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EXPLANATORY FACTORS THAT CONTRIBUTE TO MV-22 READINESS

by

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The MV-22 Osprey is a critical component of national defense as it provides the Marine Air-Ground Task Force (MAGTF) with long-range, assault support capabilities to transport combat troops and equipment from ships and land bases to the battlefield. The MV-22 fleet has yet to maintain its readiness expectations; given the number of variables that contribute to squadron readiness, it is difficult to determine what resources to reallocate to guarantee consistent performance. This study examined the multiple variables that contribute to squadron performance and determined which are accurate predictors of readiness. Descriptive statistics and linear regression were used utilizing panel data from every Marine active-duty, deploying MV-22 squadron from fiscal years 2013 to 2020 to examine the relationship between multiple maintenance and operations factors and readiness. The graphical analysis highlighted the correlation between multiple explanatory variables and squadron MC% as well as consistent timeframes where most squadrons experience a decrease in readiness with different factors affecting their recovery. The results of the multivariate regression models showed the relationship between numerous Integrated Product Support (IPS) elements and squadron MC% whereas a sensitivity analysis conducted using Monte Carlo simulation showed that significant improvements in aircraft design and manpower allocation will increase the probability of achieving the CNO's MV-22 readiness goal.

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ABSTRACT

The MV-22 Osprey is a critical component of national defense as it provides the Marine Air-Ground Task Force (MAGTF) with long-range, assault support capabilities to transport combat troops and equipment from ships and land bases to the battlefield. The MV-22 fleet has yet to maintain its readiness expectations; given the number of variables that contribute to squadron readiness, it is difficult to determine what resources to reallocate to guarantee consistent performance. This study examined the multiple variables that contribute to squadron performance and determined which are accurate predictors of readiness. Descriptive statistics and linear regression were used utilizing panel data from every Marine active-duty, deploying MV-22 squadron from fiscal years 2013 to 2020 to examine the relationship between multiple maintenance and operations factors and readiness. The graphical analysis highlighted the correlation between multiple explanatory variables and squadron MC% as well as consistent timeframes where most squadrons experience a decrease in readiness with different factors affecting their recovery. The results of the multivariate regression models showed the relationship between numerous Integrated Product Support (IPS) elements and squadron MC% whereas a sensitivity analysis conducted using Monte Carlo simulation showed that significant improvements in aircraft design and manpower allocation will increase the probability of achieving the CNO's MV-22 readiness goal.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	Air Combat Element
AFSC	Air Force Specialty Code
AMO	Aircraft Maintenance Officer
AMSRR	Aviation Maintenance Supply Readiness Reporting
AMSRR	Aviation Maintenance Supply Readiness Reporting
AMTRP	Aviation Maintenance Training Readiness Program
ASM	Advanced Skills Management
AVGAC	Average Aircraft
AWM	Awaiting Maintenance
AWP	Awaiting Parts
CDI	Collateral Duty Inspector
CDQAR	Collateral Duty Quality Assurance Representative
CE	Command Element
CNAF	Commander Naval Air Forces
CND	Cannot Duplicate
CNO	Chief of Naval Operations
DAU	Defense Acquisitions University
DECKPLATE	Decision Knowledge Programming for Logistics Analysis and Technical Evaluation
D-Level	Depot Level
DMMH/W/D	Direct Maintenance Man-Hours Per Worker Per Day
DOD	Department of Defense
DOSS	Department of Safety and Standardization
DRRS-MC	Defense Readiness Reporting System-Marine Corps
EIS	Equipment in Service
EOS	Equipment Out of Service
FMC	Full Mission Capable
FY	Fiscal Year
GAO	Government Accountability Office
GCE	Ground Combat Element

HQMC	Headquarters Marine Corps
Hrs	Hours
I-Level	Intermediate Level
IOC	Initial Operating Capability
IPS	Integrated Product Support
IW	In Work
LCE	Logistics Combat Element
MAF	Maintenance Action Form
MAG	Marine Aircraft Group
MAGTF	Marine Air-Ground Task Force
MALDT	Mean Administrative and Logistics Time
MALS	Marine Aviation Logistics Squadron
MAW	Marine Aircraft Wing
MC	Mission Capable
MCCRAT	Marine Aviation Commander's Current Readiness Assessment Tool
MCO	Marine Corps Order
MET	Mission Essential Tasks
MLR	Multivariate Linear Regression
MOS	Military Occupational Specialty
M_{PT}	Mean Preventative Maintenance Time
MRF-D	Maritime Rotational Force-Darwin
MTBF	Mean Time Before Failure
MTBPM	Mean Time Before Preventative Maintenance
MTTR	Mean Time to Repair
NAE	Naval Aviation Enterprise
NALCOMIS	Naval Aviation Logistics Command Management Information System
NAVAIR	Naval Air Systems Command
NMC	Non-Mission Capable
NMCD	Non-Mission Capable/Depot
NMCM	Non-Mission Capable/Maintenance

NMCS	Non-Mission Capable/Supply
OEF	Operation Enduring Freedom
OIMA	Optimized Intermediate Maintenance Activity
O-Level	Organizational Level
OLS	Ordinary Least Squares
OOMA	Optimized Organizational Maintenance Activity
Org Code	Organizational Code
PMC	Partial Mission Capable
P_{remote}	Probability of Remote Maintenance
QAR	Quality Assurance Representative
QCL	Qualification/Certification/License
R-Supply	Relational Supply
RMC	Required Maintainer Competency
ROMO	Range of Military Operations
RTOK	Re-Test Ok
SFF	Safe for Flight
SHOAM	System Health Operational Analysis Model
SPMAGTF-CR-AF	Special Marine Air-Ground Task Force Crisis Response Central AFRICOM
SPMAGTF-CR-CC	Special Marine Air-Ground Task Force Crisis Response Central Command
TEC	Type Equipment Code
TEEP	Training Exercise and Employment Plan
TFDW	Total Force Data Warehouse
TMS	Type/Model/Series
USMC	United States Marine Corps
WUC	Work Unit Code

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I. INTRODUCTION

A. BACKGROUND

Marine Corps Aviation is a critical component of national defense as tactical aircraft provide the Marine Air-Ground Task Force (MAGTF) with offensive air support, assault support, anti-air warfare, air reconnaissance, and electronic warfare capabilities (Headquarters Marine Corps [HQMC], 2001a). The Marine Corps is required to maintain "no less than three air wings" to satisfy its Title 10 requirements, which includes providing combined arms "in the seizure or defense of advanced naval bases and providing security detachments for the protection of naval property at naval stations and bases" (National Security Act of 1947, 1947).

The MV-22 Osprey is the Marine Corps' medium-lift assault support aircraft dedicated to transporting troops and equipment throughout the battlespace and is designed to operate from amphibious naval vessels, day, or night, in all weather conditions. To support a "fight tonight" force, outlined in the 38th Commandant's Planning Guidance, MV-22 squadrons must be postured to rapidly deploy across the range of military operations (ROMO) to support expeditionary operations (HQMC, 2019a). An MV-22 squadron's ability to respond to crises is determined by its readiness level, which is a quantifiable metric used to assess the unit's ability to conduct operations. Maintaining a force that is always ready to deploy requires a continuum of resources, such as well-maintained aircraft, replacement parts, qualified and well-trained maintenance personnel, tooling, and special support equipment. Marginal changes in any of these resources will have a dramatic effect on the squadron's ability to maintain readiness levels to support expeditionary operations.

B. PROBLEM

The U.S. Department of Defense (DOD) allocates a considerable amount of the annual defense budget to aviation platform sustainment. Of the $718 billion requested by the DOD in the Fiscal Year 2020 Defense Budget, $57.7 billion was allotted to improve aviation-related systems across the services, a $2.5 billion increase from the 2019 budget request (U.S. Department of Defense [DOD] 2018, 2019). However, despite these significant outlays, the U.S. military continually struggles to maintain aviation readiness goals set by their respective departments. Most recently, the U.S. Government Accountability Office (GAO) reported that across the Departments of the Army, Navy, and Air Force, "twenty-four aircraft (types)…did not meet their annual mission capable goals for any year from fiscal year (FY) 2011 through FY 2019 and only three met their annual mission capable goals in a majority of those years" (U.S. Government Accountability Office [GAO], 2020 p. 9).

Notably, the Marine Corps' MV-22 was one of the platforms identified in the report that did not meet its readiness goals. The GAO reports that within the MV-22 program, "Maintenance costs increased each year and accounted for 50 percent of the total operations and support costs from FY 2011 through FY 2018, averaging about $568 million per year" (GAO, 2020). The Chief of Naval Operations (CNO) determines readiness thresholds for all naval aircraft models; the threshold for the MV-22 is 77% mission capable (MC). However, the data sourced from the Naval Air Systems Command (NAVAIR) used in this study shows that from FY 2013 to FY 2020, the MV-22 average monthly mission capable percent (MC%) in deployable squadrons was slightly above 50%. The average monthly MC% has also been slowly declining over the past eight years as shown in Figure 1. Table 1 shows the MC% for the MV-22 fleet as well as the average MC% for sample MV-22 squadrons operating from each Marine Air Wing (MAW). The MV-22 fleet MC% steadily decreased from a high of 59.0% in FY 2013 to 47.7% in FY 2020, reaching a low of 45.5% in 2017.

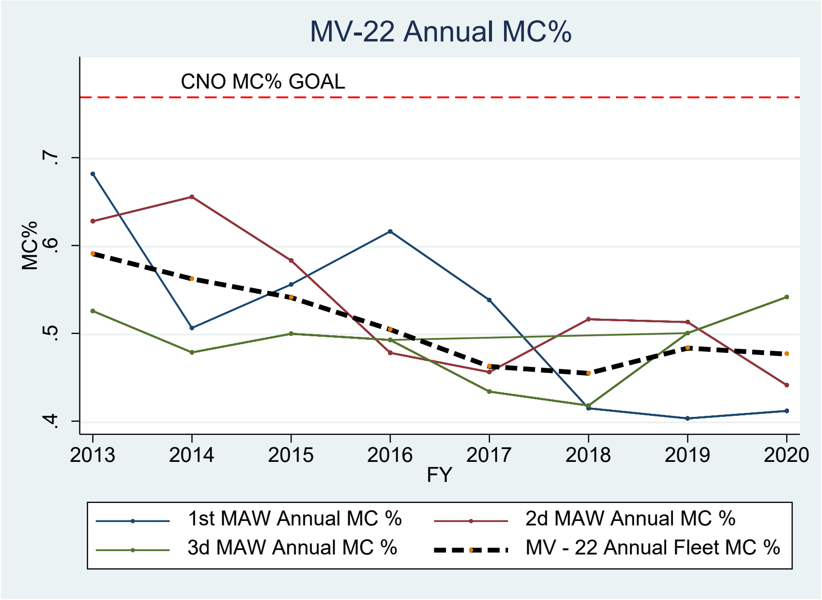

Figure 1. MV-22 Monthly MC% FY 2013-FY 2020

Table 1. Average Yearly MC% by MAW

Average Yearly MC Percent				
FY	**1st MAW**	**2d MAW**	**3d MAW**	**Fleet**
2013	68.2	62.7	52.6	59.0
2014	50.7	65.8	48.4	56.5
2015	55.6	58.4	50.0	54.1
2016	61.7	478	49.2	50.4
2017	53.9	45.7	43.6	46.3
2018	41.5	51.7	41.8	45.5
2019	40.3	51.3	50.1	48.2
2020	41.2	44.1	54.2	47.7

As mentioned in Marine Corps Order (MCO) 3710.7, the Marine Corps' Aviation Current Readiness Program, several explanatory factors influence the maintenance performance and material readiness of an MV-22 squadron, such as the number of flight hours the squadron executes, the local supply department's effectiveness, the age of the airframes, the number of qualified personnel, the experience of the maintenance personnel, and the number of hours the maintenance personnel worked during the month (HQMC, 2018). Some of the factors mentioned are more difficult for Marine leadership to control than others, for example: the squadron's deployment cycle and flight hours are often dictated by the squadron’s training exercise and employment plan (TEEP), the airframe will continue to age as the aircraft is utilized, and the number of aircraft available for assignment is limited and must be disbursed among the squadrons based on their operational requirements while continuing to maintain a depot-level maintenance aircraft induction schedule. There are, however, potential variables within the Marine Corps’ control that could be better managed and have the potential to incrementally increase MC% including the number of maintenance personnel assigned to the squadron and their experience levels, the average number of work hours per Marine per month, or daily maintenance workload management.

Moreover, Marine Corps aviation squadrons’ deployment periods follow a cyclical pattern, deploying overseas every 12–18 months. Squadrons undergo a dramatic change during the post-deployment period characterized by a change in executive leadership, new maintenance Marines and aircrew, and new personnel to train. Squadrons continually conduct local training exercises until they are technically and tactically qualified to participate in another overseas deployment. The NAVAIR data used for this research shows that MC% is consistently lower for units returning from deployment as operational expectations are minimal while the unit resets and refits personnel and equipment. This is significant because the data also shows that it takes most squadrons months to recover from this sudden drop in MC%. If the goal of a squadron is to maintain 77% MC, the Marine Corps needs to allocate these resources effectively throughout the squadron’s deployment cycle, which is likely contributing to the Marine Corps’ inability to reach the threshold set by the CNO.

C. PURPOSE

The purpose of this study is to examine what explanatory factors are statistically significant in predicting an MV-22 squadron’s average monthly MC%. This study also examines each of the factors and how they change relative to significant events across MV-22 squadrons’ deployment cycle to better understand how readiness changes with time.

1. Primary Research Questions

- What explanatory factors are statistically significant in predicting an MV-22 squadron's readiness, as measured by the total monthly MC%?

The results of the multivariate linear regression (MLR) model show that the squadron's deployment status, mean time between failure (MTBF), the percentage of aircraft that are non-mission capable because they are awaiting materials from the supply department (NMCS), the average number of aircraft per squadron, the age of the airframes in hours, the number of collateral duty quality assurance representatives (CDQARs) and quality assurance representatives (QARs), and the total flight hours are statistically significant in predicting MV-22 squadron readiness.

- How do these factors change throughout the squadron's deployment cycle?

On average, squadrons that are deployed have around 6–7% higher readiness than non-deployed squadrons. Furthermore, the mean values of each of the explanatory variables differ when squadrons are deployed suggesting multicollinearity between the squadron's deployment status and each of the explanatory factors. This is likely due to the significant differences in resource allocation between deployed and non-deployed squadrons.

2. Secondary Research Questions

- How much variability is left unexplained after modeling the statistically significant explanatory factors?

The regression models suffer from multiple violations of the ordinary least squares (OLS) regression assumptions that limit their predictive power. The coefficient of determination for the final regression model is approximately 41.9% which means roughly 58% of the variability in MC% is not explained by the regression model.

- What explanatory factors can be altered to increase the probability that MV-22 squadrons will achieve 77% average monthly MC%.

The results of the Monte Carlo simulation show that increasing both the number of CDQARs and QARs, increasing the MTBF, and reducing the NMCS percentage will increase the likelihood of achieving a mean MC% of 77%. Improving both the MTBF and NMCS percentage has a greater effect on improving MC% than increasing the number of Quality Assurance qualified personnel, however marginally improving each has the greatest impact.

D. SCOPE AND LIMITATIONS

For this research, a dataset built from aircraft readiness and maintenance qualification panel data is used to analyze the relationship between potential explanatory factors and MC%. The graphical analysis explores the summary statistics of the dependent and explanatory variables and time series linear regression is then applied to analyze how maintenance predictors affect MC%. To analyze the changes that occur during the squadron's deployment cycle, binary variables represent the squadrons' overseas deployment location, mission, and duration. Additionally, descriptive statistics analyze the variability and central tendency of the variables and Monte Carlo simulation explores a sensitivity analysis on the explanatory factors and determines which, if any, can be modified to increase average monthly MC%.

The intent of this study is to examine the characteristics that best represent the Marine MV-22 organizational level (O-level) population. However, to create a sample with similar characteristics, only deployable, active duty, MV-22 squadrons are included. Data from aircrew training, test and evaluation, presidential support, and Marine Corps Reserve squadrons are removed from the sample. This is due to the variance in manpower staffing, operational tempo, average number of aircraft, and increased reliance on civilian contractor support which will likely skew the results. The findings of this study may be relevant to these omitted units; however, more research must be conducted to better determine correlation and statistical significance.

Additionally, any inference on the causal effects that maintenance factors have on a squadron's mission capable rating is limited to readiness, personnel, and maintenance variables available through current data collection means. It is conceivable that other variables contribute to squadron readiness that is not being accurately captured. Furthermore, subjective measurements such as a unit's command climate or maintenance competence and experience are not accurately captured as there is currently not an efficient measurement for these traits. An analysis of the effects of these traits and recommendations for expanded data collection is captured in the summary, conclusion, and recommendations section.

E. ORGANIZATION OF STUDY

This thesis is organized into seven chapters. Chapter II introduces the MV-22, its role within the MAGTF, Marine Aviation and aviation maintenance, aircraft readiness, and readiness reporting. Chapter III examines previous research analogous to this thesis topic through a literary review. Chapter IV introduces the data sources and the cleaning and coding process for use in research. Chapter V describes the variables and presents the summary statistics and graphical analysis of the data. Chapter VI examines the MLR models, Monte Carlo simulation, and results. Chapter VII concludes the research by summarizing the findings and makes recommendations for policy changes and future studies.

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II. MARINE TILTROTOR AVIATION

A. MARINE AIR GROUND TASK FORCE

The Marine Corps is organized into modular elements that make up the MAGTF. The MAGTF provides the combatant commander with a crisis response force capable of conducting specific military operations for a limited duration. The force can later be expanded if the need for additional forces or capabilities is required. According to HQMC 2001a, the five types of MAGTFs include,

- Marine Expeditionary Force (MEF)
- Marine Expeditionary Force Forward (MEF Fwd)
- Marine Expeditionary Brigade (MEB)
- Marine Expeditionary Unit (MEU)
- Special Marine Air-Ground Task Force (SPMAGTF)

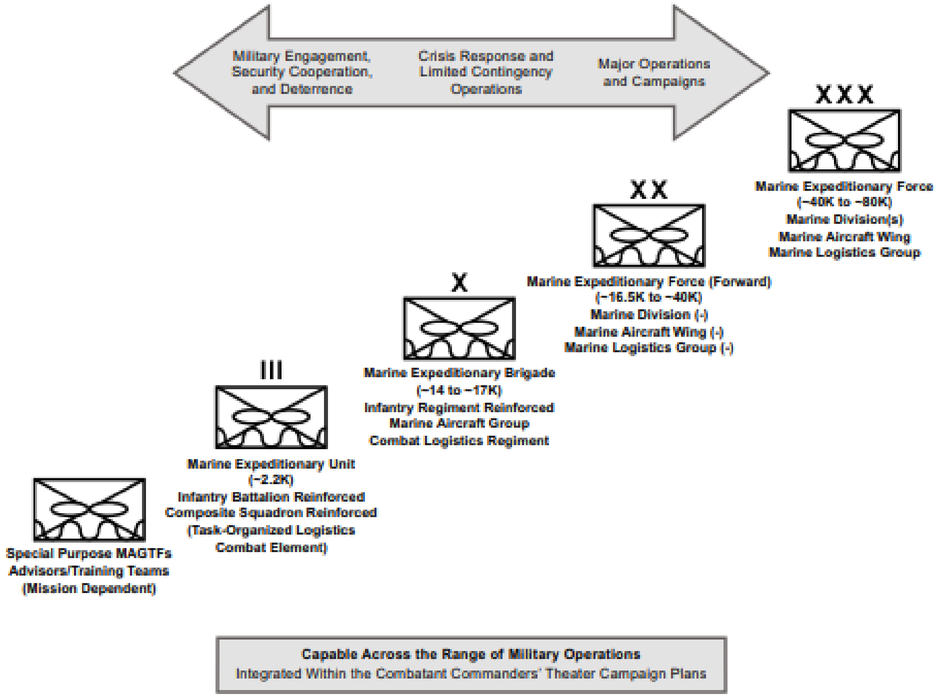

Figure 2. Types of MAGTF Organizations. Source: HQMC (2001a).

According to HQMC 2001a, the MAGTF is divided into 4 elements:

- Command Element (CE)
- Ground Combat Element (GCE)
- Air Combat Element (ACE)
- Logistics Combat Element (LCE)

The CE is the command-and-control element that includes the MAGTF commander and their staff. The GCE is organized around an infantry unit and is reinforced with armor, artillery, combat engineers, and other ground combat units as required. The ACE is composed of assault support and attack helicopters, fixed-wing strike, and transport aircraft, unmanned aerial reconnaissance aircraft, and their supporting agencies. The LCE functions as the logistics support agency and provides transportation, maintenance, engineering, food service, and medical services (HQMC, 2001a).

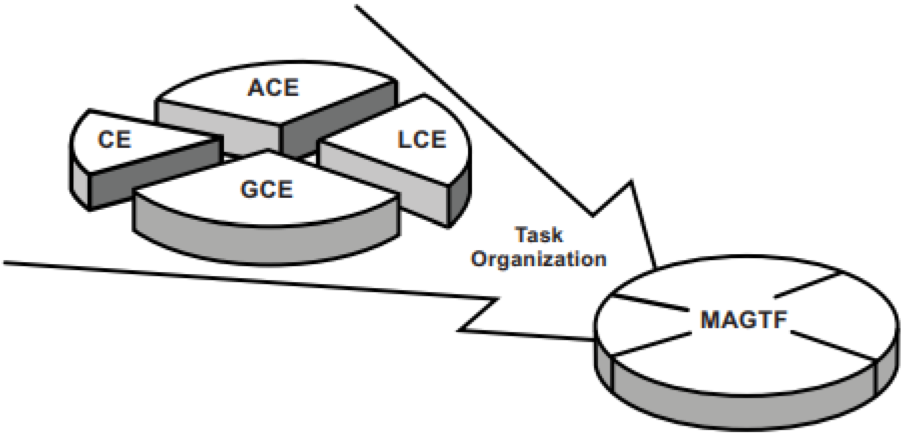

Figure 3. MAGTF Elements. Adapted from Source: HQMC (2001a).

B. MARINE AVIATION

1. Mission

The ACE provides the MAGTF commander with aviation capabilities required to conduct joint operations across the ROMO and achieve the U.S.'s strategic goals. The ACE provides mobility and fires, increasing the speed and range of the MAGTF and maximizing power projection. According to MCDP 1-0, "the ACE task-organizes to conduct air operations, project combat power, and contribute to battlespace dominance in support of the MAGTF's mission by performing some or all of the following six functions of Marine aviation" (HQMC, 2001a, pp. 2–8). The six functions of Marine Aviation include,

- Antiair warfare
- Assault support
- Electronic warfare
- Offensive air support
- Air reconnaissance
- Control of aircraft and missiles

2. Organization

The ACE does not specifically represent any specific element or unit but instead represents a unit that is specifically organized and capable of employing, as the mission dictates, any of the six functions of Marine aviation. The ACE can be tailored based on the required capabilities but are typically organized administratively at the highest level into Marine Aircraft Wings (MAWs). There are three active duty and one reserve aircraft wing in the Marine Corps. Each MAW is composed of Marine Aviation Groups (MAGs), Marine Air Control Groups, and Marine Wing Support Groups. Each MAG contains multiple squadrons of either fixed-wing or rotary-wing assets along with a Marine Aviation Logistics Squadron (MALS) to conduct supply and intermediate maintenance functions, while Marine Air Control Groups and Marine Wing Support Groups support aircraft operations through engineering, communications, air-traffic-control, airfield maintenance, and other ground support operations.

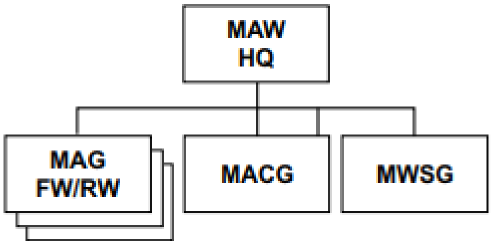

Figure 4. Notional Marine Aircraft Wing (MAW).
Source: HQMC (2018).

C. MV-22 OSPREY

1. Description and Mission

The Bell/Boeing MV-22 Osprey is a medium-lift assault support aircraft. Its mission is to “support the MAGTF commander by providing day/night all-weather assault support by transporting combat troops and equipment during expeditionary, joint, or combined operations.” (HQMC, 2019b, under “Value to The MAGTF”) The aircraft maintains a crew of two pilots and one enlisted aircrewman and can carry up to 24 troops (Naval Air Systems Command [NAVAIR], 2020). Its cabin characteristics are analogous to that of the CH-46E Sea Knight; however, it possesses two rotationally controlled nacelle turbine housings which allow the aircraft’s proprotors to transition from vertical lift to forward propelled flight. This rotating or “tilting” action of the nacelles during the transition from vertical to forward flight is what characterizes this aircraft as a tiltrotor. The aircraft’s turboprop feature allows for the aircraft to achieve a maximum speed of 280 knots with a range of around 430 nautical miles, while also carrying three times the payload of a CH-46 (Naval Air Systems Command [NAVAIR], 2020).

2. Operational History

As documented in his book, Dream Machine: The Untold History of the Notorious V-22 Osprey, Richard Whittle (2010) describes how the idea of tiltrotor technology has bewildered generations of aircraft engineers since the 1920s due to the complexity of designing a propulsion system that can transition from vertical to forward flight. It remained a challenge until the early 1980s when NAVAIR began to seriously consider the concept of a tiltrotor aircraft. After completing a lengthy acquisitions period with test flights that resulted in the deaths of dozens of service members, the MV-22 Osprey would reach its initial operating capability (IOC) milestone in 2007. That same year, VMM-263 would make the Osprey's first overseas deployment in support of Operation Iraqi Freedom (Whittle, 2010). Since then, MV-22 squadrons have deployed in support of a multitude of military operations and exercises. During the sample period used in this thesis, MV-22s squadrons routinely participated in rotational MAGTFs in support of Operation Enduring Freedom in Afghanistan, MEU operations originating from North Carolina, California, and Okinawa, Japan, crisis response in Spain and Kuwait, and the Maritime Rotational Force in Darwin Australia (MRF-D).

Figure 5. MV-22 Osprey. Source: Naval Air Systems Command (2020).

3. Squadron Composition

As presented in Figure 6, an MV-22 squadron is divided up into four departments: The Headquarters Department, Operations Department, Maintenance Department, and Department of Safety and Standardization. The Headquarters Department is usually led by the squadron's Executive Officer and is responsible for the squadron's clerical tasks such as unit and personnel administration, intelligence gathering and analysis, logistics and embarkation, and communications and information systems. The Operations Department is led by the Operations Officer and is responsible for planning and recording squadron flight training, annual training, and professional military education. The Maintenance Department is led by the Aircraft Maintenance Officer and is responsible for maintaining the squadron's assigned aircraft. The Department of Safety and Standardization (DOSS) is led by the DOSS Officer and is responsible for safety-related training, updating, and maintaining the squadron's flight publication library, and keeping the aircrew abreast of any current aircraft configuration and performance standard changes. The DOSS Officer is also the primary point of contact for any aircraft mishap investigations.

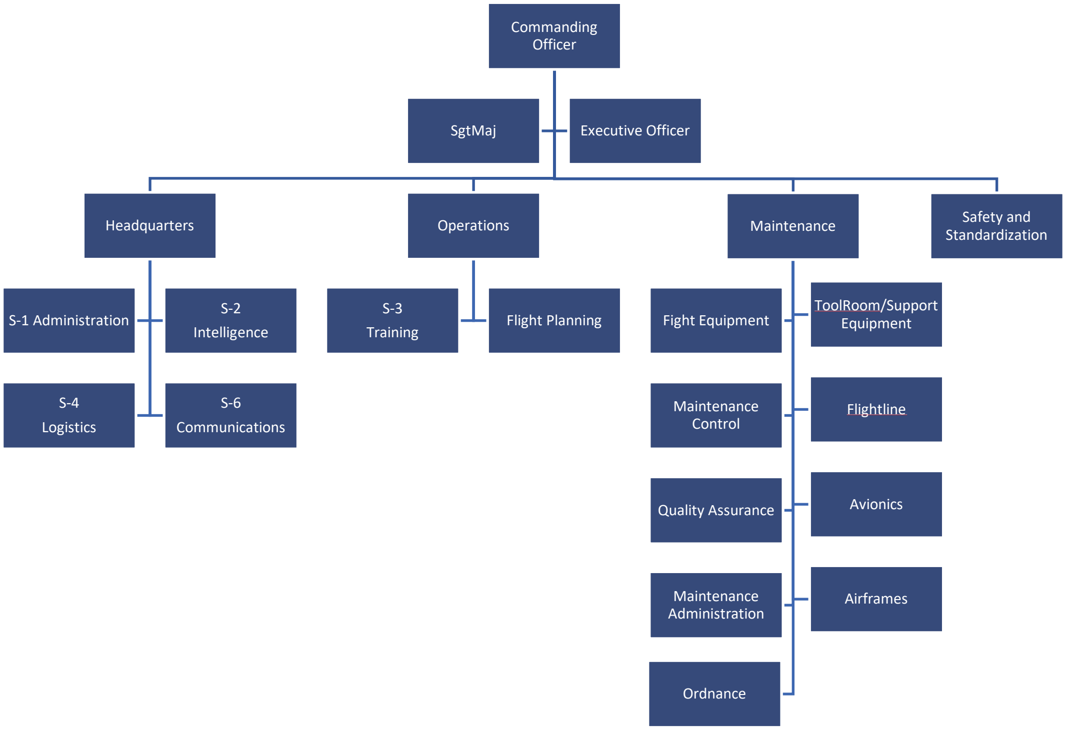

Figure 6. MV-22 Notional Squadron Composition. Adapted from CNAF (2017).

