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Hybrid Tri-Objective Optimization of F-15 Fleet Modernization Scheduling

Richard S. Danaher

HYBRID TRI-OBJECTIVE OPTIMIZATION OF F-15 FLEET MODERNIZATION SCHEDULING

THESIS

Richard Sean Danaher, Major, USAF

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Richard Sean Danaher, BS

Major, USAF

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Richard Sean Danaher, BS

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Committee Membership:

Lieutenant Colonel Bruce A. Cox, Ph.D.
Chair

Dr. Brian J. Lunday
Reader

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HYBRID TRI-OBJECTIVE OPTIMIZATION OF
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Abstract

The F-15 weapons system is vital to the Air Force's efforts to obtain air supremacy during conflict. Originally produced almost 50 years ago, technological advancement through systems modifications is necessary to ensure the Eagle's lethality and survivability against next-generation adversarial threats. The F-15 Systems Program Office faces challenges to plan aircraft inductions for five fleet modernization programs. Optimal induction schedules are developed using binary-integer linear programming models. Diverse constraints such as manpower, equipment, modification kit availability, minimum operational flight levels, and integration of scheduled depot maintenance reveal that no feasible schedule exists. Two competing objectives representing the value of fully modernized airframes and the additional workload associated with modifications are explored using the weighted sums method. To enable model solvability, penalties are associated with constraint relaxations with an aggregate penalty term incorporated into the objective function. Implementing value focused decision analysis techniques, a fleet hierarchy is established to institute aircraft precedence for instances having scarce resources shared amongst multiple fighter jets. Sensitivity analysis is employed to examine impacts of various operationally realistic future scenarios. The associated math programs are solved using a readily-available commercial solver.

Acknowledgments

At this time I wish to extend a strong sense of gratitude to several individuals who have directed, supported, and encouraged me throughout this endeavor.

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R. Sean “DAPS” Danaher

HYBRID TRI-OBJECTIVE OPTIMIZATION OF

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I. Introduction

1.1 General Issue

For almost 50 years, the F-15 Eagle has flown as the United States Air Force's backbone for both offensive and defensive counterair missions as the most versatile fighter jet in the world today. The F-15C/D diligently provides air superiority with an undefeated and unparalleled aerial combat record of 104 – 0 air-to-air kill ratio [1]. The F-15E extends the bounds of air dominance adding air strike systems, such as advanced imaging and targeting, setting the standard for all-weather, deep penetration, and day or night air-to-surface attacks. A mainstay in operations both domestic and abroad, the F-15 provides a blanket of security over the continental United States (CONUS) and abroad; permanently stationed in US Air Forces Europe (USAFE) and Pacific Air Forces (PACAF). However, the proliferation of next-generation enemy aircraft, sophisticated "double-digit" anti-aircraft missile systems and other enemy capabilities pose a significant threat to the USAF's mission of achieving air supremacy. Despite evident success, both F-15 mission design series (MDS) require drastic upgrades to ensure survivability and lethality as their demand in the USAF's wartime operational planning increases despite the age and technological currency of the aircraft. While the Department of Defense has dedicated budget allocations to the versatility and stealth capabilities of the F-35 Lightning II (i.e. Joint Strike Fighter (JSF)), combat-tested pilots advocate shared reliance on both newly procured F-35s and modernizing capabilities to the F-15 fleet to complement each other in retaining the high ground [2]. The weapons payload of the F-15E remains unrivaled in its ability to fight its way in and out of enemy inhabited airspaces. With such a diverse payload ranging across GPS, laser, and radar guided bomb units, the F-15E has time and again justified its utility as a premier air interdiction platform. Projected to remain in service past 2040, modernization to the F-15 weapon system is the key to long-term viability. The vital necessity to modernize the fleet becomes more relevant as new aircraft acquisition programs are slow to output critical levels of fighter assets to ensure any potential threat can be met head on.

In December 1969, McDonnell Douglas based out of St Louis MO, became the single source of F-15 production. The first delivery of a single-seater aircraft, later designated as the F-15A, occurred in July 1972 for proof of concept and demonstration. The follow-on, two-seater trainer labeled as the F-15B came about in 1974 as production levels increased. As the footprint for the F-15 fighter became more and more prevalent and new armament technologies concurrently became available, both the government and contractor focused efforts post-1978 to produce a more technologically advanced aircraft known today as the F-15C and F-15D [3]. Even with the more capable F-15C/D the USAF continued to operationally fly the F-15A/B until 2010 when the last F-15A officially retired. Moreover, the need for a more capable air-to-ground weapon system brought forth the evolution of the dual-role F-15E Strike Eagle in 1987. The F-15E is a strictly two-seater aircraft with an aircrew consisting of a pilot and a combat systems officer (CSO) to employ the variety of air-to-ground assets ferried by the Strike Eagle. In 1997 the Boeing Company bought out McDonnel Douglas and acquired all defense contracts associated with the F-15. At that point McDonnel Douglas had built and delivered over one thousand F-15 variants to the USAF.

The F-15 Systems Program Office (SPO) based out of the Air Force Life Cycle Management Center (AFLCMC) at Wright-Patterson AFB, OH regulates the F-15 enterprise. They determine the modification strategy to properly manage timelines, operational and maintenance costs, as well as readiness and systematic performance of the fleet consisting of 451 total aircraft scattered across 13 geographically separated locations, as seen in Figure 1. Since the mid-1960s, the F-15 SPO has exercised good stewardship and careful resource management, establishing credibility as a major weapon systems program and earning the confidence and support of Congress and taxpayers [3]. The F-15 SPO meticulously governs the reliability, availability and maintainability efforts towards amplifying F-15 tactical presence, combat pilot training, and weapons system testing. Driven by budget discipline, the SPO endeavors to expeditiously modernize the F-15 Eagle while reducing a logistics and sustainment footprint.

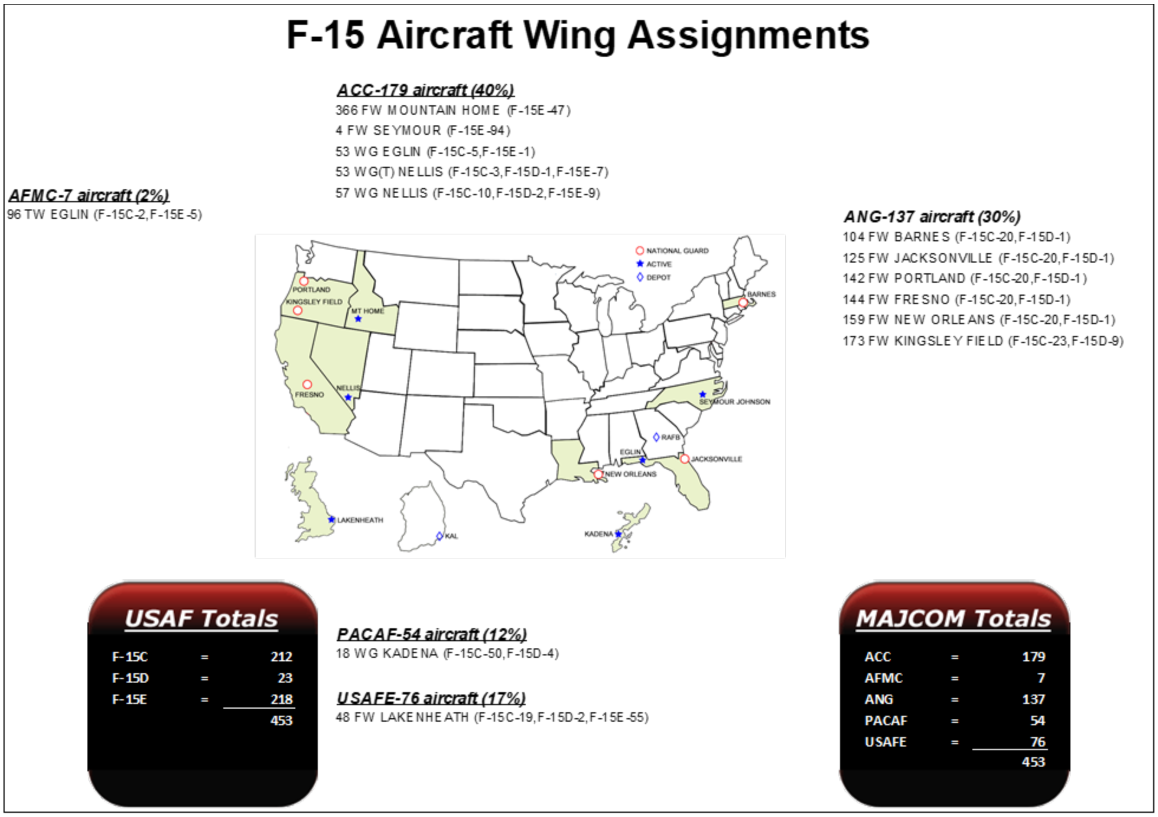

Figure 1. F-15 Fleet Disbursement
***Graphic provided through F-15 Systems Program Office** [4]

1.2 Modifications

The original concept and technological requirements for the F-15 fighter began in the late 1960s. Similar to the enhancements made from the initial F-15A/Bs to the F-15C/Ds, several presently obsolete and vulnerable components need to be replaced this time without the complete production of an entirely new aircraft. Currently, the F-15 SPO is in the midst of planning, programming, budgeting, and executing several significant updates to the Eagle weapon system to extend the service-life of the aging fleet, as well as invigorate its capabilities to find, fix, track, target, engage, and assess enemy assets in a degraded environment. Figure 2 highlights the upward trajectory of budgeting dedicated to the improvement of the F-15. Major avionics upgrades center around radar modernization (both hardware and software) and the exploitation of enhanced capabilities via precision timing, data delivery and data processing, precision registration systems, via a cockpit Heads Up Display (HUD), instrumentation digitization and modernization, central computer processing power increases, digital mission event recording systems, and an infrared (IR) based fire control system.

Air Force Instruction (AFI) 63-101 *Integrated Life Cycle Management*, dated May 9, 2017, defines modification as:

> Modifications are changes to hardware or software to satisfy an operational mission requirement by removing or adding a capability or function, enhancing technical performance or suitability, or changing the form, fit, function, and interface (F3I) of an in-service, configuration-managed AF asset.

To control and ensure that modifications are well planned and budgeted prior to execution, AFI 63-101 further stipulates:

> Permanent modifications change the configuration of an asset/software for effectiveness, suitability, survivability, service life extension, and/or reduce ownership costs of a fielded weapon system, subsystem, or item. Some permanent modifications are further designated as safety modifications.

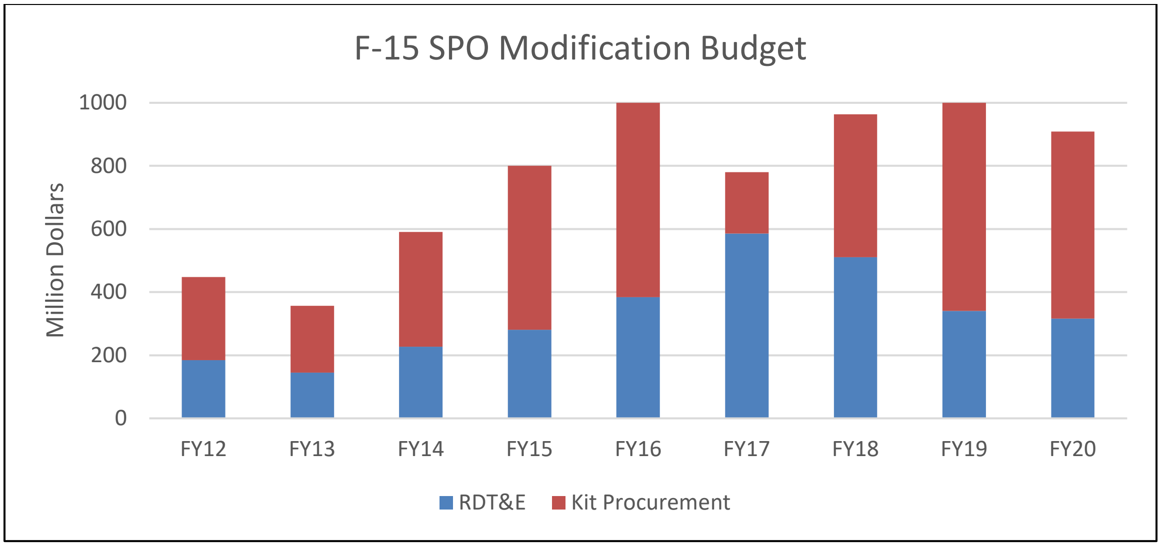

Figure 2. F-15 SPO Annual Modification Budget

Updates to the existing weapon systems will allow the status quo of manning, supply-chain management and asset alignment to remain predominantly unaltered, while giving combat tacticians a more lethal and survivable aircraft. Of five particular programs of interest, the F-15 SPO has expended over $3.4 billion in procurements and installation costs with an anticipated budget request of an additional $3.6 billion over the next 7 years, for a full cost requirement of $7.0 billion in modification costs.

The following five subsections provide additional details on the five respective modification programs of interest to the AFLCMC, which are considered in this research.

1.2.1 Fire Control Radar

The primary sensor a pilot leverages to identify the presence of aerial threats is the front end radar. The legacy Doppler radar system classified as a piloted airborne radar fire control consists of a mechanically moving transmitter/emitter under the radome nose of the aircraft. Since the 1970s, F-15C/D pilots have used the AN/APG-63v(0) or the AN/APG-63v(1), forcing pilots into what is known as *task saturation* due to simultaneously shifting focus between controlling the flight of the aircraft while directing the radar where to search for and maintain lock on a target. This effort diminishes both the area in which aircrew can find and investigate aerial objects as well as their ability to retain lock on a targeted threat. Similarly, the F-15E was originally outfitted with the AN/APG-70 mechanical scan radar. Active Electronically Scanned Arrays (AESA) introduce the ability to identify potential targets, as well as maintain track of multiple indicated airborne objects with minimal aircrew effort. Both the F-15C/D and F-15E fleets have either already received or are currently undergoing radar modification programs (RMP) as depicted in Table 1.

Table 1. F-15 Fleet Radar Modification Upgrade Status

Radar	Mechanical Scan				AESA	
	APG-63v(0)	APG-63v(1)	APG-63v(2)	APG-70	APG-63v(3)	APG-82
F-15C	58		8		145	
F-15D	5	18				
F-15E				125		93

*As of 9 Jan 20 [4]

Unfortunately the RMP workload is extensive due to challenges such as performing quality checks on wire harness connections and placing ballast counterweights throughout the aircraft to maintain proper center of gravity due to differing weights of the new versus old radar hardware. Historical data over the past five years estimates the time of completion to successfully upgrade an obsolete system for a new AESA at 138 days of depot-level activity, during which the aircraft is unavailable for flying operations. The F-15 SPO has fully committed to completing the RMP by 2024 with a projected total cost of $2.3 billion.

1.2.2 Advanced Display Core Processor

While the enhancement to the front-end AESA radar greatly increases the number of targets within the field of regard for aircrew, it also potentially oversaturates the pilot and WSO if too many objects are visible. The next significant upgrade to the F-15 weapons systems is the installation of new hardware to the aircraft's central computer known as the Advanced Display Core Processor II (ADCP II). The ADCP II will develop a common mission computer for the F-15C/D and F-15E. The current mission computers of both platforms have reached their limits of speed, memory, and throughput. Additionally, digital systems have changed the security requirements of both platforms and the older mission computers cannot be upgraded to meet these new requirements. This modification increases the processing power of the aircraft to interpret digital signals and allows enhanced interfacing and display features in real-time to the aircrew. This system changes the hardware used to illustrate sensor data to the Vertical Situational Display (VSD) and the HUD. New computer hardware supports growth beyond current Operational Flight Plans (OFP) software suites enabling the aircraft to meet the requirements for expanded datalink capabilities, sensors, electronic warfare, and forward/net-centric operations. Replacing the monochrome display with a 5x5 color display fully exploits the RMP capabilities, to include increased target tracks, mode simultaneity, and increased track data.

The faster processing capacity and ability to recognize and filter indications received from onboard sensors helps mitigate the provision of irrelevant detection data to the aircrew. The increased capability of ADCP II is has been successfully installed into

12 test and tactical development aircraft and is currently advocated by the F-15 SPO to garner a total modification budget of $673 million for testing, procurement, and installation. These upgrades are less invasive than the RMP because there is much less hardware and wiring required to accomplish the upgrade, which requires only a few days.

1.2.3 Tactical Radio

As the number of potential threats is greater than a single F-15 can engage, proper air space control and coordination is vital. Aircrew must be able to communicate with wingmen, airborne command and control (C2) assets such as the E-3 Airborne Warning and Control System (AWACS), and even leverage detections from satellite systems to overcome barriers related to the fog of war. Baseline radio transmissions occur predominantly over analog Ultra High Frequency (UHF) or across a datalink system known as Link 16. It is currently a known vulnerability that UHF transmissions can easily be jammed, denied, or distorted, resulting in failure to properly report and share information across assets involved in combat. Consequences of poor communication can result in redundant efforts, lack of coverage, and even fratricide if pilots are unable to accurately identify a friend from a foe. The National Security Agency (NSA) recognizes this vulnerability within the Link 16 system and now mandates compliance of cryptographic modernization. Furthermore, a Federal Aviation Association (FAA) mandate requires all fielded Link-16 terminals incorporate a frequency re-mapping capability by 2025.

The Multi-function Information Distribution System – Joint Tactical Radio (MIDS-JTR) harnesses new encryption technology and remaps frequency utilization to diminish adversarial waveform jamming. Since the digital reception of track data from potential targets can now be integrated from off-board sensors, the harmonious interaction of the MIDS-JTR and ADCP II is vital. As both the radio and processing upgrade require similar skill-sets of installation of avionics and electronics, the SPO has demonstrated a seamless concurrent effort of installation on six total aircraft. At a budgeted cost of $317 million the SPO projects to upgrade over 80% of the F-15 fleet.

1.2.4 Service Life Extension

The average number of years in service for the F-15 fleet is both inspiring and devastating. Inspiring by the length of time the F-15 has been the keystone to air superiority, but devastating considering how long and how much strain has been demanded on the aircraft. Table 2 depicts the average age and flying hours of each MDS within the fleet.

Table 2. Active F-15 Service Life and Flight Hours

	Number of Aircraft	Oldest Aircraft (years)	Youngest Aircraft (years)	Avg Age (years)	Most Flying Hours	Least Flying Hours	Avg Flying Hours
F-15C	210	40.2	29.9	35.3	10,962	6,941	8,658
F-15D	23	39.6	32.2	34.9	6,293	9,859	8146
F-15E	218	32.0	14.9	27.4	13,164	3,861	7,768
Total	451			31.4			8203

*As of 9 Jan 20 [4]

Because even the most recently delivered F-15C and F-15D are nearly the same age as the oldest F-15E, a Service-Life Extension Program (SLEP) is necessary to ensure airworthiness of these aircraft. The F-15C/D SLEP for the longeron addresses a potential safety of flight issue of the airframe's structural integrity. The F-15 SPO has determined that an aggressive replacement of the longitudinal structural component of the aircraft's fuselage is required. Similar to the chassis of a car, the longerons act as the backbone for the airframe. Analysis of material fatigue has been performed across the fleet, and currently any F-15C that undergoes the Time Compliance Technical Order (TCTO) for non-destructive inspection (NDI) of the longerons has a 100% fail rate for being beyond acceptable tolerances. An NDI failure results in the immediate grounding of the aircraft until appropriate repair to the aircraft structure. Across the fleet, over 30 aircraft are temporary limited from flying until projected kits for the Longeron Replacement Program (LRP) are available, likely in March 2020. The F-15 SPO is projected to complete 178 F-15C/Ds with a dollar value of over $143 million budgeted.

1.2.5 Electronic Protection

The DoD is allocating over $2 billion over the next ten years to increase the survivability of the F-15 within a highly contested environment. Towards this end the aircraft must overcome susceptibility of being identified and struck by an enemy missile. Unlike the F-35 JSF and F-22 Raptor, the adoption of stealth technology is not viable for the F-15 platform. Therefore the preferred, feasible option is to increase situational awareness to aircrew regarding when and to what degree they are vulnerable, to prompt the execution of evasive tactics. The Eagle Passive/Active Warning and Survivability System (EPAWSS) upgrade will significantly improve the F-15's capability to autonomously and automatically detect, identify, and locate radio frequency (RF) threats as well as to provide the ability to deny, degrade, deceive, disrupt, and defeat RF and electro-optical / infrared (EO/IR) threat systems in contested and unplanned operations within highly contested environments through 2040.

F-15 EPAWSS will replace the current 1970’s analog technology known as Tactical Electronic Warfare Systems (TEWS), which consists of the AN/ALR-56C Radar Warning Receiver (RWR), the AN/ALQ-135 Internal Countermeasure Set (ICS), and the AN/ALE-45 Countermeasures Dispenser System (CMDS), a combination of components collectively designed for combat operations in environments defended by 1980s-era, radar-based ground and air threats. Advanced electronic protection will provide indication, type, and position of ground-based RF threats as well as the indication, type, and bearing of airborne threats with the situational awareness needed to avoid, engage, or negate the threat. EPAWSS will also prevent RF and IR threat systems from detecting or acquiring accurate targeting information prior to threat engagement to complicate and/or negate an enemy threat targeting solution. If prevention fails, EPAWSS will effectively counter enemy weapons using components such as chaff, flares, decoys, and jamming. The service has called the legacy system "technologically obsolete" and has assessed that the EPAWSS radar warning receiver, jammer, flare dispenser, and decoy will greatly improve the F-15's self-protection capability [5].

The EPAWSS modification is the most rigorous undertaking of fleet modernization; the invasive maintenance is extensive, requiring full wing removal. Research and development has already invested over $755 million and resulted in the successful installation on three test aircraft. However, acquisition interruptions have occurred inhibiting entrance into Full-Rate Initial Production (FRIP) state meaning modernization kits are not yet be available for operational forces. While the F-15 SPO is confident to promptly resolve EPAWSS kit procurement delays, timelines still remain uncertain about kit delivery and installation.

1.2.6 Planning, Programming, Budgeting and Execution

As the head the USAF acquisition process, the Secretary of the Air Force (SECAF) has recognized the imperative of improving the F-15 fleet and has budgeted nearly $1 billion in over the past decade to implement replacing technologies installed in the 1980s [6]. With the intent of overhauling the survivability systems, it is essential that proper induction and management of support infrastructure has prepared depots to implement such a tremendous endeavor.

The latest major development impacting the future of the F-15 fleet occurred recently with the signing of the Fiscal Year (FY) 2020 National Defense Authorization Act (NDAA) into law on December 20, 2019. Within the congressionally-directed, presidentially-approved budget allocations, the decision was made to initialize the procurement of a brand new, fully-updated version of the Eagle known as the F-15EX. The F-15EX is slated to become the most versatile version of the F-15; its newly manufactured design will have the upgrades already in work to the fielded fleet and include even more modern capabilities. While this aircraft acquisition is a significant victory for retaining the F-15's presence as the predominant air-to-ground strike fighter, the costs to acquire such a substantial program of record force the limitation of available funding to the current operational fleet.

The F-15 SPO is constantly challenged when considering overlapping timelines and limited resources for keeping the currently active 451 F-15s air worthy, tactically relevant, and available for national defense strategy requirements. Exemplified by the lack of funding due to the upcoming production of the F-15EX, the program office strives to preserve the aging fleet active for as long as it can until F-15EX production levels sufficiently meet combat demand. With the FY2020 NDAA now forcing the long-serving F-15C/D MDS to (eventually) retire, the immediate need to have a predictive model showing the status and availability of the fleet is more important than ever. Due to congressional funding varying year-to-year, the F-15 SPO desires long-term understanding dynamically adjusted objectives through a reprogrammable model based on shifting inputs. Tunable model parameters allow this research to inform the F-15 SPO Weapons Integration Team (WIT) of resource consumption and operational impacts associated with multiple realistic "what if" scenarios.

1.3 Problem Statement

The AFLCMC F-15 SPO seeks a robust mathematical scheduling model to balance expeditiously modernizing the F-15C/D/E Total Force fleet against reducing workloads associated with hardware installations, all while adhering to unique modification timelines, limited resources, and aircraft operational availability.

1.4 Research Objectives/Questions/Hypotheses

1. What is an appropriate mathematical programming model for optimal F-15 modernization scheduling?
2. What constraints are most limiting, and what are the benefits of relaxing them?
3. Is there a trade-space between modernizing the fleet as quickly as possible and minimizing the workload of maintenance events installing modernization kits?

1.5 Scope

Research will be conducted assuming current posture, plans, programs, and budgets regarding the F-15. Based on present efforts and developing technologies, this research will investigate opportunities available to the F-15 SPO to manage 451 aircraft across the 13 different geographical air bases. Model development examine activity beyond 2032, as it is assumed that all identified modifications (RMP, ADCP II, MIDS-JITR, LRP, and EPAWSS) must be completed by that date.

1.6 Methodology

This research uses techniques in multi-objective optimization and scheduling theory to determine the best modernization and workload schedule to balance the number of maintenance events, timeliness of modernization, and additional resource requirements. The model accounts for specific aircraft, by quarter, along with their location, F-15 model variant, and mission. Constraints on aircraft availability, resource availability, and modernization precedence order are included. Decision analysis techniques are applied to develop a hierarchal preference of aircraft and investigate the sensitivity of model output based on the multiple objectives of the F-15 SPO WIT.

