NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MBA PROFESSIONAL PROJECT

ALLOCATING AIRCRAFT TO RESERVE MARITIME PATROL (VP) SQUADRONS: AN EXERCISE IN OPTIMIZATION MODELING

December 2018

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2018	**3. REPORT TYPE AND DATES COVERED** MBA Professional Project	
4. TITLE AND SUBTITLE ALLOCATING AIRCRAFT TO RESERVE MARITIME PATROL (VP) SQUADRONS: AN EXERCISE IN OPTIMIZATION MODELING			**5. FUNDING NUMBERS**
6. AUTHOR(S) Stephen C. Lovelace, Michael G. Garcia, and James L. Foster			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Reserve P-3 squadrons are directed to maintain a complement of six aircraft in their inventory. This number was determined through the application of a concept known as the crew seat ratio (CSR). While implementation of the CSR provides an accurate means of determining what is required operationally, further application results in excessive aircraft assignments, stressing maintenance capacities. The CSR assumes all aircrew will attain scheduled proficiency and readiness requirements. However, only deploying aircrew are expected to pursue readiness requirements throughout the FRTP. Therefore, applying a consistent ratio to all aircrew results in assigning more aircraft than what is required. The assignment of six aircraft can be burdensome, as reserve maintenance departments are at a disadvantage and not adequately staffed to support that many aircraft. This thesis performs multiple analyses in optimization modeling to determine the minimum ("best-fit") number of aircraft assignments for day-to-day operations while maintaining the requisite support for the active duty component. It accounts for constraints resulting from individual training and proficiency requirements, aircrew readiness and qualification requirements, and maintenance practices and capabilities. This thesis examines the development and application of The Orion Model (TOM), and demonstrates feasibility with an optimal solution of four aircraft assigned per squadron.

14. SUBJECT TERMS VP, P-3, maritime patrol, maintenance, aircraft assignments, PAA, optimization, modeling, readiness, scheduling, manning			**15. NUMBER OF PAGES** 53
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF BUSINESS ADMINISTRATION

from the

NAVAL POSTGRADUATE SCHOOL
December 2018

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Active Component
AMSRR	Aviation Management Supply and Readiness System
ASW	Anti-submarine warfare
ASuW	Anti-surface warfare
CSR	Crew seat ratio
DoD	Department of Defense
FRTP	Fleet readiness training plan
FTS	Full Time Support
GAMS	General Algebraic Modeling System
HASM	Hornet Assignment Sundown Model
ILP	Integer Linear Program
ISR	Intelligence, surveillance, and reconnaissance
MC	Mission capable
MPRF	Maritime Patrol and Reconnaissance Force
NATOPS	Naval Air Training and Operating Procedures Standardization
NMC	Not mission capable
NTA	Navy Tactical Assignment
OSD (AT&L)	Office of the Under Secretary of Defense for Acquisition, Technology and Logistics
PAA	Primary Aircraft Authorized
SELRES	Selective Reserve
TNR	Training and readiness
TOM	The Orion Model
USMC	United States Marine Corps
UCR	Unit Cost Relationship

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ACKNOWLEDGMENTS

We would like to thank Dr. Eddine Dahel for introducing us to the subject of modeling and for recognizing value in this thesis topic. Although we may not have worked together, his enthusiasm for the modeling and his lessons in its applicability to solving complex business problems proved invaluable. Professor Gregory Mislick did a tremendous job of taking independent MBA subject matter and integrating all of it to teach students common-sense approaches to solving DoD financial issues. He has a unique ability to shine light on student doubts, and if he didn't know the answer, he knew where to find one. Immediately upon meeting Dr. Emily Craparo for the first time, we knew she would be a welcome addition to the team. She understood exactly what we wanted to do and needed to do within 30 seconds of us pitching our thesis to her. Her expertise, insight, and detail orientation are peerless. Her saintly patience and willingness to tough it out with us were greatly appreciated. Lastly, we would like to thank Dr. Ryan Sullivan. His welcoming personality, ability to analyze a problem from many aspects, and succinct problem identification and resolution made this thesis a more enjoyable experience. Without the knowledge, commitment, and guidance of these experts, this work would not have been possible.

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I. INTRODUCTION

A. OVERVIEW

The Maritime Patrol and Reconnaissance Force (MPRF) began transitioning from the Lockheed Martin P-3C Orion to the Boeing P-8A Poseidon in 2013 (Office of the Under Secretary of Defense for Acquisition, Technology and Logistics [OUSD(AT&L)], 2016). As Active Component (AC) squadrons were pulled from their respective fleet readiness training plans (FRTP) to enter the six-month transition period, gaps in operational coverage concerning the anti-submarine warfare (ASW), anti-surface warfare (ASuW), and intelligence, surveillance, reconnaissance (ISR) mission sets were identified. To maintain transition continuity and minimize the loss of tactical coverage overseas, the Navy resourced Patrol Squadrons SIX TWO and SIX NINE (the two reserve squadrons of MPRF) to fill those gaps in the operational deployment plan. Figure 1 shows a side-by-side comparison of the P-3 and P-8.

Figure 1. P-8 Poseidon Platform Upgrade from the P-3C Orion.
Source: Battle Machines at battle-machines.org, (2018).

While the reserve component continued to meet the demands of the operational cycle through 2017, eventually the age of the P-3 platform, the diminishing support infrastructure (in contrast to the expansion of the P-8 support infrastructure), and limitations regarding the size and part time nature of a reserve force began to have a negative effect on the health of assigned aircraft. In early 2018 there was a growing concern that the workload associated with keeping six aircraft (the required number of aircraft assigned to a reserve squadron) in flyable and mission ready status stressed daily maintenance department capacity.

B. INTENT

This thesis performs multiple analyses in optimization modeling to determine the minimum ("best-fit") number of aircraft assignments for day-to-day operations while maintaining the requisite operational support for the active duty component. It draws on constraints from individual proficiency requirements, aircrew readiness qualifications, and scheduled and unscheduled maintenance practices. Naturally, unexpected events such as aircrew availability or repairs taking longer than scheduled risk rendering the optimal solution infeasible, however those concerns were mitigated with a conservative approach in applying the constraint values in the model.

C. VALUE-ADDED

Utilizing General Algebraic Modeling System (GAMS) software to develop an optimization model known as The Orion Model (TOM), the research team applied aircrew proficiency and readiness constraints from NATOPS General Flight and Operating Instructions Manual (OPNAV 3710.7) and the P-3 Wing Training Manual (COMPATRECONGRUINST 3500.25E). The model applied additional constraints from scheduled aircraft inspection cycles (found in instruction NA-01-75PAA-IMP-6-3) and unscheduled discrepancy maintenance efforts (data from historical 3M reports). Altogether, GAMS analyzed 2,641 decision variables and 1,278 constraints derived from these sources, and resulted in reserve capability with four aircraft.

