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Forecasting the Demand of the F414-GE-400 Engine at NAS Lemoore

16 December 2008

by

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Abstract

The purpose of this research is to forecast the repair demand of the F414-GE-400 aircraft engine and determine if the Fleet Readiness Center (FRC) West, located at Naval Air Station (NAS) Lemoore, will be able to meet increased demand in the near future. Our methodology was to collect current history of intermediate-level repair of the F414-GE-400 and estimate its increase based on the arrival of additional engines procured by the Navy. The objective of this research is to build an optimization model to determine if present manning levels are adequate to perform the forecasted demand for engine repair. The result of our analysis provides decision-makers with information regarding the best alternatives to meet increased demand.

Keywords: Fleet Readiness Center (FRC), Forecast, F414-GE-400, F414 engine, F/A-18E/F/G aircraft, Super Hornet, Supply Chain Management (SCM), Optimization

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List of Abbreviations and Acronyms

AB	Afterburner
AD	Aviation Machinist's Mate
AIMD	Aircraft Intermediate Maintenance Department
AWP	Awaiting Parts
BAH	Basic Allowance for Housing
BCM	Beyond Capable Maintenance
CDI	Collateral Duty Inspector
CNO	Chief of Naval Operations
CONUS	Continental United States
COMNAVAIRFOR	Commander Naval Air Forces
DoN	Department of the Navy
EOT	Engine Operating Time
FICA	Federal Insurance Contributions Act
FRC	Fleet Readiness Center
FY	Fiscal Year
LUI	Life-used Indices
LPT	Low-power Turbine
GE	General Electric
HPC	High-pressure Compressor
HPT	High-pressure Turbine
IECAMS	In-flight Engine and Conditioning and Monitoring System
IMA	Intermediate Maintenance Activity
MO	Maintenance Officer
MRP	Material Resource Planning
MTBF	Mean Time between Failure
MTSR	Mean Time since Repair
NADEP	Navy Depot (Maintenance Level or Station)
NAMP	Naval Aviation Maintenance Procedures
NAE	Naval Aircraft Enterprise

NAS	Naval Air Station
NAVAIR	Naval Air Systems Command
NMCS	Non-mission Capable Status
NRFI	Non-ready for Issue
OCONUS	Outside Continental United States
PMA-265	Program Manager-Air Super Hornet, Hornet and Growler
PMCS	Partial Mission Capable Status
RFI	Ready for Issue
PRG	Propulsion Readiness Goal
RPA	Retired Pay Accrual
SAME	Similar to Automated Maintenance Environment
SCM	Supply Chain Management
SRC	Scheduled Removal Components
TAT	Turnaround Time
TRR	Time to Reliably Replenish
QA	Quality Assurance
QAO	Quality Assurance Officer
QAR	Quality Assurance Representative
VEN	Variable Exhaust Nozzles

I. Introduction

A. Background

The F414-GE-400 engine is the power plant used to push the F/A-18E/F Super Hornets and the E/A-18G Growler through the sky. The Navy's inventory level, as of July 2008, for the three types of aircraft is 351. Each aircraft requires two engines, equating to 702 engines (spares not included). The Growler is the replacement for the aging fleet of E/A-6B Prowlers. The Department of the Navy (DoN) plans to purchase 49 additional Growlers through fiscal year 2009 (DoN, 2008) and home base them in Whidbey Island, WA, adding 98 additional engines to the total inventory. The F414-GE-400 engine is modular in design, which eases the maintenance effort and cycle time.

Demand for intermediate, maintenance-level repair of the F414-GE-400 will increase as the Navy procures more Super Hornets and Growlers to replace aging aircraft. The Navy will need to purchase additional Super Hornets due to a gap between Hornet retirement and F-35 Joint Strike Fighter (JSF) squadrons standing up.

Carrier-based Aircraft Intermediate Maintenance Departments (AIMD) repair damaged or high-time[1] engines during deployments. In most other cases, when an engine is removed from an aircraft for its next level of maintenance, it is shipped to Fleet Readiness Center West (FRC West, located at NAS Lemoore, CA) for repair. FRC West inspects engine modules and removes those in need of repair and ships the module(s) to FRC Southeast (located at NAS Jacksonville, FL). FRC Southeast's depot facility repairs the individual modules.

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[1] High-time occurs when a part reaches an inspection point or life-limit.

The goal of FRC West is to support the fleet's demand of F414-GE-400 engines and its activity in Bahrain, Japan; El Centro, CA; China Lake, CA; Point Mugu, CA; Fallon, NV; Oceana, VA; Patuxent River, MD; and Key West, FL. To maintain this support, FRC West keeps a pool of modules referred to as the "Module Super Market." Figure 1 provides a visual image of the engine discussed in this report.

Figure 1. F414-GE-400 Aircraft Engine
(Volvo Aero, 2008)

B. Research Objectives

The objective of this report is to analyze current historical data to determine a forecasting model that accurately predicts engine demand. We assess the proper capacity level for the Power Plant division, F414-GE-400 engine repair work center in FRC West based on forecasted engine demand. Through research and analysis, we provide decision-makers with essential information that will improve F/A-18E/F and EA-18G readiness.

C. Research Questions

Our research attempts to answer one primary question: Is the current capacity of FRC West's Power Plants Division adequate to meet forecasted engine repair demand? To assist in answering this primary question, we assess:

- Current engine repair demand,

- The forecasting method currently used to estimate engine demand, and
- The impact of Super Hornet and Growler engine procurement in the system if demand is not properly forecasted.

D. Methodology

Our research approach for this project is comprised of detailed literature reviews, interviews and data analysis. We also conducted a literature review of forecasting models found in supply chain management (SCM) theories in academic books, professional journals and websites. Additionally, we revisited maintenance procedures outlined in the Naval Aviation Maintenance Program (NAMP), (Commander, Naval Air Forces, 2008a).

To generate the forecast model, we conducted an in-depth review of current historical data gathered by various organizations involved with the logistics, management and repair of the F414-GE-400 aircraft engine. These members are Program Manager Air Super Hornet, Hornet and Growler (PMA-265), Naval Air Systems Command (NAVAIR), GE, FRC West and FRC Southeast. We also conducted comprehensive interviews with F414-GE-400 maintenance managers and repair personnel during site visits to NAVAIR, FRC West and FRC Southeast. This ensured full understanding of the complexities that each member faces, allowing us to account for extenuating circumstances that may not appear in the data.

E. Report Organization

We assembled this project in a manner that develops readers' understanding and knowledge of the research question. Chapter I provides a foundation for the research project. It presents background information, the research objective, research questions, and methodology. Chapter II presents a general background in naval aviation maintenance, indicating some of its intricacies. The different levels of maintenance and their role in the repair process are discussed. Additionally, a brief breakdown of the F414-GE-400 engine is provided. Chapter III explores the various supply chain management techniques used to develop informed forecasting and optimization models. Chapter IV contains a data analysis. Chapter V includes results, recommendations and areas for further research, and Chapter VI presents the conclusions.

II. Background

In this section, we explain the complexities in naval aviation maintenance. First, we introduce readers to the driving doctrine, the NAMP, and the different levels at which maintenance is performed. Second, we define FRCs and Intermediate Maintenance Activities (IMA). Third, we present a brief overview of FRC West's organizational structure. Fourth, we give a brief definition of FRC Southeast and its role within the fleet. Fifth, we define the engine characteristics along with a brief description of all six modules. Finally, we provide an explanation as to how modules are forecasted and funded for repair through FRC Southeast to support the fleet and FRC West.

A. Naval Aviation Maintenance Program

The Chief of Naval Operations (CNO) established the NAMP in order to set standards and guidelines for the three levels of maintenance in naval aviation. As time progressed and systems became more complex, the NAMP changed to capture concepts utilized in the civilian industry. This established metrics in cost savings. The latest version of the NAMP incorporates new policies for FRCs and AIRspeed[2]. The objective of the NAMP is to improve aviation material readiness and safety standards within the Navy and the Marine Corps (Commander, Naval Air Forces, 2008b).

1. Levels of Maintenance

The NAMP is based on three levels of maintenance: Organizational, Intermediate and Depot. The Navy established these levels to facilitate better management of personnel, material and funds. The result was maximum availability

[2] AIRSpeed is a set of management tools used to analyze current processes in order to reduce cost and increase efficiency.

of aircraft to the fleet. The NAMP provides standard operating procedures for establishing and maintaining each level of the organization.

a. Organizational Level Maintenance

Organizational Level Maintenance activity is the lowest level of maintenance in which mechanics perform the day-to-day scheduled and unscheduled maintenance on aircraft. Scheduled maintenance is performed on two schedules: hourly and calendar. Hourly inspections are based on how many hours the aircraft flew or the total amount of engine hours operated. They are conducted within a time interval of +/- 10% of the inspection time (e.g., a 100-hour inspection can be completed between 90 and 110 hours). Calendar inspections are based on days and weeks. They are performed within +/- 3 days from the scheduled date. For example, an 84-day inspection can be performed any time between day 81 and day 87 (Commander, Naval Air Forces, 2008b).

b. Intermediate Level Maintenance

Intermediate Level Maintenance activity is the second level of maintenance defined within the NAMP. It is performed at IMAs or AIMDs and is supported by the FRCs. The Navy recently established a structure in which IMAs and AIMDs, formerly stand-alone activities, now fall under the control of the FRCs. The FRC brings a concept of combining highly skilled and knowledgeable depot artisans with Navy sailors, enabling minimal depot-level repairs to be performed at the local IMAs and AIMDs. The Navy implemented this measure in an effort to reduce costs and increase availability of Ready-for-Issue (RFI) components (Commander, Naval Air Forces, 2008b, pp. 3-5).

c. Depot Level Maintenance

Depot Level Maintenance activity is the Navy's most in-depth maintenance facility and falls under the FRCs. Within the depot facilities lie the Navy's artisans. They bring years of aviation maintenance experience that ensures operational efficiency and integrity of systems. Their abilities include manufacturing parts, as well as modifying, testing, inspecting, sampling and the reclamation of parts. The

FRC sites also provide engineering assistance to the Organizational and Intermediate Maintenance Levels in order to determine disposition of discrepancies beyond their maintenance capabilities (Commander, Naval Air Forces, 2008b, p. 6).

B. Fleet Readiness Center/Intermediate Maintenance Activity

Many people assume that the FRC and the IMAs are one and the same; however, it is an integration of IMAs and depot facilities that forms the FRC concept. The Navy created the FRCs to facilitate the implementation of Lean Six Sigma practices throughout naval aviation maintenance and to reduce turn-around-time (TAT), beyond capable maintenance (BCM) and cost. Commander, Naval Air Forces (2008c) states that the elements of the FRC are built upon a foundation of the following concepts:

- Total Force Management–People/Human Resource,
- Financial Management,
- Data Analysis,
- Maintenance Information Systems/IT,
- Logistics,
- Engineering and Technical Authority,
- Supply Chain Management,
- Maintenance Processes, and
- Quality Assurance.

It is through management of these elements that the six FRCs can implement measures of continuous improvement while satisfying the customer at a reduced cost.