1.7 Assumptions/Limitations

Aircraft will not be considered for redirection or realignment from one base to another to appease availability constraints. Historical lookback indicates that permanent changes in aircraft stations is atypical; the most recent aircraft basing swap was in September 2016 and resulted from swapping a test-coded aircraft with a combat-coded asset.

Cost associations for Contractor Field Teams (CFTs) will not be estimated due to the uncertainty of available fiscal funding and unknown skillsets/manning required to perform each modification. The model will show value of staging a CFT Team at a particular base, along with projected workflow and required duration.

Costs associated with kit procurement will not be considered. Estimated numbers of kits available per interval will be based on projected Required Assets Available (RAA) listings based on budgetary projections. The model will show if and when it is advantageous to procure additional kits prior to current projections. RAND research implicates the utility of codependent installation and procurement scheduling, as evidence shows that the two efforts work in concert and cost savings ultimately exist with proper timeline efficiency [7].

While a specific modification can be decomposed into two distinct kits known as A and B, and each can be completed in unique phases, for purposes of this general model, the entire modification will occur during a single phase as it is assumed that both kits will be readily available at the time of modification induction.

Schedule timelines for estimated maintenance workloads will be measured by 90 day intervals to initiate and fully install modification kits. While this sacrifices a high degree of precision and accuracy of not specifying an exact number of work flow days, using the conservative construct of fiscal quarters still allows program manager adequate detail to best allocate resources and understating binding constraints.

1.8 Implications

This research will indicate whether it is feasible to accomplish all desired modifications within the projected funding timelines. The model output will inform the F-15 SPO what resource areas require immediate focus to mitigate possible limitations in the near future. The optimal schedule output by the model can be used by F-15 program managers to plan induction and modernization. Tunable input parameters will serve to provide insight into how programmatic and/or resources changes will impact modernization timelines and thus fleet status for the next 12 years.

II. Literature Review

2.1 Chapter Overview

This chapter contains insights and reviews previously investigated methods to understand and resolve the issues facing the F-15 SPO's attempts to optimally schedule modernization efforts that address conflicting objectives. A study of how the F-15 SPO quantifies fleet management through aircraft maintenance metrics can garner understanding on what elements relate to operational need and workload. Furthermore, understanding opportunities and limitations due to scheduled, periodic depot-level maintenance (PDM) provides insights on resources required for modification/modernization. Finally, research on related efforts was completed to discover potential solution methodologies that leverage scheduling theory, multi-objective optimization, and/or decision analysis techniques.

2.2 F-15 Systems Program

The F-15 SPO is comprised of a team of program managers dedicated to the cradle-to-grave sustainment of the Eagle fleet. Asides from potential cost savings of minimizing the number of actions modernizing the fleet through consolidated modification efforts, the SPO also knows that the fewer times aircraft have to undergo extensive maintenance means more aircraft that are operationally available for aircrew requirements.

2.2.1 Fleet Management

> "The most important objective in the aviation industry, whether with civilian airliners or military aircraft, is that airplanes make money in the air and not on the ground. Having iron on the ramp, or flight line, is an airplane ready to produce a sortie. A sortie is a successful take-off and landing. It is what the Air

> Force is paid to do. The Air Force's mission is to train and equip its units to fight the nation's air and space wars. Quite simply, a flying wings mission is to fly airplanes. Flying airplanes is how the Air Force train, prepare for war, and maintain continuous wartime capability." [8]

The F-15 SPO consists of multiple personnel investigating, producing, assessing, and reporting actions and opportunities to a Senior Materiel Leader or Program Manager (PM), who makes decisions regarding the management of the aircraft fleet. Researching published, governing directives over these decision-makers helps shape scope and defines criteria of optimality of resource allocation. Additionally, institutional policy also indicates other key stakeholders and the roles of these individuals as related to informing, making, or executing a fleet-related decision. One the primary Air Force publications, Air Force Instruction (AFI) 63-101, *Integrated Life Cycle Management*, establishes the relationship between the PM, SPO, and MAJCOM as modification efforts related to requirements, fielding, infrastructure, and support are planned and implemented [9].

Treating the relationship between SPO and operational units as an analogy of vendor and customer derives the dichotomy of two conflicting institutional directives: (1) maximum weapon system availability and (2) ensuring affordable and predictable total ownership cost [9]. While cost can more simply be quantified, availability needs clear definition. The Department of Defense defines operational availability as:

> The percentage of time that a system or group of systems within a unit are operationally capable of performing an assigned mission and can be expressed as (uptime/(uptime + downtime)). Determining the optimum value for Operational Availability requires a comprehensive analysis of the system and its planned use as identified in the planned operating environment, operating tempo, reliability alternatives, maintenance approaches, and supply chain solutions[10].

The need for fighter aircraft to consistently be on-hand to fly is driven by the Ready Aircrew Program (RAP) which “ensures [RAP] missions are oriented to developing basic combat skills, or practicing tactical employment simulating conditions anticipated in the unit mission” [11]. The RAP and aircrew readiness is the inherent consumer demand to which the F-15 SPO is accountable supply with aircraft on a daily basis.

Recognizing the F-15 SPO’s responsibility providing aircrew the means to train and fight shows how imperative both the quantity and quality of available aircraft availability is to training. Negative training can result if aircrew do have relevant, state-of-the-art aircraft to gain tactical expertise. Furthermore, as discussed in Section 1.2.4, the lifespan and historical strain on the F-15 fleet has resulted in component failures and structural fatigue increasing risks to flight safety. To overcome these tactical and structural deficiencies, the F-15 SPO needs to adhere to established operational metrics and constraints to continually provide warfighters with safe and reliable aircraft while the fleet undergoes modification.

The best-known metric for measuring an aerial unit’s performance and readiness is the MC rate, which quantifies how many aircraft are expected to be available for flying at a given time [12]. It is used as an indicator to understanding several other embedded metrics, such as how often aircraft break, how long a broken aircraft takes to fix, and how many aircraft are broken at a given time. The real-time status and condition of an aircraft is determined by categories prescribed by AFI 21-103, *Equipment Inventory, Status and Utilization Reporting*. Aircraft status and codes are logged and tracked to illustrate whether an aircraft is flight worthy and, if so, to what degree. Aircraft are coded as fully mission capable (FMC), partial mission capable (PMC), or non-mission capable (NMC) [13]. Noting how MC rate is calculating using Equation (1), the concept of "possessed hours" shows how time is specified. Possession indicates which entity is responsible for the oversight of that aircraft or group of aircraft. When an aircraft is stood down from a flyable condition for extensive modification, the F-15 SPO takes possession or accountability of the aircraft from the operational unit, thereby affecting modifications without negatively impacting the squadron's MC rate. The possession hours or total time in modification serves as the measure to best evaluate the SPO's impact to the operational fleet availability.

$$\boldsymbol{MC\ Rate = \frac{FMC\ Hours + PMC\ Hours}{Possessed\ Hours}\ x\ 100} \quad (1)$$

Another metric that motivates the F-15 SPO to limit the amount and duration of aircraft possessed for modification maintenance is the Utilization (UTE) rate. UTE rate is the ability of a unit to appropriately execute the mission, and is calculated as a ratio of the number of sorties flown to number of aircraft on station, i.e., it is the average number of flying hours logged per allocated aircraft on a base. If a unit fails to meet the sortie UTE rate, the number of sorties per aircraft is lower than programmed [12]. Similarly, hourly UTE rate is used to help understand the quality of training rather than what is known as "punching holes in the sky". While several sorties can be launched, the average sortie duration (ASD) may be short and does not provide ample time for pilots to execute all necessary training functions. When units' maintenance teams meet the programmed sortie UTE rate and pilot operators achieve the programmed hourly UTE rate, the squadron as a whole can successfully execute the annual flying-hour program (FHP). The Air Force's FHP comprises the number of hours needed to attain and maintain combat readiness and capability for its aircrews, to test weapon systems and tactics, and to meet collateral requirements, such as air shows, demonstration rides for important personnel, and ferrying aircraft [14].

$$\textbf{\textit{Sortie UTE Rate}} = \frac{\textbf{\textit{Sorties Flown}}}{\textbf{\textit{Primary Aircraft Inventory}}} \tag{2}$$

$$\textbf{\textit{Hourly UTE Rate}} = \frac{\textbf{\textit{Hours Flown}}}{\textbf{\textit{Primary Aircraft Inventory}}} \tag{3}$$

The systemic impact to the FHP is quantified by the UTE rates units achieve, therefore it is important to understand how the F-15 SPO can directly or indirectly influence these metrics. Both Equations (2) and (3) employ the concept of what historically was Primary Aircraft Inventory, which now includes other assets such as missiles and is collectively referred to as Primary Aerospace Vehicle Inventory (PAI). AFI 16-402 defines PAI as assigned aircraft authorized to a unit for performance of its operational mission. The primary authorization forms the basis for the allocation of operating resources to include manpower, support equipment, and flying-hour funds. Using Equation (4) the SPO monitors the Total Aerospace Vehicle Inventory (TAI) and Backup Aerospace Vehicle Inventory (BAI) and attrition reserve as an associated value dictated by mission requirements and allocations to operating forces for mission, training, test, or maintenance functions [15]. BAI is defined as aircraft above the primary mission inventory to permit scheduled and unscheduled depot level maintenance, modifications, inspections, repair, and certain other mitigating circumstances without reduction of aircraft available for the assigned mission. Other mitigating circumstances may include specialized maintenance requirements, medium duration home station modifications, and unique squadron sizing and location [15]. Currently, there are no attrition reserve assets available for the F-15 because each individual aircraft is considered to affect (and maximize) the PAI and BAI.

$$\boldsymbol{TAI = PAI + BAI + Attrition\ Reserve} \tag{4}$$

The F-15 SPO aims to mitigate the negative impact to the warfighter caused by inducting too many aircraft for too many single modernization actions. Striving to adhere to the bounds of BAI quantifies the necessary parameters to minimizing F-15 SPO possession of aircraft within the fleet while optimizing the modification schedule.

2.2.2 Scheduled Maintenance

Despite best efforts of design and continual oversight, aircraft suffer strain that inevitably results in broken parts which require repair. Scheduled maintenance establishes a foundation to abate severe mishaps and common breaks by tracking aircraft flying hours and scheduling when such maintenance will occur. Proactive maintenance is performed both in the field by operational units themselves and in facilities known as military depots. Depot facilities and personnel sustain complex weapon systems with the help of private-sector defense contractors [16]. Depot-level maintenance oversees extensive and invasive activities to overlook an entire aircraft to identify critical structural issues and repair parts in a more centralized location.

Operational aircraft are closely tracked according to Effective Flying Hours (EFH) to predict Programmed Depot Maintenance (PDM). Since PDM is scheduled on a reoccurring cycle throughout an aircraft's lifespan, PDM is often synonymously referred to as *periodic* depot maintenance. To understand the impact PDM has on performance of the F-15 weapons system, understanding what is important to Air Force operators and their ability to accomplish their mission is essential. Many efforts have been dedicated to determine the appropriate timeline for when to schedule PDM during the life-cycle of an aircraft. Whether the best induction policy is condition-based due the MC rate [17] or related to the EFH [18], a corresponding technical order (TO) is published and strictly followed. After a site visit in July, 2019 to the F-15 depot facility at Warner Robins AFB, GA, depot induction schedulers confirmed firm adherence to TO precedent [19].

The F-15 fleet adheres to strict PDM TO-dictated timelines on when to undergo depot-level maintenance. Research into TO 00-25-4 *Depot Maintenance of Aerospace Vehicles and Training Equipment* (2019) finds that F-15C/D variants will be inducted for PDM at 78 calendar months after the previous PDM completion. Similarly, the F-15E now has a 90-month cycle between PDM completion and re-induction. The TO does allow some flexibility regarding the precise timeline; within ±90 days, an aircraft can be waivered to either enter early or delay induction based on several factors such as operational requirements, depot capacity, *et cetera* [20]. However, after passing 90 days beyond the scheduled induction time, the aircraft is considered grounded and will only be permitted flyable for purposes directly related to delivery to the F-15 depot. Using the flexibility of a 270-day induction window into the model will be advantageous when having to balance workload capacity and unit aircraft availability.

2.3. Scheduling Theory

Scheduling when and where to accomplish modification upgrades is the root of this research effort. After years of sustaining the F-15 fleet, it is well known that PDM backlogs exist due to lack of sufficient resources to adequately return aircraft to service. To properly plan and anticipate manpower, facility, and equipment needs, the SPO anticipates a programmable schedule that will provide proper lead time to address any identified shortfalls.

Desires to fully maximize resources of depot capacities and capabilities of mandate leveraging job scheduling techniques. Scheduling is a decision-making process used to deal with the allocation of resources and tasks given over periods of time with the goal to optimize one or more objectives [21]. In 1971, Richard Karp defined job sequencing as a complex problem defined by input of an execution factor of time satisfying a series of deadlines and imposing associated penalties for failing to meet the deadlines [22].

Merely understanding that this problem is following a job sequence is insufficient to model and solve it. There are several subsets of job sequencing and scheduling problems, so it is imperative to recognize which particular case or cases under which this particular challenge falls. A flexible job shop is a generalization of the job shop and the parallel machine environments. Instead of a certain number of machines in series, there are a certain number of work centers and, at each work center, a number of identical machines operating in parallel [21]. Regarding F-15 fleet modernization, the ability to accomplish modifications in synchronization as similar kit installations necessitate similar tasks and therefore remove redundant efforts.

Knowing the limitations of modernization capacities is essential to formulate constraints. In *Competing through Manufacturing*, Hayes and Wheelwright outline eight assumptions and definitions constituting that Capacity [23] :

1. depends on the interaction of various resource constraints
2. is mix dependent
3. is technology based
4. is dynamic
5. is location specific
6. may not be sustainable
7. depends on management policies
8. is storable

Recognizing each depot and base have unique attributes, suitability to host certain modification efforts must be determined and set as parameters. For instance, unique equipment only present at locations where PDM is performed therefore eliminating options of CFTs performing certain activities at off-site locations.

When supply, in this case capacity, can often not meet demand, scheduling theory implements a technique to address the failure of an instance to comply with set requirements. In scheduling theory, a model is provoked to find a solution based on the reward of completing a particular task on time, or it can otherwise incur a penalty if delivered past a deadline [24]. It is beneficial to think of time as a capacity or limitation, and the same principle can be reverse-engineered to consider as resource capacities as `soft', incurring similar penalties for violating constrained conditions.

Parametric penalties can be advantageous for both keeping a model (artificially) feasible to investigate the conditions pertaining to binding constraints [25]. Current bounds may render the problem infeasible, and additional resources may be acquirable but at a penalizing cost to the optimal solution. In the case of the F-15 PDM induction timelines, a significant shortfall is notable because more aircraft are due to arrive for scheduled maintenance, and so a work backlog will cause overworked technicians and require additional space to locate aircraft in queue.

2.4 Optimization

Research was next accomplished to investigate suitable techniques to formulate a mathematical model in order to achieve an optimal schedule for F-15 fleet modernization.

2.4.1 Mixed Integer Problems

Often when dealing with scheduling or optimality problems in general, certain variables or parameters cannot be considered continuous. It is not suitable for a factory-line to produce half a car or a doctor to treat a partial amount of a patient. In such cases, variables must be treated as discrete. A variable is discrete if it is limited to a countable set of values [26].

Despite the notion that aircraft can be disassembled and cannibalized for parts, it is safe to assume that a pilot cannot safely fly half an aircraft. The model formulation utilizes integer-valued numbers of available (or unavailable) aircraft as a whole entity. The divisibility assumption inherent in linear programming formulations assumes partial decision variable values are possible and includes them in a continuous solution space. Mixed-integer programming institutes a discrete condition that imposes integer-restrictions on a subset of the math programming formulation's decision variables [27]. Using Mixed-Integer Programming (MIP) to service an entire aircraft, install a complete modification kit, and dedicate an entire bay-space eliminates the model's consideration of unrealistically modernizing an aircraft in a piece-wise format.

The ultimate question regarding when and where to schedule an aircraft for modification can be solved using binary decisions, and binary information. An experienced technician will assume an aircraft either is FMC or not. An aircraft is possessed by the SPO for work and not available to a unit for flying, or it is. While this may seem restrictive, the simplicity of representing information and decisions with a 0 or 1 can be beneficial [28]. Equation (1) shows that, even aircraft in a degraded, yet flyable state, still contribute to MC rate and aircrew training. Imposing binary restrictions on all decision variables in a MIP further pragmatically restricts the solution space in the form of a Binary Integer Program (BIP).

2.4.2 Deterministic versus Stochastic Modeling

There are fundamentally two classes of optimization problems as they pertain to parametric certitude. Deterministic optimization problems assume actions can be predicted with certainty in both requirements and outcomes [29]. Stochastic programming is concerned with uncertainty in parameters and deals with problems with probabilistic model inputs and outputs; such problems can be challenging to capture and to resolve via a single, prescribed solution.

The question of whether this scheduling problem should be deterministic or stochastic in nature is determined by the consistency of support resources and aircraft induction rates. A similar effort to demonstrate the volatility of scheduled maintenance timeline for the F-16 SLEP showed that there are many issues that can influence delivery timelines [28]. This research establishes a baseline deterministic BIP model to meet immediate SPO needs and investigates solutions that show significant promise; stochastic programming techniques are left (and recommended) for future research [30].

2.4.3 Multi-Objective Optimization

An optimization problem seeks values for decision variables to either maximize, or minimize, an objective function among the set of all possible values of decision variables that satisfy the given constraints [31]. An objective function is a measure, or function of measures, of merit or regret which drive the solution.

Charged and empowered by the DoD, the F-15 SPO aspires to meet intents set forth in the 2018 National Defense Strategy (NDS) to: “Deliver performance at the speed of relevance” and “Drive budget discipline and affordability to achieve solvency”[32]. According to the F-15 SPO Integration Team, there is a recognized inverse relationship between increasing induction rates versus the associated aggregation of modification and maintenance effort by dedicated technicians and thus the number of aircraft left available to fly, as depicted in Table 3 [31].

Table 3. Aircraft Availability vs Modification

	Concentrated Effort	Segregated Effort
Fast Induction	Utilize CFT Daily Aircraft Availability low	Utilize PDM Daily Aircraft Availability low
Slow Induction	Utilize PDM and CFT Daily Aircraft Availability high	Utilize PDM Daily Aircraft Availability high

Table 3 motivates the creation of the two goals investigated in this research. First: Rapidly modernize the F-15 fleet. Second: Minimize the associated workload with modernization and maintenance efforts. These two goals are inversely related, that is they inherently compete, an increase in the number of modification efforts accelerates timeline for aircraft modernization but induces an associated increase in workload.

There are several techniques used to handle models with multiple objectives. With interest to optimal scheduling based on preferences, this research examines four techniques. First, preemptive goal programing (aka the lexicographic method), appropriate for when a clear prioritization between objectives can be established. Second, non-preemptive goal programming, where a single objective function is formed minimizing the, possible weighted, deviations from each goal. Third, the weighted sums approach which creates a single objective function via a weighted sum of the multiple objectives. Fourth, hybrid approaches which combine some of these above techniques.

2.4.3.1 Preemptive Goal Programming

The first issue related to understanding how to best comply with both goals is to specify the desirable outcome preemptively. Preemptive goal programming is appropriate when goals or objectives can be satisfied in an ordinal sequence [33]. The two competing objectives of quickly executing aircraft modernization while minimizing the associated workload demand a more thorough investigation of tradeoffs then preemptive techniques provide.

Given that modernization resources, such as manpower, equipment and modernization kits are limited, an assessment of the F-15 fleet is critical to establish a lexicographic ranking of the fleet. Constrained scheduling problems create an inherent struggle for limited resource assets, and the development of a Multiarmed Bandit (MAB) problem ensues. By its nature, a MAB has several elements, or arms, pulling or seeking simultaneously against constraints and resources [34]. In conjunction with the F-15 SPO this research identified and weighted aircraft attributes and utilizing value focused thinking developed a lexicographic ranking of the F-15 fleet. This rank ordering provides a monotonically non-increasing value for each aircraft in the fleet which is incorporated into the objective function. This determines which particular aircraft will be selected for a maintenance task at any given time [35].

2.4.3.2 Non-preemptive Goal Programming

A major problem in goal programming may still reside when decision-makers cannot easily provide ranking criteria to be representative to quantify their true aspirations [36]. When goals or objectives are commensurable, or not measured by the same standard, non-preemptive goal programming is a well-known, well-accepted approach [37]. Non-preemptive goal programming explores means to optimize a problem through utility of deviations.

Addressed in Section 2.3, penalties for deviating away from known constraints can be incorporated into an objective function in order to discourage certain behaviors. This inclusion technique may be more advantageous as it allows relaxation of original "hard" constraints such as capacity to become "soft" constraints ultimately providing a newly adjusted, informatively feasible solution [38]. Deviations can inform the number and criticality of relaxation to prevent infeasibility from known, binding constraints [39].

The F-15 SPO acknowledges that current resource availability is insufficient to meet modernization demands regardless of the two NDS directed objectives. Constraints to facility capabilities, kit procurement timelines, and even impact to aircraft availability can be relaxed based on complexity and criticality to find a feasible solution to scheduling modernization. Inclusion of an aggregate penalty function and the desire to minimize its impact to an optimization problem helps inform the F-15 SPO to know precisely which constraint is binding and when.

2.4.3.3 The Weighted Sum Method

Even though two or more goals do not have the same measureable standard, they can each be represented to through attribute-weighting bias [40]. Recognizing the variability of theses biases presents techniques to identify alternative courses of actions or schedules aid in the resolution of the fundamental objective. Alternatives also give insight into critical paths to achieve the desired end state [41] . Using an additive value model quantitatively assesses the trade-offs between objectives by evaluating the alternatives' contribution to the final value [42]. Use of decision analysis swing weight or the weighted sum method establishes a relationship between the two means objectives. Given appropriate weights on the different objectives, a single objective function can be appropriate formulated, as represented via Equation (5).

$$\boldsymbol{v(x) = \sum_{i=1}^{n} w_i v_i(x_i)} \tag{5}$$

These associated weights can easily be subjective therefore implementing sensitivity analysis to shows how the final value changes as preferences shift can help understand the robustness of prescribed solutions to parametric uncertainty [41]. Often times in optimization, there may not be a single perfect solution, but several if not many "good" solutions may exist. These suitable alternatives are called Pareto optimal solutions or efficient solutions [43]. An important characteristic of a Pareto optimal solution within the context of multi-objective optimization is that it is not possible to increase the value of one objective function without decreasing the value of another [21]. Acknowledging and analyzing the trade-off between one objectives enables a decision-maker to identify a balanced course of action.

In determination of preference, techniques in decision analysis help illustrate synergies when balancing competing goals. Despite being calculably different as it is hard to precisely quantify modernization against the costs associated to heavy workload, the two outcomes can still be compared. Both have a presumable value to be F-15 SPO and the two objectives can be compared as means objectives which facilitate a larger fundamental objective [44]. The fundamental objective in this case is the primary directive to as boosting the Air Forces credibility's of a major weapons system [3]. The use of the two means objectives as expeditious modernization and minimizing workload help to stimulate the generation of alternatives[44].

2.4.3.4 Hybrid Methods

Given the complexity of this problem this research leveraged a hybrid multi-objective function, combining weighted sums methodology for rapidly modernizing F-15 fleet while minimizing workload with a penalty term.

The inclusion of a penalty function to the variably weighted desires of minimizing workload while increasing warfighting technology into the field now supposes more factors directly influencing an objective value. A simple approach would be to aggregate final outcome based on splitting weighting preferences between the three unique elements. While this approach can still be informative, the ability to derive trade-offs becomes complicated as now increasing emphasis in one focus now impact two areas. The bias of distributing variable, preferential weights between multiple factors can complicate sensitivity analysis [45].

Although penalizing deviations of constraints can be assessed to the objective function with intent minimize all penalties and negative impact to an optimal value, it is not an element of preemptive ordering its weight or significance to the solution. The inclusion of the penalties allows for insights to preserve feasibility but still provides a unique solution between the interaction of the two weighted objectives [46]. Intent to limiting interactions between weighting bias amongst three terms in a hybrid tri-objective function drives utility of both a weighted sums function and a separate penalty function. A hybrid goal programming model with additive weights exclusive to the two predicated goals provides clear insights to trade-off. Pairing the weighted sum approach with a separate penalty function term seeking additional capacities and resources only when necessary to preserve feasibility determines relative costs to achieve a viable solution.

2.5 Summary

Efforts investigating key principles related to fleet management, PDM scheduling, and optimization methodologies provide insight to refine the scope of the underlying problem while providing means to identify a solution for optimally scheduling depot-level maintenance for the F-15 fleet.

III. Methodology

3.1 Chapter Overview

In this chapter a real world baseline establishes for the problem of interest, detailing current modernization and flight status of the F-15 fleet. Additionally, baseline available resources and future projections generate initial constraints. Finally, this research formulates and presents a mathematical model along with associated sets, parameters, and variables.

3.2 Set Definitions

All active 451 aircraft are unique, but they share many common attribute categories, such as MDS, basing location, classification (i.e. testing vs combat), and current wiring. Specified by tail number, an aircraft's identifiable traits dictate which modifications are required, where modifications can be accomplished, and the relative value of each airframe. Data detailing aircraft characteristics and maintenance history was pulled from the Eagle Modification Action Program (EMAP) listed through the USAF's Fleet Scheduling Systems [4].