Two substantial benefits can be derived from this result. First, a squadron performed significantly more maintenance with six aircraft (53 days a month) when compared to four aircraft (36 days). A reduction in the primary aircraft authorized ("PAA," or the number of aircraft assigned to a squadron), would increase maintenance capacity by 204 days annually. Additionally, a cost analysis could reveal how much money the DoD spends on the maintenance of two unnecessary aircraft.

Second, the successful application of TOM would prove to be of further use in future aircraft procurements. Recently, the reserve component of MPRF has been authorized to transition to the P-8A Poseidon aircraft sometime in the early to mid-2020s. Table 1 shows the Average Procurement Unit Cost for a P-8A Poseidon is \$197M in FY10\$.

Table 1. Average Procurement Unit Cost per P-8 in FY10\$M.
Source: OUSD (AT&L) (2016).

Item	BY 2010 \$M Original UCR Baseline (Jun 2004 APB)	BY 2010 \$M Current Estimate (Dec 2015 SAR)	% Change
Program Acquisition Unit Cost			
Cost	30271.9	30046.0	
Quantity	115	114	
Unit Cost	263.234	263.561	+0.12
Average Procurement Unit Cost			
Cost	22791.2	21508.5	
Quantity	108	109	
Unit Cost	211.030	197.326	-6.49

Normalized to FY18\$, that amount would be \$223,157,082.90. If both reserve squadrons are able to accomplish their objectives with two less aircraft assigned, then the Department of Defense could recognize significant cost savings of approximately \$892 in FY18\$M.

D. PREVIOUS WORKS

While no other work directly contributes to optimization modeling being applied to the allocation of unit level resources, this thesis will add to a growing Department of Defense effort to use modeling in identifying constraints, streamlining processes, and reducing unnecessary spending. Two Naval Postgraduate School theses in particular proved helpful in model development: *Optimizing training event schedules at Naval Air Station Fallon* (Slye, 2018) discussed the utilization of optimization modeling to schedule congested airspace blocks for local area F-18 training events. *Optimization of USMC Hornet inventory (*Zerr, 2016) served to employ optimization modeling in an effort to efficiently schedule remaining USMC F-18 Hornet service life hours as the community transitions to the F-35B. These theses assisted in defining the foundation upon which the P-3 reserve aircraft model was developed.

E. REPORT FLOW

The following chapter will provide a more detailed discussion on how the MPRF ended up in its present state. A literature review of previous works in modeling will then be discussed. From there, Chapter III will detail the development of TOM. Chapter IV will explain constraint sources, the development of the constraints, the application of constraints into TOM, and various scenario analyses. This thesis will end with conclusions based on findings, and make suggestions for further research or alternative model development.

II. BACKGROUND

A. HISTORICAL CONTEXT

The reserve component has always maintained a steady presence in the maritime patrol operational landscape. The thesis titled *Comparative cost analysis of P-3 active and reserve aviation forces: The economics of proposed force mix alternatives* summarizes findings in 1991's *Report on the Navy's Total Force* by providing insights in how the Reserve Component fit into the operational matrix. Historically, "both forces (AC and RC) are similarly manned, equipped, and have similar wartime missions. In most of the cases examined, active and reserve units were manned at, or near, full authorization levels," (Wrinkle & Carson, 1991). The justification behind similar asset allocations was that a reserve squadron should be able to seamlessly integrate into the maritime patrol deployment plan causing minimal disruption in coverage. During the Cold War years, P-3 Orion capabilities were in high demand. Conducting anti-submarine warfare missions to deter Russian military activity proved to be a continuous cycle; so much so that operational commitments had to be shared between 24 active duty squadrons and 13 reserve squadrons. Utilizing the reserve force was a smart decision financially as they incurred an annual cost of $14.6M in FY91 dollars, which was 44.5% less than active duty squadrons (Wrinkle & Carson, 1991). Arguments in favor for the employment of a reserve force were sound.

While the active and reserve component of MPRF enjoyed robust employment through the 1980s and early 1990s (defense spending reached a then all-time high of $325M in 1985) (GAO, 1992), the collapse of the Soviet Union ushered in the post-Cold War era, and set the stage for fiscal hawkishness in the DoD: "The United States has shifted its strategy from containment of the former Soviet Union to ensuring regional stability by focusing on strategic deterrence, overseas presence, and crisis response while maintaining an ability to rebuild, or reconstitute, a large force should a global threat reemerge" (GAO, 1992). This strategic shift served as the basis for a budgetary re-prioritization known as Base Force: "the Base Force is considered the minimum force structure required to address future regional contingencies against various potential threats" (GAO, 1992). One of the core goals of Base Force was to reduce military spending to $214M annually by 1997. Figure 2 details projected DoD budgets in an attempt to align appropriations with Base Force strategic objectives. In the wake of Base Force spending cuts, operational elements of the DoD needed to better justify budget outlays.

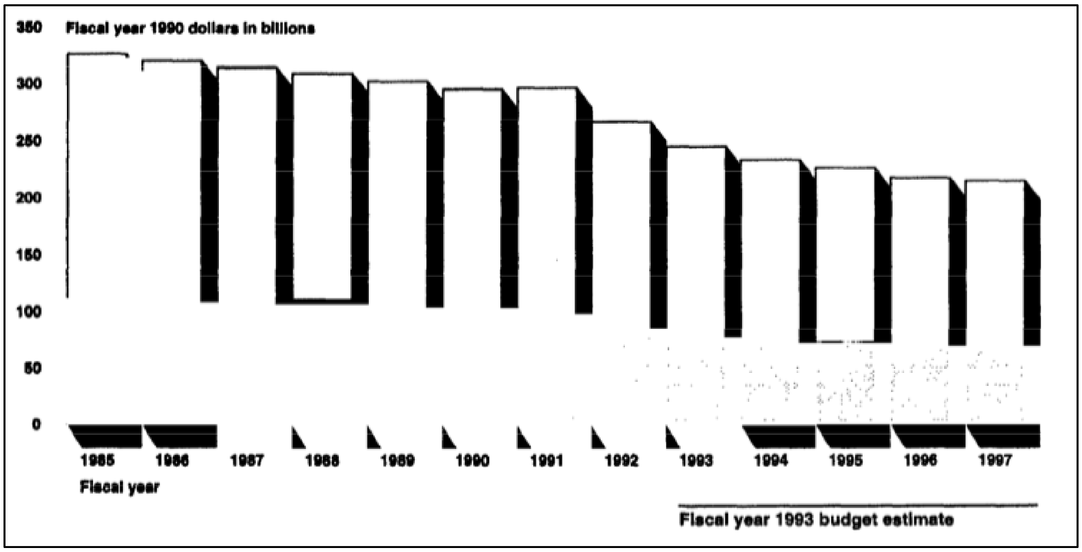

Figure 2. Base Force Budget Changes. Source: GAO (1993).