Marine Corps deployable active duty MV-22 squadrons are located at five distinct bases: MCB Camp Pendleton, California; MCAS Miramar, California; MCAS New River, North Carolina; MCB Hawaii, Kaneohe, Hawaii; and MCAS Futenma, Okinawa, Japan, as shown in Table 2. MV-22 squadrons located in Hawaii and Japan fall under the command of 1st MAW, MV-22 squadrons located in North Carolina fall under the command of 2d MAW, and MV-22 squadrons located in California fall under the command of 3d MAW. Each duty location has its own MAG to support MV-22 aircraft at the respective location as shown in Table 2. Each of the squadrons was located at their respective duty locations throughout the sample timeframe except for VMM-268 and VMM-362. VMM-268 and VMM-362 transitioned from the CH-46 in MCAS Miramar and were then relocated to MCB Hawaii in 2016 and 2018, respectively.

Table 2. List of Sample MV-22 Squadrons

First Marine Aircraft Wing		**Second Marine Aircraft Wing**	**Third Marine Aircraft Wing**	
Marine Aircraft Group 24	**Marine Aircraft Group 36**	**Marine Aircraft Group 26**	**Marine Aircraft Group 16**	**Marine Aircraft Group 39**
MCB Hawaii	**MCAS Futenma**	**MCAS New River**	**MCAS Miramar**	**MCB Camp Pendleton**
VMM-268	VMM-262	VMM-162	VMM-161	VMM-164
VMM-362	VMM-265	VMM-261	VMM-163	VMM-364
		VMM-263	VMM-165	
		VMM-264	VMM-166	
		VMM-266	VMM-268[1]	
		VMM-365	VMM-362	
			VMM-363[2]	

[1] VMM-268 operated the MV-22 at MCAS Miramar from April 2014 to July 2016.

[2] VMM-363 operated the MV-22 at MCAS Miramar from May 2012 to June 2018.

D. AIRCRAFT READINESS

1. Aircraft Availability

The 2019 Aviation Plan (AVPLAN) states the goal of Marine aviation is to "attain and maintain combat readiness to support expeditionary maneuver warfare" (HQMC, 2019b, under "Ready to Fight"). The ACE does this through maintaining aircraft and aircrews that can execute all the squadron's mission essential tasks (METs). An MV-22 squadron is staffed to support twelve aircraft. However, the number of aircraft assigned to a squadron can fluctuate depending on several factors, such as the squadron's priority in the MAG's training plan or the depot-level maintenance induction schedule. To generate a sortie, the squadron's Maintenance Control division will select aircraft to assign to the flight crew, have the aircraft prepared, and certify the aircraft "safe for flight" (SFF). The SFF certification ensures the aircraft complies with all current technical directives, all outstanding inspections have been completed, no outstanding maintenance actions are pending that would render the aircraft "not flight worthy," and that the aircraft is configured for the mission.

The guidelines for safety of flight determinations are outlined in COMNAVFORINST 4790.2 Naval Aviation Maintenance Program (NAMP). For an aircraft to be considered flight-worthy, it must be in an MC status. If an aircraft is not flightworthy, it will be in a non-mission capable (NMC) status. If an aircraft is not flightworthy because it is awaiting a maintenance action, it will be in a non-mission capable/maintenance (NMCM) status. If an aircraft is non-mission capable because it is waiting for a component or material that will return the aircraft to a flyable status, the aircraft will be non-mission capable/supply (NMCS). If an aircraft is undergoing depot-level maintenance, it will be considered non-mission capable/depot (NMCD). If an aircraft is still flightworthy but has a system degraded that will not allow the aircraft to utilize its full complement of weapons or navigational aids, the aircraft will be considered partial mission capable (PMC). A listing of a PMC aircraft's restrictions is in the MV-22 Mission Essential Subsystem Matrices. Like NMC statuses, a PMC aircraft that is waiting for a replacement part from the supply department will be NMCS while an aircraft that is PMC waiting for a maintenance action to be performed will be PMCS. An aircraft that can perform all assigned missions is considered full mission capable (FMC) (CNAF, 2017).

Additionally, the NAMP explains how flight hours are captured. Each aircraft accumulates hours based on its operational status. The aircraft will accumulate Equipment in Service Hours (EISHrs) for every hour it is assigned to a squadron and not undergoing depot-level repair. The squadron's total EIS hours equals the total number of hours that aircraft was MC, NMCS, or NMCM. For every hour an aircraft is NMCD, it accumulates Equipment Out of Service (EOS) hours. The sum of NMCM hours (NMCMHrs) and NMCS hours (NMCSHrs) equals the total non-mission capable hours (NMCHrs) for that month. The MC hours (MCHrs) represent the total monthly number of hours that all assigned aircraft were MC during the month and is calculated by subtracting the NMC hours from the EIS hours and dividing by the EISHrs. MC% represents the average monthly percentage of aircraft that are in an MC status out of those that are assigned and is calculated by multiplying the MCHrs by 100. Since aircraft undergoing depot-level repairs do not accumulate EIS hours, NMCD hours are removed from consideration when determining monthly MCHrs or MC% (CNAF 2017).

$$\text{NMCHrs} = \text{NMCSHrs} + \text{NMCMHrs} \tag{1}$$

$$\text{EISHrs} = \text{MCHrs} + \text{NMCHrs} \tag{2}$$

$$\text{MC\%}=\frac{\text{EISHrs-(NMCSHrs+NMCMHrs)}}{\text{EISHrs}}*100 \tag{3}$$

2. Readiness Reporting

Squadron readiness is reported in three different ways, the first of which is the Naval Aviation Logistics Command Management Information System (NALCOMIS). According to HQMC 2001b, NALCOMIS is the primary information and configuration management system that maintenance and logistics personnel use to track aircraft material management. NALCOMIS has two configurations, the Optimized Organizational Maintenance Activity (OOMA) and the Optimized Intermediate Maintenance Activity (OIMA). OOMA is used at the organizational level to monitor aircraft, engines, support equipment, scheduled and unscheduled maintenance, and operating hours, aircrew and maintenance personnel, aircraft and equipment assignment, and deployment. OOMA will also transfer material requisitions to the OIMA which perform many of the same functions as OOMA to manage intermediate level maintenance. OIMA also includes stocking and warehousing functions that integrate with the Relational Supply (R-Supply) inventory management information system to order, track, and receive material requisitions and assist in financial management (HQMC, 2001b).

Aircraft readiness is also reported daily utilizing the Aviation Maintenance Supply Readiness Reporting System (AMSRR). AMSRR is a web-based reporting system that details the aircraft status of each squadron aircraft along with any outstanding, high-priority supply requisitions. AMSRR provides a summary for both military and civilian maintenance and logistic leadership to address areas of immediate concern. Unlike OOMA and OIMA that continually record and report data, AMSRR reports are only submitted by maintenance and supply leadership once per workday.

Lastly, the Defense Readiness Reporting System-Marine Corps (DRRS-MC) is used to report the squadron's monthly operational capability, which is their ability to satisfy the unit's core METs. According to MCO 3000.13B, "DRRS-MC data directly reports on the unit readiness and capability, and capacity to meet requirements pillars while supporting analysis on the remaining pillars" (HQMC, 2020, p 1–1). The five pillars of institutional readiness are

- Unit Readiness
- Capability and Capacity to Meet Requirements
- High-Quality People
- Infrastructure Sustainment
- Equipment Modernization

The flow of aircraft status and material reporting is shown in Figure 7. OOMA records all aircraft maintenance and supply transactions and reports in real-time. The data from OOMA is input by the squadron's maintenance leadership every workday into the

AMSRR web portal. The aircraft readiness data from AMSRR is reported to DRRS-MC monthly.

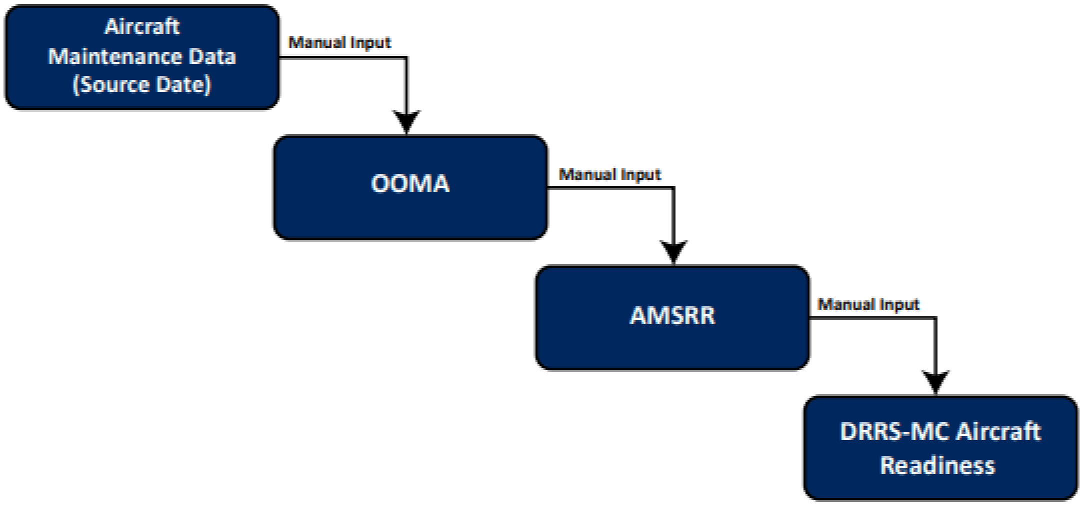

Figure 7. The Flow of Information from Maintenance System to Readiness Reporting System Source: DOD Inspector General (2018).

E. MARINE AVIATION MAINTENANCE

1. Naval Aviation Maintenance Program

Marine Aviation Maintenance is governed by the NAMP. The NAMP standardizes the roles and responsibilities of O-level, intermediate level (I-level), and depot level (D-level) activities. The objective of the NAMP is "to achieve the aviation material readiness and safety standards established by the Chief of Naval Operations (CNO) and CNAF in coordination with the Commandant of the Marine Corps (CMC)." (CNAF, 2017, p.1.2.2) The NAMP is sponsored by the CNO, managed by CNAF, and updated periodically to ensure safe and relevant maintenance operations. All changes are reviewed by a NAMP working committee (CNAF, 2017).

2. Organization

An MV-22 squadron's maintenance department is led by the Aviation Maintenance Officer, who is typically an aviator at the rank of Major. He is assisted by an Assistant Aircraft Maintenance Officer whose military occupational specialty (MOS) is aircraft maintenance officer. The NAMP task organizes the maintenance department into divisions and work centers, shown in Figure 8. Four of which perform mostly administrative functions and are commonly referred to as "non-production" divisions. The Maintenance Control Division is responsible for delegating scheduled and unscheduled maintenance tasks, assigning aircraft, preparing the daily flight schedule, and certifying aircraft "safe for flight." The Quality Assurance Division is responsible for overseeing and auditing the NAMP's maintenance programs and adherence to all technical maintenance publications. The Maintenance Administration Division is responsible for aircraft documentation to include all maintenance and flight records and the incorporation of technical directives. The Tool Control Division is responsible for issuing and maintaining the squadron's tools, individual material readiness listing assets, and support equipment.

Four divisions perform scheduled and unscheduled maintenance on MV-22 aircraft and equipment, known as "production," divisions. The Airframes Division is responsible for metal and composite work on the aircraft's airframe and support structures, including the treatment and removal of corrosion. They are also responsible for maintaining the aircraft's hydraulic systems, wheels, and tires. The Avionics Division is responsible for troubleshooting and maintaining electrical, communications, navigation, weapons, and countermeasures systems. The Flightline Division is responsible for maintaining and repairing engines, proprotor, and drive system components. The Flightline Division is also responsible for the execution of daily and post-flight maintenance inspections. The Ordnance Division is responsible for loading and maintaining the aircraft's crew-served defensive weapons systems and countermeasures dispensing system.

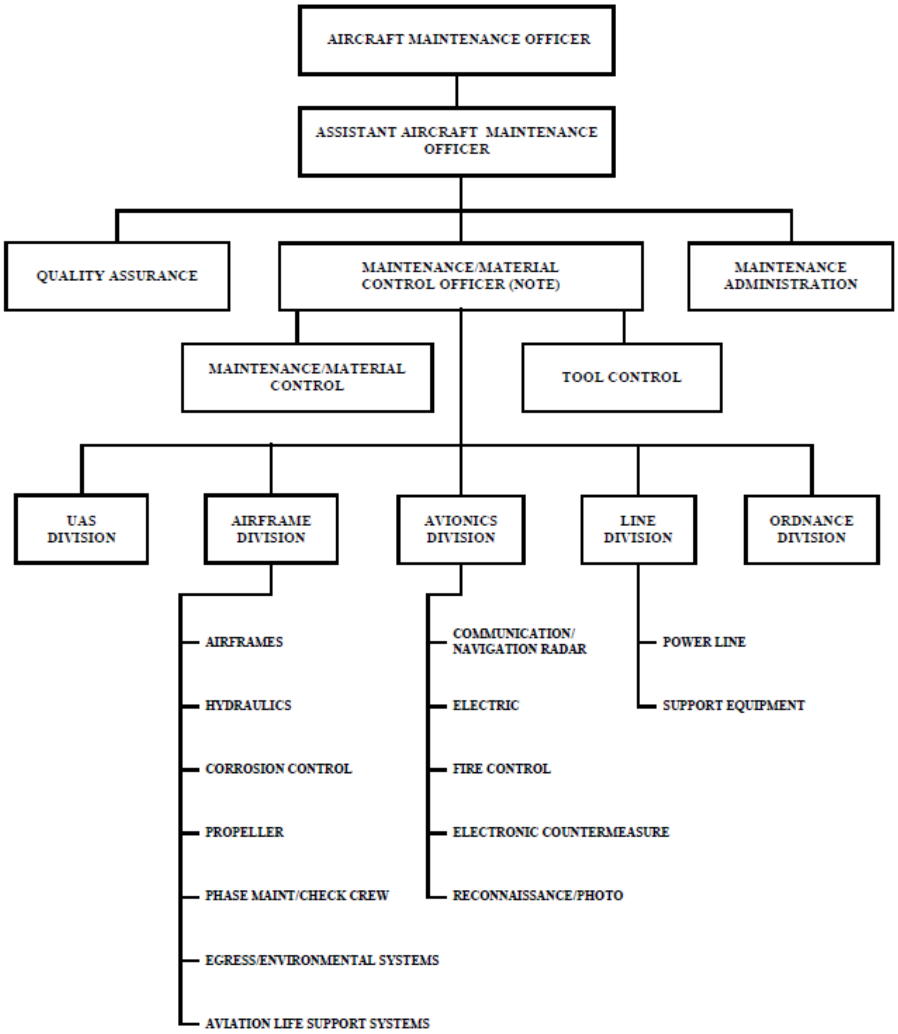

Figure 8. O-Level Maintenance Department Line and Staff Relationship (Marine Corps). Source: CNAF (2017).

3. Maintenance Qualifications

To ensure safe and efficient maintenance and flight operations, three maintenance qualifications are required to certify the work performed by maintenance personnel is conducted following technical publications and local regulations. The QAR is the highest technical qualification within the squadron and they are predominately located within the Quality Assurance Division. QARs are extremely skilled on their respective platforms and have completely satisfied their Aviation Maintenance Training Readiness Program (AMTRP) syllabus, which records individual maintenance training and skills. QARs are responsible for NAMP program adherence as well as the overall safety and efficiency of the maintenance department. They are also responsible for monitoring and training maintenance personnel as well as recommending personnel for maintenance qualifications. The two additional qualifications that are held within the production divisions are the Collateral Duty Inspector (CDI) and CDQAR qualifications. CDIs inspect all the scheduled and unscheduled maintenance actions that are performed by personnel within their division. CDQARs are more experienced maintenance personnel and perform the duties of a QAR within the division. Like CDIs they will inspect all maintenance actions performed within their respective work center but can inspect work performed by other work centers if they have a sufficient level of training in that respective area.

CDI is the most junior QA qualification and most Marines become eligible for the CDI qualification at the paygrade of E-4 or three years-time in service. CDQAR is the next senior QA qualification and most Marines become eligible for the CDQAR qualification at the paygrade of E-5 or about four to five years-time in service. QAR is the most senior QA qualification and most Marines become eligible for the QA qualification at the paygrade of E-6 or around six to seven years-time in service. The most current NAMP update in 2017 included a new provision that placed a minimum rank requirement to achieve these maintenance qualifications where there was not one before. It specifies the following paygrade required for QA qualification eligibility.

- CDI – Paygrade of E-4.
- CDQAR – Paygrade of E-5
- QAR – Paygrade of E-6.

The 2017 NAMP Change Proposal Memorandum states the justification for the change as to simply eliminate squadrons/IMAs from assigning junior personnel to QA functions. The NAMP does however provide simple procedures for relief when the paygrade requirement cannot be met due to manpower shortages (Ainsworth, 2017).

F. SUMMARY

Marine Aviation enhances the speed, range, and lethality of the MAGTF, and the MV-22 provides the combatant commander a more mobile and responsive force. The MV-

22 is a significant improvement over its predecessor and its tiltrotor technology is a significant engineering achievement. Maximizing the operational availability of any military airframe requires a multitude of resources and a well-trained cadre of maintenance personnel and aircrew. However, given the underwhelming historical readiness figures for the MV-22 fleet, a closer examination into the allocation of resources may indicate areas of improvement to increase readiness levels and optimize operational availability.

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III. LITERATURE REVIEW

A. INTRODUCTION

The purpose of this section is to analyze publications that are analogous to the problem presented in this research project. This helps identify gaps in the current library of research and assist in determining how this thesis can best address the Marine Corps' MV-22 readiness shortfalls through a close examination of work written by other professionals and academics who have used relevant tools to address similar operational readiness, material and manpower resourcing, and management issues.

B. AVIATION READINESS ISSUES

Many articles have been written that highlight the U.S. military's struggle to maintain its aircraft fleet, the most recent and comprehensive of which was a study conducted by the GAO titled *Weapon System Sustainment: Aircraft Mission Capable Rates Generally Did Not Meet Goals and Cost of Sustaining Selected Weapons Systems Varied Widely*. Released in November 2020, the study examined the material condition and operations and support cost for 46 aircraft platforms across the Departments of the Army, Navy, and Air Force from FY 2011 to FY 2019, shown in Figure 9. Of the 46 aircraft they examined, six were five percentage points below their mission-capable goals, 18 were six to 15% below their mission-capable goal, and 19 were over 15 percentage points below their goal during the eight years (GAO, 2020, p. 9).

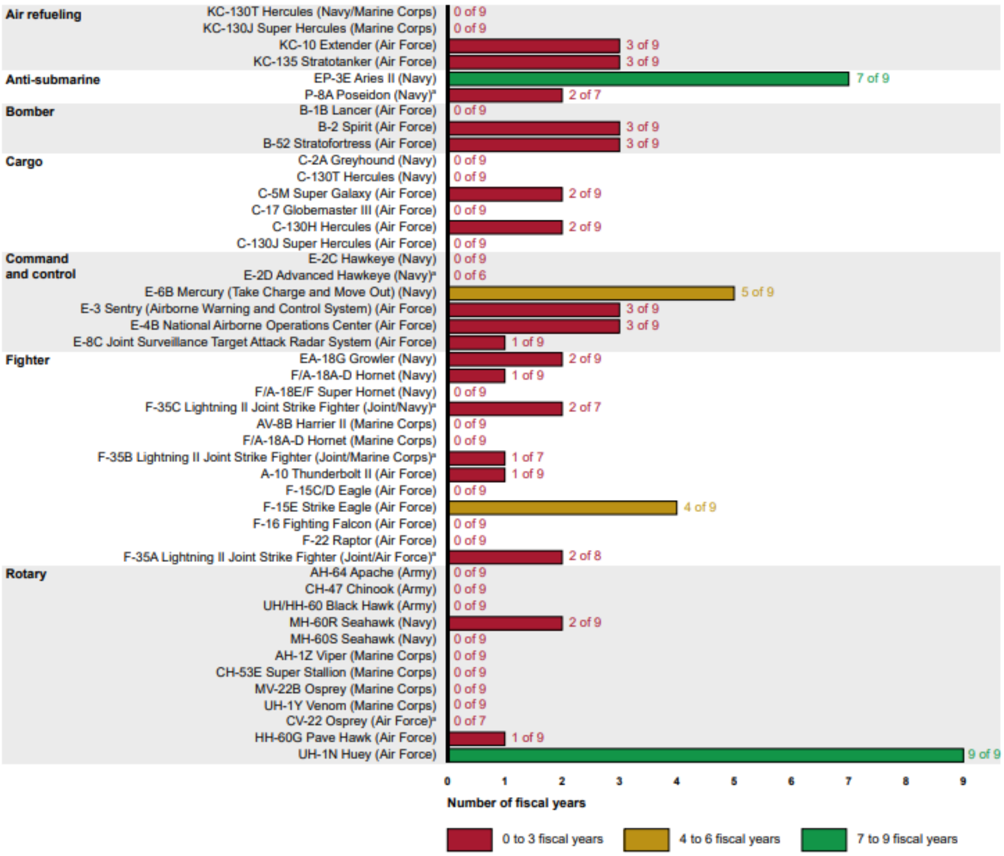
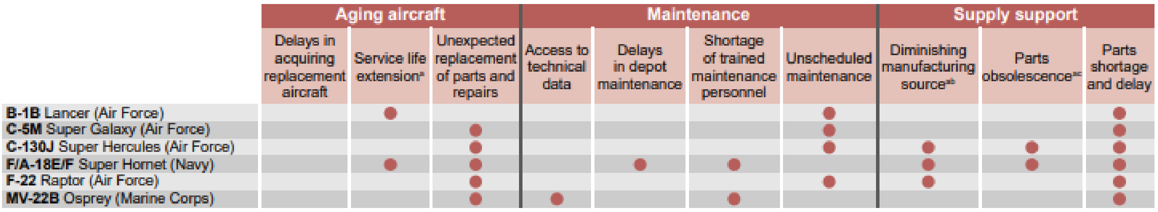


Figure 9. Number of Times Selected Aircraft Met Their Annual Mission Capable Goal, Fiscal Years 2011–2019. Source: GAO (2020).

Most notably, the MV-22 platform failed to meet its annual mission-capable goal once during this timeframe. Some of the challenges they highlighted shown in Figure 10 included unexpected replacement of parts and repairs, access to technical data, shortage of trained maintenance personnel, and parts shortages and delays. Additionally, according to government officials in the GAO report, "unavailability due to depot, maintenance, and supply issues, increased from FY 2011 to FY 2019 because of issues with corrosion, engineering delays, and supply shortages" (GAO, 2020 p. 190). Furthermore, the GAO's independent analysis found that the most challenging sustainment issues are addressing corrosion found during depot level repair, retrofitting older airframes with updated equipment to reduce unique aircraft configurations, and increasing spare parts availability.

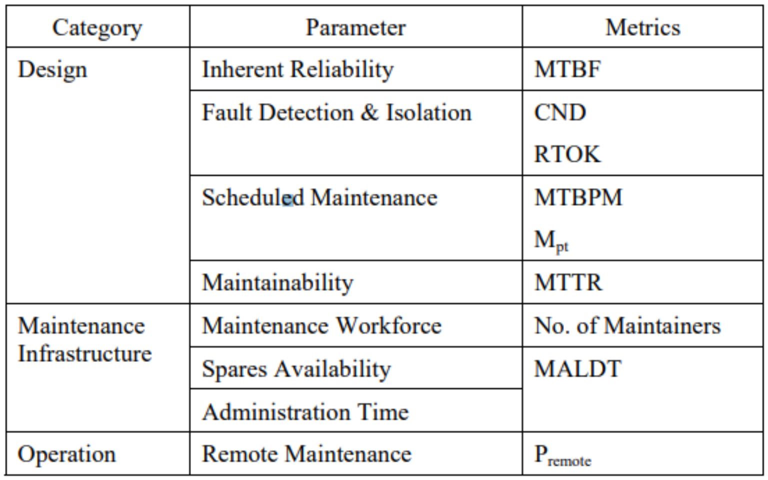


	Aging aircraft			Maintenance				Supply support		
	Delays in acquiring replacement aircraft	Service life extension[a]	Unexpected replacement of parts and repairs	Access to technical data	Delays in depot maintenance	Shortage of trained maintenance personnel	Unscheduled maintenance	Diminishing manufacturing source[ab]	Parts obsolescence[ac]	Parts shortage and delay
B-1B Lancer (Air Force)		●					●			●
C-5M Super Galaxy (Air Force)			●				●			●
C-130J Super Hercules (Air Force)			●				●	●	●	●
F/A-18E/F Super Hornet (Navy)		●	●		●	●		●	●	●
F-22 Raptor (Air Force)			●				●	●		●
MV-22B Osprey (Marine Corps)			●	●		●				●

Figure 10. Selected Challenges Affecting Some of the Selected Department of Defense Aircraft. Source: GAO (2020).

C. PARAMETERS THAT INFLUENCE AIRCRAFT AVAILABILITY

Employees from The Boeing Company conducted a study that analyzed the numerous factors that contribute to long-range bomber and strike aircraft availability (Andresen & Williams, 2011). The authors separated these factors into three categories, shown in Figure 11: aircraft design, maintenance infrastructure, and operations. They found that the design of the aircraft is extremely important as increasingly complex components and avionics systems must be reliable and maintainable. Furthermore, aircraft diagnostics and fault isolation infrastructure are key to maintaining these systems and have a major influence on aircraft availability. Their primary metric for the reliability of the aircraft is MTBF or the average time between unscheduled NMC events while Cannot Duplicates (CND) and Re-test Oks (RTOK) measure the number of fault isolations that can either not be duplicated by maintenance personnel on the aircraft or by other diagnostic test means. The mean time between preventative maintenance (MTBPM) measures the amount of time between scheduled maintenance events while Mean Preventative Maintenance Time (M_{pt}) measures the amount of time it takes to perform the preventative maintenance tasks. The primary means of measuring maintainability is the Mean Time to Repair (MTTR). The maintenance workforce is measured by the number of available maintainers while spares availability and time to complete administrative tasks are captured by Mean Administrative and Logistics Time (MALDT). The effect of flight operations is captured by the probability of having to conduct maintenance away from the home location or remote maintenance (P_{remote}).



Category	Parameter	Metrics
Design	Inherent Reliability	MTBF
	Fault Detection & Isolation	CND RTOK
	Scheduled Maintenance	MTBPM M_{pt}
	Maintainability	MTTR
Maintenance Infrastructure	Maintenance Workforce	No. of Maintainers
	Spares Availability	MALDT
	Administration Time	
Operation	Remote Maintenance	P_{remote}

Figure 11. Availability Influencing Parameters and Metrics. Source: Andresen and Williams (2011).