3.2.1 Mission Design Series

Breaking down the composition of the F-15 fleet to the most basic classification of the C, D, and E variants is necessary for several reasons. MDS is an official designation for aerospace vehicles used to represent a specific category of aerospace vehicles for operations, support, and documentation purposes [47]. F-15C/Ds are focused on air-to-air engagements and tactics, whereas the dual-role F-15E Strike Eagle's air-to ground interdiction brings a different effect to the battlespace. Furthermore, even though there are large similarities between the F-15C/D and F-15E models, they neither fly nor operate the same, and therefore aircrew are not interchangeable in tactics or in standard flight procedures. Even a seasoned F-15E pilot cannot simply step into the cockpit of an F-15C and safely fly the aircraft without adhering to a rigorous training program unique to that particular MDS. Additionally, the MDS categorization is utilized by both the F-15 SPO and Congress for appropriating and budgeting of funding requirements. The amount of money available to the different F-15 MDS predicates the level of support and sustainment to either the F-15C/Ds or the F-15Es. Certain resources (i.e. funding for additional manpower or upgrade kits) may be unique to one MDS and not the projected for installation across the entire fleet. Of the 451 active aircraft inventory, there are 210 F-15Cs, 23 F-15Ds, and 218 F-15Es. While single-seat F-15Cs and dual-seat Ds are categorically the same MDS, it is important to acknowledge the underlying distinction between the two because even combat capable F-15Ds serve a unique purpose. The F-15D's backseat allows for familiarity rides to flight engineers, maintainers, aerospace physiologists, and even pilots of other aircraft to understand how the mission is executed and what conditions aircrew find themselves in during combat training.

3.2.2 Aircraft Location

Basing of individual jets illustrates how the jet fits into strategic plans within an area of responsibility (AOR) as well as the operational possession and sustainment requirements. The F-15 fleet and its mission sets span the globe, ranging from missile defense in the Indo-Pacific theater, air interdiction across Europe, as well as homeland missions and aircrew training. Furthermore, despite no permanent presence within the

Central Command (CENTCOM) AOR, all fighter wings (FWs) at one time or another have historically deployed to support efforts within the Middle East, Bosnia, and Afghanistan. Any single unit may be required to service a short-notice combat role, hence the balance of the fleet assigned across all F-15 units is imperative.

Knowing each aircraft's location also indicates which of two entities, active duty (AD) USAF and Air National Guard (ANG), has operational oversight. Several different AD Major Commands (MAJCOMs), such as Air Combat Command (ACC), USAFE, PACAF, and Air Force Materiel Command (AFMC), employ assigned F-15s to execute required counterair activities. Although dedicated to homeland defense mission in nature, ANG FWs posture themselves to execute a secondary purpose of forward-deploying and augmenting AD units. Table 4 depicts the allocation of the F-15 inventory across six AD units, to include test wings (TW) out of Eglin AFB and Nellis AFB, and six ANG FWs. It is important to note that Kingsley Field near Klamath Falls, OR hosts the F-15C/D basic fighter course for both ANG and AD aircrew and Seymour Johnson AFB in Goldsboro, NC trains F-15E pilots and CSOs.

Table 4. F-15 fleet location across basing locations and quantity of aircraft assigned

Base	Location	Command	Wing	Squadron	PAI F-15C/D	TAI F-15C/D	PAI F-15E	TAI F-15E
BARNES	WESTFIELD, MA	ANG	104 FW	131 FS	18	21	0	0
EGLIN	DESTIN, FL	AFMC	96 TW	40 FTS	2	2	4	5
		ACC	53 WG	85 TES	4	5	1	1
FRESNO	FRESNO, FL	ANG	144 FW	194 FS	18	21	0	0
JACKSONVILLE	JACKSONVILLE, FL	ANG	125 FW	159 FS	18	21	0	0
KADENA	OKINAWA, JAPAN	PACAF	18 WG	44 FS	24	26	0	0
				67 FS	24	27	0	0
KINGSLEY FIELD	KLAMATH FALLS, OR	ANG	173 FW	114 FS	26	31	0	0
LAKENHEATH	SUFFOLK, ENGLAND	USAFE	48 FW	492 FS	0	0	24	27
				493 FS	18	21	0	0
				494 FS	0	0	24	28
MOUNTAIN HOME	BOISE, ID	ACC	366 FW	389 FS	0	0	18	21
				391 FS	0	0	24	26
NELLIS	LAS VEGAS, NV	ACC	57 WG	17 WPS	0	0	5	9
			53 WG	422 TES	4	4	5	7
			57 WG	433 WPS	7	12	0	0
NEW ORLEANS	NEW ORLEANS, LA	ANG	159 FW	122 FS	18	21	0	0
PORTLAND	PORTLAND, OR	ANG	142 FW	123 FS	18	21	0	0
SEYMOUR JOHNSON AFB	GOLDSBORO, NC	ACC	4 FW	333 FS	0	0	21	25
				334 FS	0	0	18	20
				335 FS	0	0	24	24
				336 FS	0	0	24	25
				Total	**199**	**232**	**192**	**218**

*As of 9 Jan 2020 [4]

3.2.3 Aircraft Categorization

Within each MDS, individual jets maybe tasked via classification codes corresponding to functions such as training, combat, and test. Appropriate categorization sets of aircraft recognizes their unique assignments. Individual aircraft tail numbers are identified for a specific purpose such as training aircrew, test, and evaluation, or combat. These classification codes establish the necessity and readiness requirements of each aircraft when cases of support prioritization arise. If a particular aircraft is coded for combat, it is scrutinized more heavily in its ability to accomplish the mission and also takes precedent in queue for support. A simple example would be if gun systems were to fail on both an aircraft coded for combat and another aircraft coded for training and a critical part was needed. Regardless of location, time of break, or several other factors, the combat aircraft takes priority and the training aircraft would wait until another part is available. These purpose identification codes (PICs) labeled in AFI 21-103 indicate how the F-15 broken up into four main functions. Table 5 defines the four applicable PICs along with how the F-15 inventory is segregated.

Table 5. F-15 fleet composition based on purpose identification code

PIC	Short Title	Definition	F-15C	F-15D	F-15E	Total
CB	Combat Tactics Development and Equipment Evaluation	Aerospace vehicles assigned or possessed for developing, improving, or evaluating operational employment ability (i.e., OT&E)	8	1	8	17
CC	Combat	Aerospace vehicles assigned or possessed for the primary mission of delivering munitions or destructive materials against or engaged in direct contact with enemy forces.	168	11	154	333
EI	Test	Aerospace vehicles assigned or possessed for complete system evaluation or for testing to improve the capabilities of the aerospace vehicle designated	2	0	5	7
TF	Training	Aerospace vehicles assigned or possessed to accomplish student training combat crew training or dissimilar air combat training or combat crew training	32	11	51	95

*As of 9 Jan 2020 [4]

Aircraft identified as test jets are typically the first aircraft to receive a modification or change to the weapon system configuration for quality control purposes. These jets prove the flight worthiness of a design change and also determine whether established criteria are within acceptable standards to install new technology across the rest of the fleet. Similarly aircraft that are slated for tactics development and equipment evaluation may not have extensive changes to the airframe as say a true test coded jet, however unique prototypical modifications may not be suitable for immediate combat activities.

The precedence of PICs allows for both the program office and FW leadership to know precisely how to achieve a balanced fleet and trained aircrew. While aircrew are continually trained and receive upgrade qualifications in combat coded aircraft, the availability of training assets at bases like Kingsley Field and Seymour Johnson AFB also have combat ready fighter squadrons to support. While purpose codes are not permanent, as programmatically it is possible for one aircraft to change one PIC to another, any changes to functionality may require additional costs due an aircraft condition and previous functionality configuration. Test jets may have additional instrumentation installed and changing functionality may result in additional costs to modify for training or combat purposes.

3.2.4 Aircraft Wiring

Over the past 50 years that the F-15C/D have been operationally flying, several modifications have occurred to allow the aircraft to remain relevant and capable of employing advanced avionics and weapon systems. In 2009 the F-15 SPO released Time Compliance Technical Order (TCTO) 1F-15-1551 (Long Term Fleet Rewire). F-15C/D aircraft underwent extensive replacements of wiring harnesses to allow greater connection fidelity between components. Aircraft completely overhauled are categorized as a "Golden Eagle" or part of "Gold Fleet" whereas aircraft less modified are "Silver" and aircraft that did not undergo any rewiring modification are referred to as "Bronze".

Table 6. F-15 fleet composition based on wring replacement

MDS	Golden Eagle	Silver Eagle	Bronze Eagle	F-15E	Grand Total
F-15C	153	42	15		210
F-15D	18	3	2		23
F-15E				218	218
Grand Total	171	45	17	218	451

Insights from Table 6 show that not all F-15C/Ds are suitable or even capable of receiving further modifications due to the limitation of wiring capacities.

3.3 Establishing Relative Aircraft Prioritization

The mathematical model in this research acknowledges non-homogeneity of the F-15 fleet. Modernization assets are limited and scarce resources should be allocated respecting a priorities within the fleet. Once aircraft are itemized within their appropriate sets utilizing each element of criteria such as location, MDS, and primary function, a ranking or value system can be imposed to delineate aircraft and finally a hierarchy of aircraft of the F-15 fleet can be created.

3.3.1 Relative Scoring

The leading prioritization factor is MDS. Speaking with decision-makers at the F-15 SPO, it is easily discernable that the F-15E takes precedence over the F-15C/D MDS. The F-15E is still very prominent with its fighter strike package exceeding other aircraft such as the F-35, F-22, or even the versatile F-16, both Congress and the SPO place heavy emphasis on sustaining and improving the Strike Eagle. The F-15D, due to its small numbers, and also its inherent value as trainer is seemingly more important than the F-15C alone. Working with representatives from the SPO, a baseline value of an F-15E being twice as important as an F-15C was agreed upon. Additionally, a ranking of F-15D above the F-15C as 50% better allowed for a notional division across the different variants with a relative score shown in Table 7.

Table 7. Mission Design Series Ranking

MDS	RANK	RELATIVE SCORE
F-15C	3	1.0
F-15D	2	1.5
F-15E	1	2.0

Ranking locations against one another while working with the SPO proves how challenging it is to set precedence to different mission-sets and AORs. Discussions and reasoning to understand the differences and criticality of each base shaped a result that notionally is palatable to the SPO for operational support. Setting ANG stations as a baseline value and adjusting the other bases relatively proved most effective. Establishing the highest and lowest elements of the location spectrum gave the upper and lower bounds. Lakenheath for its high demand across the European theater was given the highest value as four times more important than the average ANG base. Meanwhile, Kinglsey Field, due to its less likely demand to support a combat mission was agreeably given less than half of the value of another peer ANG base. Table 8 shows how the preliminary values of 12 different locations and their ranking agreed upon by the F-15 SPO.

Establishing a ranking system for the aircraft PIC classification is simpler since the criteria is scalable and already inherently categorical. In terms of the focus on upgrading the aircraft and determining the first candidates, test coded aircraft were set with a value three times the baseline value of a training aircraft. Similarly, a combat coded tail number is awarded a relative score twice that of a training coded aircraft where as a combat tactics PIC rests between the two. The ranking values used in this model for PIC prioritization is found in Table 9.

Table 8. F-15 rank and relative scoring based on operationally assigned base

BASE	RANK	RELATIVE SCORE
BARNES	5	1.0
EGLIN	4	2.0
FRESNO	5	1.0
JACKSONVILLE	5	1.0
KADENA	3	3.0
KINGSLEY FIELD	6	0.4
LAKENHEATH	1	4.0
MOUNTAIN HOME	2	3.2
NELLIS	4	2.0
NEW ORLEANS	5	1.0
PORTLAND	5	1.0
SEYMOUR	2	3.2

Table 9. Purpose Identification Code Ranking

PIC	RANK	RELATIVE SCORE
CB – Combat Tactics	3	1.5
CC - Combat	2	2.0
EI - Test	1	3.0
TF - Training	4	1.0

Finally, the emphasis of how much modification an F-15 has already undergone in regards to rewiring illustrates the areas of interest the SPO has on the fleet. Aircraft that have not received any rewiring efforts are significantly less a concern than the others that have already completed such invasive and laborious maintenance. Results in Table 10 show that an F-15E and a Golden Eagle F-15C/D are 10 times superior to a Bronze aircraft.

Table 10. F-15 Rewiring Ranking

WIRING	RANK	RELATIVE SCORE
Bronze	3	1.0
Golden Eagle	1	10.0
Silver Eagle	2	8.0
E-Model	1	10.0

3.3.2 Normative Scoring

Once each aircraft has received a particular score for each criterion, the next step is to balance the influence each individual category has to a composite score of the aircraft. Individual attributes (location, MDS, wiring, and PIC) are considered equal as to determining the value of an aircraft. To ensure that no single category supersedes another based on its own internal relative scoring, the values must be normalized.

The first step is adjudicate the relative proportions of scores within a single category to understand the influence of that single attribute. After determining the total amount of points within a particular category, each element within is allocated its proportion to that categorical sum. Table 11 illustrates the summation of scoring given the relative score of an aircraft's MDS and the final proportional score after normalization (element's value as numerator over the total denominator).

Table 11. Mission Design Series Proportional Value

MDS	RANK	RELATIVE SCORE	PROPORTIONAL VALUE
F-15C	3	1.0	0.222
F-15D	2	1.5	0.333
F-15E	1	2.0	0.444
Total		**4.5**	**1.000**

Now each individual category awards a proportional value between 0 and 1, hence the degree of influence of categorical transcendence can be controlled via a composite score calculated for each individual aircraft.   The collective scores for each individual scores are then ranked from highest to lowest between 1 and 451.

Due to several aircraft having similar properties (e.g. combat coded F-15Es located at Seymour Johnson) these aircraft consequently will be awarded the same points across all the categories and subsequently an equal rank. The preliminary hierarchy system still demands a "tie breaker" to establish rank order. For purposes of this model, the number of flying hours of each aircraft is normalized against the fleet as a comparison between the maximum and minimum value. Using Equation 2 to normalize flying hours results in each aircraft having a value between 0 and 1 with the aircraft with the highest amount of flying hours having the lowest value of 0 and the more recent and the least strained aircraft with the maximum value of 1. Augmenting the relative composite scores with normalized flight hours allows fleet hierarchy of 451 monotonically ranked aircraft.

This methodology ensures flight hours are used as a "tie breaker", but cannot change the relative rankings from the composite scoring. The final ranking position is then again normalized as an aggregate score and is used as a value in the model. Table 12 provides an example of several aircraft, their unique attributes, and associated scores to provide a concrete example of this process. The model score is the mathematical program value input to identify aircraft by priorities in cases where a precedence decision is required.

$$\textbf{Normalized Flight Hours} = \frac{\textbf{Individual Hours} - \textbf{Fleet}_{\textbf{Min}}}{\textbf{Fleet}_{\textbf{Max}} - \textbf{Fleet}_{\textbf{Min}}} \qquad (6)$$

Table 12. Aircraft Hierarchy and Model Scores

Tail Number	Model	Base	Wiring	PIC	Preemptive Score	Preemptive Rank	Flight Hours	Adjusted Rank	Final Rank	Model Score
87-0180	F-15E	Eglin	E-Model	EI	1.2770	1	4236.2	1.0329	**1**	**1.000**
Score	*0.4444*	*0.0877*	*0.3448*	*0.4000*			*0.0329*			
86-0184	F-15E	Eglin	E-Model	EI	1.2770	1	4447.4	1.0549	**2**	**0.9978**
Score	*0.4444*	*0.0877*	*0.3448*	*0.4000*			*0.0549*		⋮	
01-2004	F-15E	Lakenheath	E-Model	CC	1.2313	6	4312.8	6.0408	**6**	**0.9889**
Score	*0.4444*	*0.1754*	*0.3448*	*0.2667*			*0.0408*		⋮	
00-3001	F-15E	Lakenheath	E-Model	CC	1.2313	6	4936.9	6.1058	**8**	**0.9822**
Score	*0.4444*	*0.1754*	*0.3448*	*0.2667*			*0.1058*		⋮	
91-0308	F-15E	Lakenheath	E-Model	CC	1.2313	6	9064.4	6.5353	**60**	**0.8689**
Score	*0.4444*	*0.1754*	*0.3448*	*0.2667*			*0.5354*			
92-0366	F-15E	Mountain Home	E-Model	CC	1.1963	61	5388.6	61.1528	**61**	**0.8666**
Score	*0.4444*	*0.1404*	*0.3448*	*0.2667*			*0.1528*		⋮	
84-0046	F-15D	Lakenheath	Gold	CC	1.1203	160	6354.3	160.2533	**160**	**0.6467**
Score	*0.3333*	*0.1754*	*0.3448*	*0.2667*			*0.2533*		⋮	
80-0020	F-15C	Kingsley Field	Bronze	TF	0.4076	437	9518.8	437.5827	**450**	**0.0022**
Score	*0.2222*	*0.0175*	*0.0345*	*0.1333*			*0.5826*			
78-0487	F-15C	Kingsley Field	Bronze	TF	0.4076	437	9630.1	437.5942	**451**	**0.0000**
Score	*0.2222*	*0.0175*	*0.0345*	*0.1333*			*0.5942*			

3.4 Resource Parameters

Defining the solution space requires determining the bounding parameters. The key resources of interest and concern to the F-15 SPO are the unique workload capabilities and capacities of the locations where modifications can occur, the procurement timeline for each modification kit and even the aircraft. Discussion with members of the F-15 SPO, Warner Robins Scheduling Office, and review of Program of Memorandums (POMs) and Program Element Monitors (PEMs) from congressional budget allocations shaped the parameters and pragmatic boundaries of the model.

3.4.1 Modification Locations

Limited locations exist where modernization activities can occur, and even less locations support depot maintenance as equipment and skill-sets are scarce. The assigned location for an aircraft brings additional constraints and opportunities for both scheduled and unscheduled maintenance activities. In the case of the 53 F-15C/D stationed overseas at Kadena Air Base (AB), Japan, the F-15 SPO has for almost two decades contracted work from outside the depot at Warner Robins AFB to both alleviate the workflow as well as mitigate funding and time requirements associated with transoceanic travel. Depot-level maintenance for Kadena AB is contracted out to Korean Airlines (KAL) based at Kimhae Air Base near Pusan, Korea. This affords greater flexibility as it is only a 2-hr flight and can be accomplished in a single-ship formation. This is vastly different than the standard practices required to bring an aircraft based out of Lakenheath AB, England. Currently transatlantic flights of F-15s required movement of formations of a least two for wingman support as well as significant planning time to coordinate air refueling from a supporting tanker. These actions alone delay both the induction and return to service of aircraft scheduled for depot maintenance. The F-15 SPO has recently investigated potential cost savings of generating a PDM facility somewhere within the European theater. Aircraft stationing also dictates eligibility to undergo maintenance at an alternative location other than solely homestation implementing a CFT.

Table 13 captures the facilities available to varying aircraft as well as which facilities are approved for full level PDM and which are limited only to CFT.

Table 13. Operational base alignment of acceptable alternate locations executing modernization efforts

Base	Depot	CFT	
	Warner Robins, GA	Kelly, TX	TBD ANG
Barnes	Y	Y	Y
Eglin	Y	Y	
Fresno	Y	Y	Y
Kadena*			
Jacksonville	Y	Y	Y
Lakenheath**	Y	Y	
Mountain Home	Y	Y	
Nellis	Y	Y	
New Orleans	Y	Y	Y
Portland	Y	Y	Y
Seymour Johnson	Y	Y	

** Depot serviced by Korean Airlines in Kimhae, Korea*
*** Pending USAFE Depot*

Not only are there limitations on where to perform depot and modernization actions, but each facility also has a maximum capacity during a particular time interval. Venues are limited by both workforce and physical space. It is anticipated these parameters will induce the most binding constraints. Thus, it is important to recognize how much impact the limiting factors of capacity have on the optimal schedule.

In addition to maximum workload and aircraft housing capacities, certain venues are contractually obligated to perform a required minimum amount of work. An example would be Warner Robins AFB where, if too few aircraft flow through during a particular period of time, the idle workforce and associated resources may be reallocated elsewhere. An issue arises when demand returns to nominal values which may no longer be supportable due to this realignment of personnel and equipment. Similarly, if it is determine to standup a CFT to go to a particular base in lieu of performing modifications at a depot facility, then that contract would have an associated sunken cost requiring an expected minimum amount of aircraft to undergo modification during the contracted period of time.

Table 14 reports the projected minimum requirements and maximum capacities by location. Currently, Warner Robins AFB is aggressively developing more bay space with the anticipation to high more maintenance workers over the next few years to be able to assume the large demand of aircraft induction and servicing. Likewise, contracts and decisions are in work for the standing up of a CFT location at Kelly AFB, TX as well establish a 5-year USAFE depot point somewhere in the European theater (this would abate transatlantic requirements of induction).

Table 14. Modernization location shown with maximum workload capacity and minimum contractual requirements

Modification Location	Capacity/Required							
	FY20Q1	FY20Q2	FY20Q3	FY20Q4	FY21Q1	FY21Q3	FY22Q1	FY28Q1
Warner Robins, GA	8/6	8/6	10/8	12/9	16/12	18/14	20/15	20/15
CFT Kelly, TX	0	0	0	0	4/2	4/2	4/2	4/2
Eglin, FL	2/1	2/1	2/1	2/1	2/1	2/1	2/1	2/1
Mountain Home, ID	3/2	3/2	3/2	3/2	3/2	3/2	3/2	3/2
Seymour Johnson, NC	6/3	6/3	6/3	6/3	6/3	6/3	6/3	6/3
ANG Collective CFT	2/1	2/1	2/1	2/1	2/1	2/1	2/1	2/1
ANG Single Base	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/1
Lakenheath, England	2/1	2/1	2/1	2/1	2/1	2/1	2/1	2/1
TBD USAFE Depot	0	0	0	0	0	0	5/3	0
Kadena, Japan	2/1	2/1	2/1	2/1	2/1	2/1	2/1	2/1
Kimhae Airport, Korea	3/2	3/2	3/2	3/2	3/2	3/2	3/2	3/2

3.4.2 Modification Kit Availability

Knowing the number of available modifications kits at a given time drives resource allocation capacities. Arguably as important, associating this number with a variable representing extra, currently unbudgeted kits provides insight into how changes to this parameter impacts scheduling. Budgetary constraints dynamical occur and, to off-set these challenges, the USAF does not purchase hundreds of kits immediately in a single procurement. Instead, the use of planning, programming, budgeting, and execution schedule expenditures over time and, as a result, modification kits are delivered in batches as well. While there is always the possibility of delaying or speeding up the delivery of products, the anticipated asset levels from congressionally approved budgets help establish a baseline of the Required Assets Available (RAA). Notionally, RAAs are what the government expects the contractor to deliver within a certain period of time when money is obligated to purchase the item.

Table 15 presents the F-15 SPO's initial plan to procure and install the various modification kits onto which F-15 MDS.

Table 15. Procurement timeline of modification kits based on negotiated required assets available given as number of F-15C/D|F-15E

	RMP F-15E	**ADCP II** F-15C/D|F-15E	**MID-JTRS** F-15C/D|F-15E	**LRP** F-15C/D	**EPAWSS** F-15C/D|F-15E
Previously Completed	88	12	6	1	1|2
FY20	24	10|27	10|31	2	0|1
FY21	24	60|30	60|36	47	0|15
FY22	24	63|28	63|33	57	0|22
FY23	24	13|63	13|62	59	0|27
FY24	24	0|56	95|56		0|33
FY25	10	0|14			0|33
FY26					0|33
FY27					0|33
FY28					0|18
Total	**218**	**146|218**	**146|218**	**178**	**1|218**

3.4.3 Modification Duration and Synergies

One of the most important goals of this research is to leverage the synergies of simultaneously scheduling multiple upgrades to individual aircraft either at a depot or by a CFT to accelerate the overall completion timeline for fleet upgrades. The consolidation of modernization efforts requires understanding of each modification workflow. Since an aircraft has to undergo thorough inspections, component removal and restoration, operational checks, and other similar tasks associated to different modifications, the opportunity to perform multiple modifications simultaneously may present time savings. For example, an aircraft that undergoes standard PDM is typically inactive and unavailable for 180 days, i.e., two sequential quarters. Likewise, CFT technicians historically take two quarters to install an APG-82 radar at an F-15E field unit. To attempt both of these tasks individually requires an estimated four quarters, a year's worth of time where the aircraft is not available for operational requirements or combat pilot training. The F-15 SPO recognizes the chance to streamline processes and merge as many efforts together as possible to reduce the amount of time an aircraft is down for modification. Thus far, the depot team at Warner Robins AFB has successfully delivered five aircraft each via concurrent PDM and RMP maintenance. The average flow time endures approximately 261 days or roughly three fiscal quarters to complete both the mandatory scheduled maintenance and the radar upgrade. Effective scheduling and exploiting workload synergies in the aforementioned instance generates a time savings equivalent of having a single aircraft available for 15 months.

Given six different major tasks (i.e., PDM, RMP, APDC II, MIDS-JTR, EPAWSS, and LRP), there are 2^6 mathematically possible combinations or 64 unique courses of action (COAs) that can be explored for time savings. Certain COAs may not be feasible such as an F-15E which does require RMP update does not require longeron replacement associated with LRP. Additionally, the EPAWSS modification will no longer be a requirement for the F-15C due to loss of funding. The resulting number of varying COAs for sequencing maintenance operations are 39 different combination, each with a specific timeline. Speaking with the F-15 SPO to evaluate the complexities and synergies of modification options ultimately derives anticipated timelines of each modification consolidation COA in Table 16. These interval timelines spanning one to four quarters depict for how long an aircraft is possessed by the SPO to undergo modernization. A COA's length of time also means that an aircraft scheduled to undergo a specific maintenance or modification COA is ineligible to be undergo another COA until the first scheduled event fully concludes.