B. THE MPRF METHOD

To mitigate the risk associated with less funding (less flight hours, less training, less opportunity to maintain operational readiness, etc.), the maritime patrol and reconnaissance force set out to justify their budget through planning to support major combat operations. Through numerous wartime scenario analyses, it was determined that an active duty P-3 Orion squadron should have twelve combat ready aircrews with nine P-3 aircraft, and reserve squadrons were to have nine aircrews, with six aircraft, as promulgated by the Training & Readiness Matrix for MPRA (Commander, Patrol and Reconnaissance Group [CPRG], 2018). While a reserve P-3 squadron is built to accommodate nine aircrews, only three are required to maintain combat readiness qualifications (tactical NTAs as delineated on the P-3 Reserve Component Training & Readiness Matrix).

The reserve PAA of six is an extended application of a concept known as the crew seat ratio (CSR). It applies a constant factor to both readiness attaining, and non-readiness attaining aircrews, and does not consider what is required for operational preparedness and what isn't. While the CSR approach to resource allocation was sound, it failed to account for the operational scope and limitations of the reserve force.

C. DISADVANTAGE OF THE RESERVE FORCE

The basis of this research was grounded in the perception that the workload necessary to maintain six aircraft was too much for a reserve maintenance department. The concern stemmed from the fact that reserve squadrons are staffed at personnel levels less than active duty squadrons, but were responsible for similar quantities of resources. One such metric of this is summarized in Table 2 comparing maintenance personnel to PAAs of both reserve and active duty squadrons.

Table 2. Comparison of Reserve vs. Active Maintenance Personnel to Aircraft

	# Maintenance Personnel	PAA	Ratio of Personnel to Aircraft
Reserve Squadron	~75	6	13.1:1
Active Squadron (P-3)	~250	9	27.8:1
Active Squadron (P-8)	~250	7	35.7:1

As depicted above, a reserve squadron can assign approximately 13 maintainers per aircraft, compared to 28 per aircraft at an active duty P-3 squadron. Also consider that when an active duty squadron transitions to the P-8, that ratio increases to 36:1 due to a lower PAA. Clearly, a reserve maintenance department is not designed to handle the workload associated with maintaining similar stable size to that of an active duty squadron. This deficit is further compounded but the part-time nature of the reserve force, meaning that although 75 maintainers can be assigned to a squadron, generally only 35-40 personnel are present on any given day.

D. AIRCRAFT STATUS OBSERVATIONS

During an eight-month timeframe (November 2016 to June 2017), VP-69 encountered four months with four aircraft, and four months with five aircraft. The assumption was that aircraft health was negatively impacted by a seemingly overwhelming amount of maintenance required to take care of six aircraft, and that aircraft status would improve with four aircraft. That assumption didn't necessarily turn out to be the case. An Aviation Management Supply and Readiness Report (AMSRR) with the aforementioned date range shows that data to support the claim that too many aircraft impede readiness are mixed (Stephen Lovelace, unpublished data). As observed in Figure 3, there are no discernable conclusions that can be drawn about aircraft health as a function of PAA.

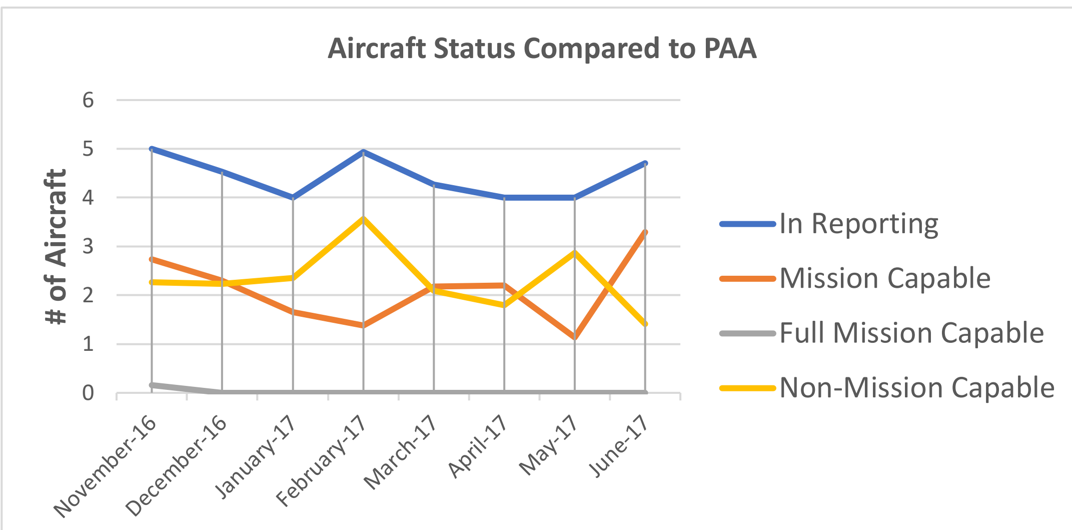

Figure 3. Aircraft Status Compared to PAA

A more detailed analysis of this data reveals that with an assignment of four aircraft, an average of 1.9 aircraft were mission capable (MC), and 2.3 aircraft were non-mission capable (NMC). With an assignment of five aircraft, 2.1 were MC and 2.3 were NMC. While NMC rates remained unchanged, MC rates improved slightly from 1.9 to 2.1 with five aircraft assigned. This runs counter to the assumption that less aircraft would result in healthier status; perhaps a larger sample size would reveal more definitive results in future analyses.

Regardless of the results, it was necessary to continue with TOM development to identify an optimal solution for aircraft assignments. This would promote the discovery of efficiencies in maintenance scheduling, and the potential to achieve cost savings in maintenance practices and future aircraft acquisitions.

E. LITERATURE REVIEW

When diving into previous works done, there are multiple works on aviation with regards to either inventory maintenance requirements and operations or scheduling and operations within the Department of the Navy. There were none found that looks at all three aspects of operation requirements, maintenance, and inventory optimization specifically at the unit level.

Scheduling maintenance activities has continued to be revisited by military strategist and planners. Efficiency is targeted by both the unit level and the larger wing level to execute mission. In Pippin (1998), a model was developed to look at UH-60 Blackhawk battalions to manage hour allocations with readiness for helicopter battalions. Inputs where flight data for the Blackhawk battalion through a range of operations that the UH-60 historically conducted. His results showed that a measured steady interval of aircraft scheduled to arrive into maintenance at set times both resulted in no backlogs and having an ample number of helicopters available to execute their mission set.

In similar works, Baker (2000) also looked at larger aircraft maintenance scheduling in that of depot level maintenance in the Navy and more specifically, the EA-6B Prowler depot. Similar to Pippin in that their model was to ultimately avoid any backlog from maintenance and scheduling. This model looks to schedule monthly maintenance for the Prowler depot while maintaining enough aircraft in the fleet available for normal flight operations and missions. Baker, while using this model, found ways to efficiently schedule the sequencing of depot level maintenance to avoid backlogs to avoid causing issues with the operational Navy EA-6B force.