The study found that one-third of the downtime of the Air Force’s long-range bomber fleet was down for depot inspection and refurbishment, shown in Figure 12. Of the remaining NMC time, 76% was spent NMCM, 15% was spent NMCS and 9% was both NMCS and NMCM. Of the NMCM time, 80% was NMCM/unscheduled (NMCMU). The trend was similar in long-range strike aircraft where 57% of the downtime was attributed to NMCM, 27% was NMCS and 22% was both NMCM and NMCS, shown in Figure 13. Unscheduled maintenance also made up 76% of the total NMCM time (Andresen Williams, 2011)

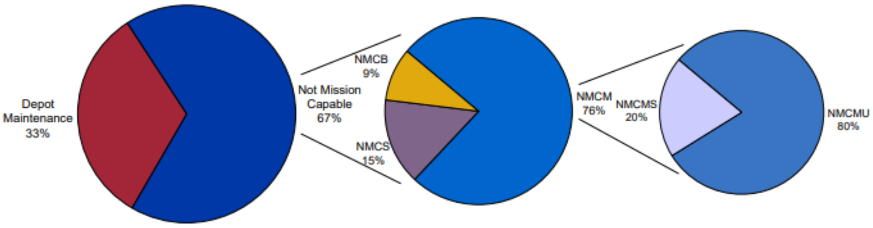


Figure 12. Long-Range Bomber Aircraft Unavailability. Source: Andresen and Williams (2011)

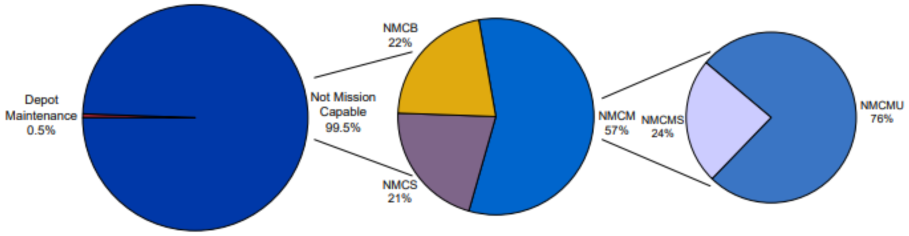
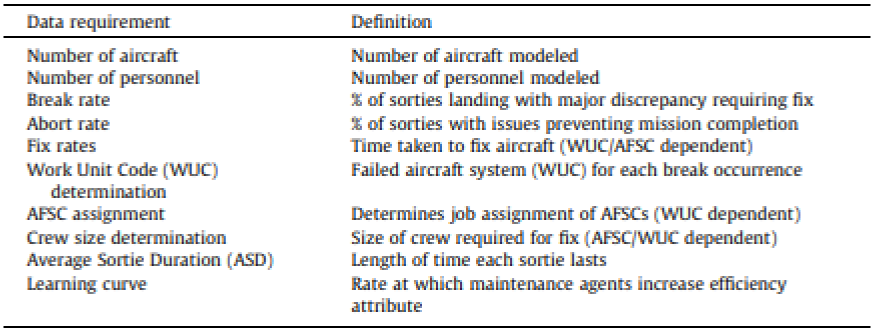


Figure 13. Long-Range Strike Aircraft Unavailability. Source: Andresen and Williams (2011).

The author's used their proprietary System Health Operational Analysis Model (SHOAM), a stochastic discrete event simulation tool to conduct a sensitivity analysis on each of the performance metrics to understand how aircraft availability is influenced by marginal changes in each parameter. They found that "a 20% improvement in avionics structures, and propulsion inherent reliability results in more than a 3% improvement in operational availability" (Andresen and Williams, 2011, p. 7-7). They also found that increases in maintainability are sensitive to changes and that increasing manpower, availability of spare parts, resources at repair locations, and improving the maintenance concept and management decisions all positively influence aircraft availability (Andresen and Williams, 2011). These findings are relevant to this study because of the homogeneity of the performance metrics. The Boeing Company and U.S. Air Force's approach to aircraft maintenance theory are similar to the Marine Corps' approach and the maintenance infrastructure and processes are analogous; many of the same performance metrics used by Boeing in their SHOAM model are applicable and the data is readily available.

D. AIRCRAFT MAINTENANCE MANPOWER

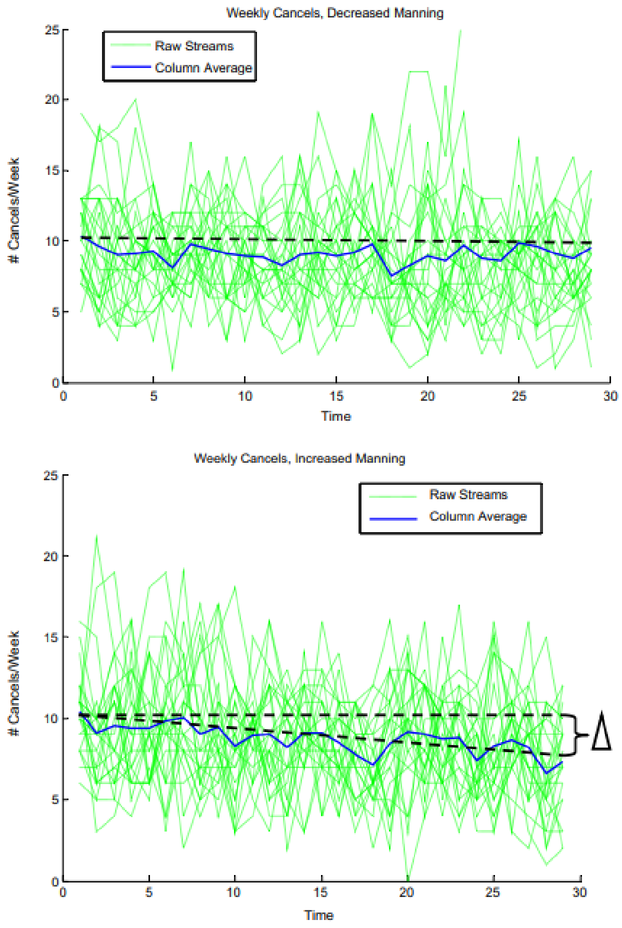
Members of the Air Force Analysis for Lessons Learned and the Department of Operational Sciences from the Air Force Institute of Technology published a study that examined the effect that qualified aircraft maintenance personnel had on manpower utilization and aircraft sortie generation, as measured by the number of weekly flight cancelations (MacKenzie, Miller, Hill, & Chambal, 2012). They used an agent-based simulation model with historical data from a single fighter aircraft squadron to measure the relationship between the different maintenance work centers and their experience levels. They also simulated both a 10% increase and decrease in manning levels to better understand how the number of weekly flight cancellations responds to manpower fluctuations. They simulated multiple historical maintenance factors shown in Figure 14, such as the number of aircraft, number of personnel, break rate, abort rate, fix rates, fix rates, and average sortie duration. They also simulated multiple work unit codes (WUCs), the crew size, and the Air Force Specialty Code Assignment, (AFSC). WUCs are codes given to identify aircraft subsystems and AFSCs are Air Force military occupation codes representing the Airman's primary occupation specialty. AFSCs were limited to Crew Chiefs, Avionics, Electro-Environmental, and Jet Propulsion in their research. They also added a variable for the maintainer learning curve or the rate at which maintenance personnel's skills improve, based on qualitative input from Air Force senior leaders. This would account for the increase in worker efficiency over time (MacKenzie, Miller, Hill, & Chambal, 2012).



Data requirement	Definition
Number of aircraft	Number of aircraft modeled
Number of personnel	Number of personnel modeled
Break rate	% of sorties landing with major discrepancy requiring fix
Abort rate	% of sorties with issues preventing mission completion
Fix rates	Time taken to fix aircraft (WUC/AFSC dependent)
Work Unit Code (WUC) determination	Failed aircraft system (WUC) for each break occurrence
AFSC assignment	Determines job assignment of AFSCs (WUC dependent)
Crew size determination	Size of crew required for fix (AFSC/WUC dependent)
Average Sortie Duration (ASD)	Length of time each sortie lasts
Learning curve	Rate at which maintenance agents increase efficiency attribute

Figure 14. Agent-Based Modeling Data Requirements and Definitions
Source: MacKenzie, Miller, Hill, and Chambal (2012).

In the author's research, they found that the utilization rate of many AFSCs is affected by the manning levels of the others. This is contrary to their assumption that since AFSCs work independently and there is no cross-sharing of job tasks, there is no significant relationship between the AFSCs. This indicates that increased levels of specific AFSCs may be required as extended maintenance is increased. Furthermore, weekly cancellations were reduced under circumstances where manning was at increased levels shown in Figure 15. The flat slope of the weekly cancelations indicates that the maintenance department is in what they call “survival-mode” or can only maintain a consistent level of performance. (MacKenzie, Miller, Hill, & Chambal, 2012, p.97) Conversely, with increased manning levels, the number of weekly cancellations slowly decreased providing evidence of an increase in worker efficiency. This publication justifies the inclusion of Marine manning levels and qualifications by work center for use in this research project. While qualified maintenance personnel is required to certify aircraft safe for flight and inspect work orders, the extent to which the number of personnel and qualifications from different work centers affects the squadron’s readiness is a potential indicator of how to best improve MV-22 MC%.


Weekly Cancels, Decreased Manning

Weekly Cancels, Increased Manning

Figure 15. Comparison of Cancellations per Week.
Source: MacKenzie et al. (2012).

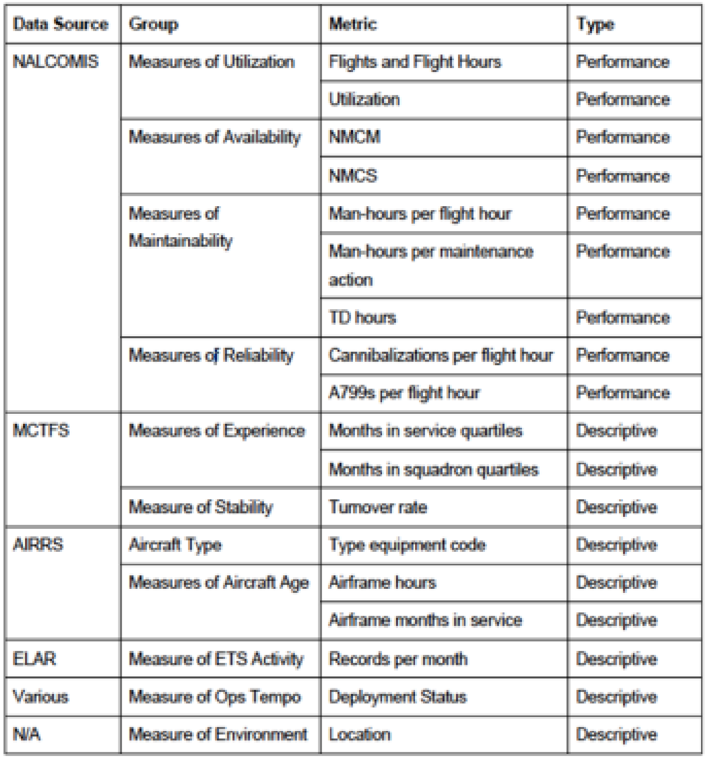
E. EXPLANATORY FACTORS FOR MARINE AVIATION

In his thesis research project, Chesterton (2005) uses multivariate regression to examine the relationship between numerous maintenance explanatory factors and maintenance performance as defined by the amount of time it took maintainers to perform maintenance actions or man-hours per maintenance action. He attributed maintenance performance to time efficiency stating:

> How should maintainer performance be measured? The speed and correctness with which maintenance actions are conducted are important aspects of performance, although they may be difficult to quantify. External factors, such as the availability of repair parts and the operations tempo of the squadron, also affect measures that may be used to describe maintenance

> performance. Therefore, we use man-hours per maintenance action as a measure of performance, due to its direct relationship to the actions of the maintainers, and to limits the effects of external confounding factors (p. XV).

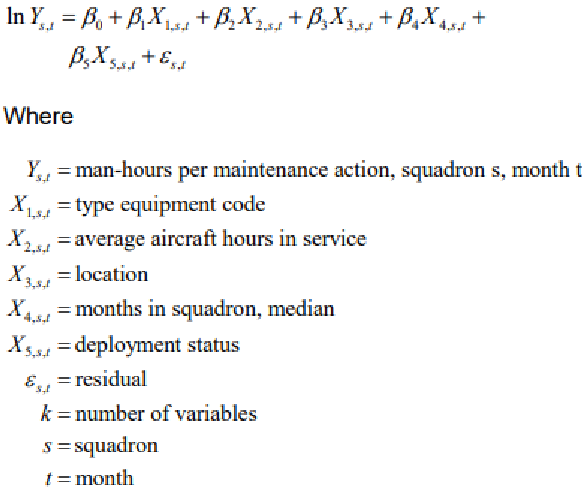
Chesterton (2005) examined 13 F/A-18 squadrons across the Marine Corps with time series data spanning two years and defined numerous measures of efficiency with maintenance and flight data from NALCOMIS and The Navy Inventory and Readiness Reporting System as well as support from engineering technical services using the from Engineering Technical Service Local Request system, shown in Figure 16. He also created measurements of maintainer experience level through time in service and time in squadron data source through The Marine Corps Total Force System, the Marines Corps' personnel, and payroll operating system.



Data Source	Group	Metric	Type
NALCOMIS	Measures of Utilization	Flights and Flight Hours	Performance
		Utilization	Performance
	Measures of Availability	NMCM	Performance
		NMCS	Performance
	Measures of Maintainability	Man-hours per flight hour	Performance
		Man-hours per maintenance action	Performance
		TD hours	Performance
	Measures of Reliability	Cannibalizations per flight hour	Performance
		A799s per flight hour	Performance
MCTFS	Measures of Experience	Months in service quartiles	Descriptive
		Months in squadron quartiles	Descriptive
	Measure of Stability	Turnover rate	Descriptive
AIRRS	Aircraft Type	Type equipment code	Descriptive
	Measures of Aircraft Age	Airframe hours	Descriptive
		Airframe months in service	Descriptive
ELAR	Measure of ETS Activity	Records per month	Descriptive
Various	Measure of Ops Tempo	Deployment Status	Descriptive
N/A	Measure of Environment	Location	Descriptive

Figure 16. Chesterton's Variables. Source: Chesterton (2005).

Chesterton (2005) regressed the aircrafts' type equipment code (TEC) which represents a unique aircraft type within the F/A-18 model platform, average aircraft hours in service, duty station location, the median months in the squadron of maintenance personnel, and deployment status. He found that TEC, average aircraft hours in service, location, median months in the squadron, and deployment status were all significant variables that predicted manhours per maintenance action.



$$\ln Y_{s,t} = \beta_0 + \beta_1 X_{1,s,t} + \beta_2 X_{2,s,t} + \beta_3 X_{3,s,t} + \beta_4 X_{4,s,t} + \beta_5 X_{5,s,t} + \varepsilon_{s,t}$$

Where

$Y_{s,t}$ = man-hours per maintenance action, squadron s, month t
$X_{1,s,t}$ = type equipment code
$X_{2,s,t}$ = average aircraft hours in service
$X_{3,s,t}$ = location
$X_{4,s,t}$ = months in squadron, median
$X_{5,s,t}$ = deployment status
$\varepsilon_{s,t}$ = residual
k = number of variables
s = squadron
t = month

Figure 17. Chesterton's Regression Model. Source Chesterton (2005).

However, Chesterton (2005) suffered from a relatively low coefficient of determination (r-squared value) of approximately 0.48 meaning his model only explained roughly 48% of the variability across F/A-18 squadrons. This study looks to improve on Chesterton's work through a larger sample size and more significant independent variables to improve the predictive power of the regression model. This study also uses Monte Carlo simulation to conduct a sensitivity analysis on the model to improve resource allocation and increase MC%.

F. READINESS PREDICTORS

This research also seeks to expand upon the research conducted by Germershausen and Steele in their Naval Postgraduate School (NPS) thesis *The Effect of USMC Enlisted*

Aviation Maintenance Qualification on Aviation Readiness. The basis of their research was that:

> The problem is created by this system that a mechanic could theoretically possess an aviation maintenance Military Occupational Specialty (MOS), but have no authority to fix aircraft or increase readiness. Assuming that aviation measures its outcomes in terms of successful operations and readiness, proper values should be assigned to qualifications. Human capital resulting from training is not formally valued as a maintainer ad no monetary value has been assigned to qualifications in providing a basis for proper reenlistment incentives. In a country that places a high demand on its Marine Corps, and in a world that is growing increasingly technical, there is cause for concern of improper staffing and retention process (p. 3).

Germershausen and Steele (2015) used multivariate analysis to determine the effect that enlisted maintenance qualifications have on readiness. They created a time series data set with maintenance data from 2012 to 2015 sourced from the Decision Knowledge Programming for Logistics Analysis and Technical Evaluation (DECKPLATE) and Marine Aviation Commander's Current Readiness Assessment Tool (MCCRAT).

Table 3. Germershausen and Steele's Time Series Regression Model Adapted from Germershausen and Steele (2015).

Variables	**Definitions**
< CDI	Less than a CDI
CDI	CDI
CDQAR	CDQAR
QAR	QAR
Highest Qual	Highest Qualification
Pvt	Private
PFC	Private First Class
LCpl	Lance Corporal
Cpl	Corporal
Sgt	Sergeant
SSgt	Staff Sergeant
GySgt	Gunnery Sergeant
Active	Qualification is Active
AFQT_SCORE	AFQT overall test score
Married	Married
Number of Dependents	Number of dependents
White	Race is White

Variables	Definitions
YOS	Years of Service
RBAP	RBA Percentage
HMH	Heavy Helicopter Squadron
HMLA	Light Attack Helicopter Squadron
VMM	Tiltrotor Squadron
activeCDI	Active CDI interaction variable
activeCDQAR	Active CDQAR interaction variable
activeQAR	Active QAR interaction variable
NMCS	Non-mission capable supply percentage
NCO	Non-commissioned officer
SNCO	Staff non-commissioned officer

Steele and Germershausen’s time series regression models were used to determine the impact that multiple variables shown in Table 3, had on readiness percentage. They used a squadron’s MC% as their dependent variable. They used the number of qualifications, the average number of aircraft, NMCS hours, and deployed status to determine likely predictors of increasing a squadron’s mission capable percentage; their regression model is shown in Figure 18. They found that while the variables affected helicopter squadrons differently depending on the type of aircraft, the number of qualifications had a positive effect on mission-capable ratings, meaning a squadron with more qualified personnel typically had higher mission capable percentages than those with less qualified individuals. Their final models also had a higher R-squared value than the Chesterton model, roughly ranging from 76.1% to 87.7% across all three Marine rotary-wing type squadrons (Steele & Germershausen 2015).

$$Y_{s,t,q} = \beta_0 + \beta_1 X_{1,s,t,q} + \beta_2 X_{2,s,t,q} + \beta_3 X_{3,s,t,q} + \beta_4 X_{4,s,t,q} + \varepsilon$$

Where
$Y_{s,t,q}$ = readiness percentage MC
$X_{1,s,t,q}$ = total qualifications
$X_{2,s,t,q}$ = total planes
$X_{3,s,t,q}$ = NMCS hours
$X_{4,s,t,q}$ = deployed
$\varepsilon_{s,t,q}$ = residual
s = squadron type
t = month year
q = qualification type

Figure 18. Germershausen and Steele's Time Series Regression Model. Source: Germershausen and Steele (2015).

This study improves on Steele and Germershausen's findings by adding more accurate explanatory variables to the regression model as there are likely more predictors of readiness than just NMCS percentage, number of planes, qualifications, and deployment status. The sample size is also increased in this study and examines qualification contributions by each production work center. This study also focuses specifically on the MV-22 platform to go beyond the positive or negative contributions of qualified personnel, but also seek to determine what if any variables when modified, can increase the probability of meeting the platform's annual readiness goal. This study also introduces time as a significant factor by examining how each explanatory variable is affected across a squadron's deployment cycle.

G. SUMMARY

GAO (2020) emphasizes the severity of the Marine Corps' operational availability problem and highlights the need for further analysis. The subsequent scholarly sources represent previous research that analyzes Marine Aviation readiness as well as tools and methods used in measuring operational availability. The amount of analytical research on Marine O-level readiness factors is sparse and there is a significant gap in measuring the impact that specific aviation resources have on Marine O-level squadron readiness. This thesis looks to close this research gap by measuring the impact of numerous MV-22 product support and operational variables and creating a mathematical model that is sufficient in predicting how operational availability will be affected through changes in resource allocation.

IV. DATA SOURCES, CLEANING, AND CODING

1. Introduction

Data collection for this research begins with the familiarization of sources that contain historical O-level squadron data. The three primary data warehouses that provide the panel data for this study are MCCRAT, DECKPLATE, and the Total Force Data Warehouse (TFDW). Additionally, the units' Command Chronologies, a historical record of the unit's significant activities, verify deployment assignment. All data from MCCRAT, TFDW, and the Command Chronologies were provided via email request. All DECKPLATE data was retrieved by the author from the DECKPLATE online portal. The timeframe for the panel data is limited to no earlier than 2012 which is when MCCRAT began capturing qualifications, certifications, and licenses (QCLs).

In aggregating the data, two Microsoft Excel spreadsheets were compiled, one with MCCRAT qualifications and one with DECKPLATE readiness data. Additional DECKPLATE data was later extracted and added to the readiness spreadsheet while the TFDW manpower data was added to the MCCRAT spreadsheet. The two spreadsheets were then merged using Stata 16, which was also used for the graphical and regression analysis. Both MCCRAT and DECKPLATE identify months where squadrons had personnel deployed overseas however the data is sorted differently requiring additional verification of the overseas location and aircraft allocation using the units' Command Chronologies.

2. Sample Squadrons

To make the best comparison between squadrons, data is only from active duty MV-22 squadrons that routinely deploy in support of the MAGTF; all others are removed because they have specific manpower and personnel requirements that are specific to their mission and unlike that of tactical MV-22 squadrons. Additionally, squadrons that have been operating continuously from October 2012 to September 2020 have 96 months-worth of readiness and qualification data. However, some squadrons have data missing due to being commissioned, decommissioned, or transitioning from CH-46 to MV-22.

Additionally, some squadrons have months with a high number of EIS hours, number of Marines, and QA qualified Marines, but do not have recorded maintenance or flight hours during the month. This appears most often during major squadron movements or transitions such as VMM-363's movement to Kuwait for the first SPMAGTF Crisis Response Central Command (SPMAGTF-CR-CC) deployment along with their subsequent squadron relocation to Hawaii, VMM-268's relocation to Hawaii, and VMM-165's transition to Kuwait for SPMAGTF-CR-CC. This results in seven months of unreliable data being recorded and therefore dropped from inclusion for this study. Table 4 displays the sample squadrons along with the number of months of observations while Figure 19 shows the monthly sample distribution by MAW.

Table 4. Sample Squadrons

Squadron	**Months of Observation**	**Omission Rationale**
VMM-161	96	
VMM-162	96	
VMM-163	96	
VMM-164	63	Transitioned to MV-22B in Aug 2015
VMM-165	95	1 Month of unreliable data
VMM-166	96	
VMM-261	96	
VMM-262	85	Transitioned to MV-22B Sep 2013
VMM-263	96	
VMM-264	92	Decommissioned June 2020
VMM-265	96	
VMM-266	96	
VMM-268	75	Transitioned to MV-22B in April 2014, 3 months of unreliable data
VMM-362	23	Commissioned in October 2018
VMM-363	96	3 months of unreliable data
VMM-364	69	Transitioned to MV-22B in Jan 2015
VMM-365	96	
Total	1,458	

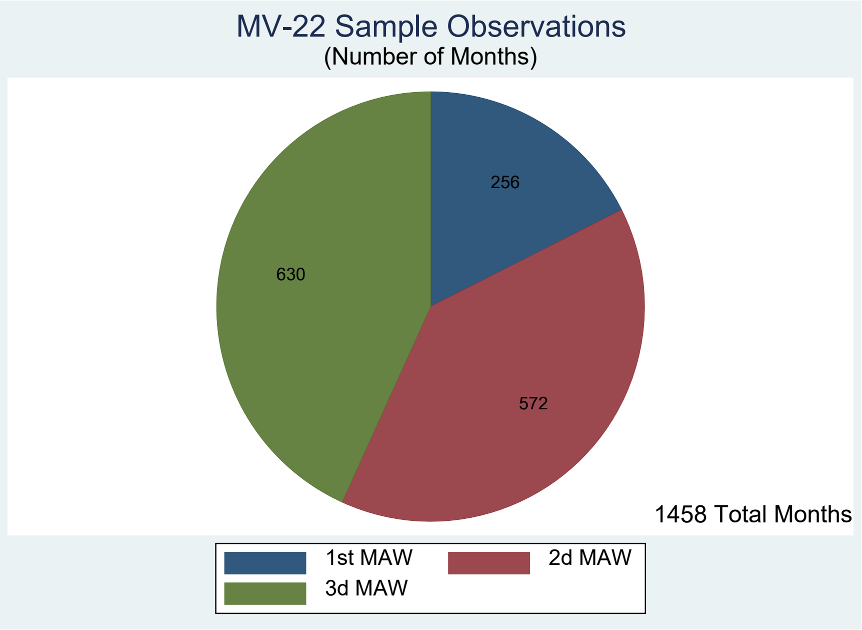
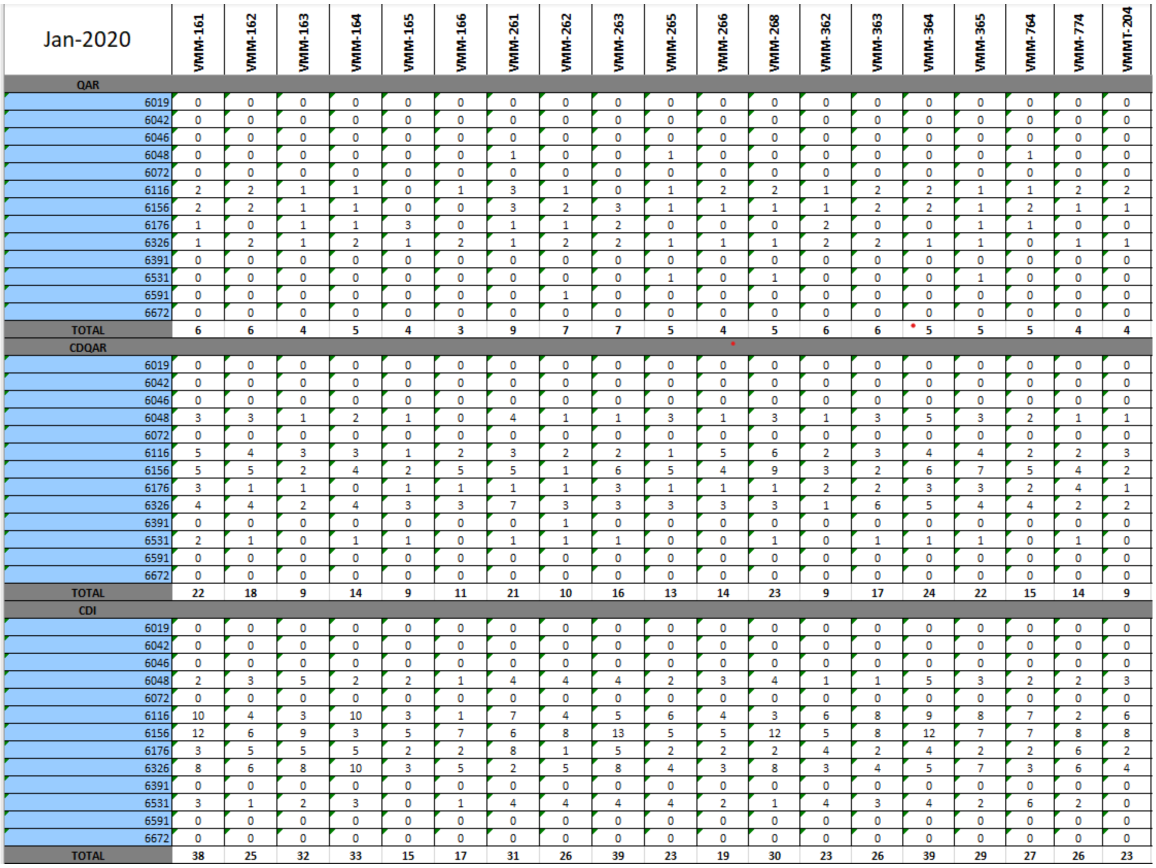


Figure 19. MV-22 Sample Distribution by MAW

3. Panel Data

a. MCCRAT Qualifications

MCCRAT is a database that compiles Naval Aviation Enterprise (NAE) performance metrics with guidance from the Deputy Commandant of Aviation. It is used as a tool to quickly measure and assess each unit's maintenance personnel capability based on the required maintainer competency (RMC) data (N. James, email to author, December 21, 2020) shown in Figure 20. The RMC data is populated from the Advance Skills Management (ASM) tool that each unit uses to track maintainer qualifications and competency. Some of the metrics include the number of personnel who possess specific QCLs such as the CDI/CDQAR/QAR qualifications. The number of monthly qualified CDIs, CDQARs, and QARs for this study is sourced from MCCRAT.