Table 16. Duration to complete convergence of modifications

Days to Complete	Courses of Action (COAs)	Number of COAS
0-90	ADCP II; MIDS; ADCP II/MIDS	3
91-180	PDM; RMP; LRP; PDM/ADCP II; PDM/MIDS; PDM/LRP; RMP/ADCP II; RMP/MIDS; ADCP II/LRP; MIDS/LRP; PDM/ADCP II/MIDS; PDM/ADCP II/LRP; PDM/MIDS/LRP; RMP/ADCP II/MIDS; ADCP II/MIDS/LRP; PDM/ADCP II/MIDS/LRP	15
181-270	EPAWSS; PDM/RMP; PDM/EPAWSS; RMP/EPAWSS; EPAWSS/ADCP II; EPAWSS/MIDS; PDM/RMP/ADCP II; PDM/RMP/MIDS; PDM/ADCP II/EPAWSS; PDM/MIDS/EPAWSS; PDM/RMP/EPAWSS; EPAWSS/ADCP II/MIDS; RMP/ADCP II/EPAWSS; RMP/MIDS/EPAWSS; PDM/ADCP II/MIDS/EPAWSS; PDM/RMP/ADCP II/MIDS; PDM/RMP/ADCP II/EPAWSS; PDM/RMP/MIDS/EPAWSS; RMP/EPAWSS/ADCP II/MIDS;	19
270-360	PDM/RMP/ADCP II/MIDS/EPAWSS;	1

3.4.4 Aircraft Availability

In order to respect the training needs of operational aircrew, identifying which aircraft to undergo a specific consolidation of modifications at an identified location during a scheduled fiscal quarter requires prudence that not too many aircraft are under extensive maintenance at a single time. Stated in Section 2.1, the number of available aircraft at any given moment is essential to the overall mission of a FW. While there exist published standards for the number of aircraft at each base, MAJCOM, and even fleet-wide MDS to be fully-mission capable, the complexities and limitations of maintenance and sustainment of fighter aircraft makes these values more of a goal than an absolute constraint. A side-by-side comparison of how historically close the F-15 came to achieving availability expectations was accomplished investigating both the past year (FY19) in Table 17 and the past four years (FY15-FY19) in Table 18 to determine a more pragmatic constraint value to set within the optimization model.

These tables show how even day-to-day repairs compounded with heavy, scheduled overhauls in PDM impact the fragility of aircraft availability. To meet the expected standard, the F-15 SPO needs to minimize its modernization workload, which is calculated as “depot possessed”. The concept of aircraft possessed by the depot is not simply aircraft at a depot location but more to the degree of work that is accomplished. Field-level maintenance is comprised of the standard day-to-day actions of returning aircraft to a flyable condition. Depot-level work can be accomplished either at a designated depot or even in the field by an approved team of technicians. The possession value is relatable to accountability regarding which entity is responsible for the work to be accomplished. Noting how difficult it has historically been to achieve the actual availability meet the expected standard manifests the critical nature of the F-15 SPO trying to decrease its possession footprint as much as possible. Note that in this analysis, several aircraft tails are currently not active due to incidents such as crashes or ground failures that are beyond repair. These tails are included within the evaluated totals because it is essential to show the footprint of fleet maintenance across all aircraft, to include those that suffer from catastrophic events.

Table 17. FY19 Report of aircraft availability given an expected amount to be in a flyable condition and what is actually achieved based on F-15 SPO possession

	# of Tails	Expected Standard		Actual		Depot Possessed	
		Avg #	%	Avg #	%	Avg #	%
Fleet	451	277.26	61.34	262.54	58.06	68.1	15.03
F-15C	211	120.27	57.00	121.59	57.5	30.67	14.46
F-15D	23	13.11	57.00	10.9	47.85	6.9	30.00
F-15E	218	143.88	66.00	130.06	59.68	30.54	14.01

Table 18. FY15-19 Report of aircraft availability given an expected amount to be in a flyable condition and what is actually achieved based on F-15 SPO possession

	# of Tails	Expected		Actual		Depot Possessed	
		Avg #	%	Avg #	Avg %	#	%
Fleet	455	289	63.67	271.2	59.54	64.27	14.13
F-15C	212	130.23	61.51	124.52	58.77	29.67	14.00
F-15D	25	15.5	61.63	13.67	53.28	3.59	14.36
F-15E	218	143.88	66	133.02	61.02	31.01	14.22

From Table 18's historical data of relatively 14% of F-15s are in possession of the SPO for depot-level maintenance, a value can be composed for each individual base, shown in Table 19, to ensure that a reasonable amount of aircraft are available to accomplish daily flying activities. Acknowledging previously that aircraft are integer values, in case where the amount of aircraft from a given base exceed the 14% in modification possession mark is due to rounding up to the next full aircraft.

Table 19. Amount of aircraft permissible to be in work from each individual base

Base	Total	On Hand #	Depot Poss'd #	On Hand %	Depot Poss'd %
Barnes	21	18	3	85.7%	14.3%
Eglin	13	11	2	84.6%	15.4%
Fresno	21	18	3	85.7%	14.3%
Jacksonville	21	18	3	85.7%	14.3%
Kadena	53	45	8	84.9%	15.1%
Kingsley Field	31	27	5	84.4%	16.1%
Lakenheath	76	65	11	85.5%	14.5%
Mountain Home	47	40	7	85.1%	14.9%
Nellis	32	27	5	84.4%	15.6%
New Orleans	21	18	3	85.7%	14.3%
Portland	21	18	3	85.7%	14.3%
Seymour Johnson	94	80	14	85.1%	14.9%

3.5 Timeline Conditions

The final fundamental principle to explore in a scheduling model is to tune the model's perspective of time and sequencing. The model must be incentivized or mandated to accomplish a given task against an identified timescale.

The first mandatory condition addressed to adherence to the F-15 SPO PDM induction plan. Aircraft must undergo depot maintenance according to dates or prior arrival and completion. Given that technical order guidance affords a window of ±90 days of the scheduled date, aircraft can easily be inducted either a quarter ahead or quarter behind schedule without disrupting operational flying. If an aircraft enters into PDM in the early years of the model's 12-year timeline of interest, another cycle of PDM will consequently be scheduled and executed.

To instill a predisposition to accomplish a single or all modernization tasks, setting a suspense date for modification(s) completion can obligate the model to find a feasible schedule. Establishing certain timelines for either an entire subset or for all aircraft to be in a certain modernization status can accommodate fixed needs of the F-15 SPO. In this model, the initial concept it to mandate that all F-15E must be fully modernized by the end of the FY31. These parameters can be more specific, e.g., requiring a certain modification be completed before a designated date or prior to another event. Conditions such as any prototypes would have to be first installed into a test aircraft and given a reasonable amount of time to demonstrate acceptability through test and evaluation. Other conditions may be more subjective yet pragmatic. Even though an optimization model will try to minimize redundant efforts by synergizing modifications, additional constraints must be applied to refuse induction when it may not seem pragmatic. Cases of such events would be preventing induction of an aircraft for scheduled PDM directly before or after it has been unavailable for a modification that took place in the field.

Finally, to motivate an optimization model to seek early accomplishment of modification tasks, a reward depleting over time induces the model to install modification kits as soon as possible. Using an exponential single value function shown in Equation (7) a relationship between the highest value of the first time interval and a lowest value at the end gives that decreasing value of time is non-linear [48]. For purposes of this research, a unique value is attributed to each quarter for the 12 years of time to complete modifications, with a value of 1 in the first quarter and a 0 in the last quarter. Selecting 1 April 2028, as an appropriate midvalue due to the projected timelines of EPAWSS procurement, derives the value of ρ as 25.56 in Equation (7) to produces a convex relationship of value over time [48]. Figure 3, can be derived to induce the model to expedite modernization without mandating a strict timeline.

$$V_i(x_i) = \frac{1-e^{-(High-x)/\rho}}{1-e^{-(High-Low)/\rho}} \tag{7}$$

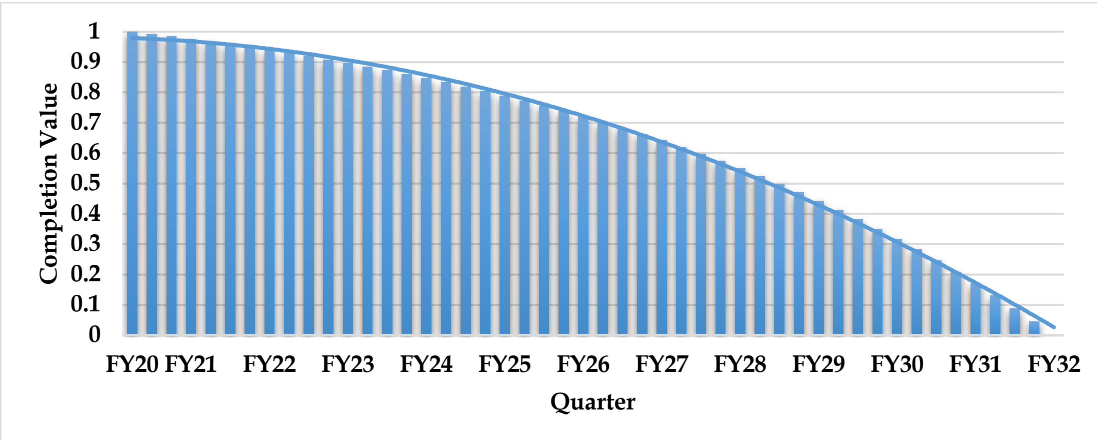

Figure 3. Value associated to completion per quarter

3.6 Objective Swing Weights

While this research investigates what limitations inhibit the F-15 SPO's capability to deliver an advanced weapons systems to warfighting operators, there are more subjective considerations and goals that also require inquiry. Decision-makers for program budget are conflicted between an expedited modernization effort and alternatives may present trade-offs regarding budget. To both effectively provide a fully capable F-15 to the field and efficiently converge as many modifications as possible motivates a multi-objective optimization approach. The two goals are: expediting modernization and minimizing workload. These goals are in competition and employing summed/swing weight coefficients to each of the means objectives allows exploration into the range of acceptable alternatives. When emphasis on one goal increases, the other becomes less consequential within the optimal solution. Implementing Equation (5) using a convex combination of weights to each of the objectives allows exploration of alternatives. The ability to adjust these weights through affords F-15 SPO decision-makers' ease of understanding of how different intentions of increasing warfighting capability or decreasing costs can change an optimal schedule based on preference.

3.7 Mathematical Model Development

To ensure this model is programmable and ultimately solvable in a reasonable amount of time for the F-15 SPO to investigate "what if" scenarios, the feasible region of solutions must be limited to a pragmatic and usable level. The number of decision variables as well as the dimensionality of unique values can quickly go beyond what a computer program can reasonably process. Isolating the primary decision variable of identifying a unique aircraft to undergo a particular modification COA at a specified modification location in a scheduled quarter has four parameters and the dimensionality of that variable can quickly expand the solution space and require extensive processing capabilities not available to the F-15 SPO. Table 20 addresses critical assumptions to limit this binary variable from a dimensionality of over two billion possible values. Working with the F-15 SPO, discussing reasonable opportunities to scale down the solution space, the dimensionality is whittled down by a magnitude of nearly 500. The consolidation of modifications between the ADCP II and MID-JTR has been accepted culturally and accomplished concurrently due to the similarities of impact to the avionic and electronics systems the unification of these modifications is extremely palatable. Similarly, instead of allowing the model to explore seven multiple modification locations to service the ANG aircraft, the idea of instituting an East Coast and West Coast effort is to be explored. With the opportunity of aircraft from Barnes, Jacksonville, and New Orleans having exclusivity to a potential CFT in the East Coast, aircraft from Kingsley Field, Fresno, and Portland would not have to perform cross country flights; this method is also attractive to reduce the total number of locations from 17 to 12. Finally, as the FY2020 NDAA reduced funding, the F-15 SPO, has now only considers modification efforts, including typical PDM, to F-15C/D to aircraft which have undergone the full wiring modification as Gold Fleet. Elimination of 62 aircraft which were already of lesser priority reduced dimensionality to 4.5 million possible variables

Table 20. Reduction of variable dimensionality through limitation of parameters

	Aircraft (i)	Courses of Action (j)	Modification Locations (k)	Time (q)	Total Variables
Full Scale Entire Inventory, All Combinations of COAs All Locations, Time tracked by Day	451	64	17	4383	2,150,685,504
Full Scale Month Entire Inventory, All Combinations of COAs All Locations, Time tracked by Months	451	64	17	144	70,659,072
Full Scale Quarters Entire Inventory, All Combinations of COAs All Locations, Time tracked by Quarters	451	64	17	48	23,553,024
Eliminating non-plausible COAs Entire Inventory All Locations, Time tracked by Quarters	451	39	17	48	14,352,624
ADCP II and MIDS-JTRS Concurrent Entire Inventory All Locations, Time tracked by Quarters	451	19	17	48	6,992,304
F-15E and Gold Fleet ADCP II and MIDS-JTRS Concurrent All Locations, Time tracked by Quarters	389	19	17	48	6,031,056
ANG East and West Coast CFTs F-15E and Gold Fleet ADCP II and MIDS-JTRS Concurrent Time tracked by Quarters	389	19	12	48	4,257,216

3.8 Mathematical Model

The mathematical program leverages sets and subsets of aircraft, modification COAs, modification locations, and quarter intervals. A list of decision variables and model parameters is defined. Finally formulations provided depict constraint relationships to variables and means to maximize the objective function.

Sets:

$i \in I$ The set of all aircraft i={1,…,389}

Subsets
- A = Aircraft dedicated to ANG
- B = Aircraft based out of Barnes
- C = F-15C Variant
- D = F-15D Variant
- E = F-15E Variant
- F = Aircraft based out of Fresno
- G = Gold Fleet (Rewire)
- H = Aircraft permissible for Modification Site Kelly AFB
- Ja = Aircraft based out of Jacksonville
- KF = Aircraft based out of Klamath Falls
- L = Aircraft based out of Lakenheath AB
- M = Aircraft based of Mountain Home AFB
- N = Aircraft based out of Nellis AFB
- Po = Aircraft based out of Portland
- R = Aircraft already complied with RMP
- S = Aircraft based out of Seymour Johnson AFB
- T = Aircraft based out of Eglin AFB
- U = Silver Fleet (Rewire)
- WR = Aircraft permissible for PDM/Modification Site Warner Robins AFB
- X = Aircraft permissible for PDM/Modification Site USAFE Depot
- Y = Aircraft permissible for PDM/Modification Site Kimhae Depot
- Z = Aircraft based out of Kadena AB

$j \in J$ The set of modification Courses of Action (COA) j = {1,…,19}

Subsets
- P = modification COAs involving PDM
- R = modification COAs involving RMP
- A = modification COAs involving ADCP II (MIDS-JTR Concurrent)
- E = modification COAs involving EPAWSS
- L = modification COAs involving LRP
- U = modification COAs projected duration less than one quarter
- D = modification COAs projected duration greater than one quarter and less than two quarters
- T = modification COAs projected duration greater than two quarters and less than three quarters
- Q = modification COAs projected duration greater than three quarters and less than four quarters

$k \in K$ The set of modification locations $k = \{1,....,12\}$

Subsets

AE = CFT Location ANG East
AW = CFT Location ANG West
H = CFT Location Kelly AFB
L = CFT Location Lakenheath AB
M = CFT Location Mountain Home AFB
N = CFT Location Nellis AFB
S = CFT Location Seymour Johnson AFB
T = CFT Location Eglin AFB
WR = PDM/Modification Site Warner Robins AFB
X = PDM/Modification Site USAFE Depot
Y = PDM/Modification Site Kimhae Depot
Z = CFT Location Kadena AB

$p \in P$ The set of tunable penalties coefficients $p = \{1,2,3,4\}$

Subsets

1 = Penalty coefficient for violating capacity parameter
2 = Penalty coefficient for violating contract requirement parameter
3 = Penalty coefficient for violating aircraft availability parameter
4 = Penalty coefficient for violating modification kit parameter

$q \in Q$ The set of quarters throughout the timeline $q = \{1,....,48\}$

Subsets

E = Period of time in which F-15E undergoing PDM needs to be scheduled again
G = Period which Gold Fleet can be modified prior to funding cessation
X = Period of time PDM/Modification Site USAFE Depot is available

$w \in W$ The set of weights for multiobjective criteria $w = \{1,2\}$

Subsets

1 = Weight associated to objective of expediting modernizing fleet
2 = Weight associated to objective of minimizing total durational workload

Decision Variables:

$$\mu_{ijkq} = \begin{cases} 1 \text{ if modification COA } j \text{ taken for aircraft } i \text{ at modification location } k \text{ in interval } q \\ 0 \text{ else} \end{cases}$$

$$\alpha_{kq} = \begin{cases} 1 \text{ if modification location } k \text{ is active during interval } q \\ 0 \text{ else} \end{cases}$$

Parameters:

Ω	Represent summed value earned from fully modernized aircraft
ϕ_{iq}	Represents condition that aircraft *i* is fully modernized in interval *q*
ε_{ijq}	Represents the condition that aircraft *i* has undergone modification COA *j* in interval *q*
Θ	Represents the total workload incurred by modernization or PDM
T_j	Represents the number of total number of aircraft *i* which undergo subsets of modification COA *j* for at any modification location *k* in any interval *q*
ρ	Represents penalties incurred from required constraint violations to ensure model solvability
ι_p	Represents the proportional increase to capacity, contractual requirements, and availability constraints
ν_k	Represents the proportional increase to modification kit procurements
σ_{kq}	Represents the number of required additional capacity (beyond current budget) at location *k* during interval *q*
Σ_{kq}	Represents capacity of modification location *k* in interval *q*
ψ_{kq}	Represents the number of required shortfalls to meet contractual requirement at location *k* during interval *q*
Ψ_{kq}	Represents contractual requirement of modification location *k* for interval *q*
δ_{iq}	Represents the number of required additional aircraft from subsets of aircraft *i* during interval *q*
Δ_{iq}	Represents the number of available aircraft in subsets of *i* which can undergo modification for interval *q*
κ_{jq}	Represents the number of required additional kits for subsets of *j* modification COAs in interval *q*
K_{jq}	Represent the number modification kits in subset *j* that are procured and delivered in interval *q*
η_{jq}	Represents the number of on-hand for subsets of *j* modification COAs in interval *q*
χ_{jq}	Represents the number of kits consumed for subsets of *j* modification COAs in interval *q*
θ_{iq}	Represents the status of aircraft *i* is undergoing any modification COA *j* at any modification location k in interval *q*
π_{iq}	Represents the scheduled interval q for aircraft *i* to be inducted into PDM
Π_{iq}	Represents the induction into PDM for aircraft *i* in interval *q*
β_{iq}	Represents the second cycle of PDM for aircraft *i* in interval *q*
α_{Max}	Represents the maximum allowable amount of active base-level CFTs at a given time
Φ_{iq}	Represents the necessary amount of aircraft is set *i* that must be full up in interval *q*
ξ_j	Represents the necessary amount modification in set *j* that must be completed
Ξ_i	Represent the amount of aircraft in subset *i*
γ_q	Represents the associated weight to interval *q*
λ_i	Represents the associated weight to aircraft *i*
υ_q	Represents the condition if a wingman is required to transatlantic flight in interval *q*
w_w	Represents the associated swing weight in *w*

Objective Function:

$$\boldsymbol{Maximize\ \ w_1\Omega - w_2\Theta - \rho} \tag{8}$$

Subject to:

$$\boldsymbol{\Omega = \sum_{q\in Q}\gamma_q\sum_{i\in I}\lambda_i\,\phi_{iq}} \tag{9}$$

$$\boldsymbol{\phi_{iq}} \le \frac{\sum_{j\in J_A}\boldsymbol{\varepsilon_{ijq}}+\sum_{j\in J_R}\boldsymbol{\varepsilon_{ijq}}+\sum_{j\in J_E}\boldsymbol{\varepsilon_{ijq}}}{\mathbf{3}},\ \ \forall \boldsymbol{i} \in \boldsymbol{I_E}, \boldsymbol{q}\ \in \boldsymbol{Q} \tag{10}$$

$$\boldsymbol{\phi_{iq}} \le \frac{\sum_{j\in J_A}\boldsymbol{\varepsilon_{ijq}}+\sum_{j\in J_L}\boldsymbol{\varepsilon_{ijq}}}{\mathbf{2}},\ \ \forall\ \boldsymbol{i} \in \boldsymbol{I_G}, \boldsymbol{q} \in \boldsymbol{Q} \tag{11}$$

$$\boldsymbol{\varepsilon_{ijq} = \sum_{k\in K}\mu_{ijkq} + \varepsilon_{ijq-1}},\ \ \forall \boldsymbol{i \in I, q \in Q, j \in J} \tag{12}$$

$$\boldsymbol{\Theta = \sum_{j\in J_U}\mathrm{T}_j + 2\sum_{j\in J_D}\mathrm{T}_j + 3\sum_{j\in J_T}\mathrm{T}_j + 4\sum_{j\in J_Q}\mathrm{T}_j} \tag{13}$$

$$\boldsymbol{T_j = \sum_{q\in Q}\sum_{i\in I}\sum_{k\in K}\mu_{ijkq}},\ \ \forall \boldsymbol{j \in J} \tag{14}$$

$$\boldsymbol{\rho = P_1\sum_{k\in K}\sum_{q\in Q}\sigma_{kq} + P_2\sum_{k\in K}\sum_{q\in Q}\psi_{kq} + P_3\sum_{i\in I}\sum_{q\in Q}\delta_{iq} + P_4\sum_{j\in J}\sum_{q\in Q}\kappa_{jq}} \tag{15}$$

$$\boldsymbol{\sum_{i\in I}\sum_{q\in Q}\sum_{j}\varepsilon_{ijq} \ge \xi_{\mathrm{j}}},\ \ \forall \boldsymbol{j}\ \in \boldsymbol{J_A, J_R, J_E, J_L} \tag{16}$$

$$\boldsymbol{\sum_{i}\phi_{iq} \ge \Phi_q},\ \ \forall \boldsymbol{q \in Q} \tag{17}$$

$$\boldsymbol{\sum_{j\in J_P}\sum_{k\in\{K_{WR}\cup K_X\cup K_Y\}}\mu_{ijkq-1} + \sum_{j\in J_P}\sum_{k\in\{K_{WR}\cup K_X\cup K_Y\}}\mu_{ijkq} + \sum_{j\in J_P}\sum_{k\in\{K_{WR}\cup K_X\cup K_Y\}}\mu_{ijkq+1} = \Pi_{iq}},\ \ \forall \boldsymbol{i \in I, q \in Q} \tag{18}$$

$$\boldsymbol{\Pi_{iq} \le 1},\ \ \forall \boldsymbol{i \in I, q \in Q} \tag{19}$$

$$\boldsymbol{\beta_{iq+32} = \Pi_{iq}},\ \ \forall \boldsymbol{i \in I_E, q \in Q_E} \tag{20}$$

$$\boldsymbol{\Pi_{iq} \ge \pi_{iq} + \beta_{iq}},\ \ \forall \boldsymbol{i \in I, q \in Q} \tag{21}$$

$$\boldsymbol{\tau_q} \ge \frac{\sum_{i\in I_L}\sum_{j\in J}\sum_{k\in K_{WR}\cup K_H}\mu_{ijkq}}{\Xi_{\mathrm{L}}},\ \ \forall \boldsymbol{q \in Q} \tag{22}$$

$$\boldsymbol{\sum_{i\in I_L}\sum_{j\in J}\sum_{k\in\{K_{WR}\cup K_H\}}\mu_{ijkq} \ge 2 * \tau_q},\ \ \forall \boldsymbol{q \in Q} \tag{23}$$

$$\boldsymbol{\sum_{i\in I_L}\sum_{j\in J}\sum_{k\in\{K_{WR}\cup K_H\}}\mu_{ijkq} \le 6 * \tau_q},\ \ \forall \boldsymbol{q \in Q} \tag{24}$$

$$\boldsymbol{\chi_{jq} = \sum_{i\in I}\sum_{k\in K}\mu_{ijkq}},\ \ \forall \boldsymbol{j \in J_A, J_R, J_E, J_L, q \in Q} \tag{25}$$

$$\boldsymbol{\chi_{jq} + \eta_{jq} \le \mathrm{K}_{jq} + \eta_{jq-1} + \kappa_{jq}},\ \ \forall \boldsymbol{j \in J_A, J_R, J_E, J_L, q \in Q} \tag{26}$$

$$\boldsymbol{\kappa_{jq} \le \nu_k * \mathrm{K}_{jq}},\ \ \forall \boldsymbol{j \in J_A, J_R, J_E, J_L, q \in Q} \tag{27}$$

$$\boldsymbol{\sum_{i\in I}\sum_{j\in J_Q}\mu_{ijkq-3} + \sum_{i\in I}\sum_{j\in\{J_T\cup J_Q\}}\mu_{ijkq-2} + \sum_{i\in I}\sum_{j\in\{J_D\cup J_T\cup J_Q\}}\mu_{ijkq-1} + \sum_{i\in I}\sum_{j\in j}\mu_{ijkq} \le \Sigma_{kq} * \alpha_{kq} + \sigma_{kq}},\ \ \forall \boldsymbol{k \in K, q \in Q} \tag{28}$$

$$\boldsymbol{\sigma_{kq} \le \iota_p * \Sigma_{kq} * \alpha_{kq}} \quad \forall \boldsymbol{k \in K, q \in Q} \tag{29}$$