C. FRC West Lemoore

FRC West is the Navy’s major repair facility for the F414-GE-400 engine. It oversees and commands AIMD Lemoore, CA; Navy Depot (NADEP) Detachment North Island Lemoore, CA; NADEP Detachment North Island Fallon, NV; AIMD

Atlanta, GA and NAS Joint Reserve Base Fort Worth, TX. Our study takes place at AIMD Lemoore.

1. AIMD Lemoore Organization

AIMD's organizational chart (Figure 2) is comprised of six production divisions and four staff divisions. The staff and production divisions outlined in Figure 2 are directly related to the repair of the F414-GE-400 engine. The production divisions are similar to a job shop in which customers typically order one engine or submit a small batch of engines for repair.

a. Production Control

Production Control is the nerve center within an AIMD. It makes daily decisions to set maintenance priorities. Management conducts meetings at each shift to discuss and schedule workload priorities. Once the meeting is complete, each work center begins working on the priorities.

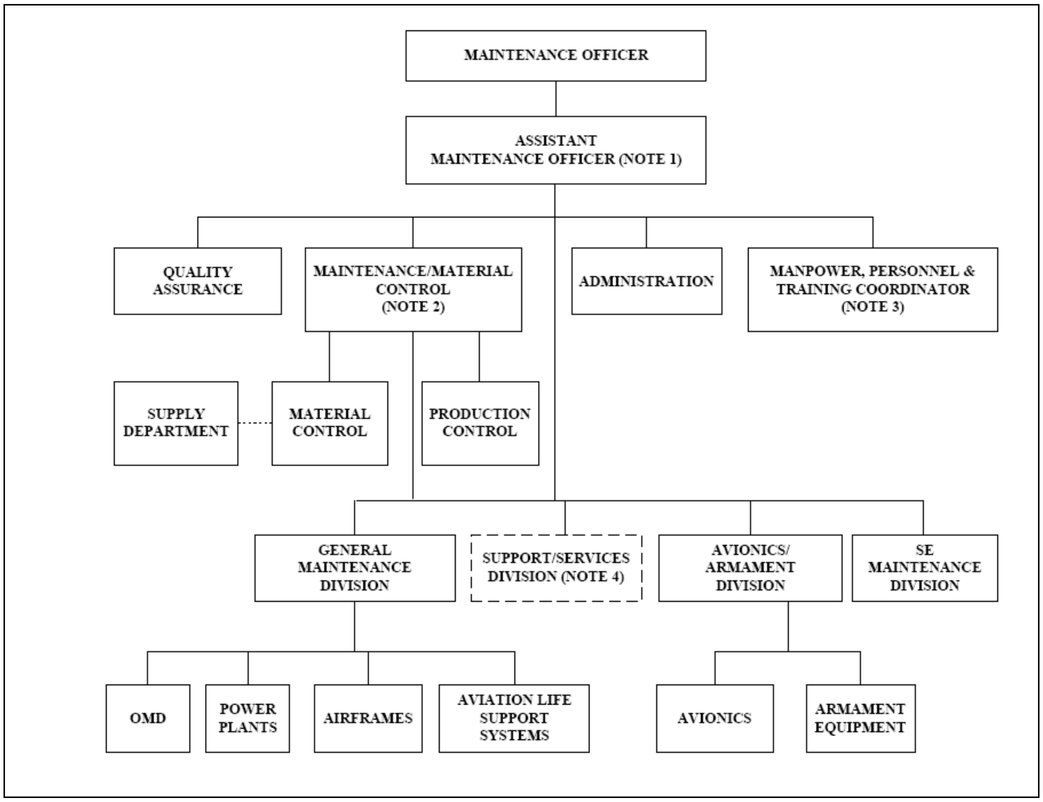

Figure 2. AIMD Organizational Chart
(Commander, Naval Air Forces, 2008b, pp. 3-122)

b. Material Control

Material Control is the hub that ships, receives, and accounts for all parts. When a part is found to be defective and the AIMD cannot repair it, it is designated BCM and the part is then ordered. When a technician orders a part, the production chief in Production Control assigns a Project Priority Code. The Project Priority Code identifies what impact that part has on the system (i.e., a part that prevents the end items from functioning within limits or assembly receives a higher priority). Material Control is also responsible for shipping and tracking all non-ready for issue (NRFI) and RFI engines inducted for repair.

c. Power Plants Division

Within each shore-based IMA, larger divisions like power plants operate under the auspices of Production Control with their own satellite Production Control.

The Power Plants Division (i.e., 400 Division within the IMA and AIMD) assigns priorities and tracks engines from the time an engine is ordered by a squadron to the time it is installed in an aircraft. It is within this division that the F414-GE-400 engine is disassembled, inspected, reassembled, tested and made RFI.

d. Quality Assurance

Quality Assurance (QA) is a staff division that works directly for the quality assurance officer (QAO). The QAO is directly responsible to the maintenance officer (MO) to ensure quality is managed throughout the entire organization. QA manages and monitors all programs within the NAMP that are specific to FRC West. To ensure quality is upheld, quality assurance representatives (QAR) or collateral duty inspectors (CDI) perform in-process and final inspections. In order to become a CDI or QAR, a person must pass an exam. Exams are written, given, maintained and reviewed for accuracy by QA. Finally, safety is the responsibility of everyone; however, QA ensures safety is paramount by conducting semi-annual work center audits.

D. FRC Southeast Jacksonville

FRC Southeast's mission is to provide organic depot and intermediate level support to the Navy and Marine Corps in support of critical weapon systems. "These weapon systems include the following aircraft: the F/A-18 Hornet, EA-6B Prowler, P-3 Orion, and H-60 Seahawk; and engines: J52, F404, F404-F1D2, F414, and TF34" (Crook, n.d., p. 1). The facility is composed of 53 buildings spread over 102 acres and employs more than 4,310 military, civilian and contract personnel. FRC Southeast repairs individual F414-GE-400 engine modules and has the capacity to repair the complete engine (Crook, n.d.).

E. F414-GE-400 Engine

The F414-GE-400 aircraft engine is employed in the Navy's newest strike fighter—the F/A-18E/F Super Hornet—and in the electronic attack EA-18G Growler.

The Navy contracted General Electric to design and build a more reliable engine with increased survivability characteristics and a reduced operational lifecycle cost of the aircraft. The design improves reliability and fuel efficiency.

1. Engine Characteristics

The F414-GE-400 engine design is a low-bypass turbofan with a split spool turbine that allows the fan and compressor modules to spin independently. The Super Hornet is capable of going above the speed of sound, requiring variable area exhaust nozzles (VEN) mounted on the tail of the Afterburner (AB) Module, allowing for quick augmented thrust in flight. The engine is 155.5 inches long, weighs 2,445 lbs and has an inlet diameter of 30.6 inches. "The engine is rated at 14,770 lbs thrust at the maximum power throttle setting without the afterburner, and 21,890 lbs of thrust at the maximum afterburner throttle setting given standard day settings of 59°F, 0 percent humidity, sea level static conditions" (Commander, Naval Air Systems Command, 1998, p. 1). The engine consists of six modules (as seen in Figure 3) and can be changed between engines (i.e., there are no matched sets of modules).

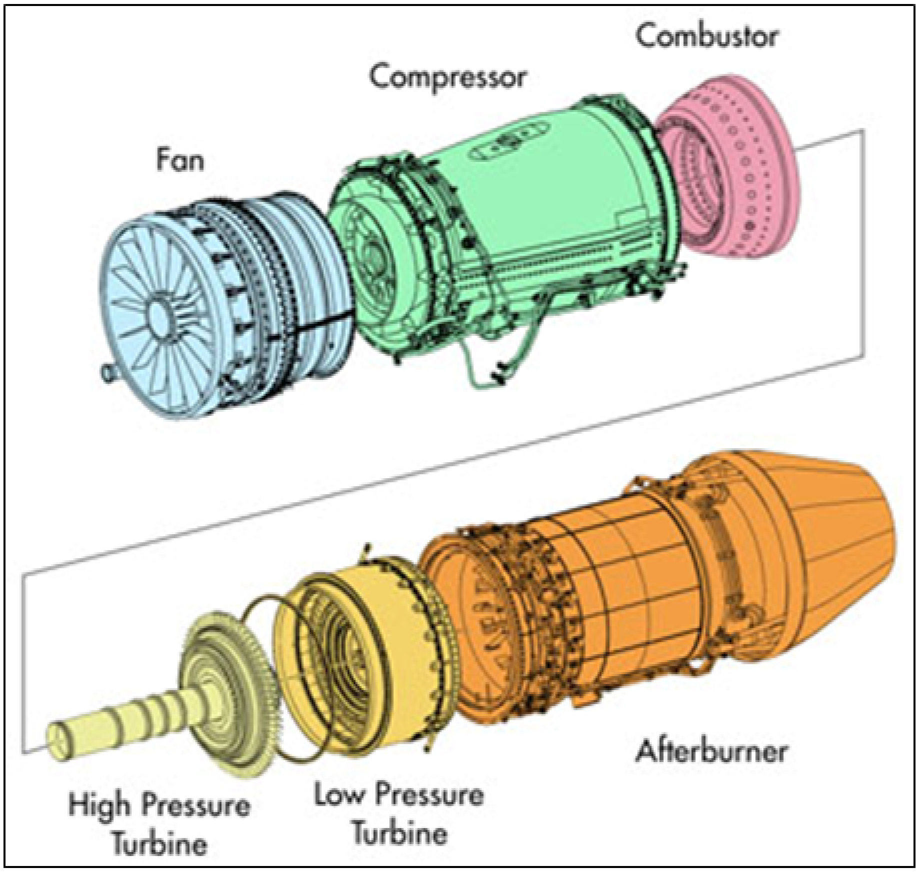

Figure 3. F414-GE-400 Engine Module Design
(Defense Industry Daily, 2008)

a. Fan Module

The Fan Module is a three-stage axial flow design. It provides 20% of the air to the Compressor Module and 80% of flow in bypass for thrust. The first stage fan blades are interchangeable at the intermediate level, provided they are replaced in sets that stay within the centrifugal balance limits. The second and third stages of the fan are a one-piece design, (i.e., the blades are connected and cannot be changed individually). The design of the second and third stage blades is a new concept, and they must be replaced at the depot because of centrifugal dynamic balance requirements. The centrifugal dynamic balancers (as presented in Figure 4) are only found in the FRC Southeast depot.

Figure 4. F414-GE-400 Centrifugal Dynamic Balancer

b. High-pressure Compressor Module

The High-pressure Compressor Module (HPC) is a seven-stage axial flow compressor that supplies air to the combustor in order to support combustion. It is housed within the outer bypass duct of the engine and is mounted just aft of the Fan Module. "The Seven-Stage Compressor uses the latest 3-D aero and clearance control features to increase efficiency by 3%. Also included are ruggedized leading edges, 3-D compound blisk hubs, non-uniform vane spacing, and probabilistic design assessment to significantly increase durability and reduce high cycle fatigue" (Global Security, 2006).

c. Combustor Module

The Combustor Module houses the fuel nozzles that atomize fuel and air to support combustion. The hot gases are directed through the inlet guide vane and directed onto the High-pressure Turbine Module (HPT). The Combustor Module is annular in design and has 30,000 laser-drilled holes to control cooling. Because the holes are laser-drilled, it has high inspection criteria for cracks that cannot be welded at the depot level. Most combustor liners are BCM'd from the depot facility for repair at the manufacturer. A picture of the combustor liner is shown in Figure 5.