Jan-2020	VMM-161	VMM-162	VMM-163	VMM-164	VMM-165	VMM-166	VMM-261	VMM-262	VMM-263	VMM-265	VMM-266	VMM-268	VMM-362	VMM-363	VMM-364	VMM-365	VMM-764	VMM-774	VMMT-204
QAR																			
6019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6042	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6046	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6048	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0
6072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6116	2	2	1	1	0	1	3	1	0	1	2	2	1	2	2	1	1	2	2
6156	2	2	1	1	0	0	3	2	3	1	1	1	1	2	2	1	2	1	1
6176	1	0	1	1	3	0	1	1	2	0	0	0	2	0	0	1	1	0	0
6326	1	2	1	2	1	2	1	2	2	1	1	1	2	2	1	1	0	1	1
6391	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6531	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0
6591	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
6672	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	6	6	4	5	4	3	9	7	7	5	4	5	6	6	5	5	5	4	4
CDQAR																			
6019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6042	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6046	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6048	3	3	1	2	1	0	4	1	1	3	1	3	1	3	5	3	2	1	1
6072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6116	5	4	3	3	1	2	3	2	2	1	5	6	2	3	4	4	2	2	3
6156	5	5	2	4	2	5	5	1	6	5	4	9	3	2	6	7	5	4	2
6176	3	1	1	0	1	1	1	1	3	1	1	1	2	2	3	3	2	4	1
6326	4	4	2	4	3	3	7	3	3	3	3	3	1	6	5	4	4	2	2
6391	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
6531	2	1	0	1	1	0	1	1	1	0	0	1	0	1	1	1	0	1	0
6591	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6672	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	22	18	9	14	9	11	21	10	16	13	14	23	9	17	24	22	15	14	9
CDI																			
6019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6042	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6046	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6048	2	3	5	2	2	1	4	4	4	2	3	4	1	1	5	3	2	2	3
6072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6116	10	4	3	10	3	1	7	4	5	6	4	3	6	8	9	8	7	2	6
6156	12	6	9	3	5	7	6	8	13	5	5	12	5	8	12	7	7	8	8
6176	3	5	5	5	2	2	8	1	5	2	2	2	4	2	4	2	2	6	2
6326	8	6	8	10	3	5	2	5	8	4	3	8	3	4	5	7	3	6	4
6391	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6531	3	1	2	3	0	1	4	4	4	4	2	1	4	3	4	2	6	2	0
6591	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6672	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	38	25	32	33	15	17	31	26	39	23	19	30	23	26	39	29	27	26	23

Source: N. James, RMC Tier II and II Worksheet email to author, December 22, 2020

Figure 20. RMC Chart of Unit Qualifications.

The purpose of the MCCRAT dataset is to provide the number of maintainers from production work centers who possess a CDI/CDQAR/QAR qualification and analyze how the number of these qualifications affects the squadron's monthly MC%. The MCCRAT dataset is organized by squadron and military occupational specialty (MOS), the Marine's military career field. Additionally, the RMC data from MCCRAT contains the QCLs on hand, the minimum QCLs required to conduct efficient maintenance operations, and the number of QCL deficiencies for every MOS in the squadron for the given timeframe. For use in this research, the number of QCLs required and the number of deficiencies are removed only leaving the on-hand quantity per month. Furthermore, several of the squadron's MOSs are either clerical or perform maintenance on safety and support equipment and do not have an impact on a squadron's MC%. These MOS's are removed leaving only the Avionics, Airframe, Flightline, and Crew Chief MOSs.

Within these four categories, the Avionics work center falls under the Avionics Division and Avionic technicians perform testing and diagnostics on electrical, communication, and navigation systems. They also remove and replace electrical components. The Airframes work center falls under the Airframe Division and Airframe mechanics are responsible for maintaining and repairing the airframe and composite structures, hydraulics, systems, wheels, brakes, and tires. The Flightline work center falls under the Flightline Division and is comprised of two MOSs, Flightline mechanics and crew chiefs. Flightline mechanics are full-time tiltrotor mechanics who perform troubleshooting and replacement of engine, fuel, proprotor, and drive systems. They also perform aircraft pre-flight and turnaround inspections. In contrast, the Crew Chiefs' primary responsibility is as enlisted aircrewmen. They perform airborne support roles such as in-flight system troubleshooting and diagnosis and pre-and post-flight inspections if the aircraft is forward-deployed away from its home location. However, to gain proficiency in these areas, they also function as Flightline mechanics when not conducting flight operations. Once approved for CDI/CDQAR/QAR qualification, mechanics in each MOS will obtain the qualification for that respective work center shown in Table 5; both tiltrotor mechanics and enlisted aircrewmen will be designated a CDI/CDQAR/QAR for the Flightline work center.

Table 5. MV-22 Production Work Center MOSs

MV-22 Production Work Center MOSs		
Avionics Work Center	**Flightline Work Center**	**Airframes Work Center**
Avionics Technician	Flightline Mechanic/Crew Chief	Airframe Mechanic
6326	6116/6176	6156

Table 6 identifies each of the unique variable names for each work center and qualification. Each qualification is unique, however, due to the similarities in their respective duties and the low variance in the number of QARs and CDQARs in the squadron, these two variables were combined into a "QA" variable shown in Table 7.

Furthermore, the CDI, CDQAR, and QAR qualifications were merged into one variable called "Qual," which represents the number of Marines who possess and advanced qualifications during that month regardless of the level of the certification.

Table 6. MCCRAT Variable Definitions

MCCRAT Data Field	Description
Month	Month data was pulled
Squadron	Aviation Squadron
Deployed	1 if squadron was deployed, 0 otherwise
AVI CDI	Avionics CDI
AVI CDQAR	Avionics CDQAR
AVI QAR	Avionics QAR
AF CDI	Airframes CDI
AF CDQAR	Airframes CDQAR
AF QAR	Airframes QAR
FL CDI	Flightline CDI
FL CDAR	Flightline CDQAR
FL QAR	Flightline QAR
CC CDI	Crew Chief CDI
CC CDQAR	Crew Chief CDQAR
CC QAR	Crew Chief QAR

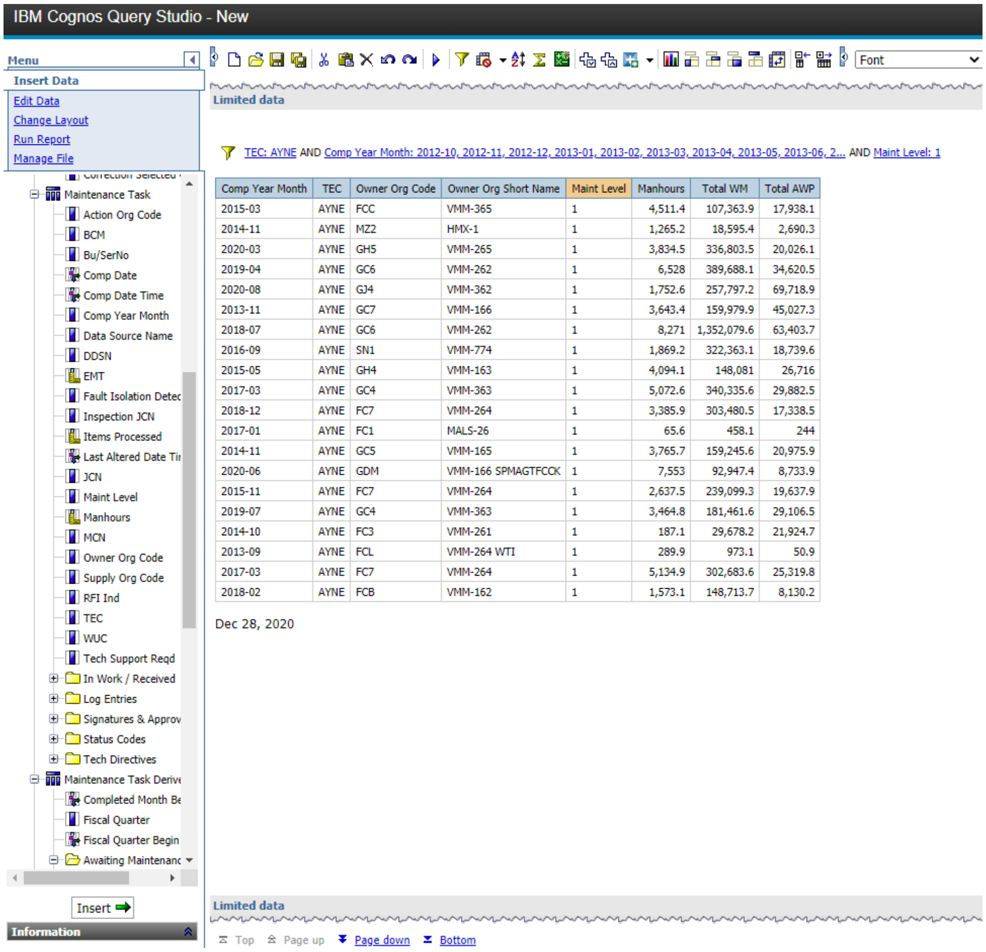
Table 7. Work Center Qualifications

CDI	CDQAR + QAR	CDI + CDQAR + QAR
AVICDI	AVIQA	AVIQUAL
AFCDI	AFQA	AFQUAL
FLCDI	FLQA	FLWCQUAL
CCCDI	CCQA	CCQUAL

b. DECKPLATE Readiness Data

DECKPLATE is an online, maintenance and logistics data management tool used by NAVAIR, NAE, and aviation maintenance leadership. It is the central repository for all material records of aviation maintenance, aircraft, support equipment, engines, and aviation depot-level repairable components. DECKPLATE has provided more than 25 years of web-enabled access with near real-time detailed data about more than 4,100

Marine Corps and Navy aircraft, wherever they are deployed (Teradata, 2016). DECKPLATE can be accessed by anyone with a user account and data reports can be pulled using IBM COGNOS. DECKPLATE has several prebuilt reports based on NAE, NAVAIR, or NAMP requirements. A common report, known as the DP-0036 report provides numerous routinely requested monthly squadron performance variables such as flight hours, the average number of aircraft assigned to the squadron, EIS hours, as well as NMCM, NMCS, MC, PMC, PMCS, and FMC percentages and hours. The DP-0036 report serves as the basis for readiness data used for this study. User-built reports can also be constructed through the Query Studio feature. Query Studio allows the user to combine and filter numerous random variables to build a dataset. Multiple Query Studio reports were built for this study to augment the data in the DP-0036 report to provide multiple potential explanatory variables. Figure 21 shows a sample user-built report constructed in Query Studio which contains MV-22 squadrons' monthly awaiting maintenance and awaiting parts hours filtered by the MV-22 TEC code (AYNE) from October 2012 to September 2020.



TEC: AYNE AND Comp Year Month: 2012-10, 2012-11, 2012-12, 2013-01, 2013-02, 2013-03, 2013-04, 2013-05, 2013-06, 2... AND Maint Level: 1

Comp Year Month	TEC	Owner Org Code	Owner Org Short Name	Maint Level	Manhours	Total WM	Total AWP
2015-03	AYNE	FCC	VMM-365	1	4,511.4	107,363.9	17,938.1
2014-11	AYNE	MZ2	HMX-1	1	1,265.2	18,595.4	2,690.3
2020-03	AYNE	GH5	VMM-265	1	3,834.5	336,803.5	20,026.1
2019-04	AYNE	GC6	VMM-262	1	6,528	389,688.1	34,620.5
2020-08	AYNE	GJ4	VMM-362	1	1,752.6	257,797.2	69,718.9
2013-11	AYNE	GC7	VMM-166	1	3,643.4	159,979.9	45,027.3
2018-07	AYNE	GC6	VMM-262	1	8,271	1,352,079.6	63,403.7
2016-09	AYNE	SN1	VMM-774	1	1,869.2	322,363.1	18,739.6
2015-05	AYNE	GH4	VMM-163	1	4,094.1	148,081	26,716
2017-03	AYNE	GC4	VMM-363	1	5,072.6	340,335.6	29,882.5
2018-12	AYNE	FC7	VMM-264	1	3,385.9	303,480.5	17,338.5
2017-01	AYNE	FC1	MALS-26	1	65.6	458.1	244
2014-11	AYNE	GC5	VMM-165	1	3,765.7	159,245.6	20,975.9
2020-06	AYNE	GDM	VMM-166 SPMAGTFCCK	1	7,553	92,947.4	8,733.9
2015-11	AYNE	FC7	VMM-264	1	2,637.5	239,099.3	19,637.9
2019-07	AYNE	GC4	VMM-363	1	3,464.8	181,461.6	29,106.5
2014-10	AYNE	FC3	VMM-261	1	187.1	29,678.2	21,924.7
2013-09	AYNE	FCL	VMM-264 WTI	1	289.9	973.1	50.9
2017-03	AYNE	FC7	VMM-264	1	5,134.9	302,683.6	25,319.8
2018-02	AYNE	FCB	VMM-162	1	1,573.1	148,713.7	8,130.2

Dec 28, 2020

Figure 21. Notional Query Studio User-Built Report Source: DECKPLATE (2020).

The time series dataset obtained from the DP-0036 report contains monthly readiness data from selected Marine MV-22 units. For use in this study, the data has to be sorted by aircraft TEC because an MV-22 squadron absorbs the entire ACE within its administrative control when combined as a MEU. Therefore, readiness reports contain all ACE aircraft, which often includes other type/model/series (TMS) aircraft. Sorting readiness reports by TEC removes the erroneous data from other TMS aircraft. Otherwise, the readiness data for MV-22 units in support of the MEU would be inaccurate due to the presence of CH-53, H-1 data, or AV-8B aircraft reporting data. The relevant data for use in this study is displayed in Table 8. After this step, multiple user reports were pulled with additional variables of interest that are likely predictors of a squadron's MC%, shown in

Table 9. Such variables include the total monthly man-hours, awaiting maintenance hours, airframe hours, and the total number of NMC work orders known as maintenance action forms (MAFs).

Table 8. DP-0036 Relevant Data Fields

Data Field	Description
Owner Org Code	Squadron Organization Code
Squadron	Aircraft Squadron Name
Comp Date	Report Month
Total Flt Hrs	Total Monthly Flight Hours
Avg Aircraft	Average Number of Aircraft Assigned
MC Hrs	Monthly Mission Capable Hours
MC %	Monthly Mission Capable Percentage
NMCS Hrs	Monthly partial mission-capable/supply hours
NMCS %	Monthly partial mission-capable/supply percentage

Table 9. Additional Variables of Interest

Report Type	**Variable**	**Source**	**Description**
Maintenance Man-Hours	MMHrs	DECKPLATE User Report	Monthly number of worker hours for production workforce
Monthly Airframe Hours	AFHrs	DECKPLATE User Report	Total number of flight hours on every airframe assigned to a squadron at that month
Awaiting Maintenance Hours	AWM	DECKPLATE User Report	Total monthly number of hours that aircraft were NMC and not in work or AWP
Number of NMC MAFS	DOWNMAFS	DECKPLATE User Report	Monthly Number NMC events

c. TFDW Manpower Data

TFDW is a data warehouse that stores monthly snapshots of personnel data extracted from two dozen data sources. It is the Marine Corps' "primary system of record and houses more than 30 years of historical manpower data from a variety of USMC and DOD systems" (Total Force Data Warehouse [TFDW], 2020 under "What is TFDW"). TFDW provides the monthly number of personnel in each of the three production work centers shown in Table 10, to analyze the impact that the total monthly number of Marines in each work center affects MC%.

Table 10. TFDW Variables

TFDW Data Field	Description
Snapshot Date	Month data was pulled
Squadron	Aviation Squadron
Platoon Number	Work Center Number
MOS	Primary MOS Code
Description	Work center description
Total	Total Number of Marines

d. Command Chronology

The Marine Corps' Command Chronology Program is a historical documentation program that records significant events in a unit's history. The purpose is to provide tangible evidence of unit and individual achievement to "foster military virtue and provide a means to extensively evaluate lessons of the past" (HQMC 2009 p. 5.1(c)(2)). The Command Chronology is a document submitted by the unit that is both qualitative and quantitative; it provides both a written account of plans, operations, and other key events as well as a snapshot of maintenance and operational data, such as monthly MC% and total monthly flight hours. The units' Command Chronologies are used to verify unit participation in MEU deployments because assignment as the MEU ACE does not generate a unique organizational code signifying assignment to the MEU.

4. Deployments

The sample MV-22 squadrons in this study have operated away from their home locations on many dozens of different military exercises and operations, with each exercise requiring a unique combination of personnel and material resources to support depending on the mission type, duration, and the number of aircraft required to support. Neither MCCRAT nor DECKPLATE provides locations of personnel, QA qualified or otherwise, deployed in support of an exercise. Therefore, the data does not support analyzing every MV-22 detachment for training during the sample period.

Both DECKPLATE and MCCRAT record squadron's overseas deployments differently. The MCCRAT data contains a binary string variable of "DEPLOYED" if the squadron was deployed overseas and "NON-DEPLOYED" if the squadron was not. The DECKPLATE data identifies the squadron with a unique organizational code (Org Code) if the squadron was deployed as the ACE in support of a SPMAGTF; however, the Org Code would reflect the status quo if the squadron was deployed in support of the MEU. Table 11 shows a sample data entry where VMM-165's Org Code changed from GC5 to GCJ when they deployed to Kuwait in 2018.

Table 11. Deployment Org Code Change

YYYY-MM	**Service**	**Owner Org Code**	**Squadron**
2018-08	USMC	GC5	VMM-165
2018-09	USMC	GC5	VMM-165
2018-10	USMC	GCJ	VMM-165 SPMAGTFCCK
2018-11	USMC	GCJ	VMM-165 SPMAGTFCCK
2018-12	USMC	GCJ	VMM-165 SPMAGTFCCK

Instances occur where squadrons have duplicate monthly entries as they have aircraft under their administrative control in multiple locations. To remove the duplicate entries, the data from the DP-0036 should be recalculated to reflect that squadron's aggregate readiness measurement. For example, before their return from the previously mentioned deployment in Kuwait, VMM-165 sent a small number of Marines back to their location at MCAS Miramar to accept aircraft from other squadrons. This means they had aircraft in both Kuwait and California, generating two monthly readiness entries. To get an accurate readiness estimation, VMM-165's data is merged and recalculated generating one entry representing VMM-165's aggregate MC% for March 2019. Table 12 shows their original entry with two Org codes for March 2019, one of which represents the squadron's contingency in support of SPMGTF-CR-CC while the other represents the squadron's contingency in Miramar, CA. Table 13 shows the aggregate readiness for the squadron after the data is merged.

Table 12. VMM-165 Original Entry

YYYY-MM	Service	Owner Org Code	Squadron	EIS Hrs	MC Hrs	MC %	AVG AC
2019-03	USMC	GC5	VMM-165	1,092	1,092	100.0%	1.5
2019-03	USMC	GCJ	VMM-165 SPMAGTFCCK	8,928	6,664	74.6%	12.0

Table 13. VMM-165's Single Entry for March 2019

YYYY-MM	Service	Owner Org Code	Squadron	EIS Hrs	MC Hrs	MC %	AVG AC
2019-03	USMC	GC5	VMM-165	9539	7756	81.31%	12.8

While the MCCRAT data set provides a binary variable representing whether the squadron was deployed, there are instances where squadrons were partially deployed whereby only a portion of their aircraft and personnel were deployed while the remainder of the squadron was operating from the unit's home location. To best capture the unit's readiness while the unit had personnel deployed overseas, the deployment variable in MCCRAT is changed to DEPLOYED if the squadron had more than 60% of its aircraft and personnel deployed overseas for more than 90 days, PART-DEPLOYED if the unit had 40%-60% of its aircraft and personnel deployed overseas for more than 90 days, and NON-DEPLOYED if the unit had less than 40% of its aircraft and personnel deployed for more than 90 days. Figure 22 shows the distribution of units that were deployed, partially deployed, or not deployed during the sample period.

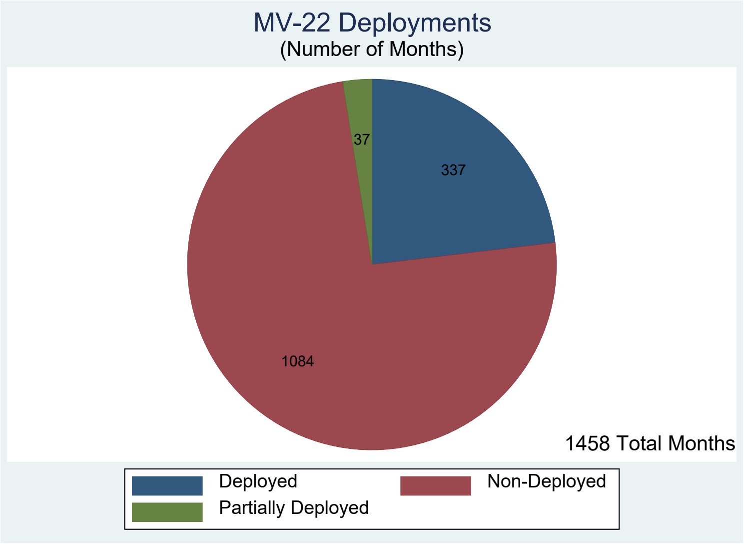


Figure 22. MV-22 Deployment Distribution

Table 14 shows the unit participation in overseas deployments by operation during the sample period. The deployments supported by the three MAWs during the sample period consisted of the following:

- Operation Enduring Freedom (OEF)
- Special MAGTF Crisis Response AFRICOM (SPMAGTF-CR-AF)
- SPMAGTF-CR-CC
- Maritime Rotational Force Darwin (MRF-D)
- MEUs

OEF began as a direct result of the actions that took place on September 11th, 2001. Combat operations are continuing at the time of this research; however, Marine MV-22 squadrons are no longer deploying to Afghanistan. The first MV-22 squadron to deploy to Afghanistan in 2009 Operation Enduring Freedom would also be the last with VMM-261 departing Helmand province in September 2014. SPMAGTF-CR-AF is a Special MAGTF based out of Morón Airbase in Spain which began in December 2013. MV-22 squadrons in Morón would operate with an entire unit’s worth of personnel and aircraft until Spring of 2017 when VMM-266 sent half their aircraft back to New River. VMM-764 replaced VMM-266 and SPMAGTF-CR-AF would be supported by roughly four to six MV-22s henceforth. SPMAGTF-CR-CC is a SPMAGTF operating out of Al-Jaber Airbase, Kuwait, which began in October 2014. Every squadron that supported SPMAGTF-CR-CC maintained a full complement of MV-22s during their deployment, except for those deployed to Kuwait from November 2016 to November 2017. During this timeframe, these squadrons only maintained around four to six aircraft. MRF-D is a rotational military force forward-deployed to Darwin Australia. MV-22 squadrons from MAG-24 have supported three iterations of MRF-D from 2017–2019. VMM-268 supported MRF-D in 2017 with 4 aircraft; however, each subsequent MV-22 deployment was supported with a full complement of MV-22s.

Marine Expeditionary Units are rotational MAGTFs that most commonly deploy aboard U.S. Naval vessels. There are seven standing rotational MEUs: the 11th, 13th, and 15th MEUs are headquartered in Camp Pendleton, California, the 22d, 24th, and 26th MEUs are headquartered in Camp Lejeune, North Carolina, and the 31st MEUs is forward-deployed in Okinawa, Japan. MEU rotations are cyclical; therefore, one CONUS East Coast and one CONUS West Coast MEU are typically deployed at any given time. While the deployed unit is operating overseas, the others are either in a pre-or post-deployment operational period. CONUS-based MEU deployments are typically deployed overseas for six to seven months (HQMC n.d.). The 31st MEU, however, does not deploy for seven continual months. This MEU will typically embark on two patrols of the U.S. 7th fleet of operations, in a year. VMM-262 and VMM-265 are the only two operational MV-22 units permanently stationed in Japan, therefore, one squadron will support the MEU each year participating in both the fall and spring patrol. Shortly after the Spring patrol, the other squadron will assume the role of the 31st MEU ACE (Groom, 2016).

Table 14. MV-22 Deployment Distribution by Operation

Deployment	**Monthly Observations**
OEF	28
SPMAGTF-CR-AF	78
SPMAGTF-CR-CC	74
MRF-D	20
MEUs	174
Total	**374**

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V. DATA DESCRIPTIONS AND GRAPHICAL ANALYSIS

1. Introduction

The purpose of this section is to describe each variable of interest and use graphical analysis to understand how the variables have changed throughout the sample period, while also providing evidence of correlation between each predictor and MC%. Furthermore, examining the relationship between each variable and squadron deployment periods helps to determine how these variables change as a squadron prepares for, executes, and completes its primary mission of supporting the MAGTF while deployed overseas. The data for each variable is broken down by MAW to determine if the findings for each variable are consistent across each Wing during the sample period. The selection of the variables of interest, shown in Table 15, is influenced by the design, maintenance infrastructure, and operational characteristics detailed in Andresen and Williams (2011) as well as the Defense Acquisitions University (DAU) Integrated Product Support (IPS) Guidebook which outlines critical design specifications and logistics support required for major defense acquisitions programs (DAU, 2019).

Table 15. Variables of Interest

Category	Measurement	Variable
Design Interface	Reliability	Airframe Hours
		MTBF
	Supportability	NMCSHrs
	Maintainability	MTTR
Manpower	Manpower Allocation	Maintenance Qualifications
		Number of Marines
Maintenance Planning and Management	Workload Management	Awaiting Maintenance Hours
	Manpower Utilization	Maintenance Man-Hours
Operations	Operational Tempo	Flight Hours
	Aircraft Assignment	Average Number of Aircraft
	Deployed Operations	Deployed
		Partially Deployed

2. Dependent Variable

As stated in Chapter II MC% represents the average number of aircraft that were flight-worthy during the month, calculated in hours. Figure 23 shows that the average monthly MC% for each Wing declines steadily over the sample period; the exception being 3d MAW’s slight increase from FY 2018 to FY 2020. Table 16 shows that the mean average monthly MC% for the MV-22 fleet was 50.5%, roughly 26.5 percentage points below the CNO’s MC% goal. 2d MAW had the highest monthly MC% during the sample period at 53.5%, while 1st and 3d MAW’s monthly MC% was roughly 5 percentage points behind at 48.5% and 48.6%, respectively.

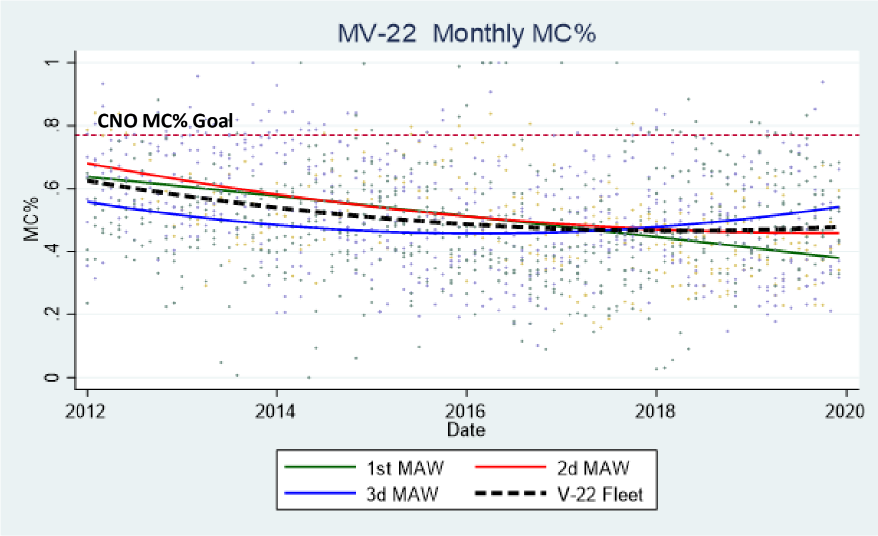

Figure 23. MV-22 Monthly MC% by MAW

Table 16. Average Monthly MC% Summary Statistics

Average Monthly MC Percent FY 2013 – FY 2020				
	1st MAW	2d MAW	3d MAW	Fleet
Mean	48.6	53.5	48.6	50.5
Std Deviation	14.9	17.5	16.8	16.9
Min	15.8	10.1	0.0	0.0
Max	84.0	1.0	1.0	1.0

3. Explanatory Variables

(1) Design Interface

The design interface product support element refers to the design characteristics of the airframe and its relationship with the other IPS elements required to support the platform. The DAU IPS Guidebook (2019) calls the design interface the "...leading element that impacts the product support elements because a well-performed design interface minimizes the logistics footprint, maximizes reliability, ensures that maintainability is user friendly and effective, and addresses the long-term issues related to obsolescence management, technology refreshment, modifications and upgrades, and overall usage under all operating conditions" (DAU, 2019, p. 63). The three measurements of effective design interface used for this study are reliability, supportability, and maintainability. Reliability measures the airframe's robustness over time, maintainability measures the degree to which maintenance personnel can return an NMC aircraft to MC, and supportability measures how responsive the program is in product resourcing throughout the aircraft's life cycle. (DAU, 2019)

(1) Airframe Hours

The number of flight hours accumulated on an airframe is recorded and documented by the OOMA server. Much like an automobile odometer, the number of airframe hours never decreases and is tracked until the aircraft's disposal. The airframe hour variable represents the total operating hours of every airframe in a squadron's possession during a given month. This is important in determining the impact that an aging airframe has on the squadron's readiness. As shown in Figure 24, the average monthly number of airframe hours per squadron has risen with utilization. Figure 24 also shows a non-linear relationship between MC% and airframe hours. The relationship between average monthly MC% shows a rapid decline as the total number of airframe hours reaches 20,000 suggesting that the average number of airframe hours may have a negative impact on MC% up to 20,000 hours. This is followed by a rapid increase up to the fleet maximum of 58,324 hours, shown in Table 17, however only 2d and 3d MAWs witnessed this increase. 1st MAW squadrons never had observations with more than 19,230 hours. This relationship is unlikely to be a result of airframe hours per squadron alone. It could also result from an increase in the number of airframes per squadron driving up the total airframe hours. The extreme values witnessed on the right side of the graph are likely a result of not only increased airframe hours but also months with a higher number of total aircraft assigned suggesting correlation between the two explanatory variables. Table 17 also shows that on average, 2d MAW has a higher number of aircraft hours per squadron than 1st and 3d MAWs.