$$\sum_{i\in I}\sum_{j\in J_Q} \boldsymbol{\mu_{ijkq-3}} + \sum_{i\in I}\sum_{j\in\{J_T\cup J_Q\}} \boldsymbol{\mu_{ijkq-2}} + \sum_{i\in I}\sum_{j\in\{J_D\cup J_T\cup J_Q\}} \boldsymbol{\mu_{ijkq-1}} + \sum_{i\in I}\sum_{j\in j} \boldsymbol{\mu_{ijkq} \ge \Psi_{kq} * \alpha_{kq} - \psi_{kq}}, \ \forall \boldsymbol{k \in K, q \in Q} \tag{30}$$

$$\boldsymbol{\psi_{kq} \le \iota_p * \Psi_{kq} * \alpha_{kq}}, \ \forall \boldsymbol{k \in K, q \in Q} \tag{31}$$

$$\sum_k \boldsymbol{\alpha_{kq} \le \alpha_{\mathrm{Max}}}, \ \forall \boldsymbol{q \in Q, k \in \{K_{AE} \cup K_{AW} \cup K_L \cup K_M \cup K_N \cup K_T \cup K_S \cup K_Z\}} \tag{32}$$

$$\sum_{j\in J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq-3}} + \sum_{j\in\{J_T\cup J_Q\}}\sum_{k\in K} \boldsymbol{\mu_{ijkq-2}} + \sum_{j\in\{J_D\cup J_T\cup J_Q\}}\sum_{k\in K} \boldsymbol{\mu_{ijkq-1}} + \sum_{j\in J}\sum_{k\in K} \boldsymbol{\mu_{ijkq} = \theta_{iq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{33}$$

$$\sum_i \boldsymbol{\theta_{iq} \le \Delta_{iq} + \delta_{iq}}, \ \forall \boldsymbol{q \in Q, i \in I_B, I_F, I_{Ja}, I_{KF}, I_L, I_M, I_N, I_O, I_{Po}, I_T, I_S, I_Z} \tag{34}$$

$$\boldsymbol{\delta_{iq} \le \iota_p * \Delta_{iq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{35}$$

$$\sum_{j\in J}\sum_{k\in K} \boldsymbol{\mu_{ijkq} \le 1}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{36}$$

$$\sum_j \sum_{k\in K}\sum_{q\in Q} \boldsymbol{\mu_{ijkq} \le 1}, \ \forall \boldsymbol{i \in I, j \in J_A, J_R, J_E, J_L} \tag{37}$$

$$\sum_{k\in K} (\boldsymbol{\mu_{ijkq} + \mu_{ijkq+1}}) \le \boldsymbol{1}, \ \forall \boldsymbol{i, j \in \{J_D \cup J_T \cup J_Q\}, q \in Q} \tag{38}$$

$$\sum_{k\in K} (\boldsymbol{\mu_{ijkq} + \mu_{ijkq+1} + \mu_{ijkq+2}}) \le \boldsymbol{1}, \ \forall \boldsymbol{i \in I, j \in \{J_T \cup J_Q\}, q \in Q} \tag{39}$$

$$\sum_{k\in K} (\boldsymbol{\mu_{ijkq} + \mu_{ijkq+1} + \mu_{ijkq+2} + \mu_{ijkq+3}}) \le \boldsymbol{1}, \ \forall \boldsymbol{i \in I, j \in J_Q, q \in Q} \tag{40}$$

$$\sum_{j\in Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq-4} \le 1} - \sum_{j\in J_P}\sum_{k\in K} \boldsymbol{\mu_{ijkq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{41}$$

$$\sum_{j\in J_T\cup J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq-3} \le 1} - \sum_{j\in J_P}\sum_{k\in K} \boldsymbol{\mu_{ijkq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{42}$$

$$\sum_{j\in J_D\cup J_T\cup J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq-2} \le 1} - \sum_{j\in J_P}\sum_{k\in K} \boldsymbol{\mu_{ijkq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{43}$$

$$\sum_{j\in J_D\cup J_T\cup J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq+2} \le 1} - \sum_{j\in J_P\cap J_D}\sum_{k\in K} \boldsymbol{\mu_{ijkq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{44}$$

$$\sum_{j\in J_T\cup J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq+3} \le 1} - \sum_{j\in J_P\cap J_T}\sum_{k\in K} \boldsymbol{\mu_{ijkq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{45}$$

$$\sum_{j\in J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq+4} \le 1} - \sum_{j\in J_P\cap J_Q}\sum_{k\in K} \boldsymbol{\mu_{ijkq}}, \ \forall \boldsymbol{i \in I, q \in Q} \tag{46}$$

$$\sum_w \boldsymbol{w_w = 1}, \ \boldsymbol{w \in W} \tag{47}$$

$$\boldsymbol{\mu_{ijkq}}; \boldsymbol{\alpha_{kq}}; \boldsymbol{\phi_{iq}}; \boldsymbol{\varepsilon_{iq}}; \boldsymbol{\tau_{iq}}; \boldsymbol{\Pi_{iq}}; \boldsymbol{\beta_{iq} = \{0, 1\}}, \ \forall \boldsymbol{i \in I, j \in j, k \in K, q \in Q} \tag{48}$$

$$\boldsymbol{\sigma_{kq}}; \boldsymbol{\psi_{kq}}; \boldsymbol{\delta_{kq}}; \boldsymbol{\kappa_{jq}}; \boldsymbol{\eta_{iq}}; \boldsymbol{\chi_{iq}}; \boldsymbol{T_j}; \boldsymbol{\theta_i} \in \mathbb{Z}_+, \ \forall \boldsymbol{i \in I, k \in K, q \in Q} \tag{49}$$

3.9 Model Explanation

The F-15 modernization schedule is modeled as a mixed-integer linear program. There exists a large number of constraints to capture the complex interwoven linkages between states. A weighted sums approach is used to explore the Pareto efficient frontier. The two objectives considered are: maximize the value of fully modernized airframes, and minimize the workload incurred with modifications and maintenance. A penalty parameter is also included in the objective function; this parameter penalizes required deviations from system constraints

3.9.1 Objective Function

The hybrid tri-objective value calculated in Equation (8) competes maximizing the total value of modernized F-15s within the fleet generated from Equations (9-12), against minimizing the total time of SPO possession and workload computed in Equations (13-14). While the objective value also recognized mandatory penalties summed in Equation (15) it is not weighted for multi-objective purposes as part of the related coefficients weighted sums approach from Equation (47).

Constraints (16) and (17) set mandated requirements that either a particular number of single modifications or fully modified aircraft occur by a certain time interval.

3.9.2 Scheduled Maintenance Constraints

Constraints (18-21) predicate adherence to scheduled PDM maintenance, either early, on-time, or one quarter permissibly later while rescheduling reoccurring PDM timelines. Transatlantic travel requirements in Equation (22) abide Constraints (22-24) regarding wingmen levels.

3.9.3 Modification Kits Constraints

Equation (25) addresses the number of consumed modification kits across the fleet while Constraints (26-27) dictate the number of required kits does not exceed the numbers available through acquisition timelines or penalizing, increased requests.

3.9.4 Workload Constraints

Capacity limitations set in Constraints (28) and (29) ensure that modification facilities do not over extend workloads without incurring a proportional penalty for additional demand. In contrast, Constraints (30) and (31) aim to employ active facilities to the greatest extent possible. Total number of active CFTs in a given time interval are limited by Constraint (32).

Similar to the location limitations regarding capacity and contractual requirements, Constraints (33-35) calculate the amount of aircraft in work from a particular subset of bases is not excessive in order to minimize operational impact.

3.9.5 Durational Constraints

The model cannot have a single aircraft undergo a modification in more than one place at a given time, hence Constraint (36) only permits one COA for all locations. Similarly, Constraint (37) pragmatically ensures an aircraft does not undergo a particular modification more than once. Since certain COAs of action require more time than others, Constraints (38-40) prohibit additional maintenance or modifications until the estimated time of completion has lapsed. Furthermore, Constraints (41-46) invoke practical maintenance practices to not undertake extensive modification in the field within a year of PDM induction.

3.9.6 Variable Definitions

Constraints (48) and (49) establish the criteria of binary or integer variables computed across the model.

3.9.7 Pre-processing Conditions

It is important to note that using these equations, preprocessing conditions must be accomplished to reflect the actual problem set. For instance, while constraints such as Equation (27) limits the amount of aircraft and particular modification location can handles, Table 13 highlights that certain aircraft from a particular subset based location cannot be modified at a particular location. In these cases, all instances of the decisions variable would be zero for these relationships. Similarly, aircraft that have historically undergone RMP prior to model implementation need not undergo the RMP modification again. Given that these interaction conditions are numerous, preprogramming has been accomplished to limit the model from searching and finding non-pragmatic solutions. Appendix B attached to this research gives insight into all the preprogramming conditions that reduce the solution space through case-specific implementation of the equations listed in Section 3.8

3.10 Model Execution

The MIP generated from this research required optimization software suitable to handle computation searching for optimality against all identified constraints and variable dimensions. The MIP was coded using the General Algebraic Modeling Software (GAMS) Version 25.1.3. High powered machines enabled by HTCondor Software was made available through the web-based NEOS Server, hosted by the Wisconsin Institute of Discovery at the University of Wisconsin in Madison [49][50][51]. The NEOS Server enabled utility of the Gurobi Optimizer Ver 9.0 [52]. Utility of this server and it associated process enabled the capacity to run multiple iterations of code simultaneously used for comparisons of changes to model parameters and weighted sums for sensitivity analysis.

3.10 Summary

The mathematical model investigates the ability to meet specific goals whether they be based on time, number of aircraft modified, and/or limitations on resources to identify a feasible schedule for planning efforts to modify aircraft based on decision-makers' preference of expediting modernization against minimizing workload.

IV. Analysis and Results

4.1 Chapter Overview

This chapter details results from optimizing a baseline scenario established with inputs the F-15 SPO based on parameters of capacities, contract requirements, and modification kit delivery timelines as provided in Tables 14, 16, and 19. It was assumed that both Kelly AFB and a USAFE depot location would become available and allow up to a potential of 4 CFTs to be optimally located, both spatially and temporally, to perform modifications at operational bases. Additionally, it is anticipated that the F-15C/D will no longer be funded beyond FY24; therefore, the model does not induct these aircraft into any further PDM or modernization efforts beyond October 1, 2023. However, it is also assumed that at least 145 of the 171 Gold wire F-15C/Ds must undergo longeron replacement. The F-15 SPO is further concerned with the degree of available ADCP II/MIDS-JTRS kits, so only 112 of the Gold Fleet were required to be fully updated.

Upon initial discussion with the F-15 SPO, there was an immediate recognition that the initial capabilities such as the capacity of the depot at Warner Robins AFB, GA, were inadequate to meet the immediate and persistent demand for scheduled PDM inductions. Due to the high influx of initial PDM inductions, a 300% proportional limitation allows the scheduling model to be solved. Despite the challenges to pragmatically execute the calculated schedule, this modification of the induction capacity parameter to enable the identification of a feasible solution was implemented at the behest of the stakeholder. Embedding the flexibility of leveraging penalties to increase capacity beyond projected limitations demonstrates to what extent and for how long depot induction capacities act as the limiting constraint to a feasible solution.

4.2 Baseline Model Results

Given the baseline scenario as established in Section 4.1, an optimal solution to modernize 218 F-15Es and 127 F-15C/Ds was found. The final objective function value of the optimal solution is inconsequential because it is not an inherently measureable unit. Thus, solutions can only be characterized via timelines and resource requirements. The baseline case uses equal weighting of the two objectives of modernization and workload in the hybrid tri-objective formulation, corresponding to an equal priority by the decision-maker. Additional Pareto efficient solutions are examined, as discussed in greater detail in Section 4.3. Tracking and understanding which constraints require additional assets above current induction capacity projections provides planning insight and justifies needs for future budget increases. Model results indicate the most binding constraint is the throughput of the depots at Warner Robins AFB and Kimhae, Korea. Even without any concurrent modernization activities occurring at depot, the baseline scenario requires more capacity to meet TO demand. As seen in Figure 4, the demand for additional throughput spikes at 250% more than each operational depot can currently provide. This demand is an immediate spike which eventually falls to sustainable levels as the proposed depot located in USAFE becomes available, taking on workload from Warner Robins in FY22. Consistently, there is an average of 25 aircraft in PDM each quarter, either undergoing modernization or standard scheduled maintenance.

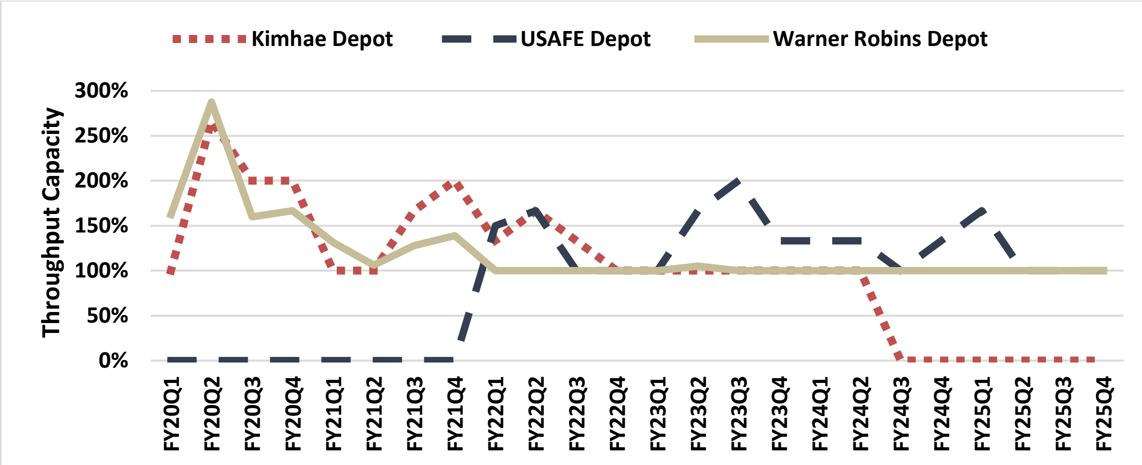

Figure 4. Depot location workloads a percentage of capacity limitations

The generation of CFTs at operational bases enables modernizations to occur in the field outside of PDM activities. The model found an ideal composition of when-and-where certain CFTs should be activated to modernize aircraft. With CFTs available, an average of 12 aircraft per quarter complete modernization efforts outside of a depot, increasing all efforts by approximately 50% of total throughput. For example, as soon as the Kelly AFB CFT becomes available, it is immediately worked to its capacity, demonstrating the need to modernize the fleet outside of PDM consolidation. Tracked by quarter, the usage of CFTs shows that contracted teams are positively augmenting the F-15 SPO's modernization efforts in concert with mandatory PDM inductions. The only time CFTs are tasked beyond maximum planned capacity is when approaching the work stoppage timeline associated with defunding the F-15C/D. In efforts to achieve the predetermined level of 112 fully modernized and 145 longeron replacements, there is a final surge period in [indicate specific quarter(s)] which impels CFTs to take on a workload above currently projected limits, as show in Figure 5.

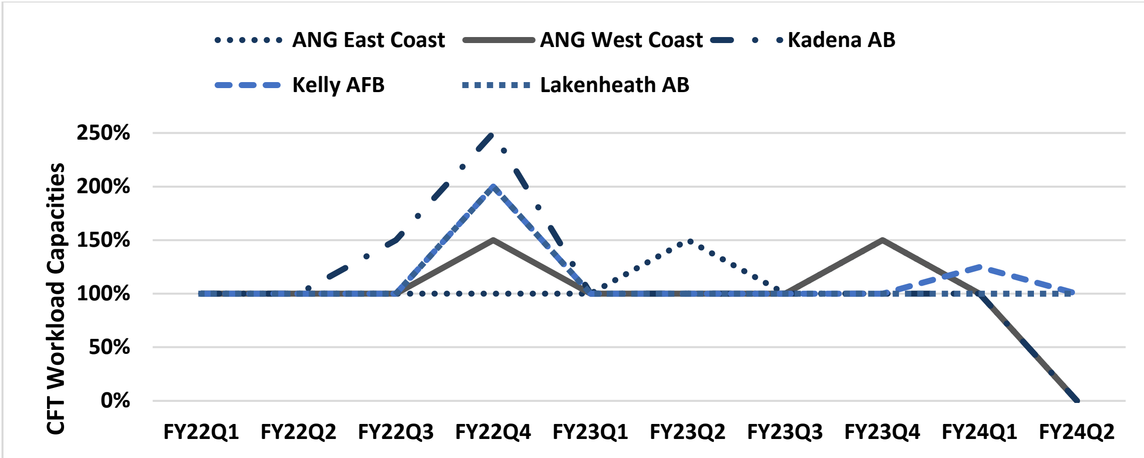

Figure 5. Contractor Field Team workloads over time to complete Gold Fleet upgrades

The next insight resulting from the optimal solution pertains to how the rate of kit consumption aligns with the anticipated manufacturing timelines of modification hardware. Knowing whether the aforementioned throughputs can benefit from the procurement of additional kits (i.e., earlier than scheduled) by taking advantage of an aircraft already undergoing work can help forecast future budget requests. While it is not necessarily easy to summon additional funding to procure more kits, it may not be as challenging as increasing a depot team's workload of 200% at a later sequence when more kits are available. Hence the penalty for additional kits is less severe, which may compel the model to procure more kits before increasing workload requirements. However, despite the comparatively cheaper expense, the model seldom sought additional kits. In actuality, the model only initiated penalties to acquire more kits 13 times. These instances corresponded to the procurement of seven additional ADCP II/MIDS-JTRS kits in FY20Q3 and six additional kits of longeron hardware in FY21Q3. Since ADCP II/MIDS-JTRS hardware is universal for both the F-15E and F-15C/D, the

F-15 SPO has a high interest in these modification kit consumptions. Figure 6 shows the rate at which these particular kits are installed and compared to the rate of manufactured kits are delivered. The model also shows that, while the request was made, additional requested kits were not immediately required for installation in the same quarter of request. Programmed constraints to the model only allow increased kit purchases during quarters with predicated deliveries. Waiting till the next scheduled delivery period would have been suboptimal versus buying early, and holding till needed. The model determined when to increase incremental deliveries to generate a sufficient stockpile inventory between intervals to meet an optimal demand of additional kits.

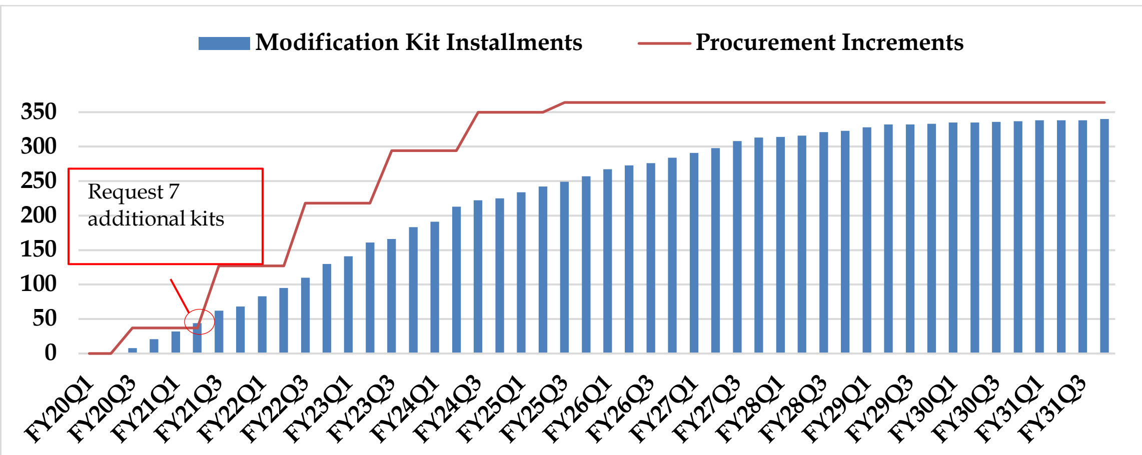

Figure 6. ADCP II/MIDS-JTR Baseline Cumulative Installation

Arguably, the easiest constraint to relax is aircraft availability by base. However, when associating this relaxation with a relatively lesser penalty, this constraint rarely ever seeks relaxation. Only twice did the model exceed permissible levels of aircraft in an unflyable maintenance status. In both of these cases, the FWs which are subject to these violations are at Mountain Home AFB and Seymour Johnson AFB. Two additional aircraft are taxed beyond the seven permissible from Mountain Home during FY26Q4, leaving 39 total aircraft on station. Only one additional jet is placed in depot-level possessed from Seymour Johnson AFB in FY27Q2, leaving 79 aircraft across four squadrons. Each of these violations only lasts for a single quarter, and sufficient levels are restored the following quarter. Each of these additionally requested aircraft represents less than 3% of each base's TAI, and the circumstantial impacts to operational requirements may be easily justifiable given lead time to know when such an event would occur.

4.3 Goal Programming Analysis

The baseline scenario assumes an equal prioritization of the weighted terms of expedited modernization and minimal workload. This section explores the sensitivity of the model to changes in these preferences. Using the same parameters in the baseline scenario, the weighting in preference between the two objectives is varied.

As previously stated in Section 4.2, the final hybrid tri-objective function values are an artificial construct between two different units of measure of number of fully modernized aircraft and time of possession. Thus, to understand how the model responds to changes in a goal priority, a new metric measuring when the F-15E fleet reaches a level of 85% modernized, or 185 fully modified aircraft with ADCP II/MIDS-JTRS, RMP, and EPAWSS, was created. After exploring 11 different weightings with intervals ranging of approximately 0.1 depicted in Table 21, the data shows that there is indeed trade-offs. It is important to note that, across each iteration, there is an average of 432 total PDM inductions across 12 years. It is essential to remove this footprint of possessed hours from the comparative models, as these are required regardless of which effort is considered because standard PDM is agnostic with respect to aircraft modifications and therefore constant across all cases. Effectively, two quarters of PDM equates to 4,380 possessed hours, which is both a cost to fund work and time away from supporting operations. However, if a modification does occur within PDM, any additional time outside of the two allocated quarters is registered and used for comparative analysis.

Table 21. Weighted Objective Values by Iteration

Weighted Sums	Iterations										
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Maximize Fully Modernized	0.999	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	.001
Minimize Possession Time	0.001	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.999

Decision-maker preference may vary between the two objectives, and analysis confirms the model does deliver more fully-modified aircraft earlier when it is less concerned with the workload to achieve this goal. Indeed, when the model focuses on modernizing quickly, it was able to find a solution to deliver 185 fully modified aircraft before April 1, 2029 with a possession footprint of nearly 2.5 million hours of aircraft undergoing modification. Comparatively, taking a heavier weighted approach of reducing workload as much as possible extends the mark of 85% fully modified by 2 years but with only a 2.1 million hour workload showing a potential savings of over 350,000 additional hours. These additional hours show that the most expeditious efforts demand four additional aircraft be possessed by the F-15 SPO for modification purposes every day. More importantly, to deliver 185 F-15Es by the third quarter of 2029 requires an average of 260,000 hours per year for 9.5 years outside of normal PDM activities. To slow the process down to the minimal workload requires 11.5 years of work averaging 185,000 hours per year. Figure 7 shows incremental changes that occur within the model as the preference between expediting modernization and minimizing workload.

Figure 7 also shows that being fully aggressive about expediting modernization requires more hours than a less emphasized approach. Sensitivity analysis shows that the same end result of 185 aircraft by April 1, 2029 can be achieved by alternative means and for 146,000 hours less in depot-level maintenance time; cutting the possession differences between the most extreme approaches in half. A lighter workload with the same delivery time is dominating solution generating a Pareto frontier of effective solutions. Seen in Figure 8, one can easily infer a linear relationship between the change timeline to 85% F-15E fully modified to number of workload hours. This output shows that, for every day to speed up delivery, there is an associated cost of 300 hours of possession to achieve that mark before April 1, 2031.