Figure 5. F414-GE-400 Combustion Liner

d. High-pressure Turbine Module

The HPT is mounted just aft of the combustor and is linked to the HPC through a common shaft that drives the HPC. "The advanced High-pressure Turbine incorporates 3-D aero design, advanced cooling, and brush seals to increase efficiency by 2% and gas path temperature capability by 150 degrees Fahrenheit with current blade materials" (Global Security, 2006).

e. Low Pressure Turbine Module

The Low Pressure Turbine (LPT) Module is a single-stage axial flow design located just aft of the HPT and is linked to the Fan Module through a common shaft that drives the fan. The HPT, along with the LPT, uses General Electrics' (GE) latest single crystal alloys. "Three-dimensional vicious flow modeling helped increase turbine efficiency more than one percentage point over previous design methods.

Thermal barrier coatings also enhance the durability of both turbines" (Global Security, 2006).

f. Afterburner Module

The AB Module includes the flameholder, liner, and variable exhaust nozzles. The AB assembly provides a selected boost in velocity by atomizing and igniting raw fuel. It is the only module that the Power Plants Division in Lemoore has full repair capability over.

2. Force Removal Time Intervals of Modules

Each module within the F414-GE-400 engine is life limited. The life-limit intervals are based on the historical performance data of past engine designs and age-exploration programs. Within the depot facility, GE engineers pick certain modules for careful disassembly and inspection. They request that artisans record and submit certain measurements for evaluation to ensure items are wearing at a correct rate. Through the age exploration of these components, the engineers make the decision to extend, shorten or maintain the same service life of the components within the modules. It should be noted that the disassembly and inspection of these modules takes a longer turnaround time (TAT), directly affecting the amount of work in progress (WIP) in the depot facility. Through age-exploration programs, the life-limits of each module can change, producing an unforeseen demand in that specific module (e.g., engineers may reduce the Fan Module life-limit if they see excessive signs of wear in the blade root of the first stage Fan Module). This would immediately reduce the service life of every engine in the fleet and increase the workload at the FRC facilities that change and repair the modules.

It is important to discuss the two types of hours that are used to determine whether an item is high time. One type is engine operating time (EOT), which is the time recorded from start-up to shutdown. The second type of hour is Life-used Indices (LUI), in which life-used is measured through nine matrices with 214 elements to track and calculate hours. The data is collected and recorded by the In-flight Engine and Conditioning and Monitoring System (IECAMS), uploaded into the aircraft's mission computers and downloaded after each flight (Hall, Leary, Lapierre, Hess, & Bladen, 2001). Once the information is downloaded, the data is sent up-line to the Simulated Automated Maintenance Environment (SAME) server. The downloaded information can be reviewed on an engine configuration report (commonly called a 72N report in the fleet). The current life-limits on the modules are listed in Table 1.

Table 1. F414-GE-400 Engine Module Life-limit
(After: FRC West, 2008)

MODULE	HOUR LIMIT	HOUR TYPE
Fan Module	4000	EOT
HPC Module	4000	EOT
Combustor Module	4000	EOT
HPT Module	1850	LUI
LPT Module	4000	EOT
Afterburner Module	3431	EOT

F. NAVAIR's Current Forecasting Method

We defined the difference between EOT and LUI hours so that readers would have an understanding of the complexity of current NAVAIR forecast models. The aircraft and engine hour data that goes up-line daily is analyzed and used with the future forecast of annual flight hours to be flown. Once the data is compiled, the analyst within NAVAIR takes into consideration historical trends of associated malfunction codes that can be correlated to one or multiple modules. The numbers generated by the forecast model are then carefully reviewed by both NAVAIR and CNAF. This allows them to set the actual fiscal year (FY) numbers for production of FRC Southeast. Table 2 displays current-year values generated by the forecast model. The right column labeled FY-09 CNAF indicates the workload of which the FRC Southeast is actually funded.

Table 2. F414-GE-400 FY-09 Engine Module Forecast
(After: Traylor, 2008)

Modules	FY-09 Original	FY-09 PMA-265 Revised	FY-09 CNAF
Fan Module	208	211	206
Compressor Module	304	188	253
HPT Module	231	233	225
LPT Module	235	178	221
Combustor Module	208	210	210

In this chapter, we described the naval aviation maintenance environment. First, we introduced the NAMP and the different levels of maintenance. Second, we defined FRCs and Intermediate Maintenance Activities (IMA). Third, we offered a brief overview of FRC West's organizational structure. Fourth, we defined FRC Southeast and their role. Fifth, we briefly depicted the engine characteristics and all six modules. Finally, we presented a brief description of how modules are forecasted and funded for repair. In Chapter III, we review literature published by academia and relate corresponding works to the research conducted during this report.

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III. Literature Review

Previous studies offer explanations and rationale behind the development and conclusions of this project and provide guidance for recommendations and suggested areas for further research. We will discuss operations within the supply chain, areas of focus in relation to current operations, remanufacturing, and supply chain strategy as they pertain to various areas of our project.

A. Introduction

We reviewed materials related to SCM, forecasting, production scheduling, and demand uncertainty to define safety stocks in intermediate maintenance operations at depot-level repair operations. These subjects were reviewed to help focus our research direction. On-site interviews were conducted in conjunction with categorical research related to the chain of events that comprise this particular supply chain. We analyzed the information gathered using academic theory and the guidance of subject-matter experts (SMEs) in order to acquire a complete vision of the organizational flow and conditions that exist within this particular network.

Previous studies by Kiefer (1996) focused on supply chain management theory on an enterprise level, with an overview of the entire supply chain, its practices and performance measures. They provided an overall basis for the desired operation and measures of effectiveness that should be taken into consideration when employing cross-functional efforts. Keifer (1996) examined the use of performance measures among supply chain members and how they were viewed within the chain. The performance measures that are used by FRC West and FRC Southwest have been tailored to their particular organizations and to each other. The areas of performance metrics similarity provide a common base for continued mutual improvement.

B. Operations within the Supply Chain

1. Supply Chain Performance

The use of metrics as an indicator of performance encourages favorable behavior and provides warning signs regarding events that are not beneficial to the performance of the entire chain. The relationship between FRC Southeast and FRC West provides an example of both shared and localized metrics. Areas of performance metric similarity provide a cross-functional synergy that benefits the supply chain. Areas of dissimilarity, in which local metrics exist, can serve as a false indicator of success for one node within the supply chain and a region of disparity for another, creating uncertainty within the chain. Lee and Billington (1992) state several important factors:

- An organization's understanding of sources of uncertainty and the magnitude of those effects can be used to discover causes of problems. Dynamics within FRC West and Southeast supply chain create forecast uncertainty.
- Members within the supply chain need to have a common mission and service goal. The relationship between FRC West and Southeast creates an environment that focuses on end-user satisfaction and mission readiness.
- As uncertainties change in FRC West and Southeast supply chain, demand becomes more or less predictable.

Demand within the supply chain at FRC Southeast and FRC West displays a degree of uncertainty due to local usage at each FRC. Random events create a dynamic environment that affects the demand, making it difficult to forecast. The possible disconnect between usage, production, and safety stock and/or buffer levels impacts cross-functional supply chain performance. Two conditions arise because of this disconnect:

- Overproduction at FRC Southeast and underutilization of on-hand stock at FRC West, or
- Underproduction at FRC Southeast and the creation of stock-outs at FRC West and backorders for FRC Southeast production plan.

Production levels that are equal to or above local usage rates at FRC Southeast allow FRC West to meet demand and keep buffer levels in the supermarket within limits. Levels of production that are under FRC usage rates lead to reduced availability at FRC and possible decreases in aircraft readiness rates.

2. NAVAIR Enterprise Strategy

The unique characteristics of customer-supplier relationships present areas for review under different circumstances than would be available within a traditional civilian-sector supply chain. The strategic relationship is centered on worldwide service to the entire naval aviation fleet.

Process improvement initiatives undertaken at the local level in an effort to adopt AIRspeed, Lean Six Sigma, and the Theory of Constraints produced beneficial results for the entire enterprise. The effects of the locally-implemented process improvement require an overall review of the supply chain to ensure that characteristics of the supply chain remain favorable.

3. Elements of the Supply Chain

For this project, we chose to research only the elements that can theoretically be modified in accordance with the NAMP and man-machine interface. Maintenance procedures and level-of-repair capability were not adjusted from what is actually allowed by FRC Southeast or FRC West. The operational leverage and the constraints presented here define aviation maintenance regulations, procedures, and relationships within the naval aviation community and support activities that comprise the NAVAIR enterprise.

Management theory and the best business practices can be adopted in the supply chain of FRC Southeast and FRC West in the areas modeled in Figure 6.

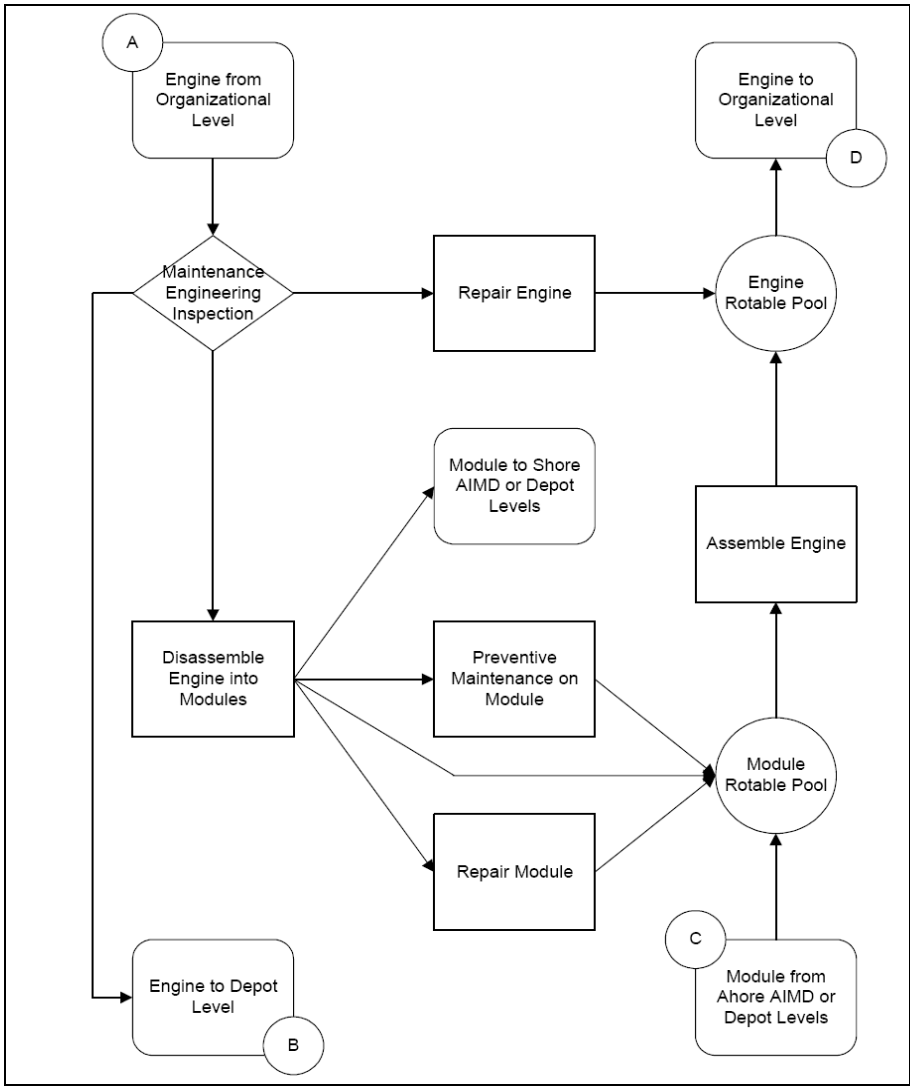

Figure 6. Intermediate and Depot Level Repair Cycle for F414-GE-400 Engine (Stearns, 1998, p. 17)

The various steps in Figure 6 form a two-party supply chain that resembles a job shop-related remanufacturing process. Several major areas can be examined to investigate a cause and effect relationship between the local activities of FRC Southeast and the Power Plants Division at FRC West. Section A represents engine entry into the FRC West system. Section B represents module entry into the FRC Southeast system. Section C highlights module entry from FRC West or FRC Southeast into the supermarket at FRC West. Section D completes the cycle with an RFI engine being issued to a squadron.