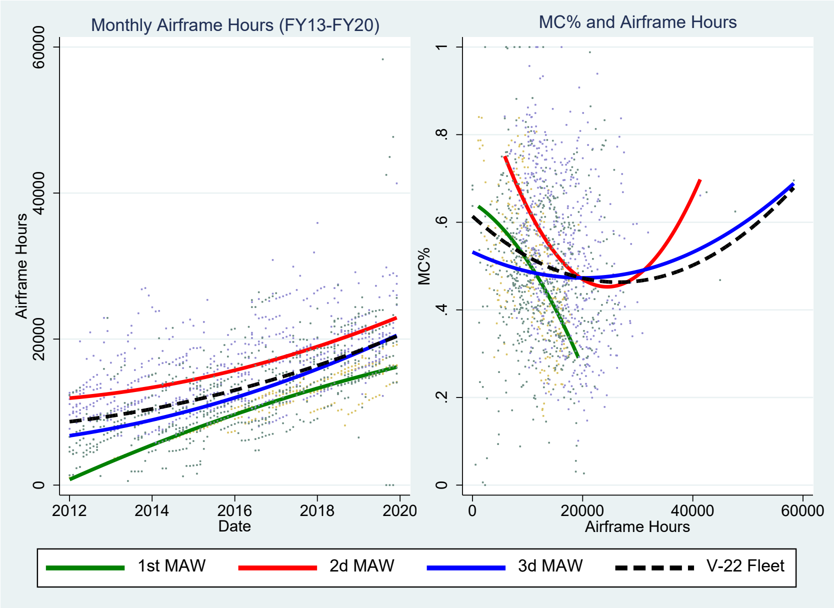

Figure 24. Monthly Average Airframe Hours by MAW

Table 17. Monthly Average Airframe Hours Summary Statistics

Average Monthly Squadron Airframe Hours				
	1st MAW	2d MAW	3d MAW	Fleet
Mean	10783	16222	12777.1	13778.6
Std Deviation	4360	5381.9	6246.7	5989.4
Min	1021.6	5841.7	0	0
Max	19230.6	41332.4	58324	58324

(2) Mean Time Before Failure

Mean time before failure (MTBF) measures the aircraft's reliability by expressing how much utility a squadron will receive before the aircraft succumbs to an unscheduled NMC event, in hours. MTBF is calculated by dividing the total number of monthly flight hours by the total number of NMCU MAFS.

$$\text{MTBF} = \frac{\text{Total Flight Hours}}{\text{Number of NMCU MAFS}} \qquad (4)$$

Figure 25 shows the monthly MTBF declined slightly over the sample period, suggesting decreased reliability. However, this effect could also come from a decrease in the civilian and military fleet knowledge base or maintainer experience, none of which are captured in this study. Figure 25 also suggests positive correlation between MC% and MTBF providing evidence that increasing the time between NMCU events would increase squadron monthly MC%. Table 18 shows the mean MTBF between MAWs during the sample timeframe is similar, about 1.2 flight hours between NMC events, indicating that there were no significant differences in MTBF between the MAWs.

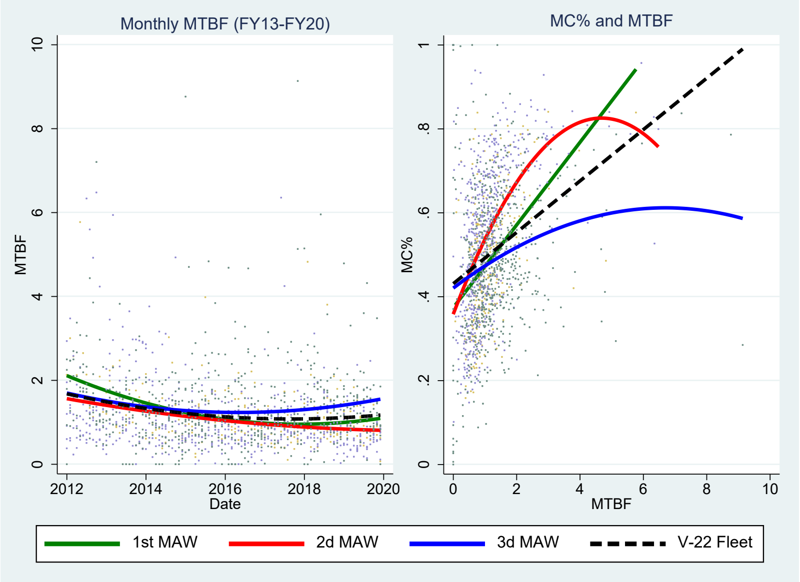

Figure 25. Relationship Between MC% and MTBF

Table 18. Monthly MTBF Summary Statistics

Average Monthly Squadron Mean Time Before Maintenance				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	1.148	1.09	1.35	1.21
Std Deviation	.679	.848	.970	.885
Min	.066	0	0	0
Max	5.769	6.476	9.136	9.136

(3) NMCS

NMCS represents the average percentage of EISHrs hours during the month that assigned aircraft were not flight-worthy, because they were waiting for high-priority requisitions to be filled by the supply department. NMCS is an aircraft status, therefore hours for multiple simultaneous requisitions are not double-counted; for example, if one aircraft is in an NMCS status waiting on one part for an hour and another aircraft is NMCS waiting for two parts for one hour, both aircraft accumulated one NMCS hour each for the hour they were NMC. Figure 26 shows that the percentage of NMCS aircraft increased over the sample time indicating that the aircraft is either increasing in supportability required or the response time of the supply system decreased. The summary statistics displayed in Table 19 shows that 2d MAW had the lowest average NMCS percentage at 12.7% while 1st MAW had the highest at 16%. Figure 26 also shows a strong negative relationship between NMCS and MC% indicating that as the number of hours that aircraft are down waiting for supply parts increases, the percentage of available aircraft decreases.

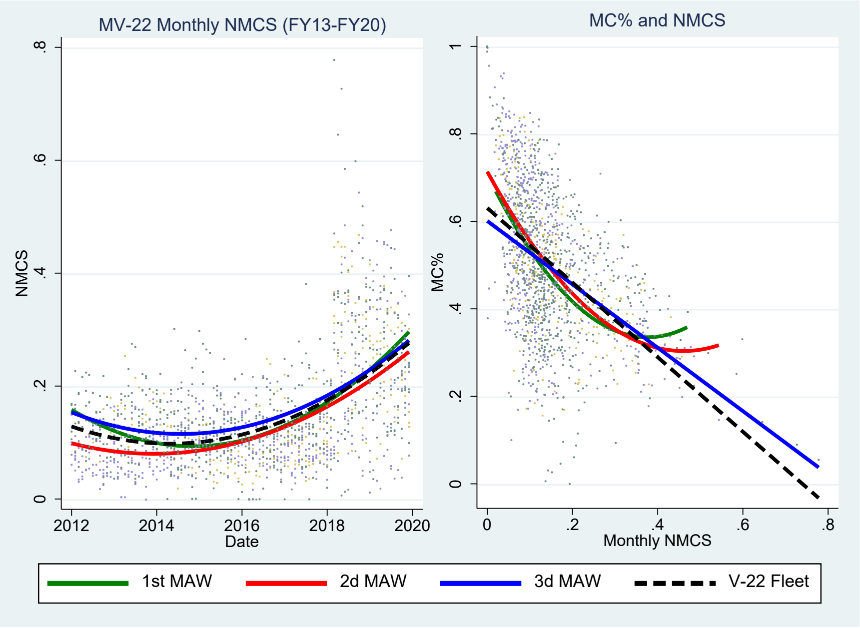

Figure 26. Monthly NMCS

Table 19. Monthly NMCS Percent Summary Statistics

Average Monthly NMCS Percent				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	16.0	12.7	15.8	14.6
Std Error	10.1	9.2	9.8	9.7
Min	2.0	0.0	0.0	0.0
Max	46.9	54.3	77.7	77.7

(4) Mean Time to Repair

The mean time to repair (MTTR) variable expresses aircraft maintainability by calculating how long it takes the maintenance department to complete an NMC task, in hours. For this study, MTTR is calculated by dividing the number of monthly maintenance man-hours by the number of monthly NMC MAFS, both scheduled and unscheduled. The inclusion of scheduled maintenance events is an important distinction as it aids in determining how quickly the maintenance department can return an NMC aircraft to MC and whether this metric is important in predicting monthly MC%. In lieu of better data, this is also a way to analyze the impact that squadron maintenance experience has on monthly

MC% as it is assumed that a more experienced maintenance department could complete NMC discrepancies more quickly and efficiently.

$$\text{MTTR} = \frac{\text{Maintenance Man-Hours}}{\text{Number of NMC MAFS}} \tag{5}$$

Next, Figure 27 shows that the MTTR steadily increased in each Wing over the sample period with 1st MAW witnessing a larger increase towards the end of the sample period than 2d or 3d MAW. Table 20 highlights this, showing that 2d MAW had the lowest mean MTTR of 9.56 hours per NMC MAF. Figure 27 also the relationship between MC and MTTR is erratic in each MAW and inconsistent across MAWs. If the assumption holds that correlation exists between maintenance experience and MTTR, this inconsistent behavior could be indicative of the variance in experience levels within each squadron's maintenance departments. Conversely, it also could be an indication that no relationship exists between MTTR and MC%.

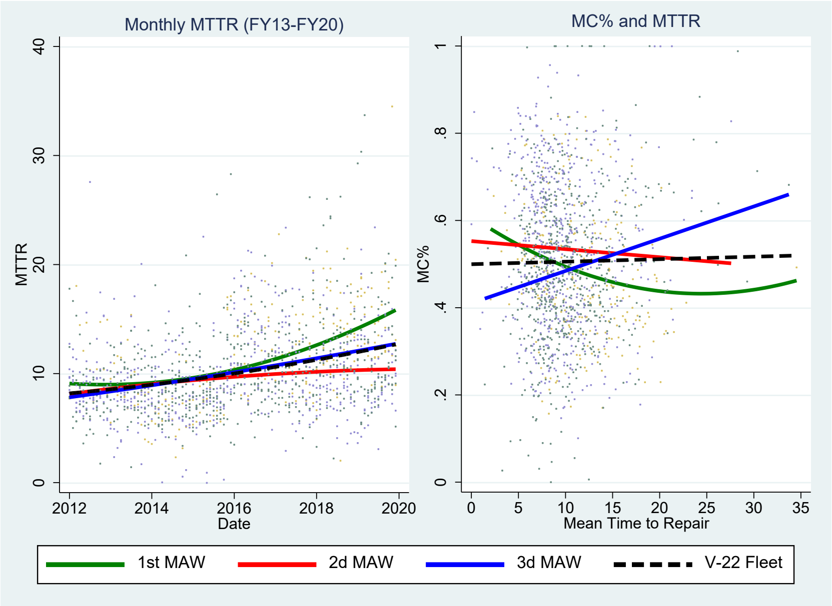

Figure 27. Monthly Mean Time to Repair

Table 20. Monthly MTTR Summary Statistics

Average Monthly MTTR				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	11.76	9.56	10.26	10.25
Std Error	4.39	3.66	4.15	4.08
Min	2.05	.009	1.425	.009
Max	34.4	27.59	33.71	34.54

b. Manpower

The manpower IPS element used for this study analyzes the effect that the number of maintenance personnel in each work center has on operational availability, while also considering the level of qualifications that that personnel have attained. This is to decide whether the current manpower levels are adequate in achieving the operational availability required to support the MAGTF and how readiness will be affected if these levels are adjusted. The two measurements used for this study include the allocation of total maintenance personnel and the number of QA qualified personnel by work center.

(1) Maintenance Qualifications

The number of maintenance qualifications expresses the average number of personnel who possess an advanced maintenance qualification for a given month. It is split between the CDI and QA variables; the CDI variable represents the monthly number of CDIs and the QA variable represents the number of CDQARs and QARs. These variables are significant because they represent the number of Marines who can certify that work has been completed per the NAMP, local regulations, and any applicable maintenance manuals. Like MTTR, this is also a way to analyze the impact that squadron maintenance experience has on monthly MC% as most of these Marines have at least four years of maintenance experience on the MV-22 platform. Figure 28 shows that the average number of CDI qualifications per squadron per month has increased across each MAW. Table 21 shows that 2d MAW had the highest average number of CDIs per squadron followed by 3d and 1st MAWs, respectively. Figure 28 also shows suggests positive correlation between the number of CDIs and MC%, however, the data from 1st MAW contradicts these findings indicating a negative relationship.

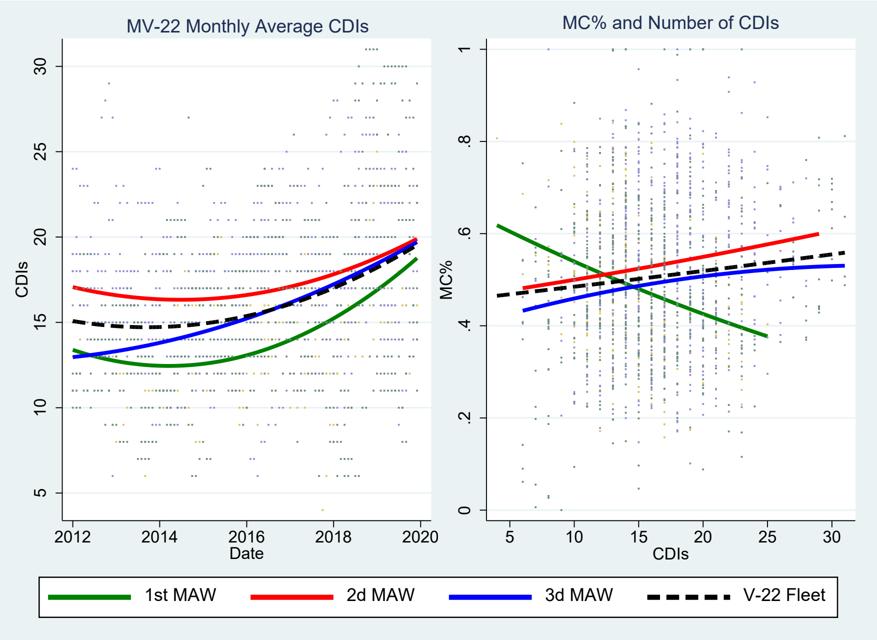

Figure 28. Monthly Average Number of CDIs

Table 21. Monthly CDI Summary Statistics

Average Monthly Number of CDI Qualifications				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	14.6	17.2	15.7	16
Std Error	3.8	4.2	5	4.6
Min	0	4	6	6
Max	25	29	31	31

Like the number of CDIs, Figure 29 shows that the number of QAs also increased over the sample period with Table 22 expressing that 2d MAW also had the highest mean number of QAs followed by 1st and 3d MAWs. Similarly, the QA data from 2d and 3d MAW also shows positive correlation between the number of QAs and MC%, with 1st MAW's data not supporting these findings.

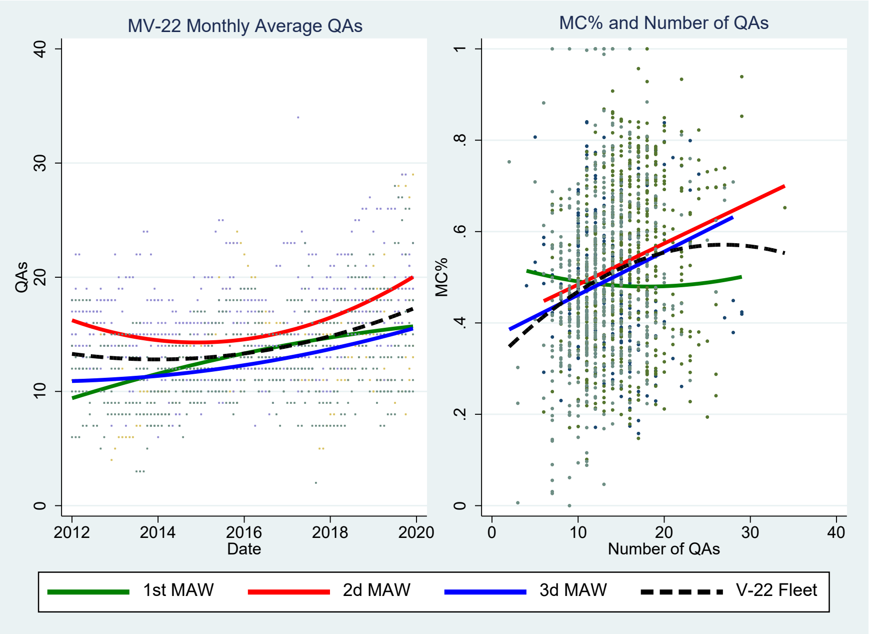

Figure 29. Average Monthly Number of QAs

Table 22. Monthly QA Summary Statistics

Average Monthly Number of QA Qualifications				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	13.6	15.1	12.6	14
Std Error	4.07	3.97	3.77	4.16
Min	4	6	2	0
Max	29	34	28	34

(2) Number of Maintenance Marines

The number of maintenance Marines variable represents the average monthly number of maintenance Marines assigned to production work centers. This variable is important in determining how the number of personnel in the workforce who are maintaining the aircraft affects squadron readiness. This variable only reflects the number of Flightline, Avionics, Airframes, and Crew Chiefs assigned to one of the production work centers during the month; Marines in those MOSs who were assigned to a non-production work center such as Maintenance Control or Tool Room were not counted as they are unlikely to perform aircraft maintenance. Figure 30 shows that the number of production work center Marines has remained relatively constant during the sample period with 1st

MAW seeing a slight increase in manpower. Table 23 shows that 3d MAW had the highest number of maintenance Marines working in production work centers at 90.1, over 10 more Marines on average than 2d MAW. Figure 30 also suggests negative correlation between MC% and the number of Marines. However, it is unlikely that increasing the number of maintenance Marines causes MC% to decrease; it is more likely that the relationship between the number of one or more of the maintenance work centers and MC% is manipulating the relationship displayed in Figure 30.

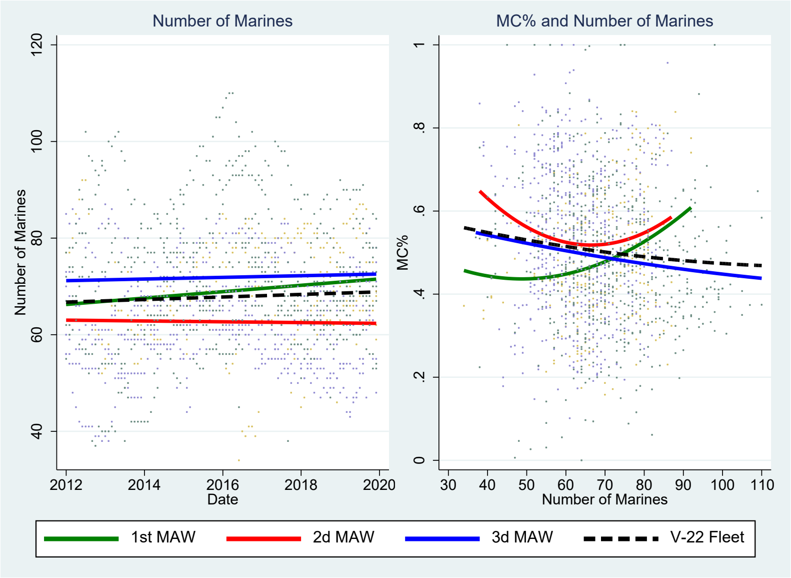

Figure 30. Monthly Number of Maintenance Marines

Table 23. Number of Maintenance Marine Summary Statistics

Average Monthly Number of Maintenance Marines Per Squadron				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	86.9	79.8	90.1	85.5
Std Error	11.8	11.7	15.1	14.1
Min	42	47	43	42
Max	114	113	134	134

c. *Maintenance Planning and Management*

The maintenance management and planning IPS element analyze the degree to which the execution of the Navy and Marine Corps' maintenance system is influencing operational availability. It also provides insight into whether maintenance leadership is effectively managing the aircraft's maintenance requirements as well as the variance in maintenance performance between squadrons. The primary measurement for maintenance management and planning used in this study is workload management expressed by AWM hours and manpower utilization expressed by direct maintenance man-hours per worker per day (DMMH/W/D).

(1) AWM Hours

NMC hours begin accumulating from the time the initial NMC MAF is logged against an aircraft until the time the last NMC MAF has been completed. In between this time, the NMC MAF is either in an in work (IW) status, awaiting parts (AWP) status, indicating that NMCS time is accumulating, or awaiting maintenance (AWM), indicating the MAF is waiting for maintenance personnel to be assigned to perform maintenance. The MAF is in an IW status while at least one maintenance Marine has assigned themself to the MAF in OOMA. The MAF is AWM when no maintainer is assigned to the MAF at which time the MAF is assigned a "Job Status" code to justify the inaction. The NAMP outlines the different Job Status codes that reflect the status of a discrepancy:

- IW. In Work
- JC. Job Complete
- M1. AWM in Depot
- M2. AWM SE/Hangar
- M3. AWM Backlog
- M4. AWM Off Shift
- M5. AWM Other
- M6. AWM Awaiting AIMD
- M7. AWM Flight Operational

- M8. AWM Awaiting Other Shops
- M9. Funding

AWM hours help determine how well the squadron manages its maintenance workload by measuring the total amount of time that Marines were not able to work on an aircraft that were in an NMCM status. The AWM hours calculated for this study represents the sum of all M2 though M9 codes on NMC discrepancies; M1 codes are not calculated because NMCD hours do not contribute to a squadron's MC%.

However, the variance in the number of aircraft accumulating AWM hours produced an extreme range of values, resulting in a poor graphical representation of AWM hours. Therefore, to graphically display the data, the natural logarithm of AWM hours was calculated and represented in Figure 31. This figure shows that the average number of AWM hours per squadron per month has slowly risen over the sample period with Table 24 showing that 2d MAW had the greatest average monthly AWM hours at 70846.9 hours, about 10,000 hours above the fleet mean. Figure 31 also shows that MC% decreases sharply as AWM hours increase.

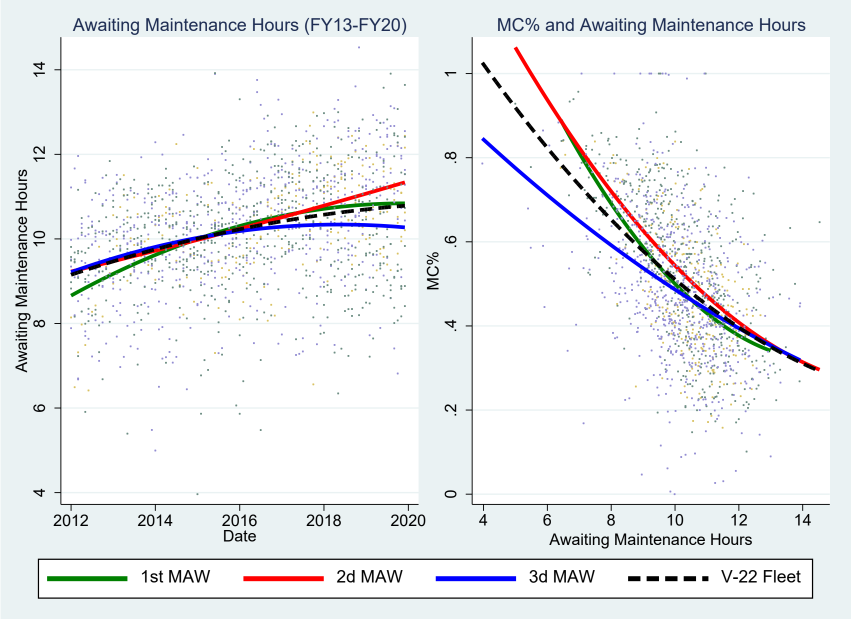

Figure 31. Monthly Awaiting Maintenance Hours

Table 24. Awaiting Maintenance Hours Summary Statistics

Average Monthly Number of Maintenance Marines				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	52496.8	70846.9	54611.9	60609.8
Std Error	58971.8	139319.6	98026.6	11499.3
Min	612	147.7	526	52.6
Max	438955.3	2043468	1112250	2043468

(2) DMMH/W/D

The DMMH/W/D variable represents the average number of hours that each Marine in production work centers worked on discrepancies while aircraft were in an NMC status during that month. This helps determine how manpower utilization affects readiness. Figure 32 shows that the DMMH/W/D has steadily increased in each MAW during the sample period. Table 25 shows that 1st MAW had the highest DMMH/W/D followed by 2d and 3d MAWs, respectively. Figure 32 also indicates negative correlation between DMMH/W/D and MC%. However, it is unlikely that MC% decreases as worker hours increase; this is more likely indicative of reverse causation in which worker hours are higher for squadrons who have a lower average MC%.

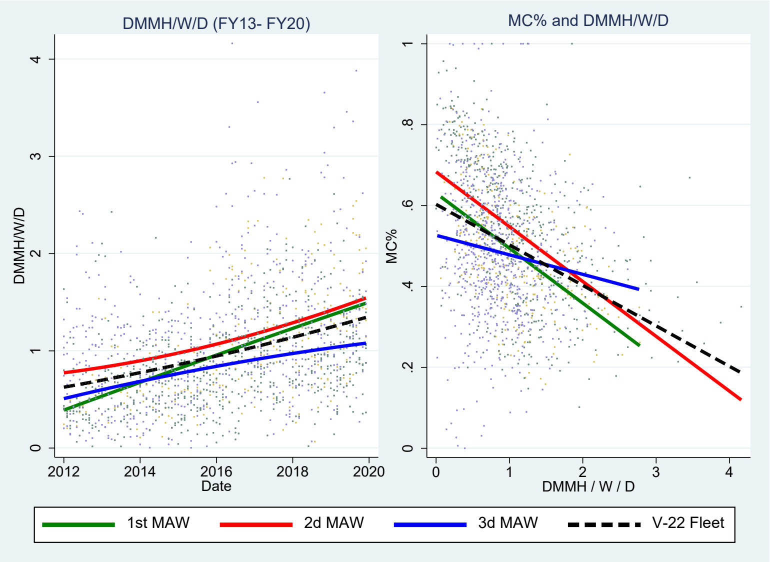

Figure 32. Monthly DMMH/W/D

Table 25. DMMH/W/D Summary Statistics

Average Monthly Man Hours				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	1.05	1.09	.837	.976
Std Error	.580	.669	.452	.581
Min	.064	0	.016	0
Max	2.77	4.16	2.76	4.16

d. Operations

The operations category helps determine how the squadron's operational tempo influences operational availability and whether readiness differs while squadrons are deployed. The measurements for squadron operations include the number of flight hours, the average number of aircraft assigned (AVGAC), and the squadron's deployment status, either fully deployed or partially deployed.