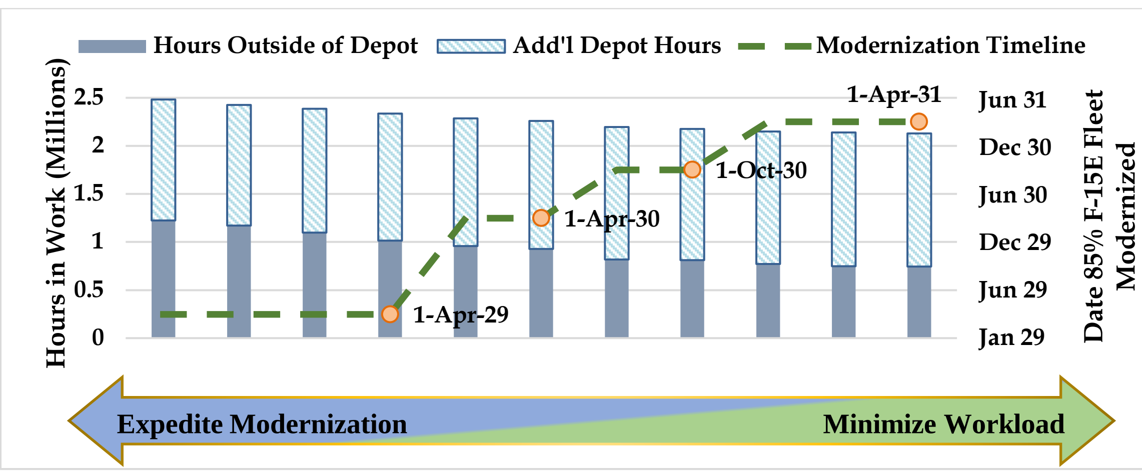

Figure 7. Comparative analysis of additional possession hours required to modernize 85% of Strike Eagle Fleet given varying goal emphasis between Expedite Modernization and Minimize Workload with Pareto solution markers

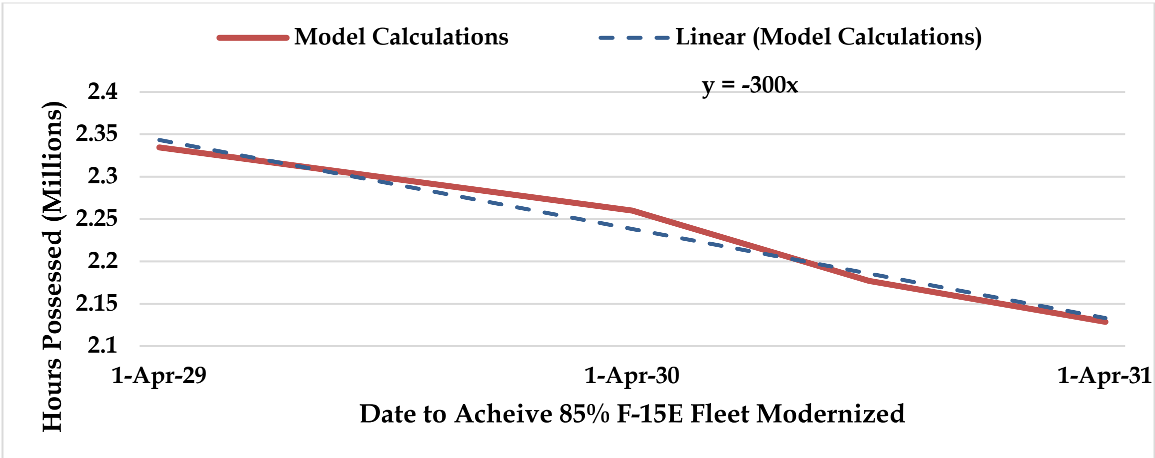

Figure 8. Trade-off analysis of Pareto solutions comparing expediting modernization and minimizing workload

The final element to explore when considering tradeoffs between objectives is the number of consolidated PDM/modernization events. Intuitively, as the relative emphasis on minimizing workload increases, the number of consolidated modifications also increases while the number of total number of invasive maintenance events decreases. Unexpectedly, the number of violations to constraints, especially dealing with workflow capacities, were relatively invariant. The most binding constraint of workload capacity violation across all 11 iterations' outputs demanded a range from 106-109 additional aircraft in modification locations exceeding initial throughput parameters. An in-depth examination of the durations of selected modification COAs also showed no significant trends. Iterations less preoccupied with minimizing workload and more aggressive to quickly modify aircraft did demand more EPAWSS kits. Understandably, these kits have the longest procurement timeline and are the more laborious to install, so the model would invest in having more on-hand to obtain a quicker modification timeline. Still, it abides by a preset of only requesting 20% of the incremental delivery for a total for 18 kits ahead of schedule delivery timeline over 4 years.

4.4 Alternate Scenario Comparisons

It is inappropriate to assume the baseline scenario details all possible planning modernization efforts. Therefore, several "What If" scenarios are investigated. Some key elements of interest tested against each other are the investment of a depot location in USAFE, the number of CFTs being reduced from four to two, and the full modernization (i.e., both ADCP II/MIDS-JTRS and LRP) of all 171 Gold Fleet F-15C/Ds, prior to loss of funding. Table 22 shows the varying conditions examined that deviate from the baseline scenario. Each alternate scenario is run against three different weighted sums values to determine how preference between the conflicting objectives affected the model's reportedly optimal solution. Each scenario uses weighted values from iterations I, VI, and XI from Table 21.

Table 22. List of conditions varied by scenario

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of CFTs	4	2	4	4	4
Number of F-15C/Ds Fully Modernized	112	112	171	112	171
USAFE Depot Available	Yes	Yes	Yes	No	No

4.4.1 Depot Utilization

Similar to the initial baseline output, depot workload is the most binding resource constraint across all scenarios. Each scenario verifies that mandatory PDM scheduled inductions are consistent with the sum of aircraft going through PDM over the course of

12 years, ranging between 427 and 431 across all 15 unique condition sets. The most common disparity occurred in Scenario 1, where the lack of additional CFTs forced the model to induct aircraft more toward the end of the 270-day period granted by technical mandate. Similarly, all scenarios consistently execute the same modification COAs within depot, regardless of a shorter or longer durational footprint. Figure 9 shows that there are advantages to using the investment in the USAFE depot for at least 4 years to alleviate the demand in PDM inductions to depot in Warner Robins, GA. Across all scenarios, during the potential 5 years operational timeline of the USAFE facility between FY22-FY26, the model sends 28 to 33 aircraft based out of Lakenheath AB through PDM, showing the potential requirement and cost savings associated with using a USAFE location. Looking into the constraints that aircraft need to be part of a formation of two or more aircraft to fly across the Atlantic with air refueling support, this means that between 12 and 16 tactical airlift missions requiring air tanker support can be eliminated during that five year period.

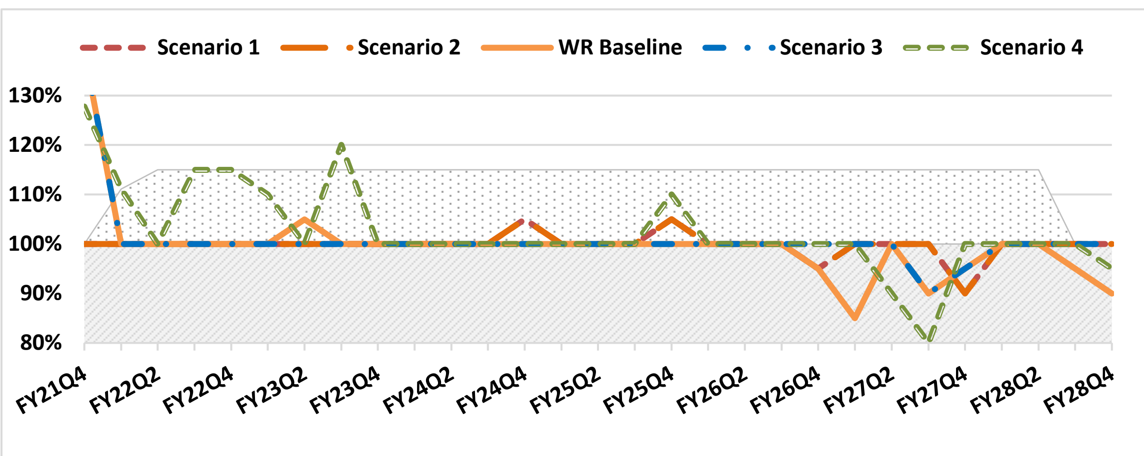

Figure 9. Warner Robins Depot Utilization Scenario Comparison

4.4.2 Contractor Field Teams

Even though depots are often worked beyond current capacities parameters, further burden of modernization falls upon the tasking of CFTs. Analysis across the competing objective functions values across all scenarios shows that the overall level of work to accomplish the task of modernizing the fleet is comparatively the same. While the model looks to only operate from a fixed number of locations to satisfy the necessary workload, even at the further extreme of preference to consolidating modifications, the additional burden is placed on the active locations to increase throughput. Extensive demands of additional capacity is especially apparent in the situation when the model must to perform a predetermined number of F-15C longeron replacements prior to the defunding timeline. While it seems counterintuitive to spend extra funds on a CFT as the F-15C/D fleet is being stood down due to excessive expense, identified limitations from model outputs now help decision-makers know what immediate choices are required to manage both budget and expectations. Consistently over all five presented conditions, the model elected to place an active CFT modification location at Kadena AB until F-15C/D funding termination. This condition is easily understandable as aircraft located in Okinawa, Japan cannot undergo maintenance at any other location aside from the dedicated depot in Korea, which is already beyond maximum capacity.

4.4.3 Modification Kit Availability

While all the scenarios investigate the variance in workload as depot and CFT workflows are binding, interest falls upon what lost opportunities could arise due to a shortfall of modification kits. The moment a bay becomes available, it is imperative the required modification kit is also available. Looking into the modification procurement timelines, a comparison of the most aggressive modernization efforts can be helpful to find what the most extreme demands are for any given modification kit. Putting full preference to expediting modernization can demonstrate what the "worst case" would be for each scenario to identify which constraints are binding on kit consumption. The assessment of each scenario in Table 23 shows that, in every case, additional kits delivered ahead of schedule are necessary to modernize as quickly as possible. Since Scenario 1 has the limitation of only two CFTs and needs only to modernize 112 F-15Cs, the limitations on means of modernization are more restricting on overall workload and the acquisition of additional kits is not as beneficial. Scenarios 1 and 2 recognize the extra utility of having the USAFE depot and fully leverages the possibility to acquire more EPAWSS kits as other resources have to be more dedicated modernizing 171 Gold Fleet F-15C/Ds when compared to Scenarios 3 and 4 when no USAFE depot is available.

Table 23. Comparison of additional Modification Kit Consumption across five assessed scenarios

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Additional RMP Kits	0	0	0	0	0
Additional ADCP II/MIDS-JTR Kits	7	0	20	1	20
Additional EPAWSS Kits	18	10	22	10	9
Additional LRP Kits	8	8	11	12	11
Total	**33**	**18**	**53**	**23**	**40**

4.4.4 Fleet Modernization

The final comparison is to compare the five presented scenarios' final outcomes to when the fleet is fully modernized as against minimizing workload. Shown previously in Section 4.3, the expected timeline to the baseline modernization can be accomplished as early as FY29Q3 or as late as FY31Q3. Looking into the possible outcomes based on the limitations of CFTs, USAFE depot, and demand to put 171 Gold Fleet aircraft through LRP and APCD II/MIDS-JTRS upgrades shows that the timelines can slip as can the amount of time required to accomplish all the modifications. In Table 24, the outcomes are relatively comparable across scenarios and can help determine whether there truly is cost savings to reduce the contractor footprint, since the demand will ultimately require the same amount of work.

Table 24. Comparison of Scenarios Accomplishing Tri-Objective of Modernization of 85% F-15E Fleet Delivery Dates and Hours of Possession

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Expedited Modernization	FY29Q3	FY29Q4	FY29Q3	FY29Q3	FY30Q1
Hours Possessed (Millions)	3.42	3.35	3.49	3.55	3.56
Minimize Workflow	FY31Q3	FY31Q1	FY31Q1	FY30Q4	FY31Q2
Hours Possessed (Millions)	3.07	3.05	3.09	3.24	3.35

4.5 Summary

The hybrid tri-objective mathematical program adequately represents the demands and capabilities of F-15 fleet modernization. The model seeks opportunities to consolidate modernization efforts and adheres to mandated requirements levels to deliver a fully modernized force at the end of the timeline. It appropriately recognizes which aircraft require modification(s) and identifies an ideal timeline to induct each aircraft into the schedule based on its associated rank value within the fleet. Using deterministic values to estimate the availability, time, and necessary workloads to accomplish the various modifications of the fleet, the model can provide insights regarding which constraints are binding and to what extent. An example of a potential schedule is provided in Appendix A. While workload capacity is most consistently the binding constraint and penalties associated with violating this constraint occur, the model only takes a penalizing action if it is absolutely necessary. Finally, use of the model satisfactorily explores tradeoff in solutions associated with different relative priorities among the two competing objectives between a focus to expedite modernization for quicker fielding of advance capabilities vis-a-vis a schedule to minimize workload.

V. Conclusions and Recommendations

5.1 Chapter Overview

This chapter discusses the insights and recommendations in both academic inquiry and program management of the F-15, resulting from the research presented.

5.2 Conclusions of Research

The ability to leverage scheduling theory and multi-objective optimization techniques to help resolve a multifaceted and complex problem presented by the F-15 SPO modernizing 451 fighter aircraft against reducing workloads has proven effective. By using goal programming and multi-objective optimization techniques searching for a best solution to appease conflicting F-15 SPO interests, this research shows how introducing penalties enabling constraint relaxation and thus solvability, a balance between objectives may still be achieved. Although aircraft availability is considered a fundamental objective of the F-15 SPO, ensuring that sufficient levels of aircraft are fully mission capable at assigned operational bases to support the day-to-day mission, the utility of using a constraint based on BAI proves to be effective to preserve this intention. However, very seldom did the scheduled workflow demand more aircraft than permissible, as this constraint was generally non-binding. Admittedly, this model is deterministic in nature, and timelines have a conservative bound to take more than the average timeline; there still may be risk of work stoppage or slowdown not anticipated in this model.

5.3 Significance of Research

This research produces a mathematically programmable model which can provide scheduling insights navigating beyond the current decade and how to plan extensive efforts in keeping the F-15 fleet survivable and lethal against a dynamic technological adversary. The ability to forecast the modernization status of 451 aircraft, modification kit procurement demand, workload budgeting, and even operational capability is a powerful instrument to examine how elements of the problem interact with each other within an optimal maintenance scheduling solution. The current model efficiently schedules over $7 billion of maintenance and important upgrades. The model's prescribed solutions retain aircraft availability at or over 85% for warfighting, affording the training and warfighting capability of over one thousand combat aircrew in an annual $1.5 billion flying hour program This scheduling tool can find opportunities for cost savings based on possession hours and the number of aircraft that have to undergo extensive maintenance. The capability to rapidly generate an optimal solution based on changes to budget can help program managers advocate for additional resources, or to assess the consequences of proposed reductions on fleet readiness. While this model was built with the F-15 weapons system in mind, this tool can easily be tailored to adhere to other major weapon systems across the USAF.

Furthermore, this model helps show the status of the F-15 fleet as the development of the F-15EX continues to proceed. Congress has authorized nearly $1 billion to manufacture eight new prototypes, and the need to know what the final F-15EX procurement levels should be rests on the status and sustainability of the legacy fleet.

Knowledge of what modernization levels the active fleet can obtain and the maintenance challenges identified by this mathematical model can advocate for increasing the projected acquisition of 44 F-15EX aircraft to 80 total aircraft over the next 12 years.

5.4 Recommendations for Action

It is recommended this mathematical model be turned over to the F-15 SPO at AFLCMC for immediate implementation into plans, programming, budgeting, and execution of activities. The refinement of this model into a tool with real-time numbers and projections from the program manager will provide shareable insight and understand critical paths when determining how to be proceed when satisficing both budget requirements and operational demands. Development into a graphical user interface and user training will also allow multiple program managers to explore what possible outcomes can occur to best understand whether a change to resources will affect the schedule. As this tool becomes more developed and users gain greater familiarization with how to use the model, it can be modified and fielded in other offices within AFLCMC.

In efforts to retain pragmatic implementation of a scheduling tool seeking optimality based on user-defined preference over multiple objectives, the techniques to define priority and establishing value should be standardized. The value of modification/modernization should be strive to become something easily communicated to users and decision-makers. While making decision analysis scoring and criteria universal may not be feasible with so many stakeholders, the F-15 SPO should aim to accommodate as many elements within the community of interest as possible. Working groups should develop signed policy of formulated reasoning based on representation of all parties to best reflect the common interests across the Air Force.

During tool development, several prototypes should investigate the adaptability of changing precedence and means of tracking aircraft value to properly inform working groups to determine which model inputs the F-15 SPO and community should formally accept. Suggested adaptations are: (1) Infusion of Aircraft Structural Integrity Program (ASIP) data, (2) whether time of completion should be cumulative and, if so, if a more convex degenerative cumulative value is more appropriate, and (3) a decision whether it is in the best interest of the aircraft fleet to cease treating modernization as a binary condition and further allocate weighted bias to generate a modification hierarchy. Doing so would introduce the concept that future modifications may be ingested by the model, and the concept of a "fully modernized" aircraft may never be a final outcome. Once again, through outreach to the entire community to include acquisitions and operators, a consensus of the prioritization over and relative value placed upon different modifications can establish a hierarchy and ensure the most critical modifications occur before others.

5.5 Recommendations for Future Research

Despite the current robustness and versatility of this model, there are several areas of improvement to make a more precise and refined product to benefit long-term schedule maintenance activities to a fleet of aircraft.

The first recommendation is to determine suitability to other weapon systems and large programs that undergo long-term sustainment and modification. The assumptions on this model are applicable to the maintenance practices for the F-15, which has different technical requirements than another fighter aircraft or even a larger airframe such as a bomber or cargo jet.   Investigation regarding whether this model can be applied to various platforms can help standardize the industry.

A second recommendation is to create a model with a higher degree of timeline fidelity. The current model only investigates fiscal quarters to consider program manager and defense contractor budgeting intervals, and there is opportunity to increase temporal fidelity to schedule specific to monthly or weekly actions. This change could be coupled with a rigorous cost analysis to match the price per hour to perform work on an aircraft at a different locations to quickly identify a net present monetary value to the total duration of all modifications.   In turn, calculated costs and benefits can also be used to evaluate the pros and cons of standing up and sustaining a geographically dispatched CFT. Furthermore, the cost for additional kits or the dynamic change in funding, which may reduce the number or projected kits, can all be affixed to deterministically calculate a dollar value to execute work within the model's scheduled timeline.

A third recommendation is to incorporate uncertainty into the model by implementing stochastic programming. The fidelity of one quarter time increments largely obviated this need in the current model, but as model fidelity is increased to months or weeks, uncertainty will play a more prominent role.

Finally, further research efforts can also investigate the efforts associated with standing down the F-15C/D fleet and introducing the F-15EX. Closing the chapter on 50 years' worth of military service by the F-15C/D fleet, the decision on where to base the final flying squadrons of legacy aircraft and where to place the latest version will require qualitative and quantitative inquiries to make data-driven decisions. Since some issues are high-level decisions about base preference, decision analysis techniques can be applied to determine the most suitable locations to consolidate aircraft from overseas as F-15C/Ds are grounded due to lack of preventive maintenance funding.

5.6 Summary

The F-15 fleet is an indispensable component in the USAF's posture as the greatest aerial power in the history of the world. Its ability to fly, fight, and win is critical as geopolitical relations continuously shift against peer and near-peer adversaries. It is insufficient to simply maintain status quo of wartime capabilities as enemy threat systems continue to make tremendous technological strides. To ensure the readiness of the F-15 fleet, the F-15 SPO must balance the demands of both combat capability and logistical support. Capacity limitations result as lack of funding, uncertain timelines, and parts availability. These constraining factors must be well identified, quantified, and overcome to speedily modify a wartime asset ready to defend the nation. This model aids decision-makers integrated into that process and delivers calculated insight that is not immediately available otherwise. Through incorporating tools from scheduling theory, multi-objective optimization, and valued focus thinking, the insights and prescribed, scenario-specific F-15 fleet maintenance and upgrade timelines obtained by solving a well-suited mathematical model helps preserve relevance and dominance of the mighty F-15 Eagle.

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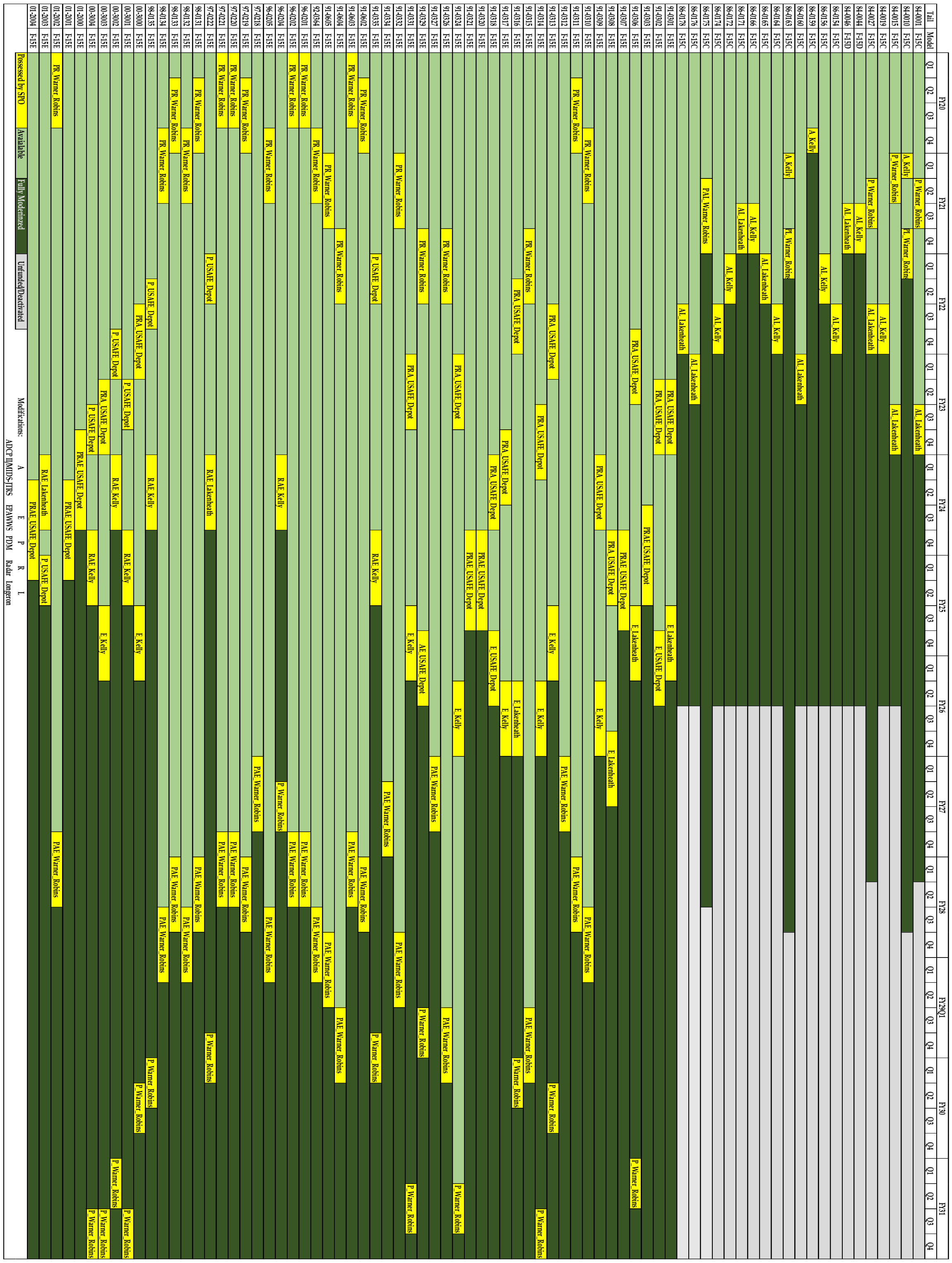
Appendix A: Example Modernization Schedule for Lakenheath Air Base