C. Areas of Focus in Relation to Current Operations

1. Shared Metrics

Performance metrics that span the entire supply chain provide a level of feedback that demonstrates direct links to customer service levels, satisfaction, operational readiness and overall efficiency.

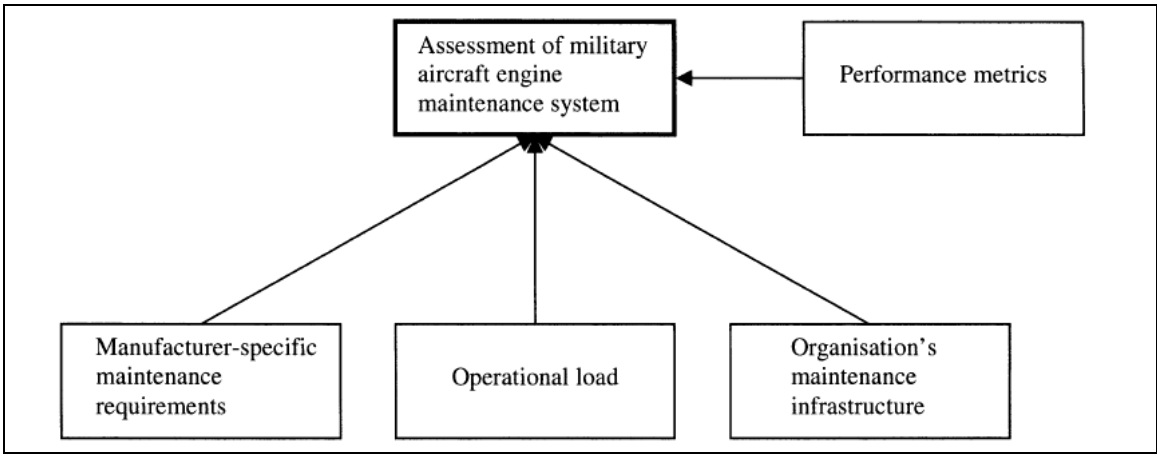

Figure 7. Intermediate and Depot Level Performance Metrics
(Adamides, Stamboulis, & Varelis, 2004, p. 958)

According to Adamides, Stamboulis and Varelis (2004), the use of these metrics can generate meaningful information that the supply chain can use. Common metrics present the user at the enterprise level with an accurate picture of overall supply chain performance, vice localized metrics that cannot be properly used outside a particular node in the chain.

2. The Use of Safety Stock

The decision of whether to reschedule or use safety stock can be mathematically approached to find the most cost-effective means of achieving the desired service levels within this system. Carlson and Yano (1986) define the uses of safety stock in the areas of supply chain service levels, scheduling, and the aversion of using unplanned/emergency production runs. Understanding the effects of various buffering systems such as safety stock and their impact on supply chain performance is key to decision-making (Carlson & Yano, 1986, p. 403). How safety stock affects system performance must be balanced with overall cost of the network. The use of safety stock and emergency setups to avoid shortages is displayed in Figure 8.

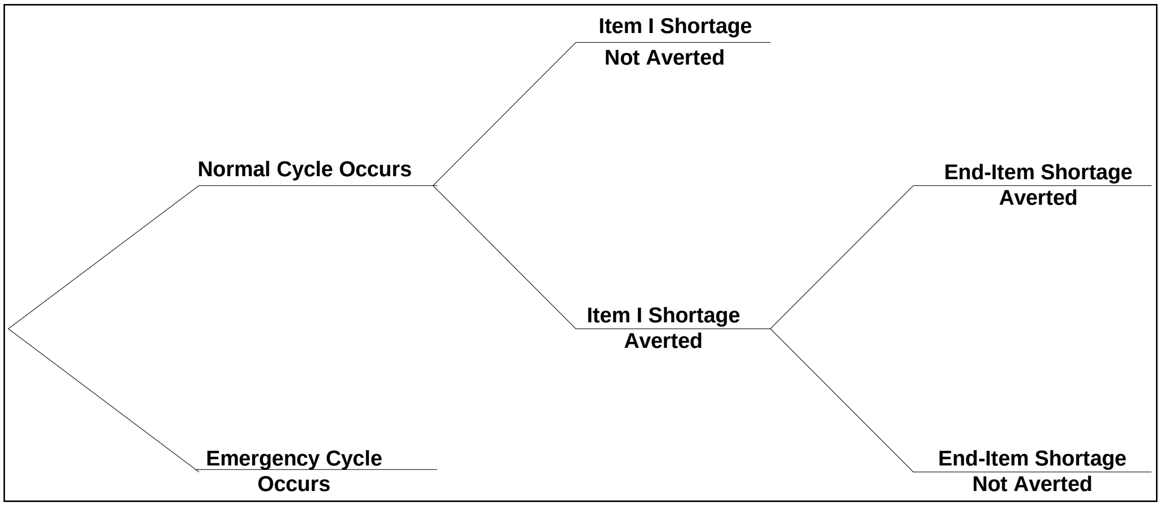

Figure 8. Production Decision Schematic (Cycles Shortage Aversion)
(Carlson & Yano, 1986, p. 411)

This process is made more complex as the number of intermediate items is increased. The modular design of the F414-GE-400 introduces six areas of unique complexity. Additional research by Benton (1991) explains the adverse effects of demand uncertainty and its impact on safety stock levels in a periodic review system that is similar to the system of FRC Southeast and FRC West. In order to achieve a higher level of service, safety stock levels must also be increased. The simulations from Benton (1991) display the relationship between lot size, cycle stock and the need for safety stock. The safety stock level required to meet the original service level increases as the system experiences more uncertainty.

3. Dealing with Uncertainty

Uncertainty within the supply chain can lead to various actions, both positive and negative, depending on an organization's role in the supply chain. The system in question does not have a recognizable holding cost, but the number of items on hand and available storage space can serve as constraints. Four types of uncertainty exist:

- Demand timing uncertainty,
- Demand quantity uncertainty,
- Supply timing uncertainty, and
- Supply quantity uncertainty. (Anderson, 1989, p. 635)

To effectively match demand to production levels within the supply chain, certain variables must be held stable or configured into a predictable sequence that allows for lead-time or order time to be adjusted in order to cope with unknowns. Safety lead-time can be employed when the order arrival and sequence is unknown. Dynamic lot-sizing models, such as those demonstrated by Anderson (1989), demonstrate how lot-size problems can arise in a Material Requirements Planning (MRP) System.

Systems that deal with uncertain demand and repairable assets, such as engine modules, can be factored into non-depletive inventory models to account for the demand and failure generated by multiple working items (Azoury, 1985, pp. 1,150-1,155).

Azoury (1985) applied Bayes' belief that by using observed data and numerically linking that data to expected outcomes through a degree of belief or probabilistic outcomes, inference could be developed. By using Bayesian methods in a periodic system, it is possible to account for new information within the decision model once it presents itself. Demand is still unknown, due to module failures, but orders can be adjusted with greater confidence given the new information (Azoury, 1985).

The FRC West production line is capable of building several engines at a time, but uncertainty can be introduced by the unavailability of certain modules required for complete throughput. The results of this uncertainty can disrupt flow, create in-process inventory, reduce throughput, and increase time to reliably replenish (TRR) since each of these metrics are tracked locally. Denardo and Lee (1996) conclude that uncertainty can be introduced in the demand for any particular end item that is modular in nature. Variances in buffer stock and time control (i.e., periodic review) can be employed to economize inventory levels while avoiding shortages.

Brill and Chaouch (1995) examined disruptions in demand and inventory planning decisions that can be employed to curb stock-outs and determine the proper stocking levels when demand increases or decreases. Their analysis of supply chain disruptions focuses on the suppliers' perspective but offers insight into how disruptions up the supply chain can affect end-user item availability. End-user demand and the ability to transfer that information to the respective supply chain manager is the driver behind the research and modeling (Brill & Chaouch, 1996). By using their technique, order quantity can be adjusted to correlate with user demand and deter disruptions to the supply chain.

Demand that is sensitive to economic fluctuations or the introduction of new system entrants (i.e., increased demand within an original/closed system) can be explained and accounted for by the research conducted by Song and Zipkin (1993). The policy-related research is meant to be used as a generalized guide and demonstrates how world demand can affect the supply chain and inventory control.

4. Inventory Control

Policy developed by Paschalidis and Liu (2003) to control inventory covers the dynamics of the manufacturing environment and efforts to hedge stock-outs, satisfying demand and balancing the fundamental tradeoff between producing and idling among manufacturers. The production policy ties safety stock and overall metrics used to determine customer satisfaction for a given service level. Production scheduling in this project is based on a monthly schedule. Once production runs are complete, the manufacturer (FRC Southeast) returns to an idle state until the next production request is received and work is scheduled. Paschalidis and Liu (2003) developed optimal baseline stock levels with respect to the assumptions that manufacturing facilities operate in a stochastic manner and are prone to failure. These failures can then be accounted for by tailoring stock levels. Additionally, they examined the presence of local inventory and the flow of information concerning the level of localized inventory in order to demonstrate the effect of communication and inventory levels within the supply chain.

According to Bourland and Yano (1994), planned idle time is effective if a system has a degree of capacity slack in order to reduce inventory cost, overtime, and setup cost, but it is not an effective tool to guard against demand uncertainty. Proper inventory techniques need to be exercised to benefit the entire supply chain rather than local links in the chain.

5. Forecasting and Scheduling

Forecasting in this uncertain environment presents a significant number of challenges that impact actions and results throughout the supply chain. Lee and Adam (1986) researched the impact of forecasting error in relation to demand and performance and cost-related consequences related to forecast inaccuracy. Production structure within an MRP system is influenced by several factors:

- The number of levels in the product structure,
- The number of parent items for a component item,
- The number of component items for a parent item (module-engine),
- The lead-time in the parent-component relationship, and
- Cost structure associated with the production process of a parent or component item. (Lee & Adam, 1986)

Material demands are forecasted based on expected fleet usage. Production schedules are developed and pool levels are maintained during each period to meet desired service levels. The production and repair process is tied together within the remanufacturing environment. FRC West and FRC Southeast share a dynamic supply chain that places unique challenges on forecasting and scheduling to meet fleet demand.