Utilizing and Integer Linear Program model for managing the U.S. Naval Helicopter fleet, Marlow and Dell (2015) model meets minimum flight requirements imposed on squadrons embarked as well as ashore. These minimum flight hour requirements are further broken down into monthly and annual requirements. Their output is the schedule in which to put individual helicopters into maintenance while continuing to manage the current fleet to meet current operations and flight requirements. Marlow and Dell prescribe from their findings, monthly flight numbers, squadrons in which to do the flights, schedule for depot level maintenance, and ultimate retirement of aircrafts.

Also looking at streamlining the EA-6B depot level maintenance, Meeks (1999) analyzed two major functional events at the maintenance depot for the Prowler, that until this time, where scheduled separately. The two maintenance events were first that of the standard depot level maintenance requirement and second, that of a wing center section replacement. Utilizing an ILP to model the issue, Meeks was looking to efficiently schedule the depot to do one of the maintenance requirements or both in combination. With the ability to do both maintenance evolutions at one time, would overall reduce the down time an aircraft was out of the operational fleet. His model found a decrease of approximately 50% of non-available aircraft with the prospect of bundling the two maintenance functions at the depot. Again, creating efficiencies and optimizing available aircraft to the fleet.

With a slightly difference background and project on Air Force fighter squadrons, Gocken (2006) analyzed complex flight schedules and resulting waste from specifically scheduling one aircraft to one pilot. His research analyzed the options of having multiple aircrafts available as well as multiple pilots scheduled for varying events vice the current method of scheduling one aircraft with one pilot. To analyze his thesis, he developed an objective function that reduced pilot tasking and thus making their availability greater for utilization on the flight schedule. This resulted in the daily flight schedule as analyzed, to have more flexibility with unforeseen adjustments.

III. THE ORION MODEL (TOM) FORMULATION

This chapter describes the formulation of The Orion Model (TOM), an optimization model designed to assist in analyzing the minimum number of aircraft required to meet squadron requirements. TOM is a discrete-time optimization model with the following input parameters:

- Required maintenance sessions per aircraft per month
- Time periods per maintenance session
- Required events per Selected Reservist (SELRES) pilot
- Required events per Full Time Support (FTS) pilot
- Maximum number of simultaneous flight events
- Maximum number of aircraft in maintenance simultaneously

TOM prescribes a schedule of maintenance and flight activities that fulfills all aircrew proficiency and readiness requirements while satisfying constraints on aircrews, aircraft, and maintenance personnel. Although the output is a schedule, it is not expected that this schedule would be utilized in practice, due in part to the unpredictability of maintenance requirements. Rather, TOM's primary purpose is to determine the *feasibility* of operating with a particular complement of aircraft under conservative maintenance assumptions. TOM was developed to be able to modify parameters as conditions warranted (the addition or subtraction of individual aircrew numbers, rescheduling of flight events, maintenance workloads taking longer or shorter than planned, etc.). The model was also designed to stress constraints under a set of given variables (i.e., with five aircraft assigned, how many maintenance periods would the squadron be able to perform, how many flight events could be accomplished, etc.).

A. TOM LIMITATIONS

The following list of limitations apply to TOM, and could be considered in future work:

- TOM is designed to generate a schedule for determining asset allocations. It is not designed to schedule flights and maintenance in practice. Because of the dynamic nature of a reserve squadron due to unpredictable personnel availability, the model output is designed to justify feasibility of asset allocations.

- TOM assumes that pilots and maintenance personnel must work simultaneous days and schedules. It does not account for maintenance personnel being able to work hours that do not interfere with flight schedules (i.e., midnight shift or no-fly days).

- Due to difficulties in the collection of maintenance data, constraint inputs for scheduled inspections are educated estimates. Attempts to identify precise scheduled downtime were impeded by the limited accessibility of P-3 maintenance instructions and data.

B. TOM ASSUMPTIONS

The following list of assumptions were made and incorporated into the design of TOM:

- TOM assumes all maintenance will occur within prescribed proration periods

- TOM assumes that all pilots remain current on flight hours and use of the simulator is minimized

- TOM assumes 30-day month for proration purposes, but only 24 are used for flight and maintenance requirements

- Assumes that every SELRES pilot reports for duty every drill weekend

- TOM assumes all individual proficiency and aircrew readiness requirements are captured in the pilot flight hour constraint

- TOM assumes an 80/20 percent split regarding local and non-local replacement parts. Those replacement parts have a wait period of one hour, and 36 hours, respectively

- TOM assumes that 80% of maintenance work is done simultaneously, and that four discrepancies are being corrected at any given point in time

C. TOM MATHEMATICAL FORMULATION

Indices and sets:

$a \in A$	aircraft
$t, t' \in T$	time periods
$p \in P$	pilots

Data:

m^{req}	required number of maintenance sessions per aircraft, per month
m_time	required time periods per maintenance session
e_p^{req}	required number of flight events for pilot p
m^{max}	maximum number of aircraft in maintenance simultaneously
e^{max}	maximum number of simultaneous flight events

Decision variables:

$E_{a,p,t}$	binary; $E_{a,p,t}$=1 if pilot p is flying an event in aircraft a at time t, 0 otherwise
$M_{a,t}$	binary; $M_{a,t}$=1 if aircraft a is in maintenance at time t, 0 otherwise

Formulation:

$$\max_{E,M} \quad z$$

$$\text{s.t.} \quad z \leq |T| - \sum_{t,p} E_{a,p,t} - m\_time \sum_{t} M_{a,t} \qquad \forall a \qquad (1)$$

$$\sum_{a,t} E_{a,p,t} \geq e_p^{req} \qquad \forall p \qquad (2)$$

$$\sum_{t} M_{a,t} \geq m^{req} \qquad \forall a \qquad (3)$$

$$\sum_{p} E_{a,p,t} + \sum_{t':t-m\_time+1 \leq t' \leq t} M_{a,t'} \leq 1 \qquad \forall a,t \qquad (4)$$

$$\sum_{a} \left(E_{a,p,t} + E_{a,p,t+1} \right) \leq 1 \qquad \forall p,t : t \text{ odd} \qquad (5)$$

$$\sum_{a,p} E_{a,p,t} \leq e^{max} \qquad \forall t \qquad (6)$$

$$\sum_{\substack{a,t': \\ t-m\_time+1 \leq t' \leq t}} M_{a,t'} \leq m^{max} \qquad \forall t \qquad (7)$$

$$M_{a,t} = 0 \qquad \forall a,t : t \geq |T| - m\_time + 2 \qquad (8)$$

$$E_{a,p,t}, M_{a,t} \in \{0,1\} \qquad \forall a, pt \qquad (9)$$

D. DISCUSSION

TOM's objective is to maximize the minimum number of idle time periods experienced by any aircraft; constraint set (1) ensures that z is equal to this value. Constraint set (2) ensures that each pilot flies the required number of events, while constraint set (3) ensures that each aircraft receives the required number of maintenance sessions. Constraint sets (4) ensures that each aircraft and pilot, respectively, participate in only one activity per time period. Constraint set (5) ensures that each pilot flies at most one event per calendar day. Constraint sets (6) and (7) enforce the maximum number of simultaneous flight events and aircraft in maintenance, respectively. Constraint set (8) ensures that all scheduled maintenance sessions can be completed within the planning horizon. Constraint set (9) declares decision variable domains.