Example schedule for Lakenheath AB on assigned MDS and modification timelines

Appendix B: GAMS Preprocessing Code

```
* Code suggests only supporting E-model Fleet and Gold Fleet(through 2023) with reduced COAs to force
APCD and MIDS to occu»
r simultaneaously, and that there can be two ANG service capacities with and East and West Coast
Scalar A _ C F T m a x 'maximum number of CFTs not including Kelly that can be active' /4/
A _ w e i g h t _ w o r k l o a d 'swing weight for multiobjective optimization (0,1)' /.7/
A_weight_expedite
A_USAFE/1/
*weight full computed as 1-weightmod
p r o p o r t i o n a l _ i n c r e a s e 'allowable slack to AoA, Capacity, and Requirements' /2.0/
k i t _ p r o p o r t i o n a l _ i n c r e a s e 'allowable slack increase to procurement levels'
/0.15/
G r e e n L i g h t U S A F E 'Determination to standup USAFE Depot' /1/
N u m b e r _ L R P _ M a n d a t o r y ' Hard number of Gold Fleet that must be LRP (Do Not include'
/145/
C a p a c i t y _ P e n a l t y 'Really hurt to make it feasible' /50/
A_Gold_Fleet_Full /112/
A_Strike_Fleet_Full /218/;
A_weight_expedite= 1- A_weight_workload;
Sets
i ' A i r c r a f t ' /1*389/
j ' C O A s ' /P, R, L, PL, PR, E, PE, RE, PRE,
A, PA, RA, AL, PRA, AE, PAE, RAE, PRAE, PAL/
q ' Q u a r t e r s ' /FY20Q1,FY20Q2, FY20Q3, FY20Q4, FY21Q1, FY21Q2, FY21Q3, FY21Q4, FY22Q1, FY22Q2,
FY2»
2Q3, FY22Q4,
FY23Q1,FY23Q2, FY23Q3, FY23Q4, FY24Q1, FY24Q2, FY24Q3, FY24Q4, FY25Q1, FY25Q2, FY2»
5Q3, FY25Q4,
FY26Q1,FY26Q2, FY26Q3, FY26Q4, FY27Q1, FY27Q2, FY27Q3, FY27Q4, FY28Q1, FY28Q2, FY2»
8Q3, FY28Q4,
FY29Q1,FY29Q2, FY29Q3, FY29Q4, FY30Q1, FY30Q2, FY30Q3, FY30Q4, FY31Q1, FY31Q2, FY3»
1Q3, FY31Q4
/
k 'Locations of Mods' /ANG_E, ANG_W, Kelly, Lakenheath, Mountain_Home, Nellis, Seymour_Johnson, Eglin,
Wa»
rner_Robins, USAFE_Depot, Kimhae, Kadena/
A(i) 'ANG Aircraft' //
B(i) 'Aircraft at BARNES' //
C(i) ' F - 1 5 C ' //
D(i) ' F - 1 5 D ' //
E(i) ' F - 1 5 E ' //
F(i) 'Aircraft at FRESNO' //
G(i) 'Gold Fleet' //
Ja(i) 'Aircraft at JACKSONVILLE' //
KF(i) 'Aircraft at KLAMATH FALLS' //
L(i) 'Aircraft at LAKENHEATH' //
M(i) 'Aircraft at MOUTAIN HOME' //
N(i) 'Aircraft at NELLIS' //
O(i) 'Aircraft at NEW ORLEANS' //
P(i) 'Aircraft at PORTLAND' //
R(i) 'APG 82 Mod Completed' //
S(i) 'Aircraft at SJ' //
T(i) 'Aircraft at EGLIN' //
U(i) 'Silver Fleet' //
Z(i) 'Aircraft at KADENA' //
LRP_Done(i) //
ADCP_Done(i) 'ADCP at least Started' //
EPAWSS_Done(i) //
M I D S _ D o n e ( i ) //
Gold_Need_PDM(i) //
* j 'COAs'
PDM(j) 'PDM' /P, PL, PR, PE, PRE, PA, PRA, PAE, PRAE, PAL
/
RMP(j) ' R M P ' /R, PR, RE, PRE, RA, PRA, RAE, PRAE
/
ADCP(j) ' A D C P ' /A, PA, RA, AL, PRA, AE, PAE, RAE, PRAE, PAL
/
EPAWSS(j) ' E P A W S S ' /E, PE, RE, PRE, AE, PAE, RAE, PRAE
/
LRP(j) ' L R P ' /L, PL, AL, PAL
/
UNO(j) 'DOS QUARTERS' /A
/
DOS(j) 'DOS QUARTERS' /P, R, L, PL, PA, RA, AL
/
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TRES(j) 'TRES QUARTERS' /PR, E, PE, RE, PRE, PRA, AE, PAE, RAE, PAL
/
QUATRO(j) /PRAE
/
Xq(q) 'Active quarters for USAFE Depot' /FY22Q1, FY22Q2, FY22Q3, FY22Q4, FY23Q1, FY23Q2, FY23Q3,
FY23Q4, FY24Q1, FY2»
4Q2, FY24Q3, FY24Q4, FY25Q1, FY25Q2, FY25Q3, FY25Q4, FY26Q1, FY26Q2, FY26Q3, FY26Q4/
PDM_Rd_1_E(q) 'Second Round of PDM for E models' /FY20Q1, FY20Q2, FY20Q3, FY20Q4, FY21Q1, FY21Q2,
FY21Q3, FY21Q4, FY2»
2Q1, FY22Q2, FY22Q3, FY22Q4, FY23Q1, FY23Q2, FY23Q3/
SLEP_Fix(q) /FY20Q1,FY20Q2,FY20Q3,FY20Q4,FY21Q1,FY21Q2,FY21Q3, FY21Q4, FY22Q1, FY22Q2, FY22Q3, FY22Q4,
FY23Q1, FY2»
3Q2, FY23Q3, FY23Q4, FY24Q1, FY24Q2, FY24Q3, FY24Q4, FY25Q1, FY25Q2, FY25Q3, FY25Q4, FY26Q1, FY26Q2,
FY26Q3, FY26Q4, FY27Q1»
, FY27Q2, FY27Q3, FY27Q4, FY28Q1, FY28Q2, FY28Q3, FY28Q4, FY29Q1, FY29Q2, FY29Q3, FY29Q4, FY30Q1,
FY30Q2, FY30Q3, FY30Q4, F»
Y31Q1, FY31Q2, FY31Q3, FY31Q4/
Immediate(q) /FY20Q1/
C_Model_Funded(q) /FY20Q1,FY20Q2, FY20Q3, FY20Q4, FY21Q1, FY21Q2, FY21Q3, FY21Q4, FY22Q1, FY22Q2,
FY22Q3, FY22Q4, FY2»
3Q1, FY23Q2, FY23Q3, FY23Q4/
C_Model_Funded_Two_Quarters_Short(q) /FY20Q1,FY20Q2,FY20Q3,FY20Q4, FY21Q1, FY21Q2, FY21Q3, FY21Q4,
FY22Q1, FY22Q2, FY2»
2Q3, FY22Q4, FY23Q1/
E_Model_Radar / FY20Q1, FY20Q2, FY20Q3, FY20Q4, FY21Q1, FY21Q2, FY21Q3, FY21Q4, FY22Q1, FY22Q2,
FY22Q3, FY22Q4, FY2»
3Q1, FY23Q2, FY23Q3, FY23Q4, FY24Q1, FY24Q2, FY24Q3, FY24Q4
/
End_Quarter_Gold(q) /FY23Q3/
End_Quarter_Strike(q) /FY30Q4/
Depot(k) 'Depot-Level Mx' /Warner_Robins, USAFE_Depot, Kimhae/
WR(k) /Warner_Robins/
USAFE(k) /USAFE_Depot/
KellyAFB(k) /Kelly/
Lak(k) /Lakenheath/
MH(k) /Mountain_Home/
Nell(k) /Nellis/
SJ(k) /Seymour_Johnson/
Egl(k) /Eglin/
Base_CFTs(k) /Kadena, ANG_E, ANG_W, Lakenheath, Mountain_Home, Nellis, Seymour_Johnson, Eglin/
* Bar(k) /Barnes/
* Fre(k) /Fresno/
Kad(k) /Kadena/
* Jac(k) /Jacksonville/
* Orl(k) /Orleans/
* Por(k) /Portland/
* Kin(k) /Kingsley/
Kim(k) /Kimhae/
ANGEast(k) /ANG_E/
ANGWest(k) /ANG_W/
;
Sets Funded_Fleet(i),Not_Funded_Fleet(i), C_Model_Not_Funded(q), W(i), H(i), X(i), Y(i), nPDM(j),
RR(i), Not_Gold(i), Three»
_PDM(j), Two_PDM(j),WminusXq(q), CandD(i), Three_nonPDM(j), Two_nonPDM(j), nG(i),
nRR(i),notTest(i),Not_PDM_Rd_1_E(q)
need_EPAWSS(i), need_ADCP(i),need_LRP(i), need_MIDS(i), CFT(k), not_ANG(i), not_Barnes(i),
not_Fresno(i), not_Jacksonv»
ille(i), not_Kinglsey(i), not_Orleans(i), not_Portland(i), not_Kadena(i), not_Kimhae(i), not_H(i),
not_Lak(i), not_MH(i), n»
ot_Nell(i), not_Eglin(i),not_SJ(i), not_WR(i), not_USAFE(i), Base_CFTs(k)
not_R(i), ANGE(i), not_ANGE(i), ANGW(i), not_ANGW(i), No_Gold_PDM(i), TAC(k),
PDM_EPAWSS(j),not_PDM_EPAWSS(j),
DyTyQ(j),TyQ(j), PD(j), PT(j), PQ(j)
;
Funded_Fleet(i) =E(i)+G(i);
Not_Funded_Fleet(i)= not Funded_Fleet(i);
C_Model_Not_Funded(q)= not C_Model_Funded(q);
W(i)= E(i)+C(i)+D(i)-Z(i);
H(i)=W(i);
X(i)=L(i);
Y(i)=Z(i);
nPDM(j) = not PDM(j);
RR(i) = E(i)- R(i)-G(i);
not_R(i)= not R(i);
Not_Gold(i) = C(i)+D(i)+E(i)-G(i);
TAC(k)=WR(k)+KellyAFB(k);
DyTyQ(j) = DOS(j)+TRES(j)+QUATRO(j);
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TyQ(j) = TRES(j)+QUATRO(j);
Three_PDM(j) = TyQ(j) - nPDM(j);
DyTyQ(j) = DOS(j)+TRES(j)+QUATRO(j);
TyQ(j) = TRES(j)+QUATRO(j);
Two_PDM(j) = DyTyQ(j)- nPDM(j);
WminusXq(q)= not Xq(q);
*CandD(i) = not E(i);
*nG(i)= CandD(i)- G(i);
nRR(i)= not RR(i)-G(i);
Three_nonPDM(j) = TyQ(j) - PDM(j);
Two_nonPDM(j) = DyTyQ(j)- PDM(j);
PDM_EPAWSS(j) = PDM(j)+EPAWSS(j);
not_PDM_EPAWSS(j) = not PDM_EPAWSS(j);
CandD(i) = not E(i);
notTest(i) = not T(i);
Not_PDM_Rd_1_E(q) = not PDM_Rd_1_E(q);
need_ADCP(i) = E(i)+G(i)-ADCP_Done(i);
need_EPAWSS(i) = E(i)-EPAWSS_Done(i);
need_LRP(i)= G(i)-LRP_Done(i);
*need_MIDS(i)= E(i)+G(i)-MIDS_Done(i);
PD(j)= PDM(j)-(not DOS(j));
PT(j)= PDM(j)-(not TRES(j));
PQ(j)= PDM(j)-(not QUATRO(j));
ANGW(i) = KF(i)+P(i)+F(i);
ANGE(i) = B(i)+Ja(i)+O(i) ;
not_ANGW(i) = not ANGW(i);
not_ANGE(i) = not ANGE(i);
not_ANG(i) = not A(i);
not_Barnes(i) = not B(i);
not_Fresno(i) = not F(i);
not_Jacksonville(i) = not Ja(i);
not_Kinglsey(i) = not KF(i);
not_Orleans(i) = not O(i);
not_Portland(i) = not P(i);
not_Kadena(i) = not Z(i);
not_Kimhae(i) = not Y(i);
not_H(i) = not H(i);
not_Lak(i) = not L(i);
not_MH(i) = not M(i);
not_Nell(i) = not N(i);
not_Eglin(i) = not T(i);
not_SJ(i) = not S(i);
not_WR(i) = not W(i);
not_USAFE(i) = not X(i);
CFT(k) = not Depot(k);
Base_CFTs(k) = CFT(k) -KellyAFB(k);
No_Gold_PDM(i) = G(i) - Gold_Need_PDM(i);
scalar
*Backup Aircraft inventory which can become depot possessed
B A I A N G /16/
B A I A N G E /8/
B A I A N G W /8/
B A I B A R /3/
B A I F R E /3/
B A I K E L /59/
B A I J A C /3/
B A I K L A /5/
B A I L A K /11/
B A I M H /7/
B A I L V /5/
B A I N O /3/
B A I P O R /3/
B A I S J /14/
B A I E G L /2/
B A I W R /59/
B A I E U R /11/
B A I K A L /8/
B A I Z Z /8/
;
;
Parameters lamda(i) 'Sum weighted values of aircraft (Removed from hard copy)'
//
;


Parameter gamma(q) 'exponential weight of quarters with 15 as the halfway point'
```

```
/
FY20Q1 1
FY20Q2 0.992277428
FY20Q3 0.984253053
FY20Q4 0.975915082
FY21Q1 0.967251258
FY21Q2 0.958248848
FY21Q3 0.948894619
FY21Q4 0.939174822
FY22Q1 0.929075169
FY22Q2 0.918580818
FY22Q3 0.907676341
FY22Q4 0.896345712
FY23Q1 0.884572276
FY23Q2 0.872338728
FY23Q3 0.859627087
FY23Q4 0.846418667
FY24Q1 0.832694056
FY24Q2 0.81843308
FY24Q3 0.803614778
FY24Q4 0.788217369
FY25Q1 0.772218221
FY25Q2 0.755593818
FY25Q3 0.738319724
FY25Q4 0.72037055
FY26Q1 0.701719913
FY26Q2 0.682340399
FY26Q3 0.662203523
FY26Q4 0.641279688
FY27Q1 0.619538139
FY27Q2 0.596946919
FY27Q3 0.573472822
FY27Q4 0.549081344
FY28Q1 0.523736636
FY28Q2 0.497401442
FY28Q3 0.470037056
FY28Q4 0.441603255
FY29Q1 0.412058247
FY29Q2 0.381358604
FY29Q3 0.349459203
FY29Q4 0.316313157
FY30Q1 0.281871746
FY30Q2 0.246084346
FY30Q3 0.208898357
FY30Q4 0.170259119
FY31Q1 0.13010984
FY31Q2 0.088391506
FY31Q3 0.045042798
FY31Q4 0.02
/;
Table sched(i,q) 'Scheduled depot induction for each tail (Removed fom Hard Copy)'
;
BINARY Variables
mod(i,j,k,q) 'decision variable'
qPDM(i,q) 'quarter PDM initiated for aircraft i'
qRMP(i,q) 'quarter RMP initiated for aircraft i'
qADCP(i,q) 'quarter ADCP initiated for aircraft i'
qMIDS(i,q) 'quarter MIDS initiated for aircraft i'
qEPAWSS(i,q) 'quarter EPAWSS initiated for aircraft i'
qSLEP(i,q) 'quarter SLEP initiated for aircraft i'
;
variables modscore_qtrs,fullscore_qtrs,
modscore_final,fullscore_final,objval,inductqtrsum,workload,possessed_hours;
Equations
o u t p u t 'objective function'
lamda_full_score (q) 'computes the sum of full with lamda per quarter'
q u a r t e r _ f u l l _ s c o r e 'sums all fulls together across all quuarters'
E_induction(i,q) 'PDM induction quarter for E-Models'
G_induction(i,q) 'PDM induction quarter for G Fleet while still funded'
inductiononce(i,q) 'only one PDM induction'
inductionqtr_Strike(i,q) 'PDM induction does not randomly occur'
inductionqtr_Two(i,q) 'PDM COA of 2 qtrs'
inductionqtr_Three(i,q) 'PDM COA of 3 qtrs'
inductionqtr_Four(i,q) 'PDM COA of 4 qtrs'
inductionqtr_Gold_Funded(i,q) 'PDM for Gold Fleet when funded'
inductionqtr_Gold_Not_Funded(i,q) 'No PDM for Gold Fleet when not funded'
inductionqtr_Not_Funded(i,q) 'No PDM when not funded'
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inductionsum_Strike(i,q) 'PDM sum for Strike'
inductionsum_Gold(i,q) 'PDM sum for Gold Fleet'
nextinductionqtrE(i,q) 'next PDM induction does not randomly occur'
OnlyOneCOA(i,q) 'Only one COA per q'
OceanicWingman(q) 'If an aircraft has to cross the pond, he needs at least one wingman'
OceanicWingmen(q) 'If an aircraft has to cross the pond, no moe than 3 at a time'
Oceanic(q) 'If an aircraft has to cross the pond, he needs some mates'
func_inwk_All_ETIC_4(q)
func_inwk_All_ETIC_3(q)
func_inwk_All_ETIC_2(q)
func_inwk_All_ETIC_1(q)
func_inwk_All_Total(q)
NextQuarterNoCoa(i,j,q)
Threequarters_OneCoa(i,j,q)
Fourquarters_OneCoa(i,j,q)
Not_right_before_PDM (i,q)
Not_two_before_PDM (i,q)
Not_three_before_PDM (i,q)
Not_four_before_PDM (i,q)
Not_one_After_PDM (i,q)
Not_two_After_PDM (i,q)
No_Depot_at_CFTs
NO_CFT_at_Depot
E_models_stay_active(i,q)
ground_Gold_Fleet_not_inducted_before_FY23(i,q)
ground_Gold_Fleet_inducted_before_FY23(i,q)
only_one_ground_date(i)
no_mods_for_gold(i,q)
check_induct(i,q)
;
positive variables
Inwk_All_ETIC_4(q),Inwk_All_ETIC_3(q),Inwk_All_ETIC_2(q),Inwk_All_ETIC_1(q),Inwk_All_Total,
strike_slack»
_qtr, strike_slack;
binary variables inductqtr,inductsum, nextinductqtr,
nextinductqtr_two,nextinductqtr_three,nextinductqtr_four, transatlanti»
c, ground_date;
* Following equations set preporgramming coniditions and PDM induction conditions
No_Depot_at_CFTs.. sum((i,PDM(j),CFT(k),q),mod(i,j,k,q))=e=0;
No_CFT_at_DEPOT.. sum((i,not_PDM_EPAWSS(j),Depot(k),q),mod(i,j,k,q))=e=0;
OnlyOneCOA(i,q) .. sum((j,k), mod(i,j,k,q)) =l=1;
NextQuarterNoCoa(i,DyTyQ(j),q).. sum(k,mod(i,j,k,q)+mod(i,j,k,q+1))=l=1;
Threequarters_OneCoa(i,TyQ(j),q).. sum(k,mod(i,j,k,q)+mod(i,j,k,q+1)+mod(i,j,k,q+2))=l=1;
Fourquarters_OneCoa(i,Quatro(j),q)..
sum(k,mod(i,j,k,q)+mod(i,j,k,q+1)+mod(i,j,k,q+2)+mod(i,j,k,q+3))=l=1;
no_mods_for_gold(G(i),C_Model_Not_Funded(q))..sum((j,k),mod(i,j,k,q))=e=0;
E_induction(E(i),q).. inductsum(i,q)=g= sched(i,q)+nextinductqtr(i,q);
G_induction(Gold_Need_PDM(i),q).. inductsum(i,q)=g= sched(i,q);
E_models_stay_active(E(i),q).. ground_date(i,q)=e= 0;
ground_Gold_Fleet_not_inducted_before_FY23(No_Gold_PDM(i),q).. ground_date(i,q)=e=sched(i,q);
ground_Gold_Fleet_inducted_before_FY23(Gold_Need_PDM(i),q).. ground_date(i,q+26) =e= inductqtr(i,q);
only_one_ground_date(i).. sum(q, ground_date(i,q))=l=1;
Not_right_before_PDM(i,q).. sum((DyTyQ(j),k),mod(i,j,k,q-1))=l=1-inductqtr(i,q);
Not_two_before_PDM(i,q).. sum((DyTyQ(j),k),mod(i,j,k,q-2))=l=1-inductqtr(i,q);
Not_three_before_PDM(i,q).. sum((TyQ(j),k),mod(i,j,k,q-3))=l=1-inductqtr(i,q);
Not_four_before_PDM(i,q).. sum((Quatro(j),k),mod(i,j,k,q-4))=l=1-inductqtr(i,q);
Not_one_After_PDM (i,q).. sum((DyTyQ(j),k),mod(i,j,k,q+3))=l=1-inductqtr(i,q);
Not_two_After_PDM (i,q).. sum((TyQ(j),k),mod(i,j,k,q+4))=l=1-inductqtr(i,q);
inductionsum_Strike(E(i),q).. inductqtr(i,q) + inductqtr(i,q-1) + inductqtr(i,q+1) =e= inductsum(i,q);
inductionsum_Gold(Gold_Need_PDM(i),q).. inductqtr(i,q) + inductqtr(i,q-1) + inductqtr(i,q+1) =e=
inductsum(i,q);
inductiononce(i,q).. inductsum(i,q) =l= 1;
inductionqtr_Strike(E(i),q).. sum((PDM(j),k), mod(i,j,k,q)) =e= inductqtr(i,q);
inductionqtr_Gold_Funded(Gold_Need_PDM(i),q).. sum((PDM(j),k), mod(i,j,k,q)) =e= inductqtr(i,q);
inductionqtr_Gold_Not_Funded(No_Gold_PDM(i),C_Model_Not_Funded(q)).. 0 =e= inductqtr(i,q);
inductionqtr_Not_Funded(Not_Funded_Fleet(i),q).. 0 =e= inductqtr(i,q);
OceanicWingmen(q).. sum((L(i),j,TAC(k)),mod(i,j,k,q))=l= 6;
Oceanic(q).. transatlantic(q) =g= sum((L(i),j,TAC(k)),mod(i,j,k,q))*(1/80);
OceanicWingman(q).. sum((L(i),j,TAC(k)),mod(i,j,k,q))=g= 2*transatlantic(q);
inductionqtr_Two(i,q)..sum((PD(j),k), mod(i,j,k,q)) =e= nextinductqtr_two(i,q);
inductionqtr_Three(i,q)..sum((PT(j),k), mod(i,j,k,q)) =e= nextinductqtr_Three(i,q);
inductionqtr_Four(i,q)..sum((PQ(j),k), mod(i,j,k,q)) =e= nextinductqtr_Four(i,q);
check_induct(i,q).. nextinductqtr_two(i,q)+nextinductqtr_Three(i,q)+nextinductqtr_Four(i,q) =l=1;
nextinductionqtrE(E(i),PDM_Rd_1_E(q)).. nextinductqtr(i,q+32) =e= inductqtr(i,q);
func_inwk_All_ETIC_4(q).. sum((i,Quatro(j),k), mod(i,j,k,q-3)) =e= Inwk_All_ETIC_4(q);
func_inwk_All_ETIC_3(q).. sum((i,TyQ(j),k), mod(i,j,k,q-2)) =e= Inwk_All_ETIC_3(q);
func_inwk_All_ETIC_2(q).. sum((i,DyTyQ(j),k), mod(i,j,k,q-1)) =e= Inwk_All_ETIC_2(q);
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func_inwk_All_ETIC_1(q).. sum((i,j,k),mod(i,j,k,q)) =e= Inwk_All_ETIC_1(q);
func_inwk_All_Total(q)..
Inwk_All_ETIC_4(q)+Inwk_All_ETIC_3(q)+Inwk_All_ETIC_2(q)+Inwk_All_ETIC_1(q)=e= Inwk_All_Total(»
q);
*Modifications
equations
modificationP(i,q) 'PDM execution per aircraft'
modificationR(i,q) 'RMP execution per aircraft'
modificationA(i,q) 'ADCP execution per aircraft'
modificationL(i,q) 'SLEP execution per aircraft'
modificationE(i,q) 'EPAWSS execution per aircraft'
modificationP_Strike_2_q(i)'PDM execution per Strike aircraft that will go through 2 PDM cycles'
modificationP_Strike_1_q(i)'PDM execution per Strike aircraft that will go through 1 PDM cycles'
modificationP_Gold_q(i) 'PDM execution per Gold Fleet aircraft that will go through 1 PDM cycles'
modificationRq(i) 'RMP execution per aircraft quarter'
modification_E_Aq(i) 'ADCP execution per Strike aircraft quarter'
modification_G_AqFunded(i) 'ADCP execution per Gold aircraft quarter'
modification_G_AqNotFunded(i) 'ADCP execution per Gold aircraft not funded'
modificationLq(i) 'SLEP execution per aircraft quarter'
modificationEq(i) 'EPAWSS execution per aircraft quarter'
modification_RMP_Done(i,j,k,q) 'Never do RMP on an already done aircraft'
modification_ADCP_Done(i,j,k,q) 'Never do ADCP on an already done aircraft'
modification_EPAWSS_Done(i,j,k,q) 'Never do EPAWSS on an already done aircraft'
modification_LRP_Done(i,j,k,q) 'Never do LRP on an already done aircraft'
modificationLq_not_funded(i)
modification_LRP_E(i,j,k,q) 'No LRP on Strike'
Req_LRP_Level
;
modificationP(i,q) .. sum((PDM(j),k), mod(i,j,k,q)) =e= qPDM(i,q);
modificationR(RR(i),q).. sum((RMP(j),k), mod(i,j,k,q))=e= qRMP(i,q);
Req_LRP_Level.. sum((RR(i),E_Model_Radar(q)), qRMP(i,q))=g=Number_LRP_Mandatory;
modification_RMP_Done(R(i),RMP(j),k,q).. mod(i,j,k,q)=e= 0;
modificationA(need_ADCP(i),q) .. sum((ADCP(j),k), mod(i,j,k,q))=e= qADCP(i,q);
modification_ADCP_Done(ADCP_Done(i),ADCP(j),k,q).. mod(i,j,k,q)=e= 0;
modificationE(need_EPAWSS(i),q) .. sum((EPAWSS(j),k), mod(i,j,k,q))=e=qEPAWSS(i,q);
modification_EPAWSS_Done(EPAWSS_Done(i),EPAWSS(j),k,q).. mod(i,j,k,q)=e= 0;
*SLEP for Golden Fleet;
modificationL(G(i),C_Model_Funded(q)) .. sum((LRP(j),k), mod(i,j,k,q))=e= qSLEP(i,q);
modification_LRP_Done(LRP_Done(i),LRP(j),k,q).. mod(i,j,k,q)=e= 0;
modification_LRP_E(E(i),LRP(j),k,q).. mod(i,j,k,q)=e= 0;
modificationP_Strike_2_q(E(i)) .. sum(PDM_Rd_1_E(q), qPDM(i,q)) =l= 2;
modificationP_Strike_1_q(E(i)) .. sum(Not_PDM_Rd_1_E(q), qPDM(i,q)) =e= 1;
modificationP_Gold_q(Gold_Need_PDM(i)) .. sum(q, qPDM(i,q)) =e= 1;
modificationP_not_Gold_q(Not_Funded_Fleet(i)) .. sum(q, qPDM(i,q)) =e= 0;
modificationRq(RR(i)).. sum(q, qRMP(i,q))=e= 1;
modification_E_Aq(E(i)) .. sum(q, qADCP(i,q))=e= 1;
modification_G_AqFunded(G(i)) .. sum(C_Model_Funded(q), qADCP(i,q))=l= 1;
modification_G_AqNotFunded(G(i)) .. sum(C_Model_Not_Funded(q), qADCP(i,q))=e= 0;
modificationEq(E(i)).. sum(q, qEPAWSS(i,q))=e=1;
modificationLq(G(i)) .. sum(C_Model_Funded(q), qSLEP(i,q))=l= 1;
modificationLq_not_funded(G(i)) .. sum(C_Model_not_Funded(q), qSLEP(i,q))=e= 0;
*RAAs Levels taken from Hard Copy
Parameter RRARMP(q) 'procured RMP kits per quarter from PEMS table'
/
/;
Parameter RRAADCP(q) 'procured RMP kits per quarter from PEMS table'
/
/;
Parameter RRAMIDS(q) 'procured RMP kits per quarter from PEMS table'
/
/;
Parameter RRASLEP(q) 'procured RMP kits per quarter from PEMS table'
/
/;
Parameter RRAEPAWSS(q) 'procured RMP kits per quarter from PEMS table'
/
/;
Integer variable onhandRMP,onhandADCP,onhandMIDS,onhandSLEP,onhandEPAWSS
consumedRMP,consumedADCP,consumedMIDS,consumedSLEP,consumedEPAWSS
slackRMP_qtr,slackADCP_qtr,slackMIDS_qtr,slackSLEP_qtr,slackEPAWSS_qtr
slackRMP_total,slackADCP_total,slackMIDS_total,slackSLEP_total,slackEPAWSS_total
slack_kits_total;
equations
*
kitsRMP(q) 'consumed RMP kits'
kitsRMPsum(q) 'constraint on RMP kits'
kitsADCP(q) 'consumed ADCP kits'
```

```
kitsADCPsum(q) 'constraint on ADCP kits'
kitsMIDS(q) 'consumed MIDS kits'
kitsMIDSsum(q) 'constraint on MIDS kits'
kitsSLEP(q) 'consumed SLEP kits'
kitsSLEPsum(q) 'constraint on SLEP kits'
kitsEPAWSS(q) 'consumed EPAWSS kits'
kitsEPAWSSsum(q) 'constraint on EPAWSS kits'
slackRMP_control(q) 'control to not go overboard on kits available'
slackADCP_control(q) 'control to not go overboard on kits available'
slackMIDS_control(q) 'control to not go overboard on kits available'
slackSLEP_control(q) 'control to not go overboard on kits available'
slackEPAWSS_control(q) 'control to not go overboard on kits available'
s l a c k R M P _ s u m _ t o t a l 'total RMP Slack'
s l a c k A D C P _ s u m _ t o t a l 'total ADCP Slack'
s l a c k M I D S _ s u m _ t o t a l 'total MIDS Slack'
s l a c k S L E P _ s u m _ t o t a l 'total SLEP Slack'
s l a c k E P A W S S _ s u m _ t o t a l 'total EPAWSS Slack'
slack_kits_sum_total
;
*
**On-Hand Kits
*
kitsRMPsum(q).. consumedRMP(q)+onhandRMP(q)=l=RRARMP(q)+onhandRMP(q-1)+slackRMP_qtr(q);
kitsRMP(q).. sum(i,qRMP(i,q))=e=consumedRMP(q);
kitsADCPsum(q).. consumedADCP(q)+onhandADCP(q)=l=RRAADCP(q)+onhandADCP(q-1)+slackADCP_qtr(q);
kitsADCP(q).. sum(i,qADCP(i,q))=e=consumedADCP(q);
kitsMIDSsum(q).. consumedMIDS(q)+onhandMIDS(q)=l=RRAMIDS(q)+onhandMIDS(q-1)+slackMIDS_qtr(q);
kitsMIDS(q).. sum(i,qMIDS(i,q))=e=consumedMIDS(q);
kitsSLEPsum(q).. consumedSLEP(q)+onhandSLEP(q)=l=RRASLEP(q)+onhandSLEP(q-1)+slackSLEP_qtr(q);
kitsSLEP(q).. sum(i,qSLEP(i,q))=e=consumedSLEP(q);
kitsEPAWSSsum(q).. consumedEPAWSS(q)+onhandEPAWSS(q)=l=RRAEPAWSS(q)+onhandEPAWSS(q-
1)+slackEPAWSS_qtr(q);
kitsEPAWSS(q).. sum(i,qEPAWSS(i,q))=e=consumedEPAWSS(q);
slackRMP_control(q).. slackRMP_qtr(q)=l=RRARMP(q)*kit_proportional_increase;
slackADCP_control(q).. slackADCP_qtr(q)=l=RRAADCP(q)*kit_proportional_increase;
slackMIDS_control(q).. slackMIDS_qtr(q)=l=onhandMIDS(q-1)*kit_proportional_increase;
slackSLEP_control(q).. slackSLEP_qtr(q)=l=onhandSLEP(q-1)*kit_proportional_increase;
slackEPAWSS_control(q).. slackEPAWSS_qtr(q)=l=RRAEPAWSS(q)*kit_proportional_increase;
slackRMP_sum_total.. sum(q, slackRMP_qtr(q))=e=slackRMP_total;
slackADCP_sum_total.. sum(q, slackADCP_qtr(q))=e=slackADCP_total;
slackMIDS_sum_total.. sum(q, slackMIDS_qtr(q))=e=slackMIDS_total;
slackSLEP_sum_total.. sum(q, slackSLEP_qtr(q))=e=slackSLEP_total;
slackEPAWSS_sum_total.. sum(q, slackEPAWSS_qtr(q))=e=slackEPAWSS_total;
slack_kits_sum_total.. slack_kits_total=e=
slackRMP_total+slackADCP_total+slackEPAWSS_total+slackSLEP_total;
*Values removed from Hard Copy
Table Capacity(k,q) 'Capacity of each Location'
;
Table Required(k,q) 'Capacity of each Location'
;
Integer Variables
*Work Variables
Inwk_Location_k_ETIC_4(k,q),Inwk_Location_k_ETIC_3(k,q),Inwk_Location_k_ETIC_2(k,q),Inwk_Location_k_ET
IC_1(k,q),Inwk_Locati»
on_k_Total(k,q),
Inwk_Base_i_ETIC_4(i,q),Inwk_Base_i_ETIC_3(i,q),Inwk_Base_i_ETIC_2(i,q),Inwk_Base_i_ETIC_1(i,q),Inwk_B
ase_i_Total(i,q)
*Slack variables
slack_k_cap, slack_k_req, slack_AoA_All, slack_AoA_Barnes, slack_AoA_Eglin, slack_AoA_Fresno,
slack_AoA_Kadena, slack_AoA_K»
inglsey,
slack_AoA_Jacksonville, slack_AoA_Lakenheath, slack_AoA_MountainHome, slack_AoA_Nellis,
slack_AoA_Orleans, slack_AoA_Portla»
nd, slack_AoA_SJ
;
binary variables
active(k,q)
;
equations
func_Inwk_Location_k_ETIC_4(k,q) 'In work for 4 quarters'
func_Inwk_Location_k_ETIC_3(k,q) 'In work for 3 quarters'
func_Inwk_Location_k_ETIC_2(k,q) 'In work for at least 2 quarters'
func_Inwk_Location_k_ETIC_1(k,q) 'In work for at least 1 quarter'
func_Inwk_Location_k_Total(k,q) 'Total at work at a location k during a quarter'
func_Inwk_Base_i_ETIC_4(i,q) 'In work for 3 quarters'
func_Inwk_Base_i_ETIC_3(i,q) 'In work for 3 quarters'
func_Inwk_Base_i_ETIC_2(i,q) 'In work for at least 2 quarters'
```

```
func_Inwk_Base_i_ETIC_1(i,q) 'In work for at least 1 quarter'
func_Inwk_Base_i_Total(i,q) 'Total at work at a location k during a quarter'
Location_k_Capacity_(k,q) 'Workload max at location k in a given quarter'
Location_k_Contract_(k,q) 'Workload min at location k in a given quarter'
Location_k_slack_cap_control(k,q) 'control to slack capacity at location k in a given quarter'
Location_k_slack_req_control(k,q) 'control to slack requirement at location k in a given quarter'
Base_Barnes_AoA(q)
Base_Eglin_AoA(q)
Base_Fresno_AoA(q)
Base_Jacksonville_AoA(q)
Base_Kadena_AoA(q)
Base_Kingsley_AoA(q)
Base_Lakenheath_AoA(q)
Base_MountainHome_AoA(q)
Base_Nellis_AoA(q)
Base_Orleans_AoA(q)
Base_Portland_AoA(q)
Base_SeymourJohnson_AoA(q)
Qtr_AoA_Slack(q)
Warner_Robins_Active(k,q)
Kelly_Active(k,q)
Max_CFTs_Fundable(q)
Kelly_Capable(i,k)
Lak_Capable(i,k)
MH_Capable(i,k)
Nellis_Capable(i,k)
SJ_Capable(i,k)
Eglin_Capable(i,k)
WR_Capable(i,k)
USAFE_Capable (i,k)
ANGE_Capable(i,k)
ANGW_Capable(i,k)
Kimhae_Capable(i,k)
Kadena_Capable (i,k)
USAFE_Depot_Not_Active_PreProcessing(k,q)
USAFE_Depot_WR_PreProcessing(k,q)
USAFE_Depot_Active_PreProcessing(k,q)
;
*In work at a specific location (k)
func_Inwk_Location_k_ETIC_4(k,q).. sum((i,Quatro(j)), mod(i,j,k,q-3)) =e= Inwk_Location_k_ETIC_4(k,q);
func_Inwk_Location_k_ETIC_3(k,q).. sum((i,TyQ(j)), mod(i,j,k,q-2)) =e= Inwk_Location_k_ETIC_3(k,q);
func_Inwk_Location_k_ETIC_2(k,q).. sum((i,DyTyQ(j)), mod(i,j,k,q-1)) =e= Inwk_Location_k_ETIC_2(k,q);
func_Inwk_Location_k_ETIC_1(k,q).. sum((i,j), mod(i,j,k,q)) =e= Inwk_Location_k_ETIC_1(k,q);
func_Inwk_Location_k_Total(k,q)..
Inwk_Location_k_ETIC_4(k,q)+Inwk_Location_k_ETIC_3(k,q)+Inwk_Location_k_ETIC_2(k,q)+I»
nwk_Location_k_ETIC_1(k,q)=e= Inwk_Location_k_Total(k,q);
func_Inwk_Base_i_ETIC_4(i,q).. sum((k,Quatro(j)), mod(i,j,k,q-3)) =e= Inwk_Base_i_ETIC_4(i,q);
func_Inwk_Base_i_ETIC_3(i,q).. sum((k,TyQ(j)), mod(i,j,k,q-2)) =e= Inwk_Base_i_ETIC_3(i,q);
func_Inwk_Base_i_ETIC_2(i,q).. sum((k,DyTyQ(j)), mod(i,j,k,q-1)) =e= Inwk_Base_i_ETIC_2(i,q);
func_Inwk_Base_i_ETIC_1(i,q).. sum((k,j), mod(i,j,k,q)) =e= Inwk_Base_i_ETIC_1(i,q);
func_Inwk_Base_i_Total(i,q)..
Inwk_Base_i_ETIC_4(i,q)+Inwk_Base_i_ETIC_3(i,q)+Inwk_Base_i_ETIC_2(i,q)+Inwk_Base_i_ETIC_»
1(i,q)=e= Inwk_Base_i_Total(i,q);
Location_k_Capacity_(k,q).. Inwk_Location_k_Total(k,q)=l=Capacity(k,q)*active(k,q)+slack_k_cap(k,q);
Location_k_Contract_(k,q).. Inwk_Location_k_Total(k,q)=g=Required(k,q)*active(k,q)-slack_k_req(k,q);
Location_k_slack_cap_control(k,q)..
slack_k_cap(k,q)=l=Capacity(k,q)*active(k,q)*proportional_increase;
Location_k_slack_req_control(k,q)..
slack_k_req(k,q)=l=Required(k,q)*active(k,q)*proportional_increase;
Base_Barnes_AoA(q).. sum(B(i),Inwk_Base_i_Total(i,q))=l= BAI_BAR+slack_AoA_Barnes(q);
Base_Eglin_AoA(q).. sum(T(i),Inwk_Base_i_Total(i,q))=l= BAI_EGL+slack_AoA_Eglin(q);
Base_Fresno_AoA(q).. sum(F(i),Inwk_Base_i_Total(i,q))=l= BAI_FRE+slack_AoA_Fresno(q);
Base_Jacksonville_AoA(q).. sum(Ja(i),Inwk_Base_i_Total(i,q))=l= BAI_JAC+slack_AoA_Jacksonville(q);
Base_Kadena_AoA(q).. sum(Z(i),Inwk_Base_i_Total(i,q))=l= BAI_ZZ+slack_AoA_Kadena(q);
Base_Kingsley_AoA(q).. sum(KF(i),Inwk_Base_i_Total(i,q))=l= BAI_KLA+slack_AoA_Kinglsey(q);
Base_Lakenheath_AoA(q).. sum(L(i),Inwk_Base_i_Total(i,q))=l= BAI_LAK+slack_AoA_Lakenheath(q);
Base_MountainHome_AoA(q).. sum(M(i),Inwk_Base_i_Total(i,q))=l= BAI_MH+slack_AoA_MountainHome(q);
Base_Nellis_AoA(q).. sum(N(i),Inwk_Base_i_Total(i,q))=l= BAI_LV+slack_AoA_Nellis(q);
Base_Orleans_AoA(q).. sum(O(i),Inwk_Base_i_Total(i,q))=l= BAI_NO+slack_AoA_Orleans(q);
Base_Portland_AoA(q).. sum(P(i),Inwk_Base_i_Total(i,q))=l= BAI_POR+slack_AoA_Portland(q);
Base_SeymourJohnson_AoA(q).. sum(S(i),Inwk_Base_i_Total(i,q))=l= BAI_SJ+slack_AoA_SJ(q);
Qtr_AoA_Slack(q).. slack_AoA_All(q)=e=slack_AoA_Barnes(q)+ slack_AoA_Eglin(q)+ slack_AoA_Fresno(q)+
slack_AoA_Kadena(q)»
+ slack_AoA_Kinglsey(q)+ slack_AoA_Jacksonville(q)+
slack_AoA_Lakenheath(q)+ slack_AoA_MountainHome(q)+ slack_AoA_Nellis(q)+ slack_Ao»
A_Orleans(q)+ slack_AoA_Portland(q)+ slack_AoA_SJ(q);
Warner_Robins_Active(WR(k),q).. active(k,q)=e=1;
```

```
Kelly_Active(KellyAFB(k),q).. active(k,q)=e=1;
USAFE_Depot_Not_Active_PreProcessing(USAFE(k),WminusXq(q)).. active(k,q)=e=0;
USAFE_Depot_Active_PreProcessing(USAFE(k),Xq(q)).. active(k,q)=e=1*GreenLightUSAFE;
USAFE_Depot_WR_PreProcessing(WR(k),Xq(q)).. sum((L(i),j),mod(i,j,k,q))=e=0;
Max_CFTs_Fundable(q).. sum(Base_CFTs(k),active(k,q))=l= A_CFTmax;
Kelly_Capable(not_H(i),KellyAFB(k)).. sum((j,q), mod(i,j,k,q))=e=0;
Lak_Capable(not_Lak(i),Lak(k)).. sum((j,q), mod(i,j,k,q))=e=0;
MH_Capable(not_MH(i),MH(k)).. sum((j,q), mod(i,j,k,q))=e=0;
Nellis_Capable(not_Nell(i),Nell(k)).. sum((j,q), mod(i,j,k,q))=e=0;
SJ_Capable(not_SJ(i),SJ(k)).. sum((j,q), mod(i,j,k,q))=e=0;
Eglin_Capable(not_Eglin(i),Egl(k)).. sum((j,q), mod(i,j,k,q))=e=0;
WR_Capable(not_WR(i),WR(k)).. sum((j,q), mod(i,j,k,q))=e=0;
USAFE_Capable (not_USAFE(i),USAFE(k)).. sum((j,q), mod(i,j,k,q))=e=0;
ANGE_Capable(not_ANGE(i),ANGEast(k)).. sum((j,q), mod(i,j,k,q))=e=0;
ANGW_Capable(not_ANGE(i),ANGWest(k)).. sum((j,q), mod(i,j,k,q))=e=0;
Kadena_Capable(not_Kadena(i),Kad(k)).. sum((j,q), mod(i,j,k,q))=e=0;
Kimhae_Capable(not_Kadena(i),Kim(k)).. sum((j,q), mod(i,j,k,q))=e=0;
binary variables
var_fullup_ALL_RMP_required
var_fullup_ALL_RMP_NOT_required
v a r _ f u l l u p _ A L L _ L R P _ r e q u i r e d 'Fullup All Mods SLEP req'
var_fullup_ALL_SLEP_Not_required
creditRMP(i,q) 'modified aircraft'
creditADCP(i,q) 'modified aircraft'
creditMIDS(i,q) 'modified aircraft'
creditEPAWSS(i,q) 'modified aircraft'
creditLRP(i,q) 'modified aircraft'
qDownforSLEP(i,q)
full;
**Fully-modified RMP required
equations
function_fullup_ALL_RMP_required(i,q) 'Fullup All Mods RMP req'
function_fullup_ALL_RMP_Not_required(i,q) 'Fullup All Mods RMP req'
function_fullup_ALL_LRP_required(i,q) 'Fullup All Mods SLEP req'
creditR(i,q) 'credit for RMP execution per aircraft'
creditA(i,q) 'ADCP execution per aircraft'
creditL(i,q) 'SLEP execution per aircraft'
creditE(i,q) 'EPAWSS execution per aircraft'
force_mods_ALL_RMP_required(i)
force_mods_ALL_RMP_NOT_required(i)
prohibit_mods_ALL_RMP_required(i)
prohibit_mods_ALL_RMP_NOT_required(i)
prohibit_mods_ALL_LRP_required(i)
EPAWSS_Done_Credit(i,q)
ADCP_Done_Credit(i,q)
RMP_Done_Credit(i,q)
LRP_Done_Credit(i,q)
required_Gold_Fleet_Modified(q)
required_Strike_Fleet_Modified(q)
;
EPAWSS_Done_Credit(EPAWSS_Done(i),q).. creditEPAWSS(i,q)=e=1;
ADCP_Done_Credit(ADCP_Done(i),q).. creditADCP(i,q)=e=1;
RMP_Done_Credit(R(i),q).. creditRMP(i,q)=e=1;
LRP_Done_Credit(LRP_Done(i),q).. creditLRP(i,q)=e=1;
creditR(RR(i),q).. creditRMP(i,q)=l= qRMP(i,q)+creditRMP(i,q-1);
creditA(need_ADCP(i),q).. creditADCP(i,q)=l= qADCP(i,q)+creditADCP(i,q-1);
creditE(need_EPAWSS(i),q).. creditEPAWSS(i,q)=l= qEPAWSS(i,q)+creditEPAWSS(i,q-1);
creditL(need_LRP(i),q).. creditLRP(i,q)=l= qSLEP(i,q)+creditLRP(i,q-1);
function_fullup_ALL_RMP_required(RR(i),q)..
3*var_fullup_ALL_RMP_required(i,q)=l=creditRMP(i,q)+creditADCP(i,q)+cred»
itEPAWSS(i,q);
force_mods_ALL_RMP_required(RR(i)).. sum(q, var_fullup_ALL_RMP_required(i,q))=g=1;
prohibit_mods_ALL_RMP_required(nRR(i))..sum(q, var_fullup_ALL_RMP_required(i,q))=e=0;
**Fully-modified RMP Not required
function_fullup_ALL_RMP_Not_required(R(i),q)..
creditADCP(i,q)+creditEPAWSS(i,q)=g=2*var_fullup_ALL_RMP_NOT_required(»
i,q);
force_mods_ALL_RMP_Not_required(R(i)).. sum(q, var_fullup_ALL_RMP_NOT_required(i,q))=g=1;
prohibit_mods_ALL_RMP_Not_required(not_R(i))..sum(q, var_fullup_ALL_RMP_NOT_required(i,q))=e=0;
**Fully-modified SLEP Required for Golden Fleet
function_fullup_ALL_LRP_required(G(i),q)..
creditADCP(i,q)+creditLRP(i,q)=g=2*var_fullup_ALL_LRP_required(i,q);
prohibit_mods_ALL_LRP_required(not_Gold(i)).. sum(q, var_fullup_ALL_LRP_required(i,q))=e=0;
Integer variable
sum_total_cap_slack, sum_total_req_slack, sum_total_AoA_slack,sum_qtr_cap_slack, sum_qtr_req_slack,
sum_qtr_AoA_sla»
ck,
```

```
fully_complied_strike,fully_complied_gold,Total_Hours,
Events_QTRs_Four,Events_QTRs_Three,Events_QTRs_Two,Events_QT»
Rs_One,Events_QTRs_Total;
Equations
Full_Up(i,q)
Sum_Full_Strikes(q) 'full up credit for each aircraft compound into a single variable'
Sum_Full_Gold(q)
qtr_cap_slack(q)
qtr_req_slack(q)
* qtr_AoA_slack(q)
sum_cap_slack
sum_req_slack
sum_AoA_slack
inwork_total_score
inwork_total_hours
Four_quarter_work
Three_quarter_work
Two_quarter_work
One_quarter_work
Total_work_Quarters
Total_work_hours
**
;
Four_quarter_work.. sum((i,Quatro(j),k,q),mod(i,j,k,q))=e=Events_QTRs_Four;
Three_quarter_work.. sum((i,Tres(j),k,q),mod(i,j,k,q))=e=Events_QTRs_Three;
Two_quarter_work.. sum((i,Dos(j),k,q),mod(i,j,k,q))=e=Events_QTRs_Two;
One_quarter_work.. sum((i,Uno(j),k,q),mod(i,j,k,q))=e=Events_QTRs_One;
Total_work_Quarters.. 4*Events_QTRs_Four+3*Events_QTRs_Three+2*Events_QTRs_Two+Events_QTRs_One=e=
Events_QTRs_Total»
;
Total_work_hours..Events_QTRs_Total*91.25*24=e=Total_Hours;
qtr_cap_slack(q).. sum(k,slack_k_cap(k,q))=e=sum_qtr_cap_slack(q);
qtr_req_slack(q).. sum(k,slack_k_req(k,q))=e=sum_qtr_req_slack(q);
* qtr_AoA_slack(q).. sum(k,slack_k_AoA(k,q))=e=sum_qtr_AoA_slack(q);
*
sum_req_slack.. sum(q,sum_qtr_req_slack(q))=e=sum_total_req_slack;
sum_cap_slack.. sum(q,sum_qtr_cap_slack(q))=l=sum_total_cap_slack;
***
sum_AoA_slack.. sum(q,slack_AoA_All(q))=e=sum_total_AoA_slack;
Full_Up(i,q).. var_fullup_ALL_RMP_required(i,q) +
var_fullup_ALL_RMP_Not_required(i,q)+var_fullup_ALL_LRP_required(»
i,q)=e= full(i,q);
Sum_Full_Strikes(q).. sum(E(i), full(i,q))=e= fully_complied_strike(q);
Sum_Full_Gold(q).. sum(G(i), full(i,q))=e= fully_complied_gold(q);
required_Gold_Fleet_Modified(End_Quarter_Gold(q)).. sum(G(i),full(i,q))=g= A_Gold_Fleet_Full;
required_Strike_Fleet_Modified(End_Quarter_Strike(q)).. sum(E(i),full(i,q))=g= A_Strike_Fleet_Full;
*output.. objval =e= -weightmod*modscore_final + weightfull*fullscore_final-sum_total_req_slack-
sum_total_AoA_slack-Capac»
ity_Penalty*sum_total_cap_slack-slack_kits_total-strike_slack;
output.. objval =e= -A_weight_workload*Events_QTRs_Total + A_weight_expedite*fullscore_final-
sum_total_req_slack-sum_tota»
l_AoA_slack-Capacity_Penalty*sum_total_cap_slack-slack_kits_total-strike_slack;
*Score calculations
*lamda_mod_score (q).. sum((i,j,k), lamda(i)*mod(i,j,k,q)) =e= modscore_qtrs(q);
lamda_mod_score (q).. sum((i,j,k), mod(i,j,k,q)) =e= modscore_qtrs(q);
lamda_full_score (q).. sum(i, lamda(i)*full(i,q)) =e= fullscore_qtrs(q);
inwork_total_score.. sum(q, Inwk_All_Total(q)/31)=e=workload;
inwork_total_hours.. sum(q, 91.25*24*Inwk_All_Total(q))=e=possessed_hours;
*quarter_mod_score.. sum(q,gamma(q)* modscore_qtrs(q))=e= modscore_final;
quarter_mod_score.. sum(q,modscore_qtrs(q))=e= modscore_final;
quarter_full_score.. sum(q, gamma(q)*fullscore_qtrs(q))=e= fullscore_final;
option intvarup=0;
option reslim = 5000;
option iterlim = 2147483647;
Model MSIP /all/;
Solve MSIP using MIP maximizing objval;
```