D. Remanufacturing Operations

1. Overview

The operational characteristics of the module repair facility most closely resemble the operations of a recoverable/repairable manufacturing facility. Operations such as this have unique characteristics due to the flow of their supply chain and demand within that chain. In most cases, this type of operation is necessary due to the expense of the end item. Guide and Srivastava (1997) investigated the inherent uncertainty and probabilistic asset routings that differ from new manufacturing activities. Uncertainties were examined in the areas of safety stock and MRP with relation to lead-time and recommended adjustments.

Guide and Srivastava (1997) recommended that safety stock does not protect against uncertainty due to imperfect knowledge concerning recovery, rebuild rates and forecast error. Safety stock does not completely curtail a stock-out event from happening, but the benefit of maintaining a proper buffer can hedge increased inventory cost while maintaining a satisfactory level of customer service.

2. Typical Layout

Figure 9 provides a general workflow through a remanufacturing process, as reviewed by Hausman and Scudder (1982). It was used as the basis of their scheduling theory, which emphasizes the following performance areas: target spare inventory level, capacity to repair, and the scheduling system.

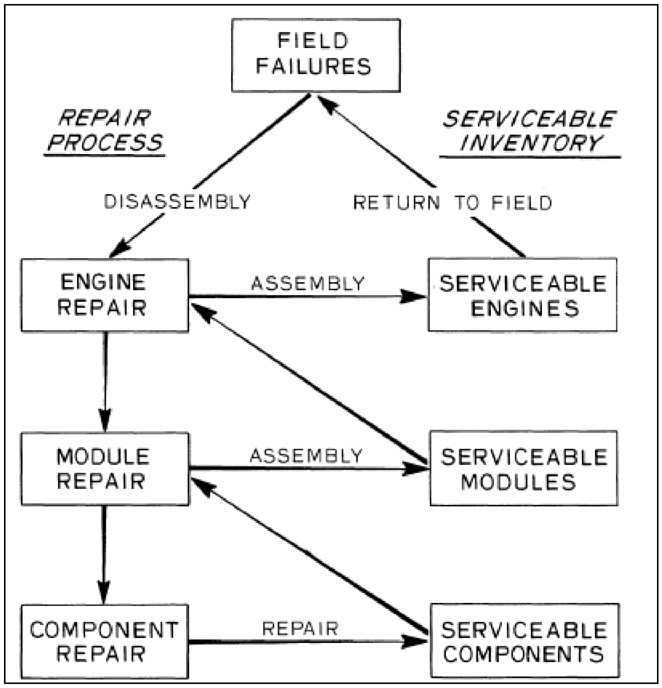

Figure 9. Remanufacturing Center Process Flow
(Hausman & Scudder, 1982, p. 1,216)

The textboxes in Figure 9 represent steps within the repair process. This system is unique due to the irregular workflow that is based on the required level of module repair and the required items for a particular repair.

Remanufacturing is unique due to its hybrid nature, inherent complexity, repair/recovery time, customer demand and presence of unknowns in relation to items required for repair. Product complexity is an overwhelming contributing factor, as demonstrated by Guide, Srivastava and Kraus (1998). Replacement times can be hedged by modularity and design-for-maintainability, but customer service levels require a proper mix of lead-time, stocking levels, and forecasting.

E. Overall Supply Chain Strategy

Accurate forecasts are collaboratively developed by supply chain partners with consistent definition of resources, and constraints can enable effective evaluation of trade-offs associated with supply chain decisions (Bowersox, Closs, & Cooper, 2007, p. 64). These forecasts can then be employed to drive MRP-based systems. Without collaborative planning, each supply chain partner tries to plan the level and timing of demand for its customer, resulting in speculative inventory and a never-ending cycle of excess and stock-out conditions (Bowersox, Closs, & Cooper, 2007, p. 63).

Matching requirements to resources and evaluating trade-offs in relation to the supply chain objectives ensures that overall strategy is accomplished throughout the enterprise. Planning based on requirements can then be integrated with available inventory, production plans, and backorder reconciliation in order to achieve desired customer service levels.

We discussed operations within the supply chain, areas of focus in relation to current operations, remanufacturing, and supply chain strategy as they pertain to various areas of our project. Next, we present the analysis portion of our project.

IV. Analysis

This chapter presents an analysis of the current historical data for the F414-GE-400 engine. First, flowcharts illustrate the path of information and material between activities and the steps in the repair process. Second, the forecasting overview describes different forecasting methods and how to measure for accuracy. Third, the time series forecast models with trend present the forecasting methods used. Finally, the optimization model defines the inputs.

A. Flowcharts

The macro and micro flowcharts demonstrate the relationships between processes and entities within the supply chain. The resultant behavior of entities can be traced to outcomes and desired goals.

Appendix A demonstrates how expected usage and demand data is sent to GE from COMNAVAIRFOR. A production schedule is coordinated and modules are then sent to FRC West. FRC West is responsible for assembling end items to service the Continental United States (CONUS) and Outside Continental United States (OCONUS) fleets and their own supermarket. Balancing supermarket buffer levels and fleet usage rates is the overarching goal of FRC West and FRC Southeast.

The work center flow diagram in Appendix B demonstrates the relationships between major module producers, the repair and assembly process at FRC West, and relation to the end user. The only module repaired by FRC West is the AB Module. FRC West manages the pool levels of the individual modules, and Work Center 41V is responsible for repairing engines based on fleet requirements.

B. Forecasting Overview

In this section, we briefly describe the different types of forecast models, the use of those models and the different measures to determine forecast accuracy.

1. Forecast Models

A forecast model is a way to estimate what may occur in the future. Managers use forecast models on a daily basis in order to estimate future demand and determine order quantities. Various methods are used to create a forecast model: Qualitative, Time-series and Causal. “Qualitative models incorporate subjective factors. Time-series models assume that the past is an indication of the future. Causal models incorporate factors that influence the quantity being forecasted” (Balakrishnan, Render, & Stair, 2007, p. 528). We chose to use the Time-series (quantitative) approach because there is ample and accurate quantitative data available. Quantitative models consist of but are not limited to moving averages, weighted moving averages, exponential smoothing, linear trend analysis, seasonality analysis, multiplicative, and additive analysis. Moving averages, weighted moving averages, and exponential smoothing forecast the next period with no trend. Double Exponential Smoothing, linear trend analysis, seasonality analysis, multiplicative, and additive analysis forecast multiple periods with a trend. We used the latter of these quantitative methods because the data indicated an upward trend, and we needed to forecast multiple periods.

2. Measures for Forecast Model Accuracy

Several measures are commonly used to determine the accuracy of a forecasting model: Mean Absolute Deviation (MAD), Mean Squared Error (MSE) and Mean Absolute Percent Error (MAPE).

MAD is the average of the errors and is calculated using the Actual Value (A_t) and Forecast Value (F_t) for a specific number of periods (T), as:

$$MAD = \sum_{t=1}^{T} \frac{|A_t - F_t|}{T}$$

MSE is the average of the square of the forecasting errors and is calculated as:

$$MSE = \sum_{t=1}^{T} \frac{\left| A_t - F_t \right|^2}{T}$$

MAPE is the average of the errors, “expressed as a percentage of the actual values,” (p. 532) and is calculated as:

$$MAPE = 100 * \sum_{t=1}^{T} \frac{\left(\frac{\left| A_t - F_t \right|}{A_t} \right)}{T}$$

C. Time-series Forecast Models with Trend

In this section, we describe the data used to develop the forecast models linear regression and double exponential smoothing. We implemented this approach because there is ample and accurate quantitative data that depicts an upward trend. Lack of seasonality, degree of variability and amount of data led to our scope.

1. Three Year Historical Data

Table 3 depicts the number of F414-GE-400 engines repaired each month from 2006 to 2008. The values in the table correspond to the quantity of engines repaired. For example, FRC West repaired 16 engines in July 2007.

Table 3. Quantity of F414-GE-400 Engines Repaired at FRC West
(After: McCray, 2008, September 10)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
FY 2006	14	8	15	14	20	22	20	7	16	18	17	16
FY 2007	15	19	16	26	15	26	23	22	19	16	19	23
FY 2008	18	21	19	28	24	20	22	12	31	27	20	

2. Linear Regression

Linear regression, commonly referred to as linear trend analysis, is a technique used to fit an equation to a series of historical data points. This equation then projects the outcome in the future. Figure 10 displays the results of this method. The graph labeled QTY RFI is the historical data. The graph labeled Forecasted Repair is the forecasted engine repair demand for FRC West. It is based on the linear equation created when applying the linear regression method to the QTY RFI. The corresponding slope is .2776 and intercept is 14.089, $y = .2776x + 14.089$, where y is the forecast and x is the time period.

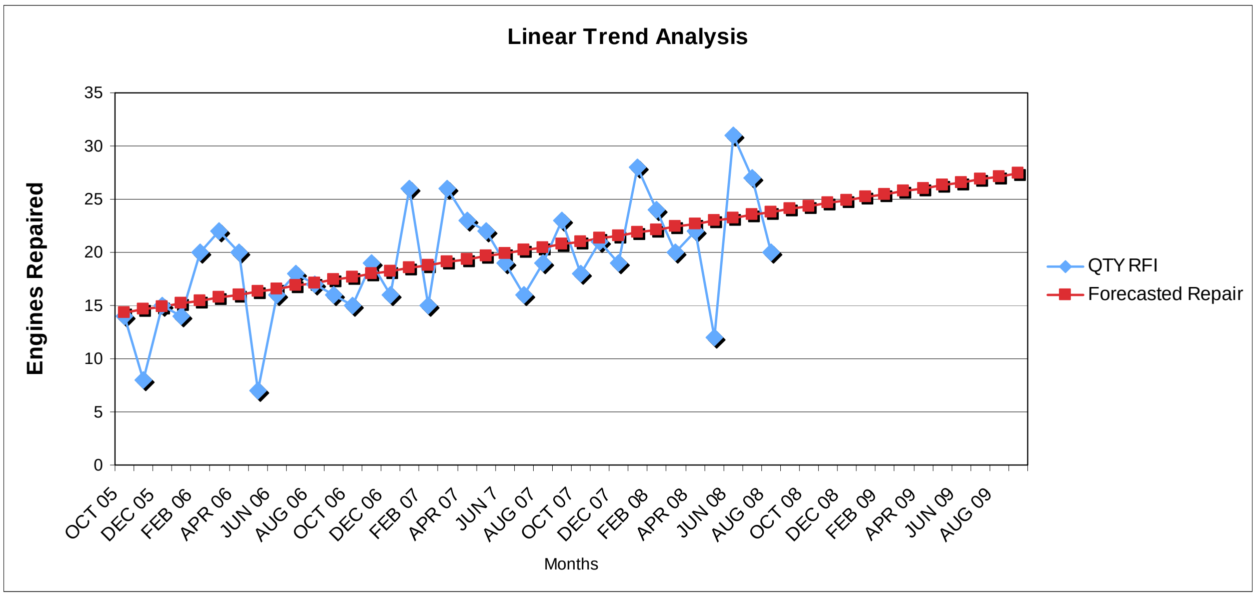

Figure 10. Historical Data with Linear Regression Trend Line

3. Double Exponential Smoothing

Double exponential smoothing is a forecast technique that "assigns exponentially decreasing weights as the observations get older. In other words, recent observations are given relatively more weight in forecasting than the older observations" (NIST/SEMATECH, 2006). This method smoothes out large variation in an effort to produce a discernable pattern. We solved the equation for α and β by minimizing MSE because large errors impact the forecast more than small errors.

