S4 combines both relaxations from S2 and S3 to create the least constrained scenario. Reducing both the number of Hornets required by 17% and the monthly flight hours by 21% still does not entirely alleviate the aircraft shortfall. Figure 27 shows that the shortage in S4 occurs at approximately the same place in the planning horizon as S3. The Hornet inventory struggles to keep pace with the requirements during 2023 through 2028 in a similar fashion to S2. In contrast to the three previous scenarios, S4 provides the most Hornets during the aircraft shortfall. During this 58 month window, the operational rotation faces an average shortage of 26 Hornets. This is 27% of the operational rotation's Hornet requirement during this time period. Again the deficit appears earlier than in S1 or S2, but represents a lower deviation from the flight hour

requirements than in any of the previous scenarios. Figure 28 shows the fraction of the required number of Hornets assigned to each squadron across the entire time horizon. Reducing the required number of Hornets and the monthly flight hour requirements lessens the burden on the inventory, but these reductions are not enough to overcome the limited service life of the Hornets.

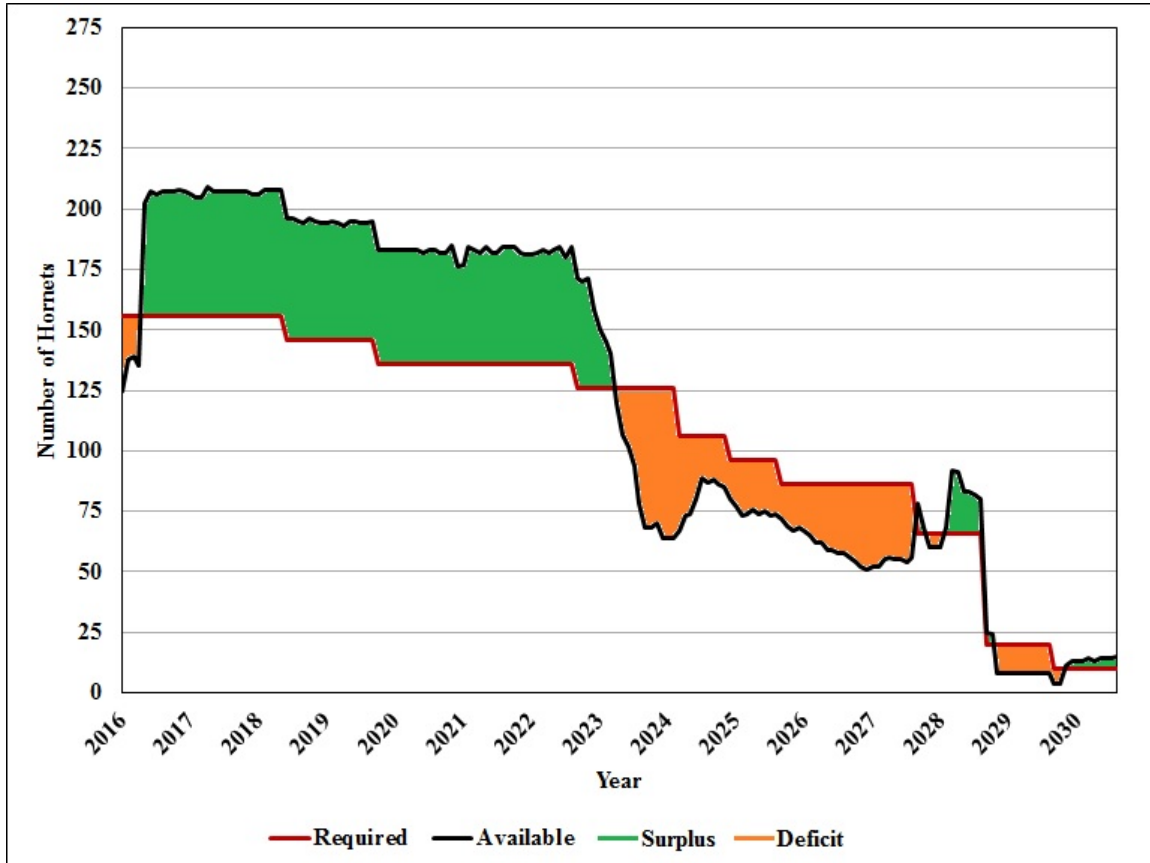
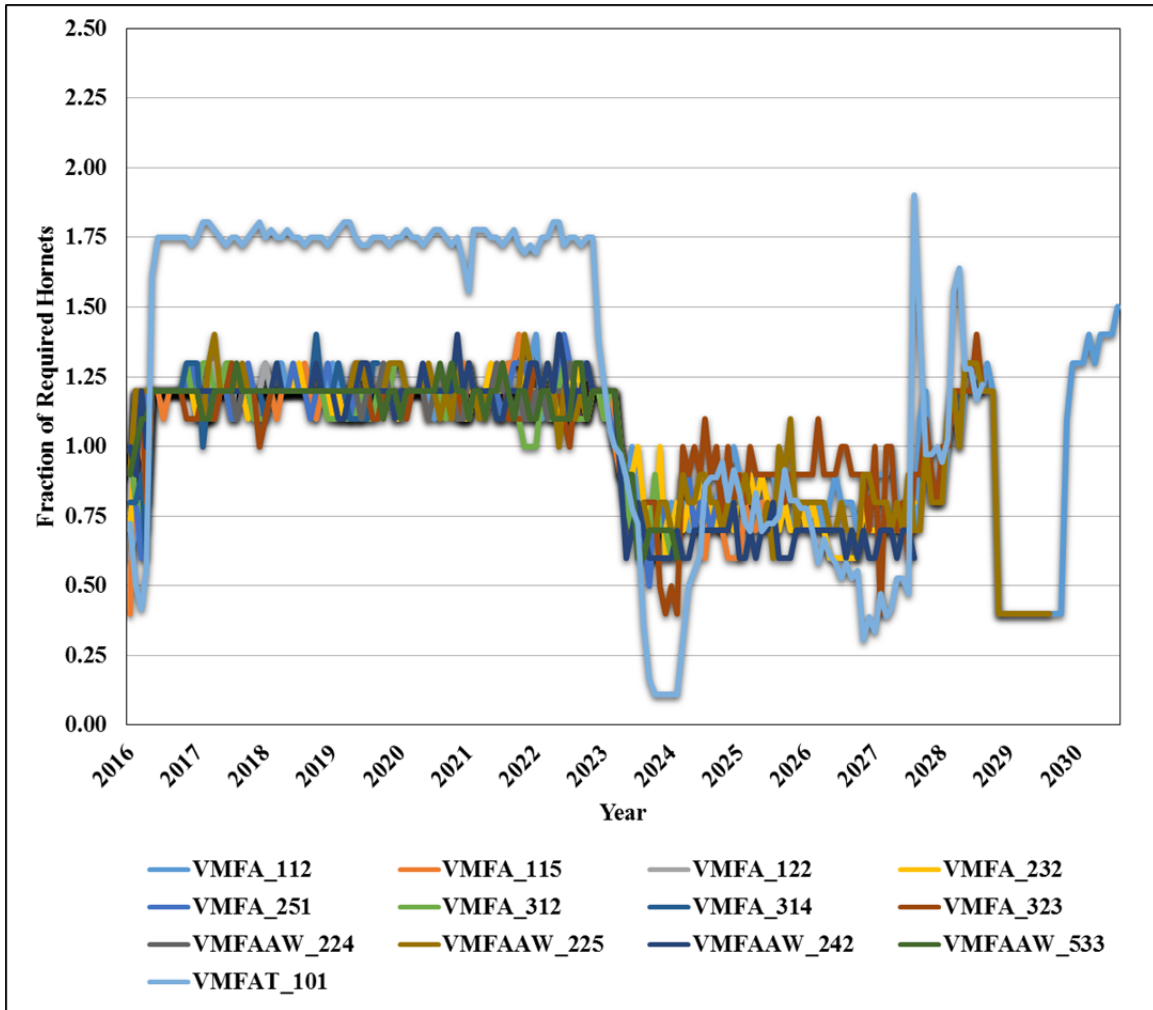


Figure 27. S4 HASM Number of Required Hornets versus Number of Hornets Available for the Operational Rotation.



This plot shows the number of Hornets assigned to each squadron across the time horizon normalized to 87% of the PMAI/PTAI values.

Figure 28. S4 HASM Hornets Assigned per Squadron Plot.

Figure 29 shows the depot prescriptions for S4 are very similar to those in S3. Again HASM takes advantage of the reduced requirements and looks to induct available Hornets into HFH maintenance during the beginning of the planning horizon. All of the necessary life extensions are completed before 2023 and this provides the greatest number of aircraft available once the shortfall begins.