(1) Flight Hours

The flight hours variable represents the average monthly flight hours executed during the month. Examining flight hours is important because a rise in flight hours increases the scheduled maintenance required as many scheduled maintenance inspections are based on total hours flown. A rise in flight hours also increases aircraft system utilization which will slowly degrade and fail with usage, increasing both unscheduled maintenance and airframe hours. Figure 33 shows that each MAW flew about the same number of hours on average during the sample timeframe and that the number of flight hours has remained relatively constant. Table 26 shows that 3d MAW had the highest flight hour average at 175.8 hours, followed closely behind by 1st and 2d MAWs. Figure 33 suggests positive correlation between flight hours and MC%, however during months where flight hours exceed 350 hours, squadrons flew more than double the fleet mean of 173.4. MC percentages at this level of increased flight operations may not be a result of flight hours alone and may have been flown during a deployment where flight operations occur more frequently, suggesting correlation between squadron deployments and flight hours.

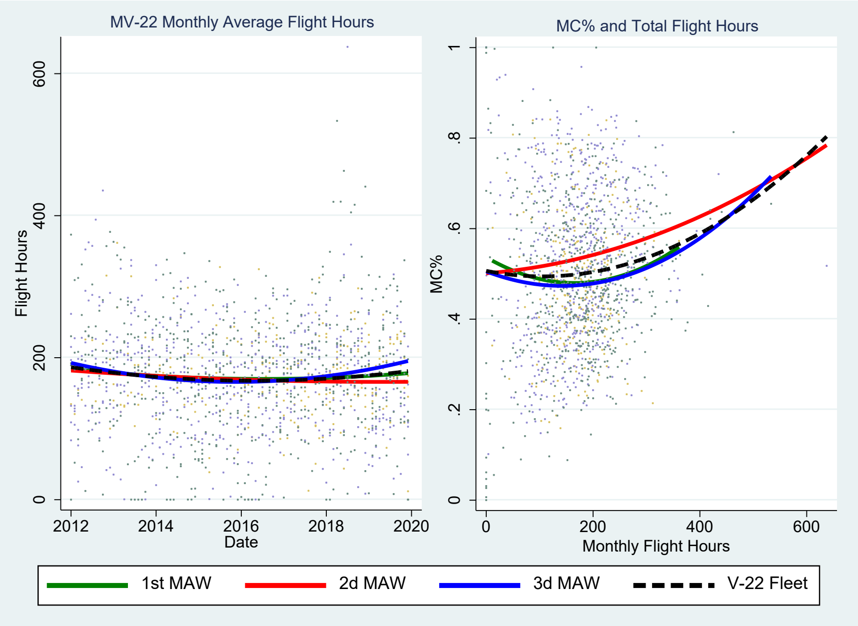

Figure 33. Average Monthly Flight Hours

Table 26. Average Monthly Flight Hour Summary Statistics

Average Monthly Total Flight Hours				
	1st MAW	2d MAW	3d MAW	Fleet
Mean	173.8	170.6	175.8	173.4
Std Error	56.8	72.5	84.16	75.4
Min	11.2	0	0	0
Max	361	637.4	533.4	637.4

(2) Average Number of Aircraft Assigned

The AVGAC variable represents the average number of aircraft assigned to a squadron during a given month. It is calculated by dividing the number of EISHrs by the number of days in the month. The AVGAC variable is not only significant in determining the relationship between the number of aircraft assigned and MC%, but also in examining the effects that the explanatory variables have on MC% while controlling for the number of aircraft assigned. This is because aircraft are routinely transferred across squadrons and not every MV-22 squadron will have the same number of aircraft assigned every month. No doctrine exists to determine the number of aircraft assigned; assignment is typically controlled by the aircraft type-commander with input from the MAGs based on operational necessity. MV-22 squadrons are built to support 12 aircraft which is typically the assignment goal; Figure 34 shows the central tendency is significantly higher as AVGAC gets closer to 12.

$$\text{AVGAC} = \frac{\text{EISHrs}}{\text{Number of Days in Month}} \tag{6}$$

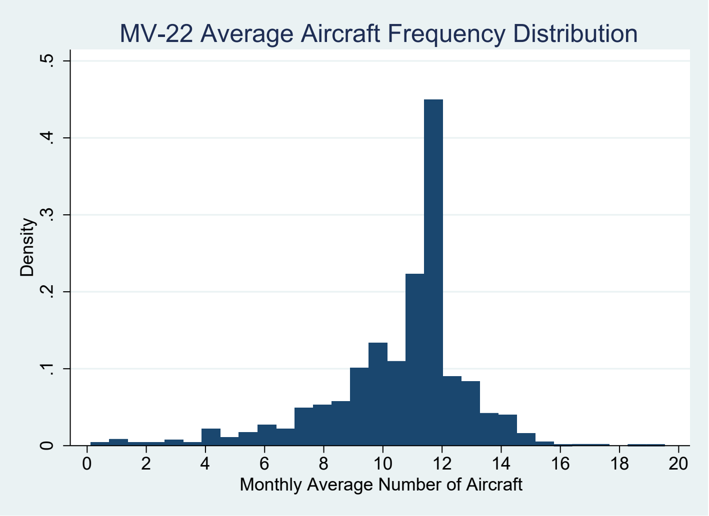

Figure 34. MV-22 Squadron Aircraft Distribution

Figure 35 shows that 1st MAW's AVGAC remained relatively stable during the sample period, while 3d MAW's increased slightly. 2d MAW saw a slight increase in AVGAC followed by a gradual decrease. Figure 35 also shows a non-linear relationship between AVGAC and MC%. As the AVGAC increases toward the mean, MC% increases. However, each Wing differs at which point this increase peaks. The MC% for 2d and 3d MAWs does not peak until they reach around fifteen aircraft. Conversely, 3d MAW saw a decline in MC% as the AVGAC reach 13, indicated that at some point there are too many aircraft to maintain and MC% suffers as a result. 1st and 2d MAW's data did not indicate this finding, likely because they recorded fewer observations with AVGAC this high and never reached the point where MC% suffered due to an overwhelming number of aircraft to maintain. The summary statistics displayed in Table 27 show that 1st MAW had the highest mean average aircraft per squadron at 11.6, while 2d and 3d MAWs averaged about 1 aircraft less at 10.59 and 10.29, respectively.

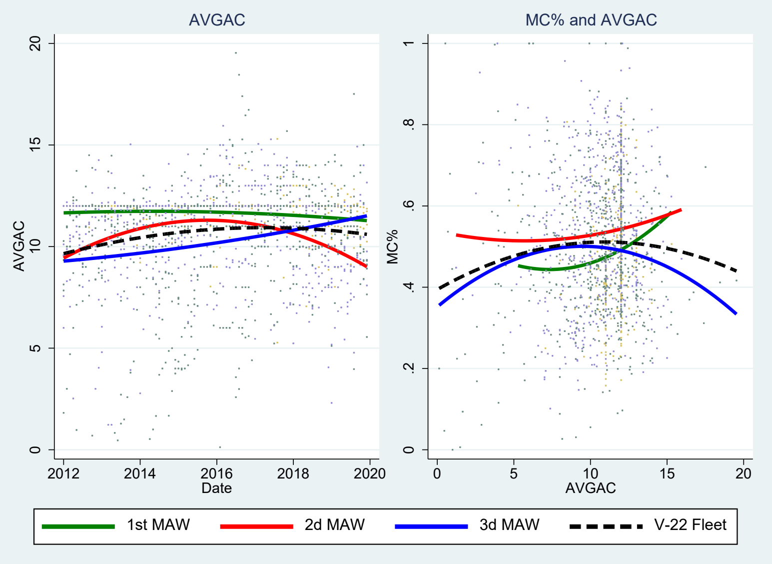

Figure 35. Monthly AVGAC

Table 27. Monthly AVGAC Summary Statistics

Average Monthly Number of Aircraft Assigned				
	1st MAW	**2d MAW**	**3d MAW**	**Fleet**
Mean	11.58	10.59	10.29	10.64
Std Error	1.06	2.23	2.83	2.41
Min	5.27	1.22	.125	.125
Max	15.29	15.94	19.53	19.53

(3) Deployments

The deployed variable represents periods where squadrons were either entirely or partially deployed in support of OEF, MRF-D, the MEU, or one of the Crisis Response Special MAGTFs. The deployed variable is critical in understanding how both MC% and the explanatory variables differ when the squadron is deployed compared to operating from their home location. Figure 36 shows that the MV-22 squadrons which supported four of the five major operations had MC% averages higher than non-deployed squadrons, the exception of which is MRF-D where squadron averages were about twelve percentage points lower than the non-deployed average.

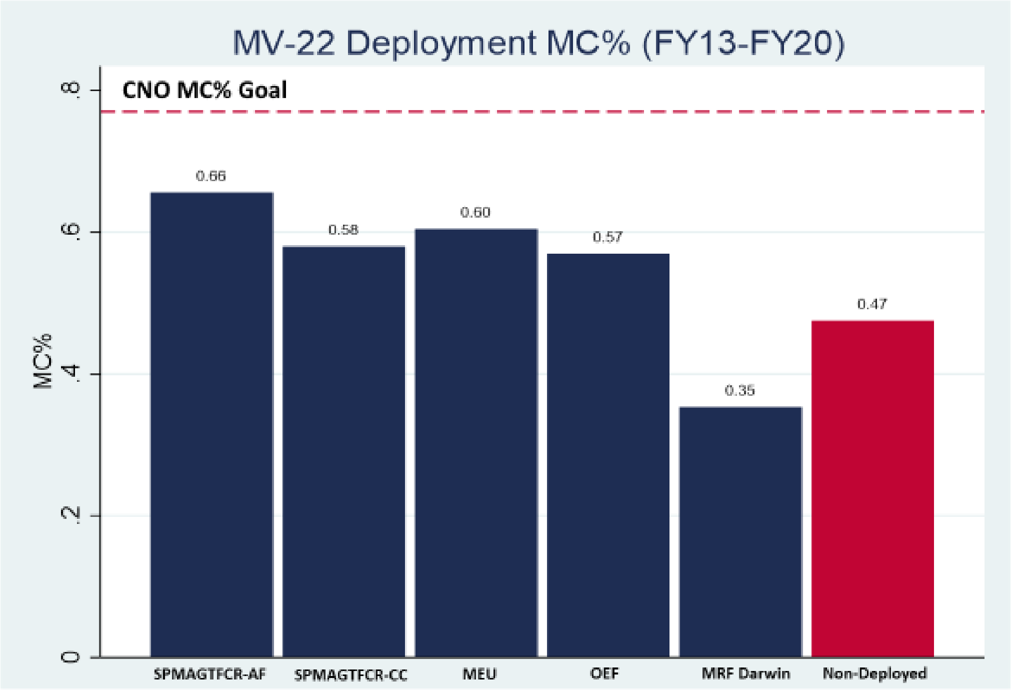

Figure 36. MV-22 MC% by Deployment

This increase in MC% experienced during the deployment period is routinely followed by a significant decrease in MC% after the squadron's return. Figure 37 shows the relationship between 2d MAW's deployment participation and MC% during the sample period. Each full and partial unit deployment sustains an MC% above the mean during the deployment, which is always followed by a significant decrease below the mean. This significant decrease in MC% appears to surpass the post-deployment leave period and remains low. The MC% recovery period varies by squadron, but in some instances, readiness did not recover until the squadron departed for the next deployment. These findings were similar for 1st and 3d MAWs. (See Appendix A: Deployment Graphs:1st and 3d MAWs)

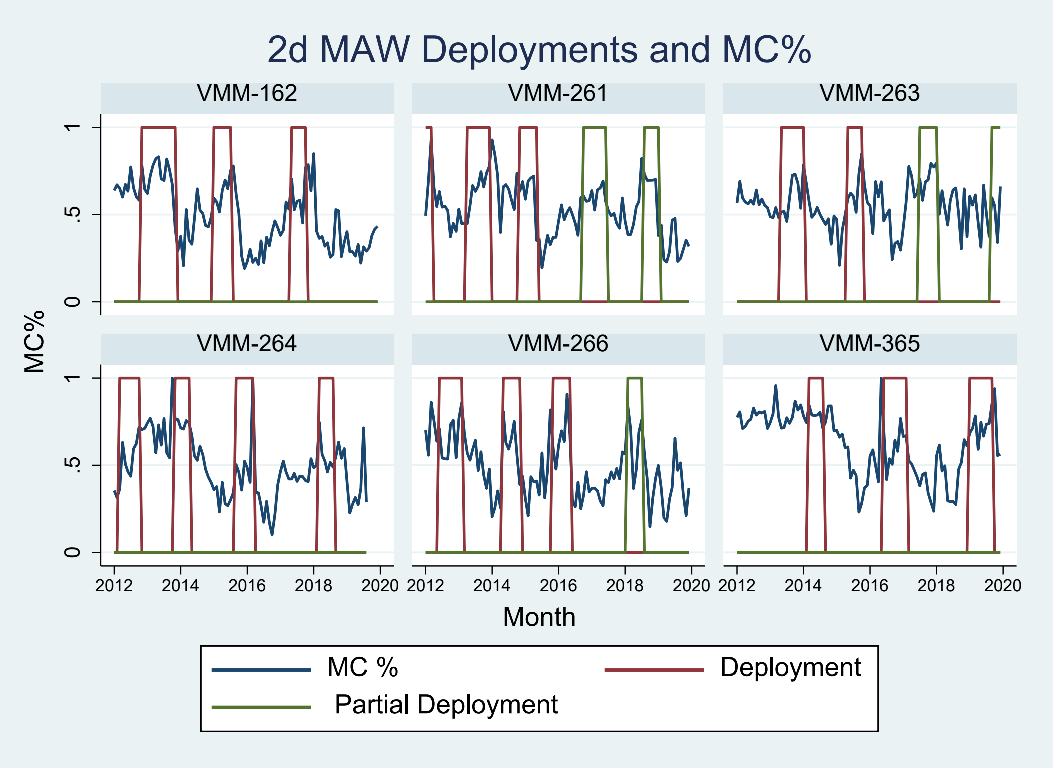

Figure 37. Deployments and 2d MAW MC%

Figures 38 and 39 show that the total number of maintenance Marines and the total number of QA qualified personnel also decreases after a deployment. This is typical as the MAG prioritizes deploying squadrons over others, meaning unit staffing levels are often at their highest during the deployment. Some Marines are also afforded the option to extend their enlistment contract to participate in the deployment, increasing the number of Marines whose contracts will end just after deployment. Marines who have just completed their initial contract have four to five years of maintenance experience and have usually attained at least a CDI qualification. Some of these Marines will be replaced by other QA-qualified Marines moving from other units, however, the majority will be replaced by junior Marines who have just completed initial maintenance training and have little to no maintenance experience.

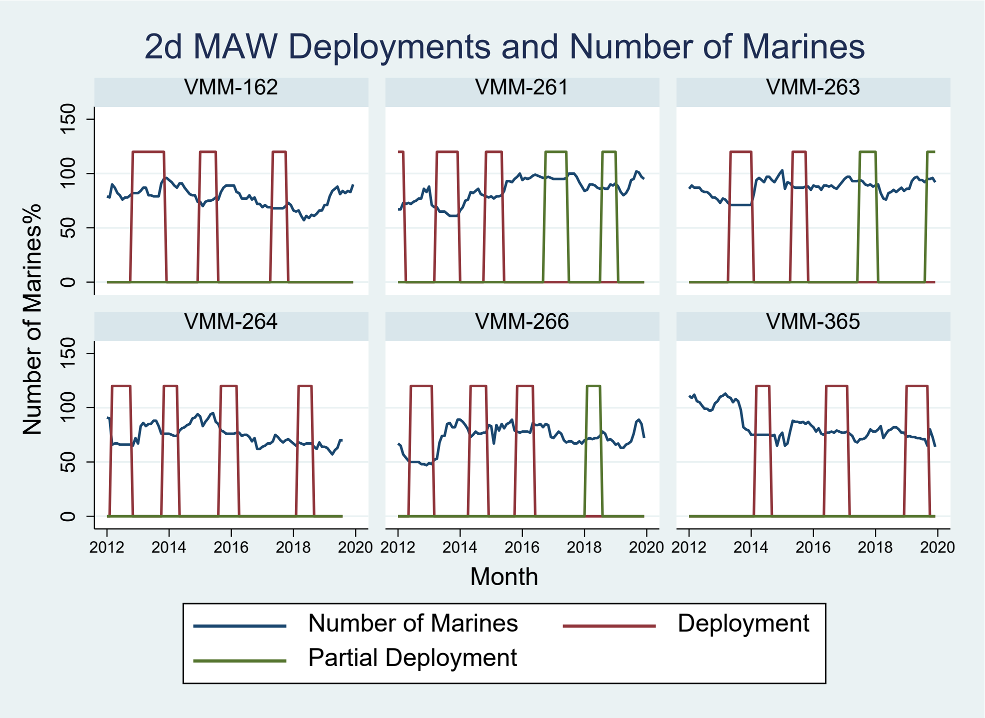

Figure 38. Deployment and 2d MAW Number of Marines

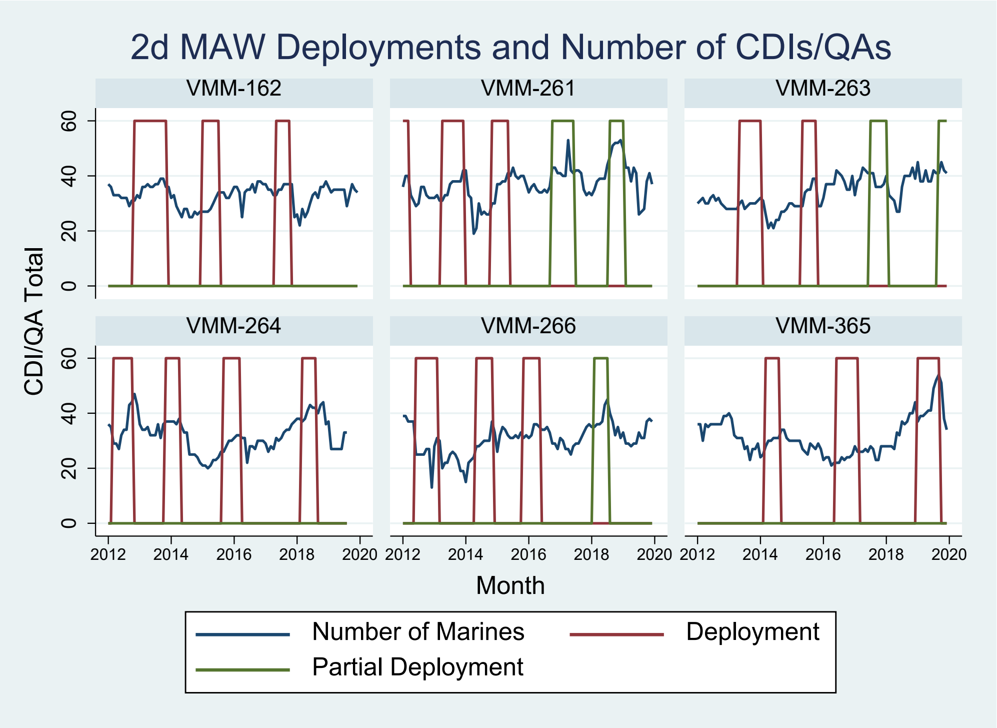

Figure 39. Deployment and 2d MAW Number of CDIs/QAs

Similarly, many of the other explanatory variables have means during the deployment periods that differ significantly from those operating from their home location, shown in Table 28. The most significant of which are the squadron's AWM hours, maintenance man-hours, and flight hours. When squadrons are not deployed, they typically fly and conduct maintenance five days a week, however during a deployment, squadrons typically fly and conduct maintenance seven days a week. Therefore, the mean AWM hours, maintenance man-hours, and flight hours for both fully and partially deployed squadrons are higher than non-deployed squadrons.

Table 28. Explanatory Variable Means During Deployments

Mean Values During Deployment			
	Deployed	**Partially Deployed**	**Non-Deployed**
AF Hrs	12334	18709	14062
MTBF	1.29	1.02	1.06
MTTR	11.5	9.86	9.87
AWM	23692	67624	71936
Maint Man-Hrs	2208.3	2081.4	1794.3
CDIs	17	20.2	15.6
QAs	14.8	20.7	13.5
Flight Hrs	212	201.3	160.4

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VI. MODELING AND SIMULATION

A. INTRODUCTION

To answer the research questions, this study uses MLR to make statistical inferences to the degree to which the independent variables predict the change in a squadron's MC%. The regression model is expanded to highlight the predictive power within the maintenance work centers then reduced because of multiple violations of the assumptions of ordinary least squares (OLS) estimation. A predictive model is then used to conduct a post-hoc analysis of the coefficients and how marginal changes in the aircraft design interface and the number of QA qualified personnel can help forecast the probability of achieving the CNO's MC% goal.

B. REGRESSION ANALYSIS

The purpose of multivariate linear regression is to estimate the relationship between the explanatory variables and dependent variable through the OLS estimation method which minimizes the variance between the observed and predicted values. These estimators allow for statistical inferences to be made when explicitly controlling for other explanatory factors. This is an extremely important and widely used tool for empirical analysis, however, to obtain unbiased estimators, several assumptions must be made as highlighted by Wooldridge (2016). These assumptions include:

- Linear model
- Random sampling
- No perfect collinearity
- Zero conditional mean
- Homoskedasticity

When these assumptions are met, the OLS estimators for the sample represent the best linear unbiased estimator of the population (Wooldridge 2016). Additionally, the coefficient of determination or r-squared value provides insight into the model's strength by assigning a value to the proportion of the variance that is being predicted by the independent variables. However numerous conditions may arise which can limit the predictive power of the model. One of which is the inclusion of irrelevant explanatory variables; this is known as overfitting the model. This forces the model to estimate not only the variance of the explanatory variables but also the unexplained variance or noise in the sample data. The second is omitted variable bias, a phenomenon that occurs when not enough relevant predictors have been presented to accurately estimate a relationship; this is commonly referred to as an underfit model.

1. Full Model

The MV-22 DECKPLATE readiness data and MCRAT qualification data were input into Stata 16 and merged using squadron as the panel variable and months as the time variable, resulting in 1458 total squadron months. The linear model begins with the nested set of predictors based on the categorical framework from Table 15, shown in Equation 7. The exhaustive list of regression models can be found in Appendix D: Comprehensive Regression Models. Additionally, because of the curvilinear relationships identified in the graphical analysis, a squared value for the AVGAC and Total Flight Hrs is introduced to accurately describe the nonlinear relationship between these variables and MC%. A fixed-effects model is used as it is assumed that the parameters are non-random. Additionally, without data to properly analyze maintenance experience, it is assumed that correlation exists between the error term, the predictor variables, and the dependent variable.

$$Y_{st} = \beta_0 + \beta_1 X_{1,s,t} + \beta_2 X_{2,s,t} + \beta_3 X_{3,s,t} + \beta_4 X_{4,s,t} + a_i + \varepsilon_{s,t} \tag{7}$$

where:

$X_{1s,\mathrm{t}}$ = Design Interface Variables
$X_{2s,\mathrm{t}}$ = Manpower Variables
$X_{3s,\mathrm{t}}$ = Maintenance Planning and Management Variables
$X_{4s,\mathrm{t}}$ = Operations Variables
a_i = Unobserved fixed effects
$\varepsilon_{s,t,}$ = Residual

s = Squadron
t = Time in Months

The results of the full model are presented in the first column of Figure 40. The overall r-squared value for the full model is only .446; therefore, the predictor variables only explain 44.6% of the variance of monthly MC%. The within r-squared value is .415 and the between r-squared value is .683, meaning that the model only explains 41.5% of the variation that occurs within the squadrons and 68.3% percent of the variation between the squadrons. According to the full model, NMCS has the greatest impact on MC% followed by DMMH/W/D and squadrons being either fully or partially deployed. However, the coefficient on DMMH/W/D is negative which is consistent with the findings from the graphical analysis. The suggestion that increased work hours will reduce MC% is contrary to common manpower principles and provides further evidence of reverse causation. Similarly, the coefficient on the number of Marines is also negative, and likely the result of variance from within the work centers.

2. Model Expansion

Both the graphical and regression analysis provided evidence of irregularities within the production work centers, therefore the number of Marines, QA, and CDI variables are divided into work centers to further analyze these irregularities and provide accurate measurements of the predictive power of each variable in each work center concerning MC%. The Crew Chief MOS is the reference variable for each work center predictor. The expanded model is expressed in Equation 9 (See Appendix D: Comprehensive Regression Models).

The results of the expanded model are shown in the second column of Figure 40. The r-squared values of the expanded model are relatively unchanged, however, the number of predictors increased to 21 which can naturally inflate the r-squared value without increasing the predictive power of the model. The AFHrs and Total Flight Hrs variables still have an extremely small coefficient, and the AWM variable is still statistically insignificant. When divided by work centers, none of the CDI variables are statistically significant and the Airframes variable is the only statistically significant variable of the work center personnel variables. However, this coefficient is negative, which is analogous to the logically invalid coefficient assigned to DMMH/W/D. This erroneous data is likely the cause of the erratic behavior shown in the graphical analysis and negative coefficient in the full model, despite the number of Marines variable being statistically significant. Conversely, all the work center QAs were found to be statistically significant.

3. Model Reduction

To prevent an overfit model, reduce multi-collinearity, and limit the impact of the extreme variance of multiple predictors, the model is reduced to only those that are significantly significant in increasing MC%, along with all QA qualification variables, shown in Equation 10, (Appendix D: Comprehensive Regression Models). The number of Marines and AWM variables are removed due to their statistical insignificance. The DMMH/W/D variable is also removed due to the reverse causation which resulted in the MTTR variable being insignificant.

The final reduced model is shown in the third column of Figure 40. The r-squared value is 0.419, slightly lower than that of the expanded model. The coefficients changed little from the expanded model as these removed variables are seemingly irrelevant. However, the changes in statistical significance in the deployed and partially deployed variables show how much unexplained variance exists within the sample, a large portion of which lies within the squadron as evidenced by the .39 within r-squared value.

The significance of each coefficient in an MLR model is interpreted as the effect that a one-unit change in the value of the explanatory variable has on the dependent variable when holding the other variables constant. According to the regression results, a unit that is deployed or partially deployed has 6.3% and 7.7% higher readiness on average, respectively than those that are not deployed. Additionally, an increase of one CDI or CDQAR per squadron increases MC% anywhere from 2% to 5%. A one-hour rise in MTBF increases readiness by about 5.5% whereas providing a squadron with one additional aircraft increases readiness by about 3%. However, due to the inverted curve expressed by the data, the impact of the AVGAC coefficient will only increase up to a specific aircraft allotment that can be effectively maintained by maintenance personnel at which point its effects will diminish. Furthermore, a 1% increase in NMCS% will reduce readiness by 0.71 percentage points.

A larger coefficient does not necessarily generate a more significant change in the independent variable; likewise, a small coefficient should not be interpreted as a much smaller change. The significance of the coefficient is also determined by the size of the unit of measurement that is applied to the coefficient. For example, the coefficient for AFHrs is -3.32e^{-6}, insinuating that AFHrs have an extremely small impact on MC. However, an increase of one airframe hour is also relatively small and deceptively insignificant, given the maximum service life of an MV-22 airframe is 10,000 hours. The mean of AFHrs during the sample period is 13,778.61 hours, which means given a squadron of around 12 aircraft, each airframe had slightly over 1,000 airframe hours. Future squadron personnel will see mean AFHrs increase exponentially throughout the life of the program therefore, given that the airframe will be utilized for multiple decades, this seemingly insignificant number will become much more meaningful as the program progresses.

Furthermore, the resources required to generate a unit one change in explanatory variables can differ greatly. The cost of generating one additional flight hour is much different than design changes required to increase the MTBF by one hour or the personnel and training costs required to increase the average number of CDIs or CDQARs in each work center throughout the fleet. This level of analysis would require a much deeper examination of total life cycle cost and resource allocation.