The results are α = .091 and β = .153. Figure 11 displays the results of this method. Again, the graph labeled QTY RFI represents the historical data. The graph labeled Dbl Exp Smoothed represents the smoothed forecast.

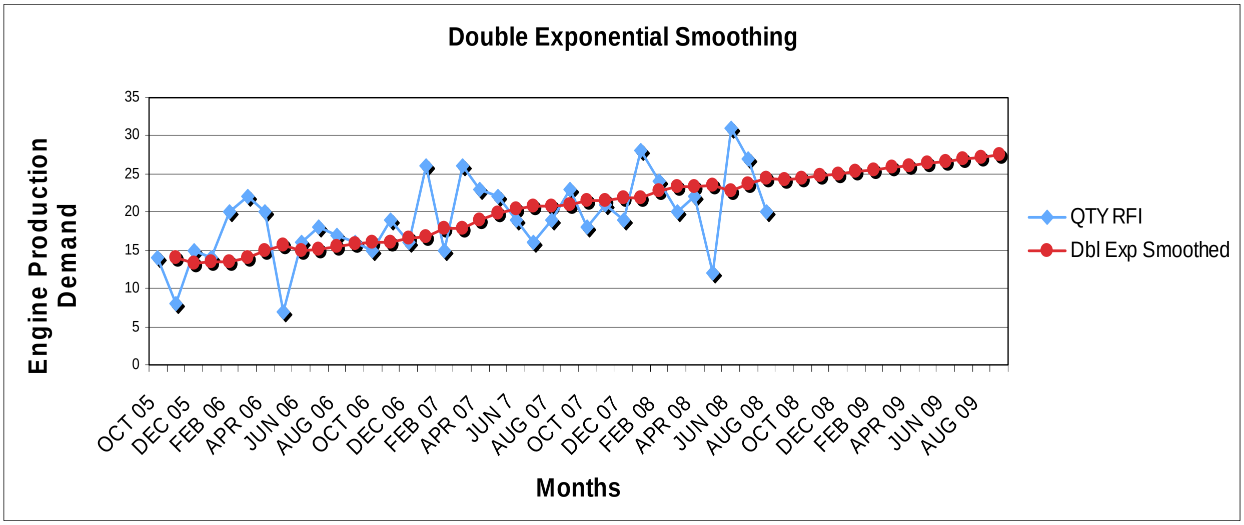

Figure 11. Historical Data with Double Exponential Smoothing and Trend Line

4. Measures of Accuracy

The measures of accuracy for the two forecasting models we implemented are listed in Table 4. To calculate these values, we used the past 24 periods. MAD states that on average, the linear regression is off by a little more than three engines and Dbl Exp Smoothing is off by four engines. When comparing the MSE, the linear regression is better than Dbl Exp Smoothing at explaining the variability. MAPE states the percentage error of engines forecasted is approximately 21% to 22%.

Table 4. Measure of Accuracy

	MAD	MSE	MAPE
Linear Regression	3.361	18.790	21.049%
Dbl Exp Smoothing	4.042	22.994	22.220%

D. Optimization Model

When scarce resources are allocated among competing activities, an optimization model is used. The scarce resources in our report are finances, people, and time to repair aircraft engines. We developed this optimization model to determine the engine repair capacity of Work Center 41V. The parameter within this optimization model is the time it takes to repair an engine within Work Center 41V. The decision variables within the optimization model are Aviation Machinist's Mates (AD) between the enlisted pay grades of E-4 to E-6. We define decision variables, objective function and constraints.

1. Decision Variables

The model uses the following decision variables:

- AD3M=Number of E-4 Aviation Machinist's Mate capable of performing the removal and replacement of six engine modules on the F414-GE-400 engine to meet maintenance demand.
- AD2M=Number of E-5 Aviation Machinist's Mate capable of performing the removal and replacement of six engine modules on the F414-GE-400 engine to meet maintenance demand.
- AD1M=Number of E-6 Aviation Machinist's Mate capable of performing the removal and replacement of six engine modules on the F414-GE-400 engine to meet maintenance demand.
- AD2I=Number of E-5 Aviation Machinist's Mate capable of performing in process and final inspections of six engine modules on the F414-GE-400 engine to meet inspection demand.
- AD1I=Number of E-6 Aviation Machinist's Mate capable of performing in process and final inspections of six engine modules on the F414-GE-400 engine to meet inspection demand.

Figure 12 depicts the relationship between these decision variables and between workers and their respective ability to perform maintenance or an inspection. These relationships form the basis for defining the decision variables. For instance, an AD3 can only satisfy maintenance demand hours; therefore, AD3M denotes the decision variable for those personnel. An AD2 can meet both maintenance demand hours and inspection demand hours; therefore, decision variables AD2M and AD2I are assigned for those personnel.

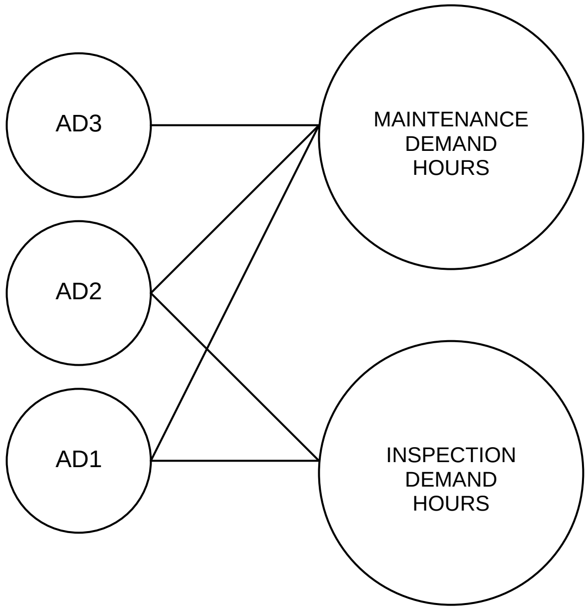

Figure 12. Decision Variable Relationship

2. Objective Function

Our objective function minimizes labor cost, which is the sum of the monthly salary paid to E-4, E-5 and E-6 maintenance personnel (salary values are shown in Table 8).

AD3M*($3,841.25)+(AD2M+AD2I)*($4,901.25)+(AD1M+AD1I)*($5,986.42)

3. Constraints

A constraint is "a restriction (stated in the form of an inequality of an equation) that inhibits (or binds) the values that can be achieved by the objective function" (Balakrishnan et. al., 2007, p. 64). The constraints of maintenance demand (D_m), inspection demand (D_i) and the number of personnel by pay grade in Work Center

41V were used to satisfy the objective function. For example, the number of AD2 CDIs multiplied by their effective capacity plus the number of AD1 CDIs multiplied by their effective capacity must be greater than or equal to inspection demand. Each person defined in the decision variable can work a maximum of 144.65 hours per month. To determine a person's effective capacity, which is used in these equations, the inverse of the effective production rate must be used. The effective production rate is explained in section 5b of this chapter.

Maintenance Demand:

AD3M*(132.49)+AD2M*(144.65)+AD1M*(156.58) $\geq D_m$

Inspection Demand:

AD2I*(144.65)+AD1I*(156.58) $\geq D_i$

Number of Personnel in each pay grade:

AD3M $\leq$ 34

AD2M+AD2I $\leq$ 6

AD1M+AD1I $\leq$ 2

4. Parameters

We will now describe the parameter in our model—the number of man-hours required to disassemble and reassemble an engine and to prepare it for the test cell.

a. TRR of Non-RFI to RFI Engine

(1) FRC West TRR Goal. Figure 13 illustrates the TRR target established by FRC West, shown as FRC West Target. The target TRR minus one day gives the TAT for Work Center 41V, which is used in the optimization model to determine the maximum number of engines that can be processed. We subtracted one day from TRR for test cell time because this process is conducted by a different work center.

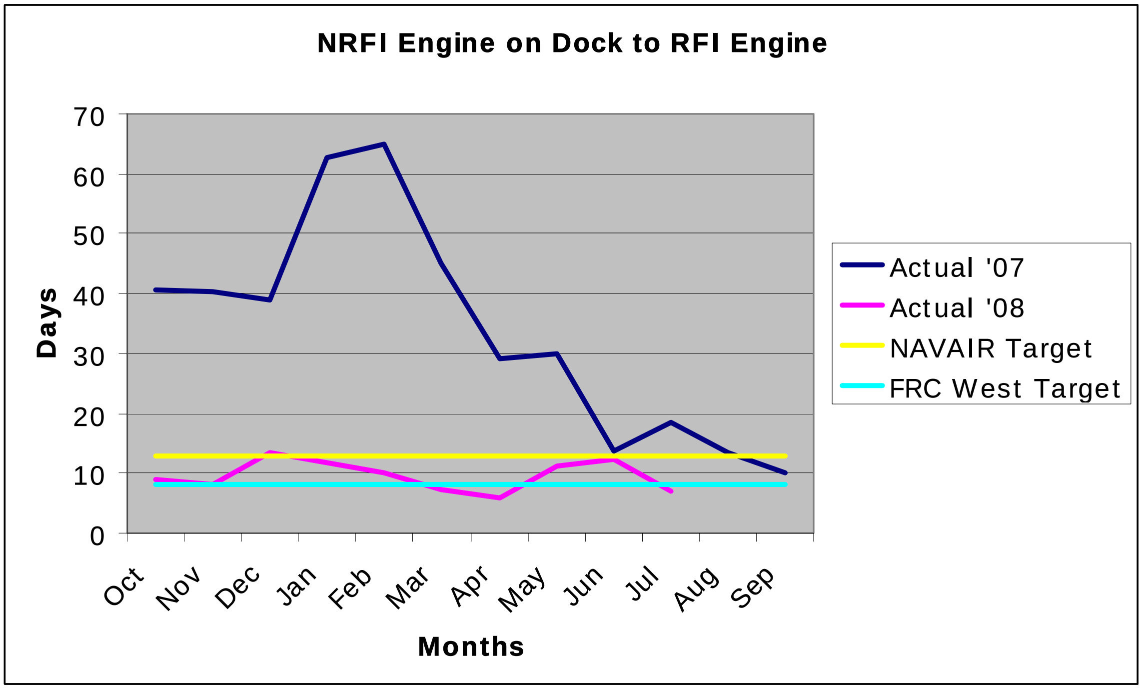

Figure 13. NRFI Engine on Dock to RFI Engine
(After: McCray, 2008, September 10)

(2) NAVAIR TRR Goal. Figure 13 also illustrates the target goal of 13 days established by NAVAIR, as seen in NAVAIR Target. Note that FRC West has met NAVAIR's goal throughout the past year, Actual '08. Following the same principle describe above, we use a TAT of 12 days[3] to calculate the number of engines that the system can process.

b. Calculating Hours to Repair Engine

The following formula calculates parameter Y, the man-hours required to repair each engine at a given TAT of seven days with a three-man crew.