IV. ANALYSIS AND PERFORMANCE

This chapter details the data sources, model implementation and performance, and associated sample results of The Orion Model (TOM). TOM generates a projected asset allocation to accomplish all required individual proficiency, aircrew readiness, scheduled maintenance, and unscheduled discrepancy maintenance. The intent of TOM is not to be used as a scheduling tool; rather it is used to decide the minimum amount of aircraft needed to accomplish the P-3 reserve component mission. The output of multiple TOM scenarios is used as confirmation. The identification of an optimal value becomes increasingly important when the reserve P-3 force transitions to the P-8.

A. DATA COLLECTION AND NORMALIZATION

Individual proficiency and aircrew readiness requirements were collected via the P-3 Wing Training Manual, the OPNAV 3710 series, and the VP RC Training and Readiness Matrix. Maintenance downtime was broken down into two components: scheduled inspections as required by NA-01-75PAA-IMP-6-3, and unscheduled maintenance as determined by sampling eight months (November 2016 to June 2017) worth of 3M Report data from VP-69.

One challenge that needed to be addressed was that individual proficiency, aircrew readiness, and maintenance practices all had non-standard periodicities, ranging anywhere from monthly to 18-month requirements. Because of the variation in periodicities, pertinent constraint data was normalized and prorated to a 12-month requirement.

1. Individual Proficiency Constraints

Minimum hours required for individual aircrew proficiency (to include pilots, flight officers, flight engineers, acoustic operators, non-acoustic operators, and inflight technicians) were collected primarily from the OPNAV 3710 and the P-3 Wing Training Manual. A breakdown of the number of assigned aircrew by seat position and their requisite annual flight hours are listed in Table 3.

Table 3. Aircrew by Seat Position and Annual P-3 Aircrew Flight Hour Requirements

Pilot Flight hour requirement		100 </= a + b	a >/= b	a = pilot flight hours
FTS/SELRES	3/24			b = pilot sim hours
NFO flight hour requirement		48 </= c + d	c >/= d	c = nfo flight hours
FTS/SELRES	2/16			d = nfo sim hours
AWF flight hour requirement		48 </= e + f	e >/= f	e = awf flight hours
FTS/SELRES	13/5			f = awf sim hours
NAW flight hour requirement		48 </= g + h	g >/= h	g = naw flight hours
FTS/SELRES	4/5			h = naw sim hours
AAW flight hour requirement		48 </= i + j	I >/= j	I = aaw flight hours
FTS/SELRES	4/14			j = aaw sim hours
AWV flight hour requirement		48 = k		k = awv flight hours
FTS/SELRES	9/0			

Pilots are required to attain 100 flight hours per year, 50 of which can be gained through training evolutions in a Level D (motion-based) simulator. A schedule relying only on aircraft hours would require 8.3 hours per month (100 hours in 12 months), and a schedule capturing only 50 hours in the plane would require 4.3 hours per month (50 hours in 12 months). This study uses a value of 6.5 hours of flight time per month. Since no other crew member would be able to allocate flight hours without pilots flying the aircraft, and since their requisite hours are less than the pilot requirement, their flight hours were rolled into the pilot constraint.

2. Aircrew Readiness Constraints

To identify constraints for aircrew readiness requirements, qualifications, periodicities, and hours per qualification were taken from the VP RC Training and Readiness Matrix and the P-3 Wing Training Manual. Table 4 shows a simplified qualification schedule of six anti-submarine (ASW), five anti-surface (ASuW), and seven intelligence/surveillance/reconnaissance (ISR) qualifications required to be maintained by readiness attaining crews. The number of times that a specific qualification was to be conducted in an aircraft and the number of hours required per qualification were then calculated, and subsequently prorated.

Table 4. Reserve Aircrew Readiness Qualifications. Source: CPRG (2018).

Qualification	Periodicity		Hours per Qual	# Flown per FRTP	# flt hours req'd per crew per FRTP	
ASW 201	1/90	Alternate Flt/Sim	2.0	3	6	
ASW Detect-to-Engage (DTE)						
ASW 202	1/90	Alternate Flt/Sim	2.0	3	6	
ASW Localization / Tracking						
ASW 203	1/180	Alternate Flt/Sim	2.0	3	6	
ASW Coordinated Ops						
ASW 204	1/720	Flt	2.5	1	2.5	
Range Torpex						
ASW 206	1/240	Alternate Flt/Sim	2.5	2	5	
Acoustic Collection Training						
ASW 207	4/240	Flt or Sim	2.0	N/A	N/A	
Basic ASW Proficiency						
ASU 201	2/365	Alternate Flt/Sim	2.0	1	2	
ASU Joint/Combined Ops						
ASU 202	1/720	Flt	1.5	1	1.5	
Depth Bomb						
ASU 203	1/180	Alternate Flt/Sim	2.0	2	4	
Harpoon						
ASU 204	2/540	Alternate Flt/Sim	1.0	1	1	
Maverick						
ASU 206	1/365	Alternate Flt/Sim	1.0	1	1	
MINEX						
ISR 201	2/365	Flt	2.0	2	4	
Maritime Surveillance						
ISR 202	2/240	Flt	2.0	3	6	
Reconnaissance						
ISR 203	4/720	Flt	2.0	4	8	
Emitter Recognition						
ISR 204	1/180	Flt	2.0	3	6	
EW Collection Trng						
ISR 206	1/120	Flt	2.0	5	10	
Overland SAR Reconnaissance						
CCC 201	3/365	Flt	2.0	2	4	
ASW C4I						
C2W 201	2/720	Sim	1.5	N/A	N/A	
Combat Arrival / Departure						
					73	FLT Hours per aircrew per FRTP (18 months)
					219	x 3 Crews
					12.2	Prorated Monthly Requirement

A single aircrew must fly 73 hours tactically during a Fleet Readiness Training Plan (FRTP) to maintain readiness; thus, three aircrews require 219 flight hours. After proration, aircrews must allocate 12.2 hours tactically per month to maintaining readiness. This requirement is also captured in the pilot flight hour constraint as each flight requires a minimum of two pilots (although on tactical events three pilots are usually scheduled) as 12.2 hours falls inside of 13 hours (for two pilots).

3. Maintenance Constraints

P-3 maintenance instruction NA-01-75PAA-IMP-6-3 and 3M reports from November 2016 to June 2017 serve as maintenance constraint data sources.