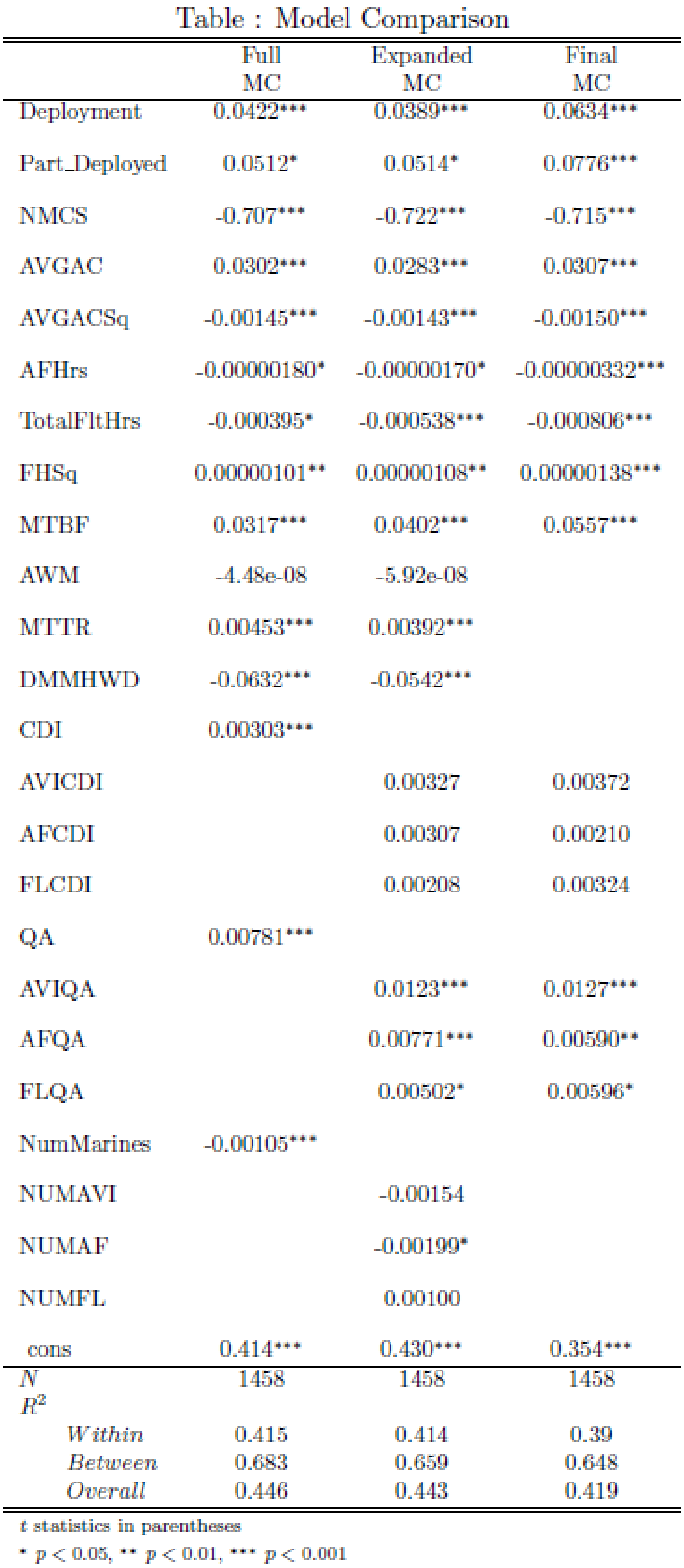

Table : Model Comparison

	Full MC	Expanded MC	Final MC
Deployment	0.0422***	0.0389***	0.0634***
Part_Deployed	0.0512*	0.0514*	0.0776***
NMCS	-0.707***	-0.722***	-0.715***
AVGAC	0.0302***	0.0283***	0.0307***
AVGACSq	-0.00145***	-0.00143***	-0.00150***
AFHrs	-0.00000180*	-0.00000170*	-0.00000332***
TotalFltHrs	-0.000395*	-0.000538***	-0.000806***
FHSq	0.00000101**	0.00000108**	0.00000138***
MTBF	0.0317***	0.0402***	0.0557***
AWM	-4.48e-08	-5.92e-08	
MTTR	0.00453***	0.00392***	
DMMHWD	-0.0632***	-0.0542***	
CDI	0.00303***		
AVICDI		0.00327	0.00372
AFCDI		0.00307	0.00210
FLCDI		0.00208	0.00324
QA	0.00781***		
AVIQA		0.0123***	0.0127***
AFQA		0.00771***	0.00590**
FLQA		0.00502*	0.00596*
NumMarines	-0.00105***		
NUMAVI		-0.00154	
NUMAF		-0.00199*	
NUMFL		0.00100	
cons	0.414***	0.430***	0.354***
N	1458	1458	1458
R^2			
Within	0.415	0.414	0.39
Between	0.683	0.659	0.648
Overall	0.446	0.443	0.419

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 40. Regression Models

C. STOCHASTIC MODELING

The purpose of the stochastic modeling is to perform a sensitivity analysis on multiple variables of interest, using the coefficients from the reduced regression model to see how marginal changes will impact the likelihood of achieving a true mean MC of .77. This happens by estimating the probability of the sample distribution when simulating the variability of the coefficients 50,000 times. The distribution of each variable, the constant, and the error term from the final model are input into Microsoft Excel and the Monte Carlo simulation was run using the Oracle Crystal Ball add-in for Excel. The control variables include full and partial deployments, AVGAC, AFHrs, and Total Flight Hrs as it is assumed that these variables will remain within the standard deviation of their means and changes are unlikely. The MTBF, NMCS, CDI, and QA variables shown in Table 29 are selected as decision variables as they are the most likely predictor variables that can reasonably be adjusted to increase MC%.

Table 29. Simulation Decision Variables

Category	Measurement	Variable
Design Interface	Reliability	MTBF
	Supportability	NMCS
Manpower	CDI	AVI CDI
		AF CDI
		FL CDI
	QA	AVI QA
		AF QA
		FL QA

1. Simulation of Marginal Improvements

The MV-22 sample mean MC is only above .77 in 99 out of 1458 observed months, with a success rate of about 6.79%. The first simulation with the decision variables at their sample means, results in a 6.74% probability of a true mean of .77, nearly identical to the historical success rate. Marginal improvements of 10%, 15%, and 20% of the sample means shown in Table 29 were simulated, which means NMCS is reduced while each work center qualification and MTBF is increased by the respective percentage shown in Table 30. The results shown in Table 30 show that improvements of 10%, 15%, and 20% in the sample means of each of these decision variables result in an 8.21%, 9.38%, and 11.83% probability of a true mean of .77, respectively.

Table 30. Decision Variable Means

Variable	**Values at Historic Mean**	**Values With**		
		10% Improvement	**15% Improvement**	**20% Improvement**
MTBF	1.216	1.337	1.398	1.45
NMCS	.146	.131	.124	.117
AVICDI	5.09	5.59	5.85	6.11
AFCDI	6.36	6.99	7.31	7.63
FLCDI	4.65	5.11	5.34	5.58
AVIQA	4.41	4.85	5.07	5.29
AFQA	5.136	5.64	5.90	6.61
FLQA	4.50	4.95	5.17	5.40
MTBF	1.216	1.337	1.398	1.45
Probability of Mean > .77	**6.74%**	**8.21%**	**9.38%**	**11.83%**

2. Simulation of Decision Variables Based on Successful Means

At current resource levels, the probability of achieving a true mean of .77 is infeasible through continual increases of the decision variables alone. However, as shown in Table 31, the sample means of each work center qualification variable and MTBF is higher in months where readiness is higher than .77. Additionally, the sample mean of NMCS is lower in months where readiness is higher than .77. Furthermore, NMCS and

MTBF both showed average improvements of 68.6% and 170.3%, respectively, during these months.

Table 31. Decision Variables When MC% is Greater Than .77

Variable	Mean	Mean when MC > .77	Difference	% Change
MTBF	1.216	2.05	.83	68.6%
NMCS	.146	.054	.92	-170.3%
AVICDI	5.09	5.13	.04	.78%
AFCDI	6.36	6.38	.02	.31%
FLCDI	4.65	4.75	.10	2.1%
AVIQA	4.41	5.16	.75	17.1%
AFQA	5.13	5.77	.64	12.47
FLQA	4.50	4.81	.31	6.88%

The next two simulations are run with manpower and design interface variables isolated to determine the distinct effects of each. Manpower is held constant at the sample mean, while NMCS and MTBF values were simulated at the sample mean when MC% is greater than .77. During the second simulation, manpower is increased by an average of one Marine in every variable while MTBF and NMCS are simulated at their sample means. The third and final simulation forecasts the effects of both NMCS and MTBF at their means when MC% is greater than .77 and each QA qualification is increased by an average of 1 Marine. The results in Table 32 show that improving the MTBF and NMCS to their means when MC has historically been greater than .77 has a greater impact on the probability of achieving a true mean of .77 than increasing each maintenance qualification by an average of one Marine. However, improving NMCS, MTBF, and increasing the number of maintenance qualifications by one Marine will increase the probability of achieving a true mean of .77 to about 22%, much higher than the historical mean of 6.79%.

Table 32. Decision Variables Simulated When Means Were Greater Than .77

Variable	**Values**		
	CDI/QA Sample Mean	**CDI/QA Increase of 1**	**CDI/QA Increase of 1**
	NMCS & MTBF Mean When MC >.77	**NMCS & MTBF Sample Mean**	**NMCS & MTBF Mean When MC >.77**
MTBF	1.337	1.398	1.45
NMCS	.131	.124	.117
AVICDI	5.59	5.85	6.11
AFCDI	6.99	7.31	7.63
FLCDI	5.11	5.34	5.58
AVIQA	4.85	5.07	5.29
AFQA	5.64	5.90	6.61
FLQA	4.95	5.17	5.40
MTBF	1.337	1.398	1.45
Probability of Mean >.77	**17.46%**	**8.33%**	**22.00%**

3. Summary

Given these results, the MLR model explains much less of the variability that exists within MV-22 squadrons than the author had hoped. The predictive power of the model is not robust enough to support an accurate estimation of each of the IPS categorical variables of interest displayed in Table 15. Numerous variables of interest are found to be statistically insignificant while others violated the assumptions of OLS. Both occurrences severely limit the predictive power of the regression model and are removed from consideration. The model does suggest that improvements in the number of QA qualified personnel, NMCS, and MTBF would have a positive effect on MC%. This inference is further substantiated by the results of the Monte Carlo simulation. It shows that increases in NMCS, MTBF, and the number of QA qualified personnel will increase the likelihood of predicting a mean of .77. Furthermore, the results of the simulation suggest that NMCS and MTBF together have a greater impact on MC% than increasing the number of QA qualifications by an average of one. However, due to the low predicting power of the regression model, the findings poorly explain the variance in both the sampling distribution and the MV-22 IPS elements. The results of the Monte Carlo simulation suggest that the likelihood of reaching the CNOs goal is seemingly small, and that increasing this probability will take more than aircraft design, supportability, and manpower improvements alone.

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VII. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY

Despite its turbulent test and evaluation period, the MV-22 Osprey has proven itself as a highly effective addition to Marine Corps aviation. MV-22 squadrons have been deployed overseas in support of countless operations, providing the MAGTF with a versatile assault support platform. However, the MV-22 program cannot sustain the CNO's MC goal of 77% MC, and the program's average during the sample period is around 26.5 percentage points below this threshold. This study examines eight years of MV-22 operational squadron historical data consisting of multiple IPS elements to understand which product support elements are significant in increasing the likelihood of meeting the CNO's 77% MC goal.

This study highlights several correlations between the IPS elements and MC%, such as NMCS, MTBF, the number of CDQARs and QARs, and the squadron's deployment status. Additionally, this study determines that the means for many explanatory variables, such as AWM, Total Flt Hrs, and DMMH/W/D, differ significantly when a squadron is fully or partially deployed. Furthermore, Monte Carlo simulation was able to determine that increases in manpower allocation and design interface characteristics would increase the likelihood of meeting the CNO's MC goal. However, due to the low predictive power of the MLR model and given the significant amount of unexplained variance, this study is unable to accurately predict optimum resource levels to increase the likelihood of achieving 77% MC.

B. CONCLUSIONS

The following conclusions are summarized to answer the research questions proposed in Chapter I.

1. Primary Research Questions

- What explanatory factors are statistically significant in predicting an MV-22 squadron's readiness, as measured by the total monthly MC%?

The results of the reduced MLR model show that the squadron's deployment status, NMCS, AVGAC, MTBF, AFHrs, number of CDQARs and QARs, and Total Flt Hrs are statistically significant in predicting MV-22 squadron readiness. This does not mean the other explanatory variables included in the model, such as the total number of personnel and the total number of CDIs, are not critical to squadron success. This means rather that there is a low degree of confidence in the predicting power of each coefficient given the sample data. Increasing the predictive power of the model by introducing additional relevant variables would likely increase the confidence of these predictors.

- How do these factors change throughout the squadron's deployment cycle?

A certain degree of correlation exists between each predictor and the squadron's deployment status. Squadrons actively deployed and squadrons preparing for deployment are the MAWs highest priority for support. As a result, the mean number of Marines, QA qualifications, and NMCS are higher while squadrons are deployed. Furthermore, a squadron works seven days a week when deployed, as opposed to five days a week when non-deployed. Therefore, mean DMMH/W/D is higher during deployments while mean AWM is lower. Additionally, squadrons see a reduction of manpower and MC during the post-deployment period. This period typically begins the month the squadron returns from deployment, however, the MC% reduction after a squadron returns from a deployment can last anywhere from a month to the squadron's departure for the next deployment.

2. Secondary research Questions

- How much variability is left unexplained after modeling the statistically significant explanatory factors?

The overall coefficient of determination for the final MLR model is .419, which means this model only explains 41.9% of the variation in squadron MC%. The within r-squared value of .39 is much lower than the between r-squared value of .648, meaning that more of the variance between squadrons is being captured than within the squadrons. The author hypothesizes that maintenance experience, as well as behavioral factors such as leadership, command climate, and work center morale, are a few of the factors that influence MC% from within the squadrons, which are not efficiently captured by the model. It is also likely that these omitted factors within the error term are correlated with the explanatory variables such as DMMH/W/D and MTBF.

- What explanatory factors can be altered to increase the probability that MV-22 squadrons will achieve 77% average monthly MC%.

The results of the Monte Carlo simulation show that increasing both manpower and design interface IPS elements will increase the likelihood of achieving a mean MC% of 77%. Improving the MTBF and NMCS variables will have a greater effect on MC% than the number of CDIs and CDQARs, however by improving MTBF and NMCS to the mean values when MC was above .77, and increasing the number of qualifications by one in each work center, will increase the likelihood of achieving a mean MC% of 77% by 22%.

C. RECOMMENDATIONS

1. Changes

Not unlike budget restrictions on large firms and corporations, Marine Aviation also faces resource limitations. In support of the MAGTF, the MV-22 program is specifically funded to support a certain level of operational availability necessary in executing its mission. If the program occasionally drops below this MC% threshold, this may not lead to an existential national security threat. However, the MV-22 platform has only met this threshold annually around 6.79% of the time from FY 2013 – FY 2020, a significant readiness shortfall that does not show signs of improvement. The results of the Monte Carlo simulation make it extremely clear that greater investment needs to be made in aircraft design, parts availability, and manpower staffing levels.

Furthermore, squadrons experience a significant resource reduction as soon as they return from an overseas deployment. This naturally occurring shift in supportability is required as resources are allocated to the deployed squadrons, however, the subsequent decline in MC% will often plague a squadron for months, if not years. Though they are not the operation priority, these non-deployed squadrons still have a responsibility to train a new cadre of maintenance Marines and aircrew. Increasing these resources to smooth out this post-deployment transition will not only increase overall MC% but will also result in more effective maintenance Marines and aircrew.

2. Area for Future Research

Data limitations, omitted variable bias, and violations of the OLS assumptions plague the MLR models and prevent a proper analysis of the optimal resourcing levels required for an increase in operational availability. The predictive power of the MLR models could be significantly improved with the addition of monthly maintenance experience, which would have likely reduced much of the unexplained variance. Additionally, a cross-sectional data set of quantitative maintenance experience would make the model more robust, as squadron maintenance skill levels likely have a significant impact on MC%. Lastly, providing maintenance leaders and researchers with the ability to pull historical squadron maintenance records from ASM would allow for a much better analysis of how maintenance skill levels increase over time and the relationship that maintenance experience has on each of the IPS elements.

A further examination of the significant decrease in MC% when a squadron returns from a deployment could likely explain why operational availability for non-deployed units is so low. Examining how resource levels are different for deployed units versus non-deployed units could assist in smoothing out this significant readiness decline. Additionally, exploring the effects of system design and supportability by aircraft subsystem could highlight areas where significant shortfalls exist in design characteristics and inventory levels. Furthermore, a cross-sectional data set of mean failure rates and supply turn-around time by WUC time could provide insight into how to prioritize resources to improvements in aircraft reliability and supportability.