Y = (3 people per engine)*(work hours based on Standard Workweek Ashore)*
(5 work days based on Standard Workweek Ashore)*(TAT)

[3] NAVAIR's TRR goal of 13 days minus one day.

$$Y = \left(\frac{3 men}{1 engine}\right) * \left(\frac{33.38 hours}{1 week}\right) * \left(\frac{1 week}{5 days}\right) * (7 days)$$

$$Y = 140.19 \, manhours \; per \; engine$$

c. Calculating the Demand Hours Required

The following formula calculates the parameter Z, man-hours required each month to meet engine repair demand, where Y is calculated above. To illustrate this calculation, we set forecasted engine demand = 23.

Z =(Y) * (forecasted engine demand)

Z = 140.19 man-hours per engine * 23 engines

Z = 3224.37 man-hours

Based on the value of Z, we consider two demands that must be met: maintenance and inspection. We understand that it is nearly impossible to specify how much CDI time is required on each job because it varies between people and tasks. Therefore, we used three variations of percentage of maintenance demand (MD) and percentage of inspection demand (ID) to cover stated variations:

MD = 90% ID = 10%

MD = 85% ID = 15%

MD = 80% ID = 20%

We solved D_m, the maintenance time to repair an engine, and D_i, the time to inspect an engine, as follows:

$$D_m = MD * Z$$
$$D_i = ID * Z$$

5. Personnel Resources

Current manning level in Work Center 41V is:

AD3 34

AD2 6

AD1 2

a. Maintenanceman

A maintenanceman is a person who possesses the required skills to remove and replace the six engine modules. To obtain such skills, sailors must attend AD-A1 “A”-school, where they learn the minimum skills to become rated as an AD. Second, sailors must attend the Center for Naval Aviation Technical Training to obtain the Navy Enlisted Classification Code 6425 (F414-GE-400 Turbofan Jet Engine Third Degree/IMA Mechanic). Upon completion of the training, sailors can perform apprentice-level maintenance on the engine, satisfying maintenance demand; however, they cannot perform in-process inspections.

b. Collateral Duty Inspector (CDI)

A CDI must meet maintenanceman requirements and possess in-depth knowledge of the F414-GE-400 engine. The NAMP states,

> Due to the importance and responsibility of duties performed by CDIs, it is imperative division officers and work center supervisors carefully screen all candidates for these assignments. CDI candidates will be required to demonstrate their knowledge and ability on the particular equipment by successfully passing a written examination that is locally prepared and administered by QA. In addition to the written examination, a locally prepared oral or practical examination may be used. (Commander, Naval Air Forces, 2008b, p. 7-11)

Based on our experience, most CDIs are at the level of E-5 or E-6, meeting both the maintenance and inspection demand.

6. Personnel Resource Capacity

a. Navy Standard Workweek Ashore

In defining the standard Navy workweek for sailors ashore, we referred to OPNAV Instruction 1000.16K (DoN, 2007). The instruction breaks down the Military Personnel–Ashore (Peacetime) CONUS and OCONUS where accompanying dependents are authorized. Figure 14 shows the workweek for a sailor at FRC West is 33.38 hours per week, accounting for training, service diversion, holidays and leave. To calculate the parameter X, hours that a sailor can work in a month, we used the following formula:

X = (33.38 hours/week)*(52 weeks/year) / (12 months/year)

X = 144.65 hours/month

(1) Accompanying dependents are authorized:

Ship Standard Workweek (Routine is 8 hours per day, 5 days per week, excluding meal hours)		40.00 hrs
Productive Workweek		**33.38 hrs**
Analysis of Duty Hours		
Total hours available weekly		40.00
Less Non-Available Time:		
Training	(1.47)	
Service Diversion	(1.00)	
Leave	(2.62)	(6.62)
Holidays	(1.53)	
Total Hours Available for Productive Work		**33.38**

Figure 14. Standard Workweek Ashore
(DoN, 2007, c-5)

b. Effective Production Rate

The effective production rate is calculated by the amount of time it takes a maintenanceman to produce at a constant rate. When an E-4 enters the work center, he or she has to learn how to use the technical manuals and tools in order to become efficient. The standard shore tour for an E-4 is 36 months, and we assume that within three months, an E-4's effective production rate will equal an E-5's. Table 5 and Figure 14 illustrate effective production rates used to calculate the capacity of FRC West. For example, one E-4 takes 152.93 hours to repair an engine.

Table 5. Effective Production Rate Calculations of E-4 to E-6.

	E-4	E-5	E-6
Effective Production Rate	12/11	12/12	12/13
Hours to Repair an Engine	140.19	140.19	140.19
Hours it would Take to repair	152.93	140.19	129.41

Table 6 gives the Total Effective Man-hours of an E-4 to E-6 within Work Center 41V.

Table 6. Work Center 41V Effective Man-hours Available

Enlisted Pay Grade	Current Availability	Maximum Work Hours per Month	Effective Capacity	Effective Production Time	Total Effective Man-hours
E-4	34	144.65	0.92	132.49	4504.66
E-5	6	144.65	1.00	144.65	867.90
E-6	2	144.65	1.08	156.58	313.16
		Total			**5685.72**

7. Programming Rates for Cost of a Sailor

In calculating the cost of a sailor, we referred to Tallant, Hedrick and Martin (2008). Table 7 calculates "initial granular programming rates for active Navy personnel and it includes a specific portion of manpower costs. These include: base pay, basic allowance for housing (BAH), basic allowance for subsistence, retired pay accrual (RPA), Federal Insurance Contributions Act (FICA), uniform allowances (enlisted personnel only), and unemployment compensation" (Tallant, Hedrick, & Martin, 2008).

Table 7. MPTE Manpower Programming Rates
(Tallant, Hedrick, & Martin, 2008, p. 27)

PR-09 Strength-Only MPN and FTS Programming Rates (STY)					
Grade	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**
O-10	252,160	259,790	267,667	275,571	283,639
O-9	236,948	244,290	251,876	259,490	267,267
O-8	218,510	225,317	232,354	239,401	246,596
O-7	197,802	203,993	210,395	216,790	223,312
O-6	178,573	184,259	190,143	196,028	202,029
O-5	150,079	154,845	159,771	164,862	170,116
O-4	129,133	133,239	137,485	141,873	146,403
O-3	106,585	109,975	113,482	117,106	120,848
O-2	87,255	90,035	92,911	95,885	98,955
O-1	67,684	69,846	72,086	74,403	76,795
W-5	144,773	149,363	154,107	159,010	164,070
W-4	130,050	134,167	138,423	142,820	147,359
W-3	112,480	116,049	119,739	123,554	127,491
W-2	97,855	100,973	104,200	107,536	110,979
Grade	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**
E9	115,928	119,601	123,401	127,327	131,381
E8	96,355	99,425	102,602	105,887	109,279
E7	85,530	88,250	91,065	93,976	96,981
E6	71,837	74,130	76,504	78,960	81,496
E5	58,815	60,679	62,609	64,607	66,669
E4	46,095	47,523	49,003	50,533	52,112
E3	36,383	37,494	38,646	39,837	41,064
E2	31,993	32,925	33,892	34,890	35,917
E1	24,815	25,552	26,318	27,110	27,924

We extracted the costs of the maintenance personnel from Table 7 and calculated them to a monthly basis to keep the same standard of a month through the optimization model. Table 8 shows the monthly costs used for each decision variable.

Table 8. Cost of Decision Variable

Rank	Decision Variable	MPTE Annual	MPTE Monthly
E-4	AD3M	$46,095.00	$3,841.25
E-5	AD2M	$58,815.00	$4,901.25
E-6	AD1M	$71,837.00	$5,986.42
E-5	AD2I	$58,815.00	$4,901.25
E-6	AD1I	$71,837.00	$5,986.42

In Chapter V, we present the analysis results, recommendations we derived from the results, and areas for further research.

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V. Results, Recommendations, and Areas for Further Research

In this chapter, we present our results and recommendations for areas of improvement or concern. We also suggest areas for further research. First, we present results obtained through a Linear Regression of historical data, Double Exponential Smoothing, and an optimization model. Next, we cover recommendations concerning manpower, quality management, cannibalization, safety stock levels, and module induction rates. Lastly, we suggest areas for further research, employing a cost-benefit analysis of FRC locations, a work center bottleneck review, and a need for a measure of corporate knowledge.

A. Results

As we look at the Navy's purchases of F414-GE-400 engines, Super Hornets and Growlers, we see a constant increase over the years. From 2006 to 2009, the Navy budgeted for and acquired 84 engines per year (DoN, 2008). Therefore, it is only logical to deduce that the number of engines FRC West will repair will rise.

1. Based on Linear Regression

Based on the linear regression of the historical data, presented above in Figure 10, the number of engines being repaired is increasing at a rate of .2776 engines per month, roughly one engine per quarter (.2776 * 3 = .8328), or 3.33 engines per year. For 2009, this means that the expected number of engines FRC West will repair will increase from 24.1 to 27.4.

2. Based on Double Exponential Smoothing

By employing the double exponential smoothing method, we show that the number of engines that will require repair is increasing by .2704 per month. That equates to approximately one engine per quarter, or 3.24 engines per year. Again, for 2009, this means the expected number of engines FRC West will repair will increase from 24.2 to 27.5.

3. Based on Optimization Model

First, we ran the optimization model with a TAT of 12 days[4] resulting in the processing of 23 engines by Work Center 41V. This equals FRC West's present repair rate (as seen in Figures 10 and 11). Therefore, if this work center's manning is reduced, they will not be able to keep up with current requirements. Second, by reducing the TAT to nine days, we concluded that FRC West will be able to process 31 engines. Third, by decreasing the TAT to seven days, it could process 40 engines. The result of each scenario is presented in Appendix C.

To come to this conclusion, we solved the model to ensure that the D_m and D_i hours required were satisfied with each variation of MD and ID. The model further concluded that regardless of the MD and ID variations utilized, FRC West could produce the same number of engines for a given TAT. In each scenario, all personnel were utilized with minimal maintenance and inspection slack time remaining. We must emphasize that this model assumes that there is no awaiting parts (AWP) condition to consider (i.e., every time a technician needed a module, it was there).

B. Recommendations

1. Manpower Review

A manpower review should be performed utilizing forecasted demand and TRR. At a minimum, forecasted demand should incorporate historical repair rate and parameters such as flight hours, operational environment, and reliability when calculating the manpower requirement. We believe that the forecasted demand will continue to increase at a constant rate because the Navy is buying more engines at

[4] NAVAIR's TRR goal of 13 days minus one day.

a constant rate of 84 engines a year (DoN, 2008). As this engine matures, more engines will require induction as they approach their high-time window.

2. Manage Quality

Careful consideration should be taken before reducing the TRR of the engine below its current level. We demonstrated mathematically that they are now operating at or near 100% capacity. The only way that TRR will continue to decrease is by eliminating the stock-outs, decreasing cannibalization actions, increasing workstations, and increasing manning. History has shown that working hard to meet the deadline does not fix the problem; it only encourages disorganization and negatively-adjusted deadlines. As quality slips in any industry so do the amount of returns. Increasing returns is the same as increasing demand—requiring more rework and an increased consumption of man-hours.