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DANAHER, RICHARD S., MAJOR, USAF

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Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
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14. ABSTRACT
The F-15 weapons system is vital to the Air Force's efforts to obtain air supremacy during conflict. Originally produced almost 50 years ago, technological advancement through systems modifications is necessary to ensure the Eagle's lethality and survivability against next-generation adversarial threats. The F-15 Systems Program Office faces challenges to plan aircraft inductions for five fleet modernization programs. Optimal induction schedules are developed using binary-integer linear programming models. Diverse constraints such as manpower, equipment, modification kit availability, minimum operational flight levels, and integration of scheduled depot maintenance reveal that no feasible schedule exists. Two competing objectives representing the value of fully modernized airframes and the additional workload associated with modifications are explored using the weighted sums method. To enable model solvability, penalties are associated with constraint relaxations with an aggregate penalty term is incorporated into the objective function. Implementing value focused decision analysis techniques, a fleet hierarchy is establishes aircraft precedence for instances having scarce resources shared amongst multiple fighter jets. Sensitivity analysis is employed to examine impacts of various operationally realistic future scenarios.

15. SUBJECT TERMS
Optimization, scheduling, F-15 modernization, aircraft maintenance, depot maintenance, job sequence, decision analysis, weighted sums, goal programming, cost benefit analysis, program management

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