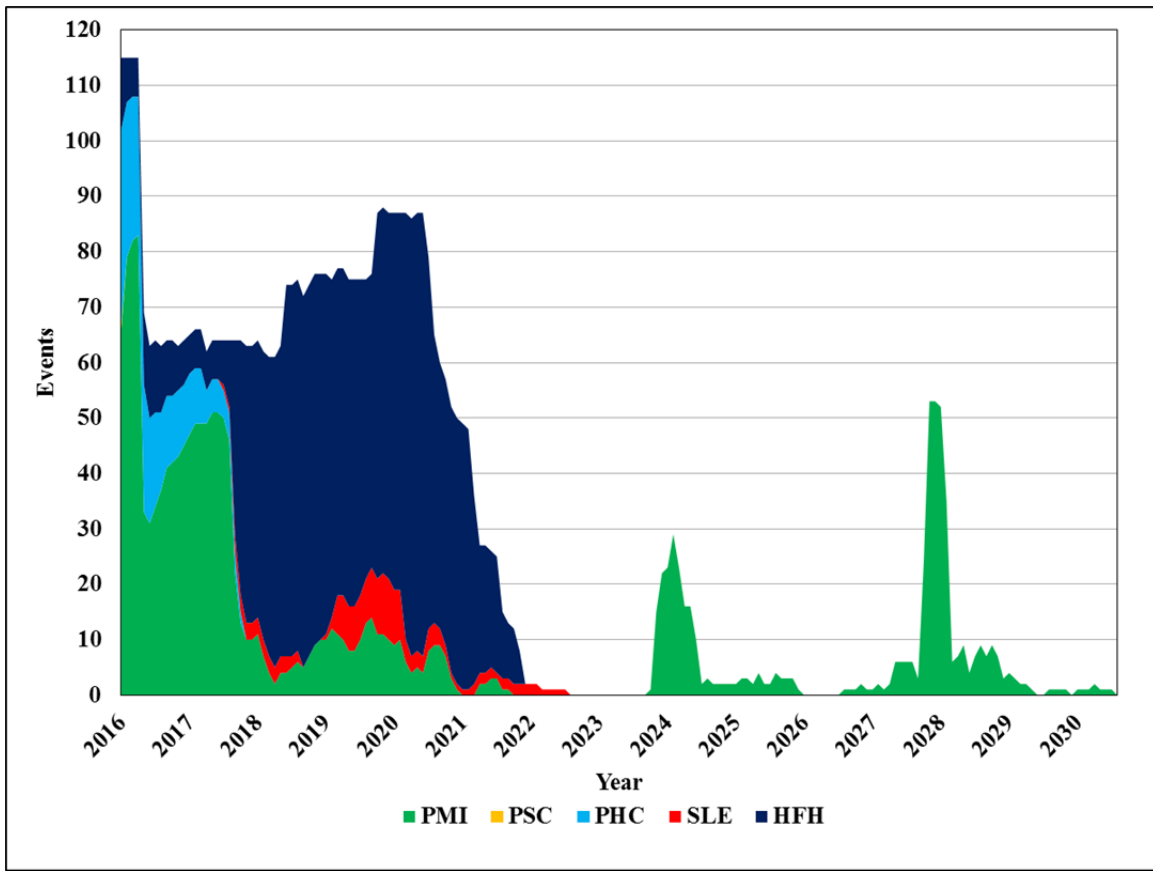


Figure 29. S4 HASM Hornets Inducted for Depot Events.

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V. CONCLUSIONS AND RECOMMENDATIONS

This chapter provides a summary of the conclusions from HASM and recommendations for follow-on work.

A. CONCLUSIONS

This thesis presents the Hornet Assignment Sundown Model (HASM) that prescribes each individual Hornet's monthly squadron assignment, utilization, maintenance, storage, and retirement over its remaining service life while ensuring each squadron satisfies (to the extent possible) monthly flight hour requirements. HASM provides an analytic tool to assist inventory managers in assigning individual Hornet squadron assignments, and it assists squadron commanders in understanding the flight hour progression of the Hornets in their squadron.

Difficulty sustaining ATARS capability within the F/A-18D squadrons emerges as an insight across all four scenarios. With only 18 specially configured Hornets, all near the same point in their service life, HASM cannot find a feasible solution that ensures assignment of at least one ATARS modified F/A-18D to each Marine Fighter Attack All Weather Squadron. In particular, this issue manifests in all four scenarios itself during June 2026 and affects both VMFA(AW)-225 and VMFA(AW)-242. Modifying additional Hornets or prioritizing ATARS equipped F/A-18D in depot maintenance for their life extensions may alleviate this capability shortfall.