Scheduled maintenance events include the 45-day inspection, the 90-day inspection, the 365-day inspection, the annual phase inspection, 600-hour engine and propeller inspections, and a 1,200-hour inspection. Monthly prorations were calculated for the 45/90/365/phase inspections by taking the hours required per NA-01-75PAA-IMP-6-3, multiplying it by the number of times that inspection will be conducted annually, and dividing by 12 months. The 600- and 1,200-hour inspections are conducted only when an engine reaches that amount of operating time. Therefore, it was not possible to capture the frequency, and thereby determine a proration value for those inspections. However, those inspections all require less than a day's work and can be mitigated by assigning a higher constraint value than what is mathematically required in the model.

To calculate the unscheduled maintenance proration value, eight months of historical 3M data from VP-69 were reviewed (November 2016 to June 2017). It was necessary to break out and analyze three complimentary components: the average number of man-hours performed per month, the average number of hours spent waiting on the arrival of replacement parts, and simultaneous maintenance work.

The process to determine the average number of man-hours performed per month was straightforward. Monthly man-hour values were provided in respective 3M reports, and an average was taken. The resultant value was 1,130.7 man-hours. This value was divided by the average number of discrepancies issued per month (145.5). This resulted in a value of 7.8 average man-hours per discrepancy. Assuming four maintenance personnel were assigned to a discrepancy simultaneously, 7.8 was divided by 4 to determine the average individual labor-hours (i.e., hours the plane is down) per discrepancy (1.94 hours).

Then it was necessary to calculate the time required to procure replacement parts. It was assumed that 80% of replacement parts could be locally sourced and obtained in a short time period (one hour). The remaining 20% of replacement parts must be ordered and shipped from non-local storage facilities, requiring an average of a day and a half (36 hours). Thus, the average expected time to procure parts for a work order was 1 hour*0.80 + 36 hours*0.2 = 8.0 hours awaiting parts.

Then 1.94 and 8.0 were summed to determine total hours per gripe the aircraft spent in a down status per discrepancy (9.94 hours).

To account for simultaneous maintenance efforts, first the average number of work orders per month was divided by the average number of aircraft assigned per the eight-month period (145.5/4.5 = 32.3 work orders per aircraft per month). It was assumed that 80% of the time, multiple work orders were being executed on an aircraft simultaneously, with an average of four simultaneous work orders. Thus, 80% was taken from 32.3 (32.3*0.8=25.84 work orders per month being worked on simultaneously); 25.84 was then divided by 4 work orders at a time to equal 6.46. To account for the 20% of work orders that are worked on individually, 20% of 32.3 was taken (32.3*0.2=6.46). 6.46+6.46=12.92 work orders per aircraft per month; 12.92 was then multiplied by 9.94 hours to get a total of 128.4 hours per aircraft per month.

Summing up the scheduled and unscheduled maintenance proration amounts, an aircraft can be expected to be down for maintenance 8.8 days per month. Table 5 highlights the unscheduled maintenance methodology and Table 6 displays the proration schedule to determine the monthly downtime per aircraft.

Table 5. Unscheduled Maintenance Methodology

Total gripes:	145.5	Hours to get "local" parts:	1	Gripes per aircraft per month:	32.3
Total man-hours:	1130.7	Hours to get "distant" parts:	36	Fraction of gripes that occur simultaneously:	0.8
Maintainers working simultaneously per gripe:	4	Fraction of parts that are "local":	0.8	Number of simultaneous gripes per occurrence:	4
Man-hours per gripe:	7.77113402	Fraction of parts that are "distant":	0.2	Hours per day:	24
Individual-hours per gripe:	1.94278351	Expected wait time for parts:	8	**Total monthly downtime per aircraft (hours):**	**128.460763**
				Total monthly downtime per aircraft (days):	**5.35253179**
Historical data					
SME estimates					
Intermediate calculations					
Final results					

Table 6. Maintenance Downtime per Aircraft per Month

Inspection	Hours per Inspection	Inspections per Year	Hours per Year	Monthly Proration (In Hours)
45 Day	39.8	8	323	26.9
90 Day	37.5	4	152	12.7
365 Day	1	1	1	0.1
Phase	504	1	504	42.0
Total Scheduled				81.7
Unscheduled Factor				128.4
Tot. Avg Downtime for MX (Hours)				210.1
Tot. Avg Downtime for MX (Days)				8.8

As depicted in Table 6, it is estimated that an aircraft will spend 8.8 days per month in a down status due to maintenance. The maintenance constraint in TOM was assigned a conservative value of 10 days.

4. Data Setup

A reserve squadron consists of both Full Time Support Officers (FTS) and Selective Reservists (SELRES). It was necessary to distinguish between the two groups since they have different training requirements. In identifying constraints for TOM, FTS pilots were designated P1-3 and SELRES pilots were designated P4-27. FTS pilots are expected to fly eight events per month (an average of twice a week). SELRES pilots are available for flight duties twice a month. This allows them to attain their requisite monthly hours over a two-day window. Realistically, SELRES pilots are also expected to perform one day of "active duty time," which would bring their monthly availability up to three days, but for the sake of conservatism, this element was not included in TOM. These constraints are consistent with training requirements as delineated per the P-3 Wing Training Manual and the OPNAV 3710.

Since it is impossible for an aircrew to achieve readiness without the presence of tactical crew members (non-pilots), and since their flight hour requirement was superseded by the pilot requirement, the assumption is that the monthly flight hours to attain readiness has been rolled into the pilot monthly requirement as well.

As discussed in Figure 4, the average total downtime per aircraft per month is 8.8 days. This number has been increased in TOM to 10 days to add an additional conservative factor. Additionally, it was determined that no more than two planes would be flying or in maintenance at any given time to capture the essence of real-world scheduling in TOM.

B. SCENARIO DEVELOPMENT

For modeling purposes, a 30-day month was initially assumed. Assigning two time periods (day check and night check) over the course of a day, TOM initially accounted for 60 time periods. It was soon realized this was an overestimation of a squadron's work schedule. A reserve squadron operates a Monday-Friday schedule plus one drill weekend a month. Therefore, six remaining weekend days (12 time periods) were removed from TOM. The updated model currently uses 48 time periods.

C. SCENARIOS

TOM was run under four separate scenarios with varying conditions to determine the minimum number of aircraft required to meet reserve P-3 objectives. Each scenario was run in GAMS (CPLEX 12.6.3.0) using the following sample matrix of inputs shown in Figure 4.

```
SETS
A aircraft /a1*a4/
T time periods /t1*t48/
P all pilots /p1*p27/
F(p) FTS pilots /p1*p3/
;
ALIAS(t,tp);

PARAMETERS
M_req  required maintenance sessions per aircraft per month /5/
Mt     time periods per maintenance session /4/
S_req  required events per sel_res pilot /2/
F_req  required events per FTS pilot /8/
R_max  maximum number of simultaneous events /2/
M_max  maximum number of aircraft in maintenance /2/
E_req(p) number of required events for pilot p
*E_M   extra maintenance session needed per this many events /8/
;
E_req(p)=S_req;
E_req(f)=F_req;

BINARY VARIABLES
E(a,p,t) is aircraft a flying with pilot p at time t
M(a,t) is aircraft a in maintenance at time t
```

Figure 4. Sample GAMS Input Data

The four scenarios ran were:

1. Baseline Scenario – This scenario was run using average proficiency, training, and maintenance values as constraints. The goal was to determine what the minimum number of aircraft assigned to a squadron should be in order to accomplish their mission.