APPENDIX A. DEPLOYMENT GRAPHS: 1ST AND 3D MAWS

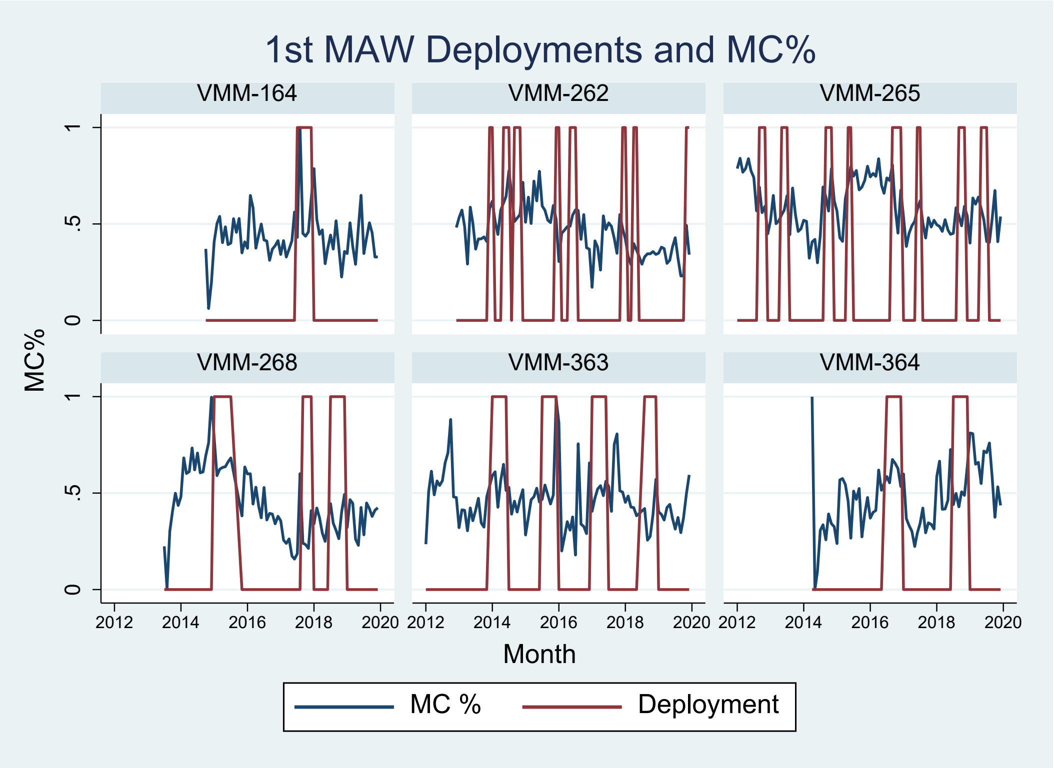


Figure 41. Deployment and 1st MAW MC%

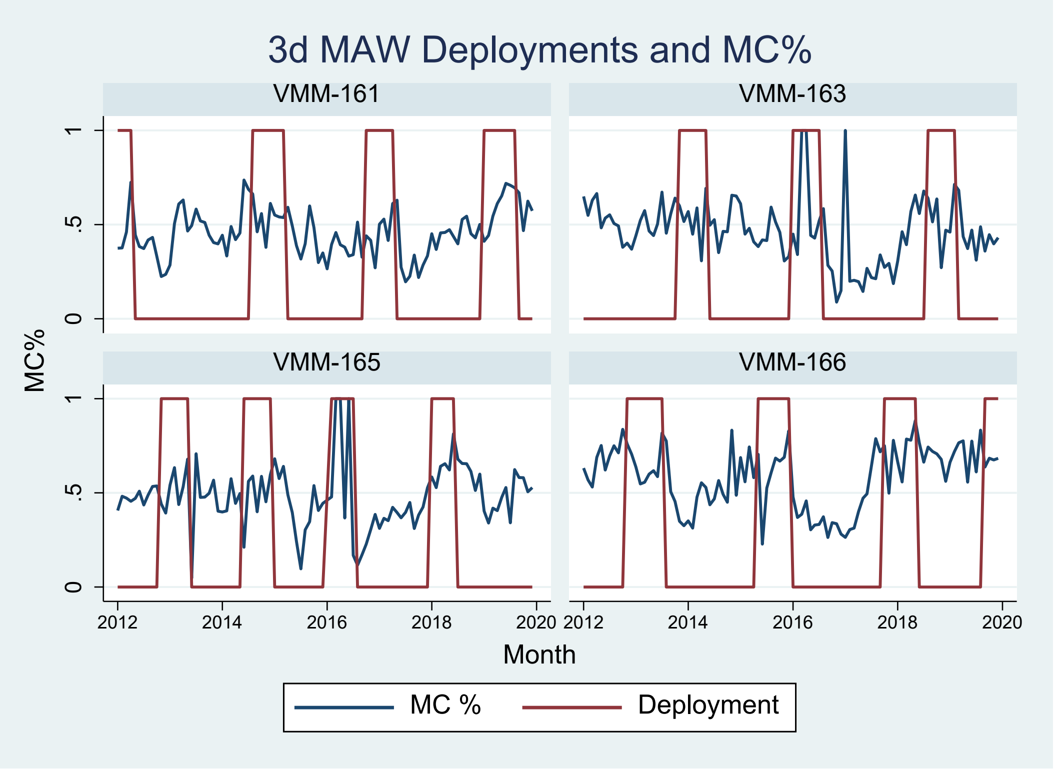


Figure 42. Deployment and 3d MAW MC%

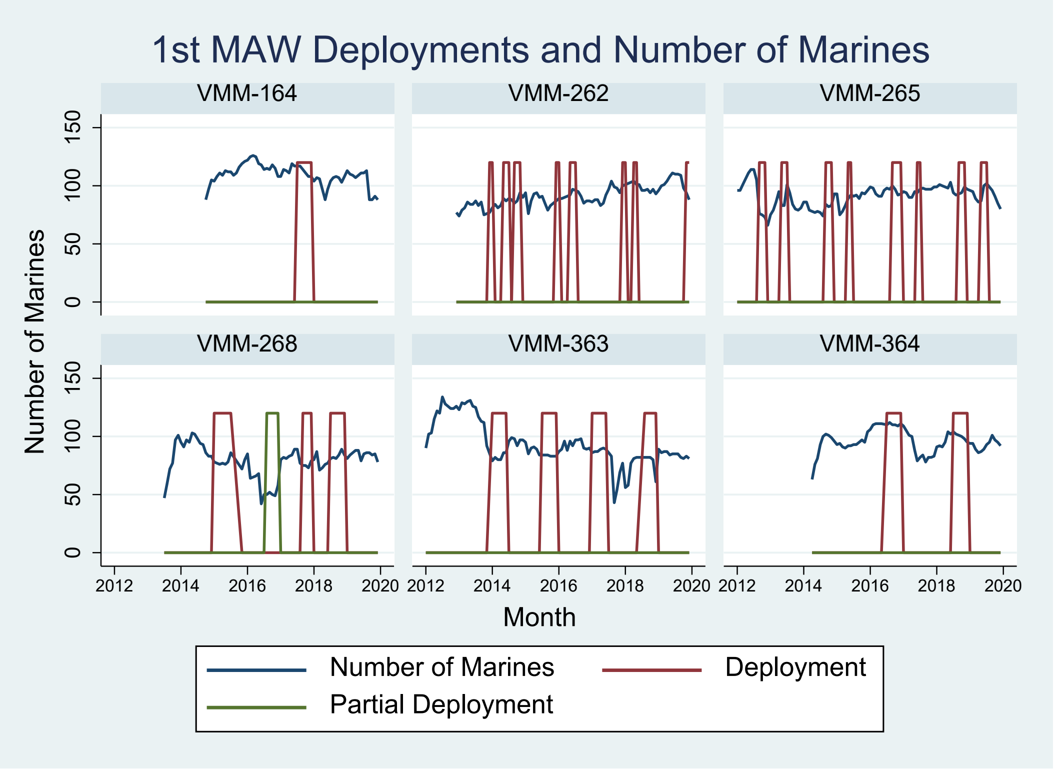


Figure 43. Deployment and 1st MAW Number of Marines

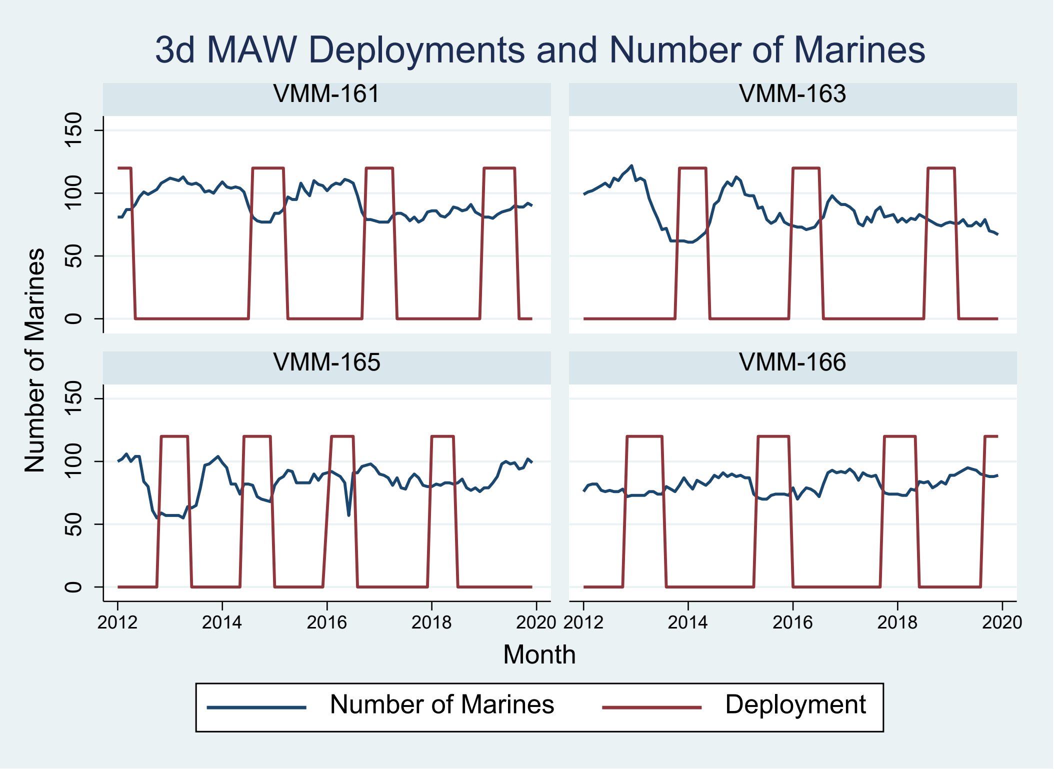


Figure 44. Deployment and 3d MAW Number of Marines

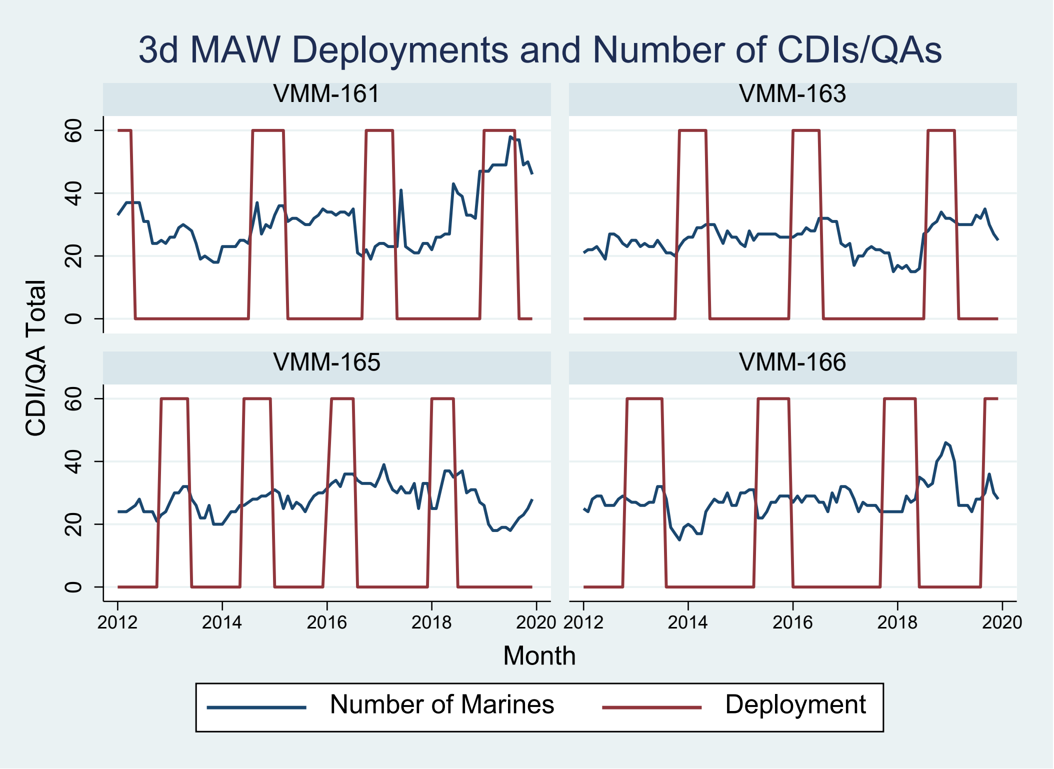


Figure 45. Deployment and 1st MAW Number of QA Qualifications

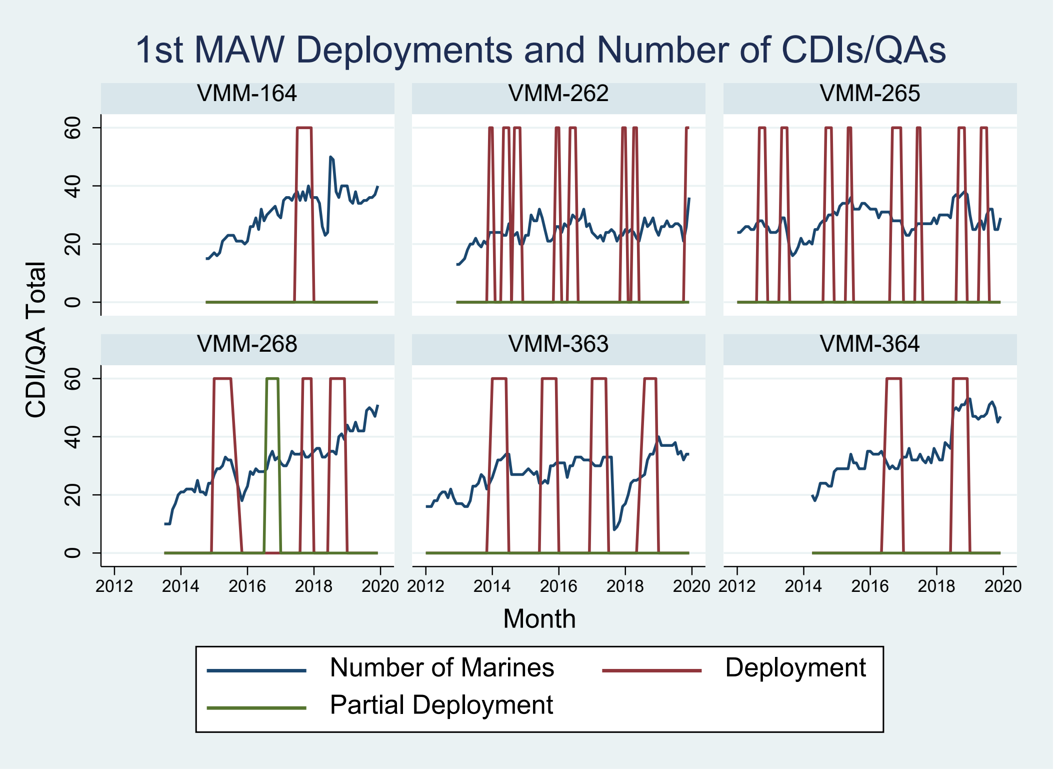
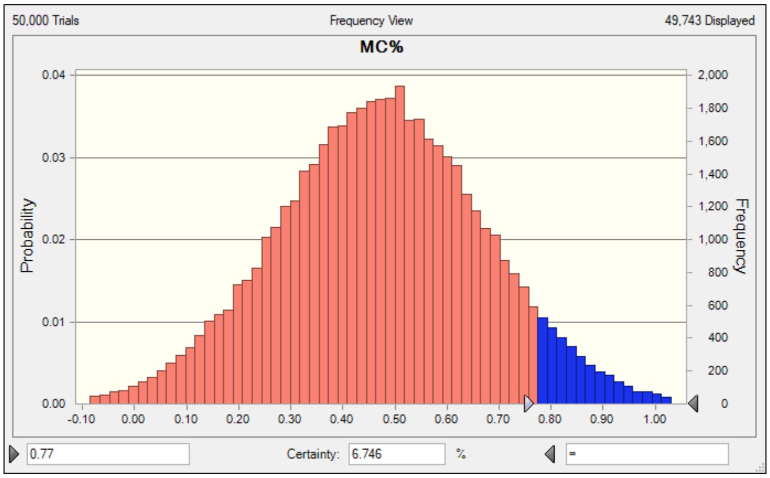


Figure 46. Deployment and 3d MAW Number of QA Qualifications

APPENDIX B. SIMULATION RESULTS

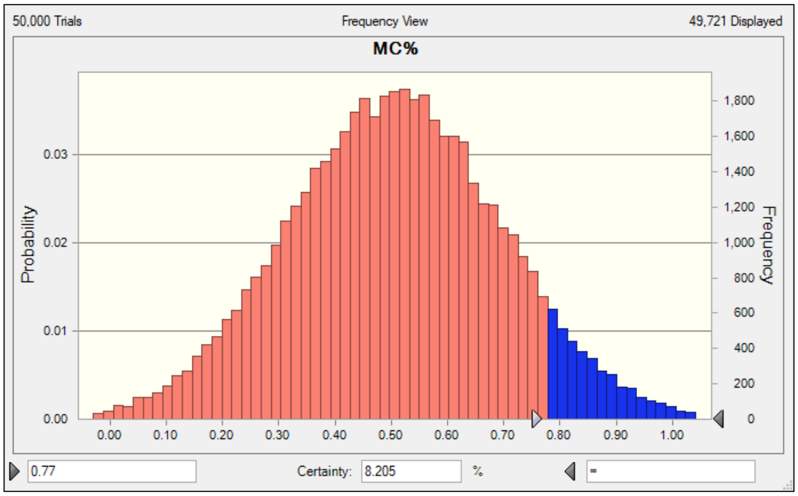


0.77

Certainty: 6.746 %

∞

Figure 47. Probability of True Mean Greater than .77 at Historic Means

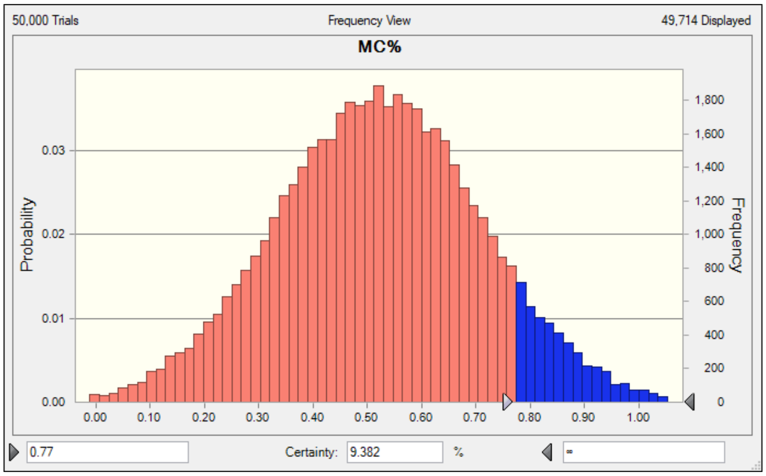


0.77

Certainty: 8.205 %

∞

Figure 48. Probability of True Mean Greater than .77 with 10% Decision Variable Improvement



50,000 Trials

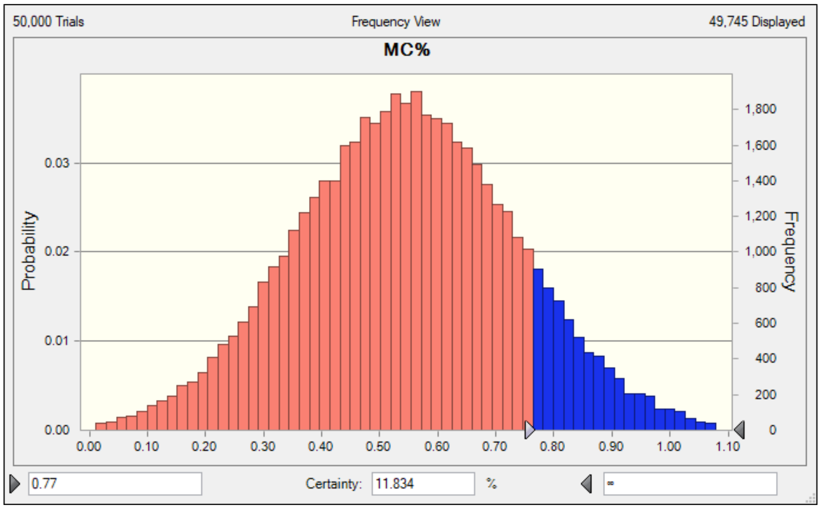
49,714 Displayed

0.77

Certainty: 9.382 %

∞

Figure 49. Probability of True Mean Greater than .77 with 15% Decision Variable Improvement



50,000 Trials

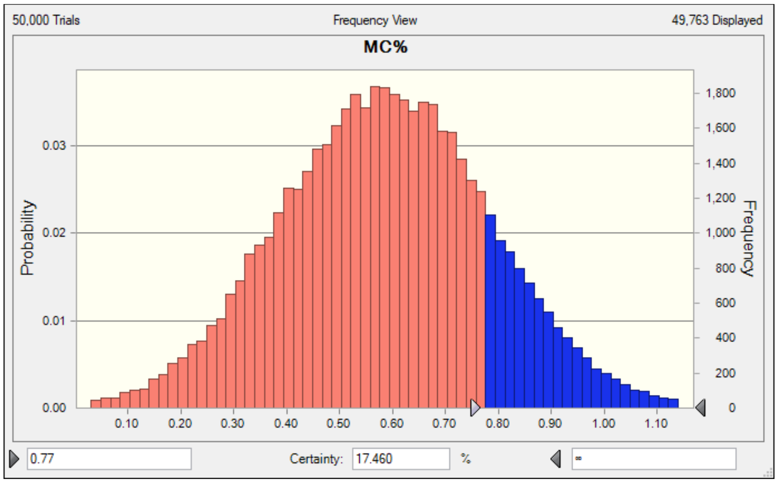
49,745 Displayed

0.77

Certainty: 11.834 %

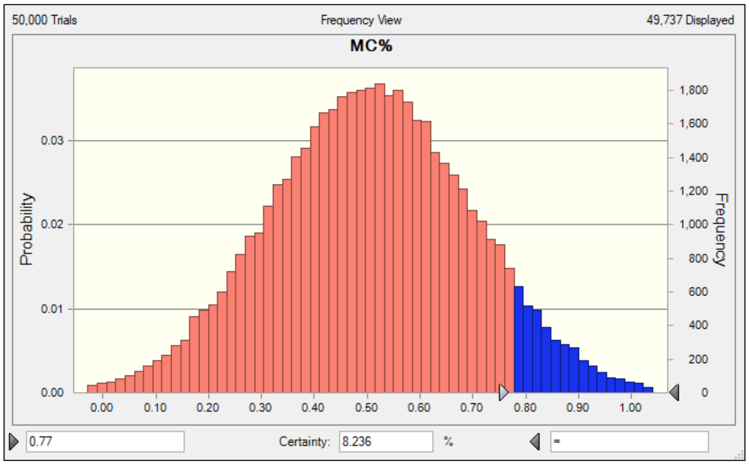
∞

Figure 50. Probability of True Mean Greater than .77 with 20% Decision Variable Improvement



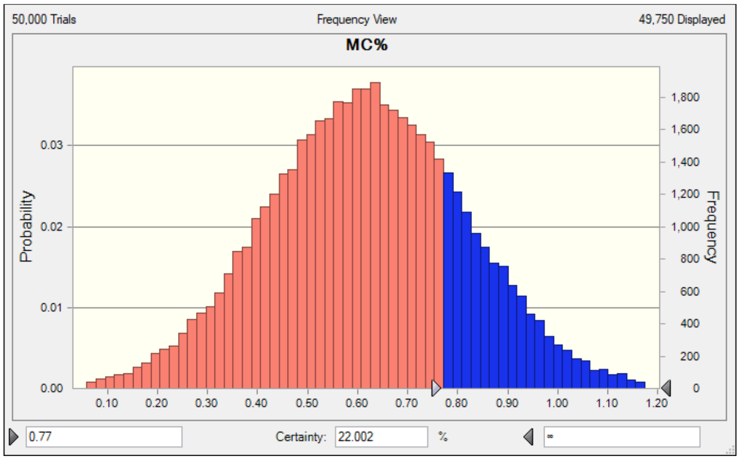
0.77 Certainty: 17.460 % ∞

Figure 51. Probability of True Mean Greater than .77 with No Manpower Increase and NMCS MTBF at Means When MC Is Above .77%



0.77 Certainty: 8.236 % ∞

Figure 52. Probability of True Mean Greater than .77 with Manpower Increase and NMCS MTBF at True Means



0.77

Certainty: 22.002 %

∞

Figure 53. Probability of True Mean Greater than .77 with Manpower Increase and NMCS MTBF at Means When MC Is Above .77%

APPENDIX C. COMPREHENSIVE REGRESSION MODELS

$$\begin{aligned}Y_{st} &= \beta_0 + \beta_1 X_{1,s,t} + \beta_2 X_{2,s,t} + \beta_3 X_{3,s,t} + \beta_4 X_{4,s,t} + \beta_5 X_{5,s,t} + \beta_6 X_{6,s,t} + \beta_7 X_{7,s,t} + \\ &\beta_8 X_{8,s,t} + \beta_9 X_{9,s,t} + \beta_{10} X_{10,s,t} + \beta_{11} X_{11,s,t} + \beta_{12} X_{12,s,t} \\ &+ \beta_{13} X_{13,s,t} + \beta_{14} X_{14,s,t} + \beta_{15} X_{15,s,t} + a_i + \varepsilon_{s,t}\end{aligned} \tag{8}$$

where:

$X_{1s,\mathrm{t}}$ = Deployed
$X_{2s,\mathrm{t}}$ = Partially Deployed
$X_{3s,\mathrm{t}}$ = NMCS
$X_{4s,\mathrm{t}}$ = AVGAC
$X_{5s,\mathrm{t}}$ = AVGAC Squared
$X_{6s,\mathrm{t}}$ = Airframe Hrs
$X_{7s,\mathrm{t}}$ = AWM Hrs
$X_{8s,\mathrm{t}}$ = Number of CDIs
$X_{9s,\mathrm{t}}$ = Number of QAs
$X_{10s,\mathrm{t}}$ = MTBF
$X_{11s,\mathrm{t}}$ = MTTR
$X_{12s,\mathrm{t}}$ = Number of Marines
$X_{13s,\mathrm{t}}$ = Total Flight Hrs
$X_{14s,\mathrm{t}}$ = Flight Hrs Squared
$X_{15s,\mathrm{t}}$ = DMMH/W/D
a_i = Unobserved fixed effects
$\varepsilon_{s,t,}$ = Residual
s = Squadron
t = Time in Months

$$\begin{aligned}&Y_{st} = \beta_0 + \beta_1 X_{1,s,t} + \beta_2 X_{2,s,t} + \beta_3 X_{3,s,t} + \beta_4 X_{4,s,t} + \beta_5 X_{5,s,t} + \beta_6 X_{6,s,t} + \beta_7 X_{7,s,t} + \\ &\beta_8 X_{8,s,t} + \beta_9 X_{9,s,t} + \beta_{10} X_{10,s,t} + \beta_{11} X_{11,s,t} + \beta_{12} X_{12,s,t} \\ &+\beta_{13} X_{13,s,t} + \beta_{14} X_{14,s,t} + \beta_{15} X_{15,s,t} + \beta_{16} X_{16,s,t} + \beta_{17} X_{17,s,t} + \beta_{18} X_{18,s,t} \\ &+\beta_{19} X_{19s,t} + \beta_{20} X_{20,s,t} + \beta_{21} X_{21,s,t} + a_i + \varepsilon_{s,t}\end{aligned} \qquad (9)$$

where:

$X_{1s,t}$ = Deployed
$X_{2s,t}$ = Partially Deployed
$X_{3s,t}$ = NMCS
$X_{4s,t}$ = AVGAC
$X_{5s,t}$ = AVGAC Hrs Squared
$X_{6s,t}$ = Airframe Hrs
$X_{7s,t}$ = AWM
$X_{8s,t}$ = Number of AVI CDIs
$X_{9s,t}$ = Number of AF CDIs
$X_{10s,t}$ = Number of FL CDIs
$X_{11s,t}$ = Number of AVI QAs
$X_{12s,t}$ = Number of AF QAs
$X_{13s,t}$ = Number of FL QAs
$X_{14s,t}$ = MTBF
$X_{15s,t}$ = MTTR
$X_{16s,t}$ = Number of AVI Marines
$X_{17s,t}$ = Number of AF Marines
$X_{18s,t}$ = Number of FL Marines
$X_{19s,t}$ = Total Flight Hrs
$X_{20s,t}$ = Flight Hrs Squared
$X_{21s,t}$ = DMMH/W/D
a_i = Unobserved fixed effects
$\varepsilon_{s,t,}$ = Residual
s = Squadron
t = Time in Months

$$\begin{aligned} Y_{st} &= \beta_0 + \beta_1 X_{1,s,t} + \beta_2 X_{2,s,t} + \beta_3 X_{3,s,t} + \beta_4 X_{4,s,t} + \beta_5 X_{5,s,t} + \beta_6 X_{6,s,t} + \beta_7 X_{7,s,t} + \\ &\beta_8 X_{8,s,t} + \beta_9 X_{9,s,t} + \beta_{10} X_{10,s,t} + \beta_{11} X_{11,s,t} + \beta_{12} X_{12,s,t} \\ &+ \beta_{13} X_{13,s,t} + \beta_{14} X_{14,s,t} + \beta_{15} X_{15,s,t} + a_i + \varepsilon_{s,t} \end{aligned} \tag{10}$$

where:

$X_{1s,\mathrm{t}}$ = Deployed
$X_{2s,\mathrm{t}}$ = Partially Deployed
$X_{3s,\mathrm{t}}$ = NMCS
$X_{4s,\mathrm{t}}$ = AVGAC
$X_{5s,\mathrm{t}}$ = AVGAC Hrs Squared
$X_{6s,\mathrm{t}}$ = Airframe
$X_{7s,\mathrm{t}}$ = Number of AVI CDIs
$X_{8s,\mathrm{t}}$ = Number of AF CDIs
$X_{9s,\mathrm{t}}$ = Number of FL CDIs
$X_{10s,\mathrm{t}}$ = Number of AVI QAs
$X_{11s,\mathrm{t}}$ = Number of AF QAs
$X_{12s,\mathrm{t}}$ = Number of FL QAs
$X_{13s,\mathrm{t}}$ = MTBF
$X_{14s,\mathrm{t}}$ = Total Flight Hrs
$X_{15s,\mathrm{t}}$ = Flight Hrs Squared
a_i = Unobserved fixed effects
$\varepsilon_{s,t,}$ = Residual
s = Squadron
t = Time in Months

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APPENDIX D. MV-22 DEPLOYMENTS FY 2013-FY 2020

Table 33. 1st MAW Deployments FY 2013-FY 2020

Year	Month	31st MEU	MRF DARWIN
2012	Oct		
	Nov		
	Dec		
2013	Jan		
	Feb	VMM-262 (CH-46)	
	Mar		
	Apr		
	May		
	Jun	VMM-265	
	Jul	VMM-265	
	Aug	VMM-265	
	Sep		
	Oct		
	Nov		
	Dec		
2014	Jan		
	Feb	VMM-265	
	Mar	VMM-265	
	Apr	VMM-265	
	May		
	Jun		
	Jul		
	Aug		
	Sep	VMM-262	
	Oct	VMM-262	
	Nov		
	Dec		
2015	Jan		
	Feb	VMM-262	
	Mar	VMM-262	
	Apr	VMM-262	
	May		

Year	Month	MEU	MRF Darwin
2015	Jun	VMM-265	
	Jul	VMM-265	
	Aug	VMM-265	
	Sep		
	Oct		
	Nov		
	Dec		
2016	Jan		
	Feb	VMM-265	
	Mar	VMM-265	
	Apr		
	May		
	Jun		
	Jul		
	Aug		
	Sep	VMM-262	
	Oct	VMM-262	
	Nov		
	Dec		
2017	Jan		
	Feb		
	Mar	VMM-262	
	Apr	VMM-262	
	May		VMM-268[1]
	Jun	VMM-265	VMM-268[1]
	Jul	VMM-265	VMM-268[1]
	Aug	VMM-265	VMM-268[1]
	Sep	VMM-265	VMM-268[1]
	Oct		
	Nov		
	Dec		
2018	Jan		
	Feb		
	Mar	VMM-265	

Year	**Month**	**MEU**	**MRF Darwin**
2018	Apr	VMM-265	
	May		
	Jun		VMM-268
	Jul		VMM-268
	Aug		VMM-268
	Sep	VMM-262	VMM-268
	Oct	VMM-262	
	Nov		
	Dec		
2019	Jan	VMM-262	
	Feb	VMM-262	
	Mar		
	Apr		VMM-363
	May		VMM-363
	Jun	VMM-265	VMM-363
	Jul	VMM-265	VMM-363
	Aug	VMM-265	VMM-363
	Sep		VMM-363
	Oct		
	Nov		
	Dec		
2020	Jan		
	Feb	VMM-265	
	Mar	VMM-265	
	Apr	VMM-265	
	May		
	Jun		
	Jul		
	Aug	VMM-262	
	Sep	VMM-262	

[1] Indicates a squadron had between 40% and 60% of its assigned aircraft deployed away from its home location more than 90 continuous days.

Table 34. 2D AND 3D MAW Deployments FY 2012-FY 2020

Year	Month	OEF	MEU-East	MEU-West	SPMAGTFCR-AF	SPMAGTFCR-CC
2012	Oct	VMM-161	VMM-261			
	Nov	VMM-161	VMM-261	VMM-268 (CH-46)		
	Dec	VMM-161	VMM-261			
2013	Jan	VMM-161/VMM-264				
	Feb	VMM-264				
	Mar	VMM-264	VMM-266			
	Apr	VMM-264	VMM-266			
	May	VMM-264	VMM-266			
	Jun	VMM-264	VMM-266			
	Jul	VMM-264	VMM-266			
	Aug	VMM-165/VMM-165	VMM-266		VMM-162	
	Sep	VMM-165	VMM-266		VMM-162	
	Oct	VMM-165	VMM-266		VMM-162	
	Nov	VMM-165	VMM-266	VMM-166	VMM-162	
	Dec	VMM-165		VMM-166	VMM-162	
2014	Jan	VMM-165		VMM-166	VMM-162	
	Feb	VMM-165/VMM-261	VMM-263	VMM-166	VMM-162	
	Mar	VMM-261	VMM-263	VMM-166	VMM-162	
	Apr	VMM-261	VMM-263	VMM-166	VMM-162	
	May	VMM-261	VMM-263		VMM-162	
	Jun	VMM-261	VMM-263		VMM-162	
	Jul	VMM-261	VMM-263		VMM-162	
	Aug	VMM-261	VMM-263	VMM-163	VMM-162/VMM-264	
	Sep	VMM-261	VMM-263	VMM-163	VMM-264	
	Oct		VMM-263	VMM-163	VMM-264	VMM-363
	Nov			VMM-163	VMM-264	VMM-363
	Dec		VMM-365	VMM-163	VMM-264	VMM-363
2015	Jan		VMM-365	VMM-163	VMM-264	VMM-363
	Feb		VMM-365	VMM-163	VMM-266	VMM-363
	Mar		VMM-365		VMM-266	VMM-363/VMM-165
	Apr		VMM-365		VMM-266	VMM-165
	May		VMM-365	VMM-161	VMM-266	VMM-165
	Jun			VMM-161	VMM-266	VMM-165
	Jul			VMM-161	VMM-266	VMM-165

Year	Month	OEF	MEU-East	MEU-West	SPMAGTF-CR-AF	SPMAGTF-CR-CC
2015	Aug			VMM-161	VMM-266/VMM-261	VMM-165
	Sep			VMM-161	VMM-261	VMM-165
	Oct		VMM-162	VMM-161	VMM-261	VMM-268
	Nov		VMM-162	VMM-161	VMM-261	VMM-268
	Dec		VMM-162	VMM-161	VMM-261	VMM-268
2016	Jan		VMM-162		VMM-261	VMM-268
	Feb		VMM-162	VMM-166	VMM-261/VMM-263	VMM-268
	Mar		VMM-162	VMM-166	VMM-263	VMM-268
	Apr		VMM-162	VMM-166	VMM-263	VMM-268/VMM-363
	May			VMM-166	VMM-263	VMM-363
	Jun		VMM-264	VMM-166	VMM-263	VMM-363
	Jul		VMM-264	VMM-166	VMM-263	VMM-363
	Aug		VMM-264	VMM-166	VMM-266	VMM-363
	Sep		VMM-264	VMM-166	VMM-266	VMM-363
	Oct		VMM-264	VMM-163	VMM-266	VMM-363/VMM-165
	Nov		VMM-264	VMM-163	VMM-266	VMM-165
	Dec		VMM-264	VMM-163	VMM-266	VMM-165
2017	Jan			VMM-163	VMM-266	VMM-165
	Feb			VMM-163	VMM-266	VMM-165
	Mar		VMM-365	VMM-163	VMM-764[1] (Reserve)	VMM-165
	Apr		VMM-365	VMM-163		VMM-165/VMM-364
	May		VMM-365			VMM-364
	Jun		VMM-365			VMM-364
	Jul		VMM-365	VMM-161		VMM-364
	Aug		VMM-365	VMM-161	VMM-261[1]	VMM-364
	Sep		VMM-365	VMM-161	VMM-261[1]	VMM-364
	Oct		VMM-365	VMM-161	VMM-261[1]	VMM-364/VMM-363
	Nov		VMM-365	VMM-161	VMM-261[1]	VMM-363
	Dec		VMM-365	VMM-161	VMM-261[1]	VMM-363
2018	Jan			VMM-161	VMM-261[1]	VMM-363
	Feb		VMM-162		VMM-261[1]	VMM-363
	Mar		VMM-162		VMM-261[1]	VMM-363
	Apr		VMM-162		VMM-263[1]	VMM-363/VMM-164

Year	Month	OEF	MEU-East	MEU-West	SPMAGTF-CR-AF	SPMAGTF-CR-CC
2018	May		VMM-162		VMM-263[1]	VMM-164
	Jun		VMM-162		VMM-263[1]	VMM-164
	Jul		VMM-162	VMM-166	VMM-263[1]	VMM-164
	Aug			VMM-166	VMM-263[1]	VMM-164
	Sep			VMM-166	VMM-263[1]	VMM-164
	Oct			VMM-166	VMM-263[1]	VMM-364/VMM-165
	Nov			VMM-166	VMM-266[1]	VMM-165
	Dec		VMM-264	VMM-166	VMM-266[1]	VMM-165
2019	Jan		VMM-264	VMM-166	VMM-266[1]	VMM-165
	Feb		VMM-264	VMM-166	VMM-266[1]	VMM-165
	Mar		VMM-264		VMM-266[1]	VMM-165
	Apr		VMM-264		VMM-266[1]	VMM-165/VMM-364
	May		VMM-264	VMM-163	VMM-266[1]	VMM-364
	Jun			VMM-163	VMM-261[1]	VMM-364
	Jul			VMM-163	VMM-261[1]	VMM-364
	Aug			VMM-163	VMM-261[1]	VMM-364
	Sep			VMM-163	VMM-261[1]	VMM-364
	Oct		VMM-365	VMM-163	VMM-261[1]	VMM-364/VMM-161
	Nov		VMM-365	VMM-163	VMM-774[1] (Reserve)	VMM-161
	Dec		VMM-365			VMM-161
2020	Jan		VMM-365			VMM-161
	Feb		VMM-365			VMM-161
	Mar		VMM-265			VMM-161
	Apr		VMM-365			VMM-161
	May		VMM-365			VMM-161
	Jun		VMM-365		VMM-263[1]	VMM-161/VMM-166
	Jul				VMM-263[1]	VMM-166
	Aug				VMM-263[1]	VMM-166
	Sep				VMM-263[1]	VMM-166

[1] Indicates a squadron had between 40% and 60% of its assigned aircraft deployed away from its home location more than 90 continuous days.

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