Within HASM, requiring a fixed "no-later-than" date for individual Hornet retirements becomes problematic. Any attempt to enforce specific time periods, such as those listed in the February 2016 F/A-18A-F & EA-18G Flight Hour Inventory Report, results in infeasibilities when requiring a minimum number of Hornets during the time window of 2023 through 2029.

The simultaneous relaxation of both the number of Hornets required per squadron and the required number of flight hours underscores the difficulty in bridging a 14 year sundown period. Because service life extensions take a long period of time, spreading

these life extensions out earlier helps to prevent significant shortfalls in the 2026 timeframe, but it does not eliminate shortfalls.

Even with optimally assigning Hornets, a shortfall is unavoidable. There are two major strategies for mitigating this shortage: reducing the monthly flight hour requirement and reducing the Hornet assignment requirement. Dropping the monthly flight hour requirement results in a shorter period of increased deficit compared to reducing the number of Hornets per squadron. Reducing the flight hour requirement pushes the shortfall further into the planning horizon while reducing the number of Hornets forces this shortage to occur earlier. While reducing the number of aircraft assigned better aligns the requirement with the reality of asset shortages, it drives the remaining Hornets into depot faster.

Managing the USMC Hornet inventory represents a difficult resource constrained problem. Table 5 illustrates the tradeoff between the duration of the shortage of Hornets in the operational rotation with the average number of Hornet deficit. USMC inventory planners must weigh the risks between a longer periods of decreased Hornet availability with more assets for the operational rotation against a shorter deficit periods with less Hornets for the operational rotation.

Table 5. Statistics of Hornet Shortages in Each Scenario.

Scenario	Duration of Shortage (Months)	Mean Number of Hornets in the Deficit	Percentage of Required Hornets Deficit During Shortage
S1	34	41 +/-23	45%
S2	34	35 +/-23	41%
S3	58	30+/-16	37%
S4	58	26+/-15	27%

B. RECOMMENDATIONS FOR FUTURE WORK

In a time when the financial strain caused by increasing commitments in overseas contingency operations and shrinking defense budgets, the USMC must make every effort to improve management of scarce assets. The rising cost and uncertain future of the

JSF only increases the need to efficiently manage the resources in the Hornet inventory. This research developed an optimization model to assist the USMC F/A-18 decision makers manage individual Hornets across the sundown phase.

As the legacy F/A-18 Hornet nears the end of its extended service life, the USMC must decide how much risk they are willing to assume in future conflicts with respect to the capability the Hornet brings to the MAGTF. Several fundamental questions must be addressed. At what point do funds reserved for the purchase of the JSF get committed to stabilize the Hornet inventory? When will the cutoff for service life extensions of the Hornet end? How many Hornets must be assigned to a squadron? It is essential that the USMC answer such questions now to allow the optimal management of the Hornet inventory to support the needs of the MAGTF in the future.

Implementing anticipated operational rotations and requirements provides a more accurate picture of the challenges facing the Hornet inventory. This thesis uses a generic, unclassified template which requires only T-2.0 utilization or variations. The actual requirements can refine what HASM prescribes for utilizations and ensure that future operational needs are met.

Adding a factor to degrade future readiness of the Hornets in the operational rotation would paint a more accurate picture of the future health of the inventory. Like most mature aircraft, the Hornet suffers from an annual decrease in readiness based on aging. Dixon (2006) estimates an annual rate of decrease of 3.5% for aircraft that have been in service longer than 12 years.

Incorporating unscheduled depot maintenance events into HASM give greater fidelity to reducing the number of Hornets available for the operational rotation. These unscheduled events remove Hornets from the operational rotation and compete for resources in both labor and capacity at the depots and satellite facilities. HASM currently ignores these events, which allow it to assign greater than 100% of the required Hornets to squadrons during the first eight years of the time horizon.

De-aggregation of depot locations as individual FRCs will address the individual aircraft capacity, labor availability, and duration for each location. HASM's single depot node does not take into consideration the varying TATs or labor rates at each FRC.

Increase the ease of use by implementing a graphical user interface (GUI) to upload data and set values for parameters. HASM's interface resides as a script in GAMS and is not intuitive to alter data. A GUI would allow an individual not familiar with the application specific language and structure of GAMS to implement changes.

This research also creates a template which can be applied to other aircraft within the DON inventory. The USMC fleet of CH-53E Super Stallions represent an interesting extension of this work. The USMC anticipates starting the transition process of CH-53E squadrons to CH-53K in FY 19. HASM's framework is uniquely qualified to assist in the management of this transition.

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