2. Maintenance Intensive Scenario – Once the minimum number of planes required were identified, maximum maintenance values were applied to

stress TOM to the breaking point. Maintenance values were determined to be the constraint to be stressed because analyses demonstrated that the greatest variability in the data resided in unscheduled discrepancy work orders.

3. Comparison Scenario – After identifying the minimum number of planes needed, a comparison was then drawn between those results and the current PAA requirement. Because flight hours flown would not change based on the number of assigned aircraft, conclusions would be drawn between scenario 1 and the current PAA and would be evaluated on the difference of maintenance days required.

4. One Aircraft in Phase Maintenance Scenario – A fourth scenario run to ensure a squadron can accomplish its mission with one aircraft in a month-long phase inspection. Instead of prorating a 30-day inspection over 12 months, this scenario runs constraints through an 11-month cycle, which effectively accounts for a month-long phase inspection.

Table 7 highlights the changes in parameters for the given scenarios.

Table 7. Input Data in TOMS Scenarios

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
# of Aircraft (*A*)	4	4	6	3
Required maintanance sessions per aircraft per month (M_req)	5	6	5	3
Time periods per maintanance session (Mt)	10	12	10	6
Required events per FTS pilot (F_req)	8	8	8	8
Required events per SELRES pilot (S_req)	2	2	2	2
Maximimum number of simultaneous events (R_max)	2	2	2	2
Maximum number of aircraft in maintanance (M_max)	2	2	2	2

TOM took less than one second to run through 2,641 decision variables (columns), and 1,278 constraints (rows).

1. Baseline Scenario Results

In determining the optimal number of aircraft, all constraints remained the same while the number of aircraft assigned *A* decreased by one. The scenario began with *A*=6 (the current PAA), and decreased by one aircraft each excursion of the model to determine the minimum number of aircraft needed. After each excursion, data analyses focused on two variables. The first was the amount of downtime observed with different values of t (time periods). The second was the total number of maintenance periods observed for all aircraft.

A feasible solution was identified as low as *A*=3, but that left minimal capacity for rescheduled flight events, or maintenance schedule overruns. This led to the conclusion that *A*=4 was the optimal solution. It allowed for all pilot training to be achieved with more capacity for maintenance work. Figure 5 represents a schedule of events when four aircraft are assigned.

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
a1	p27	p12	p14	p24	maintenance	maintenance	maintenance	maintenance	maintenance	maintenance	maintenance	maintenance
a2	p10	p20	p22	p3	maintenance	maintenance	maintenance	maintenance	p4	p3	p4	p17
a3	maintenance	maintenance	maintenance	maintenance	p2	p3	p2	p18	p21	p1	p1	p21
a4	maintenance	maintenance	maintenance	maintenance	p1	p13	p13	p23	maintenance	maintenance	maintenance	maintenance
	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
a1	p2	p1	p1	p2	p18	p17	p10	p12	maintenance	maintenance	maintenance	maintenance
a2	p3	p7	p22	p19	maintenance	maintenance	maintenance	maintenance	p8	p16	p11	downtime
a3	downtime	downtime	downtime	maintenance	maintenance	maintenance	maintenance	maintenance	maintenance	maintenance	maintenance	p25
a4	maintenance	maintenance	maintenance	maintenance	p3	p23	p2	downtime	p2	p19	p2	p16
	t25	t26	t27	t28	t29	t30	t31	t32	t33	t34	t35	t36
a1	p24	p3	p15	p27	downtime	maintenance	maintenance	maintenance	maintenance	p7	maintenance	maintenance
a2	maintenance	maintenance	maintenance	maintenance	downtime	downtime	downtime	downtime	downtime	downtime	downtime	p14
a3	p25	p9	p9	p20	downtime	p3	downtime	maintenance	maintenance	maintenance	maintenance	downtime
a4	downtime	maintenance	maintenance	maintenance	maintenance	downtime	downtime	downtime	p6	p1	downtime	p1
	t37	t38	t39	t40	t41	t42	t43	t44	t45	t46	t47	t48
a1	maintenance	maintenance	downtime	downtime	downtime	downtime	downtime	downtime	p11	downtime	downtime	downtime
a2	maintenance	maintenance	maintenance	maintenance	downtime	p1	p15	downtime	maintenance	maintenance	maintenance	maintenance
a3	p5	p2	p5	downtime	downtime	downtime	p6	downtime	maintenance	maintenance	maintenance	maintenance
a4	downtime	downtime	p8	maintenance	maintenance	maintenance	maintenance	downtime	p26	downtime	p3	p26

Figure 5. Schedule of Aircraft Events when A=4

2. Maintenance Intensive Scenario Results

The purpose of scenario 2 was to identify the most intense maintenance requirement that could be accommodated with *A*=4 aircraft. This is accomplished by manipulating *M_req* and *Mt* parameters. By manipulating these parameters, a sensitivity analysis of the most volatile resource was run. It was determined that the optimal PAA of four aircraft can take on two days of extra maintenance opportunities per month (4 time periods) and maintain feasibility. While it does not seem like much value added, it is important to remember that this value is in addition to the average daily downtime of 8.8 days, which was conservatively allocated in TOM as a 10-day constraint.

3. Comparison Scenario Results

After identifying the optimal number of aircraft, it was important to assess the projected benefit comparing the current PAA to the optimal PAA according to TOM. The importance of this comparison led to the identification of improved maintenance capacities, and significant savings in terms of repair and future acquisition costs.

To conduct this comparison, 8.8 days of maintenance downtime was applied to both a PAA of six and four aircraft. Under the current PAA of six aircraft, 106 time periods (53 days) was the required maintenance downtime for all aircraft per month. Using TOM's optimal solution of four aircraft, the number of maintenance time periods decreases to 72 (36 days). A reduction in PAA reduces the amount of time needed to keep the aircraft in flyable and/or mission ready status.

This is significant: a reduction of two aircraft in a squadron's stable size increases maintenance capacity, allowing to better absorb the impact of maintenance overruns, and pilots and aircrews can still fly their requisite number of hours and missions. This becomes especially important when considering the transition of the reserve community from P-3 to P-8, potentially scheduled in the early to mid 2020s. Being able to do the same mission while purchasing four less total aircraft (two for VP-62 and two for VP-69), could save the DoD approximately $892M in FY18$.

4. One Aircraft in Phase Maintenance Scenario Results

As demonstrated above, annual maintenance requirements were identified, normalized, and prorated to a monthly factor. This monthly factor provided a uniform unit of measurement easily accounted for in TOM. While the prorated factor was calculated accurately, it did not capture the absolute unavailability of an aircraft in a 30-day phase inspection. This scenario was run to ensure the three remaining and available aircraft would be able to handle training demands while the forth underwent a phase inspection.

While this scenario is feasible, the margin of capacity for the remaining aircraft is small. This risk can be mitigated by long term planning of phase inspections around periods of light operational requirements throughout the FRTP.

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V. CONCLUSION

TOM incorporated constraints derived from individual proficiency requirements, aircrew readiness requirements, and scheduled and unscheduled maintenance practices and prescribed a schedule of squadron activities that led to the identification of an optimal number of aircraft assignments. It was observed through multiple scenario analyses of optimization modeling that a reserve P-3 squadron can comfortably achieve operational objectives with an assignment of four aircraft.

The initial baseline scenario was run with a PAA of six, and decreased the number of aircraft by one until a feasible solution was not able to be achieved. Feasibility was achievable as low as A=3, but no excess capacity existed at that point. Therefore, it was determined that A=4 struck a good balance between flight availability and maintenance requirements. Additional scenarios stressed constraints with A=4 and determined that two additional days' worth of maintenance could be achieved while still providing requisite flight opportunities for aircrews to conduct training. The maintenance required for A=6 and A=4 were then compared. While model output data did not support an analysis of required maintenance time for either A=6 or A=4 scenarios, by incorporating historical observations in maintenance calculations, it was determined that maintenance requirements unavoidably increased with an higher PAA. Therefore, an analysis of input data revealed that a stable size of six aircraft required an additional 17 days' worth of extra maintenance to keep aircraft in a flyable status. Lastly, TOM ran a scenario where one aircraft endured a 30-day phase inspection; essentially, three aircraft would have to prove capable of handling flight requirements for a 1-month period. TOM proved feasibility under these conditions, just as the baseline scenario demonstrated capability with A=3. However, the risk associated with being unable to satisfy monthly flight requirements increased. Fortunately, this risk could be mitigated by long-term planning for scheduled phase inspections (i.e., with four aircraft, a phase inspection should only need to be conducted once every three months).

Although the data to support the hypothesis that more aircraft resulted in a higher maintenance burden and less "up status" aircraft proved to be inconclusive, the development and utilization of TOM has proven useful for several reasons. First, the 17 days of extra maintenance capacity made possible with a PAA of four will allow squadron maintenance departments to improve upon the mission capability of the aircraft (as stated in Chapter II, the number of mission capable aircraft averaged 1.9). Second, it is now possible to conduct a cost analysis to realize potential savings by not having to maintain two additional aircraft. Lastly, requiring VPs 62 and 69 to maintain four aircraft per squadron in preparation of the prospective P-8 acquisition would save the DoD approximately $892M (FY18$).

Further Research

TOM serves as a starting point for analyzing DoD business from a different point of view. However, there are several suggestions for further research. First, the legitimacy of this research would have benefitted from analysis and application of more data. Eight months of maintenance data provided too small of a sample size to make any real determination of the effect of aircraft assignments as they relate to aircraft status.

A major hurdle during this thesis was the development of a method to capture unscheduled maintenance as accurately and reasonably as possible. Replacement part percentages and wait times and simultaneous work factors were all based off of historical observations. Again, a deeper analysis of maintenance data would help identify more realistic value to these TOM inputs, which would thereby generate more accurate proration rates. Furthermore, this analysis would prove helpful in determining how wait times affect aircraft status as P-3 supply lines are steadily downsized in favor of the growing P-8 supply infrastructure.

Lastly, an aspect of the reserve component that was not integrated in TOM was the impact of the deployment cycle. Observing how TOM would respond to constraints when a certain number of aircraft and aircrew are deployed for a period of time would provide valuable insight in exactly how many aircraft a reserve P-3 squadron should be assigned.

APPENDIX TO CHAPTER IV

Additional Analysis

The premise of this research assumed that the current PAA overwhelms the capacity of a maintenance department, therefore an additional analysis was run to account for overlap as it relates to the cycles of scheduled inspections. One primary difference in this model as it compares to the baseline model, is that it accounts for delays and schedule overruns (upwards of four days) for the scheduled inspections. This model was developed in GAMS with the intention of making a binary decision on whether scheduled inspections for all aircraft could be conducted without overlap.

Results from Additional Analysis

When the model for a PAA of six aircraft was run, it was shown that there were more flight opportunities provided to the aircrew, but it came at the cost of scheduled inspection overlap (Figure A.1). Specifically, over a one-year period, two or more aircraft would be in simultaneous inspections more than 30 times. This overlap would make it much more difficult for the maintenance department to take corrective action on unscheduled discrepancies that would inevitably arise throughout the year.

When the model for a PAA of four aircraft was run, it was observed that it was possible for a maintenance department to schedule all requisite inspections without any overlap. As a result, maintenance capacity increases, improving the ability to take corrective action on unscheduled discrepancies.

	a1	a2	a3	a4	a5	a6
t1		ff1				
t2		ff1				
t3		ff1				ff1
t4		ff1				ff1
t5						ff1
t6						ff1
t7						
t8						
t9						
t10		phase				
t11		phase				
t12	ff1	phase				
t13	ff1	phase				
t14	ff1	phase				
t15	ff1	phase				
t16		phase				
t17		phase				
t18		phase				
t19		phase		n1		
t20		phase		n1		
t21		phase		n1		
t22		phase		n1		
t23		phase				
t24		phase				
t25		phase		ff1		
t26		phase		ff1		
t27		phase		ff1		
t28		phase		ff1		
t29		phase	n1			
t30		phase	n1			

Figure 6. Schedule of Inspections with Overlap

Formulation for Additional Analysis

Indices and sets:

$a \in A$ aircraft

$t, t' \in T$ time periods

$m, m' \in M$ months

$f \in F$ forty-five-day inspections

$n \in N$ ninety-day inspections

$t \in days_m$ days in month m

Data:

$ndays_m$ number of days in month m

$maint\_cap$ maximum number of aircraft in maintenance simultaneously

Decision variables:

$X^{45}_{a,f,t}$	binary; $X^{45}_{a,f,t}$=1 if aircraft a begins 45-day inspection f at time t, 0 otherwise
$X^{90}_{a,n,t}$	binary; $X^{90}_{a,n,t}$=1 if aircraft a begins 90-day inspection n at time t, 0 otherwise
$X^{365}_{a,t}$	binary; $X^{365}_{a,t}$=1 if aircraft a begins its 365-day at time t, 0 otherwise
$X^{phase}_{a,t}$	binary; $X^{phase}_{a,t}$=1 if aircraft a begins phase maintenance at time t, 0 otherwise
$TASKS_{a,t}$	number of activities aircraft a is engaged in at time t

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