3. Decrease Modules Based on MTBF

We found that the mean time between failure (MTBF) equals the mean time since repair (MTSR) (as seen in Table 9) and is decreasing on five of the six engine modules. That is to say, it is failing at a higher rate and increasing engine inductions and module demand at FRC West.

Table 9. MTSR of Engine Modules

Module	MTSR in Hours JAN-JUN 2008	MTSR in Hours JAN-DEC 2007	MTSR in Hours JAN-DEC 2006
Compressor	669	699	706
Fan	841	900	947
HPT	900	858	912
LPT	1036	1064	966
Combustor	882	901	885
Afterburner	634	664	691

C. Areas for Further Research

1. Cost-benefit Analysis to Move Depot

A cost-benefit analysis should be performed to determine if moving the F414-GE-400 depot facility in Jacksonville, FL, to FRC West is feasible. We toured both FRC Southeast and FRC West and believe that the facilities are available to support moving the required equipment to perform the depot repairs at FRC West. Before moving the depot, an analysis should be conducted to see if there are a sufficient number of skilled artisans located in or around Lemoore, CA, that could support the maintenance demand of repairing the modules.

By moving the depot to FRC West, cost savings can be realized by way of reduced shipping costs and in-transit inventory. Figure 15 is a simple illustration of spare modules in transit between FRC West and FRC Southeast. Little's Law states that I=R*T, where I is the inventory, R is the rate at which we ship and T is the time it takes to ship modules between FRC Southeast and FRC West. Time is 16 days, which equals the sum of days in Figure 15.

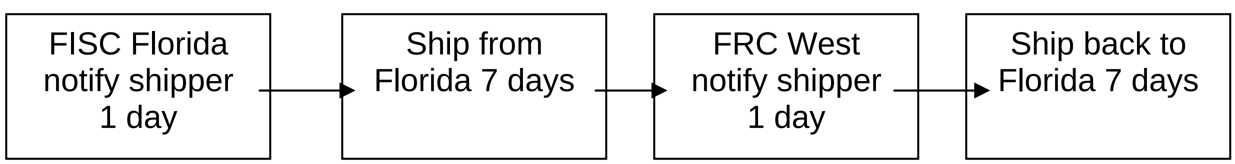

Figure 15. Inventory Shipment Flow

In this case, we are arguing that time can be reduced because shipping time between FRC Southeast and FRC West will be eliminated. As Little's Law states, if time is reduced then inventory is reduced. We present Tables 10 and 11 to illustrate a quick cost-savings analysis. In Table 10, the total number of modules shipped to

FRC West is 68%[5] of FRC Southeast's FY-09 module inductions. To determine the modules shipped per week, we divided the total number of modules by 52 (the number of weeks in a year).

Table 10. Weekly Module Demand Calculations

Modules	FRC Southeast FY-09 Module Inductions	Total # of Modules Shipped to FRC West	Modules Shipped per Week
Fan Module	206	140.08	2.69
Compressor Module	253	172.04	3.31
HPT Module	225	153.00	2.94
LPT Module	221	150.28	2.89
Combustor Module	210	142.80	2.75

Using Little's Law, we calculated the inventory in shipment. In Table 11, we multiplied the inventory in shipment by the cost of each module and then summed the cost to calculate the total cost of inventory in shipment.

Table 11. Cost of Module Inventory in Shipment

Modules	Modules Shipped per Week	Inventory in Shipment	Cost of each Module	Cost of Inventory in Shipment
Fan Module	2.69	6.16	$480,170.00	$2,956,580.82
Compressor Module	3.31	7.56	$865,302.00	$6,543,584.88
HPT Module	2.94	6.73	$214,218.00	$1,440,674.90
LPT Module	2.89	6.61	$633,456.00	$4,184,429.35
Combustor Module	2.75	6.28	$193,907.00	$1,217,139.32
Total Cost of Inventory in Shipment				**$16,342,409.27**

[5] The percentage of all engine repairs performed by FRC West last year.

By co-locating the depot and AIMD, the Navy could eliminate these modules and realize a cost savings of over $16 million. Additionally, another cost savings would be the elimination of the shipping fees.

2. Review Potential Bottleneck in Afterburner Repair Shop, Work Center 413

We found that the demand for the modules is constantly changing (i.e., the demand for one module will change and leave FRC West in an AWP situation, forcing a work stoppage or a cannibalization action). The fleet managers who maintain the engine do a great job by moving components to ensure that the supermarket stays full. For the most part, the management process works well, but it does not prevent stock-outs. When we visited FRC West, there was an AWP situation for two LPT Modules.

Another crucial bottleneck within FRC West is the repair of the AB Module due to the high AWP time of 81% of the total TRR, as shown in Figure 16. In FY-07, FRC West repaired 266 F414-GE-400 engines and 261 AB Modules, concluding that 100% of the engines inducted for repair had the AB Module repaired. Historical data over the past year shows the AB Module TRR at 14.87 days, where AWP is 12.08 and TAT is 2.79 days. That is to say that the fastest FRC West can repair an engine is set at the rate of the AB Module, assuming the AB needs to be repaired.

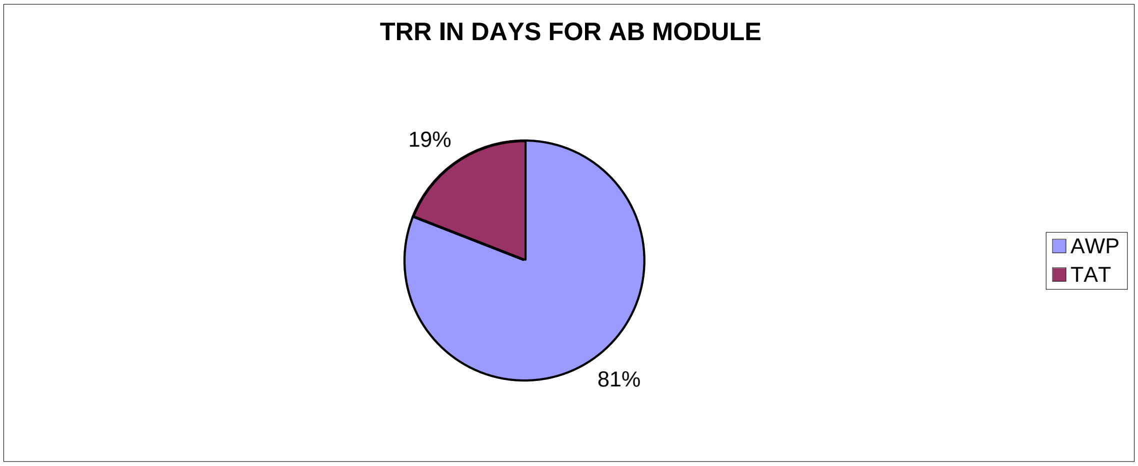

Figure 16. Percent of TRR for AWP and TAT in Days

3. Measuring Corporate Knowledge

The FRC concept was built around reducing TAT, BCMs and lowering costs by using artisans at the correct point. Within FRC West there is a team of five artisans who work within the Power Plants Division to service depot-level repairs. Through cost-benefit analysis, it was determined that the artisans were no longer required because it was not cost-effective to employ them. However, the lost corporate knowledge is irreplaceable. Many of the sailors within the Power Plants Division turn to these artisans for sound advice on module inspection limitations. Removing these artisans from FRC West will only increase the number of modules shipped to FRC Southeast for repair because the artisans are capable of performing minor repairs on site to certain modules. They also assist sailors in determining if a module should be shipped to the depot for overhaul. As managers, we must think about the cost of the corporate knowledge lost and not solely focus on the cost-savings of cutting personnel.

4. Safety Stock Evaluation

To prevent cannibalization of the safety stock within the supermarket, FRC West should be reviewed annually along with the forecasted demand and MTBF of each module. By carefully calculating the safety stock level and supplying the supermarket to meet module demand, it is possible to eliminate module AWP conditions. The optimization model we ran did not consider AWP. As managers, we should continue to push for process improvement within the supply chain to eliminate such conditions.

Once modules are in FRC West's supermarket, they should not be shipped to fill the demands of the carriers in the fleet. By doing this, managers are introducing a failure into the system. However, if supermarket assets are considered pooled assets for the entire Navy, then the consolidate modules must be appropriately calculated. That is to say, by consolidating the modules it will decrease the overall module requirement, but the supermarket pool will increase.

One must understand the safety stock levels presented in Table 12 were made to satisfy FRC West and not the fleet. That being said, if FRC supermarket is at the required level, modules should not be shipped to them; let modules sit at Fleet Industrial Supply Center Florida until a demand is created by the fleet. This will save on double shipping costs and allow the system to work more efficiently.

Table 12. RFI Engine Module Supermarket at FRC West
(After: Traylor, 2008)

	Engine	FAN	HPC	Comb	HPT	LPT	A/B
Target Size (Preliminary)	12-15	16-23	19-28	16-22	18-23	15-18	5-8
Current Status	10	37	22	7	23	39	6

VI. Conclusion

Our project introduced a current issue, gave a background description with a literature review in order to relate our course of study to the problem at hand, and then analyzed areas in which we thought relevant changes could be made. The results of the analysis section support our initial claims and provide a starting point for additional research in several areas.

We conclude that FRC West is repairing F414-GE-400 engines at nearly 100% of their manpower capacity. Using the forecasting model, we were able to determine that the rate at which the engines are arriving is increasing over time. As the engine matures and the Navy continues to procure additional F/A-18E/F Super Hornets and EA-18G Growlers, the demand will continue to increase until it reaches a constant rate. The expected demand slope will gradually decrease to zero as the engine comes to the end of its lifecycle and is replaced with a new system. At the end of the lifecycle of any system, managers should look at ways of re-allocating personnel resources and the positioning of facilities to maximize efficiency with the supply chain of new defense systems.

In our recommendations' section, we suggested that a manpower review be done for the entire FRC West Power Plants Division, taking into consideration the forecast we developed. Proper manpower levels will directly connect to the quality of the product and reduce areas of possible rework due to inefficient staffing that may cause work to be rushed. The safety stock within the supermarket should be re-evaluated as demand increases to ensure proper levels are set. Having a proper safety stock reduces the level of uncertainty and prevents a stock-out situation or cannibalization action, allowing the system to continue to operate.

Second, we suggested that a cost-benefit analysis be conducted in moving the F414-GE-400 depot from FRC Southeast to FRC West. If the benefits outweigh the cost, every effort should be made to ensure that valued artisans at FRC

Southeast are realigned to operate with current and future weapon systems in order to retain the immeasurable corporate knowledge.

Finally, we determined that the highest rate at which FRC West can produce is directly related to Work Center 413's ability to repair AB Modules. The AWP time on this bottleneck should be reduced so that the TAT of Work Centers 41V and 413 are as close as possible, maximizing the output capacity of the division. Bottleneck situations can exist in any system. Identifying these conditions and adjusting their performance will improve overall system performance and lead to greater efficiency and utilization rates. It is paramount that we stay vigilant and manage the system to its constraints.

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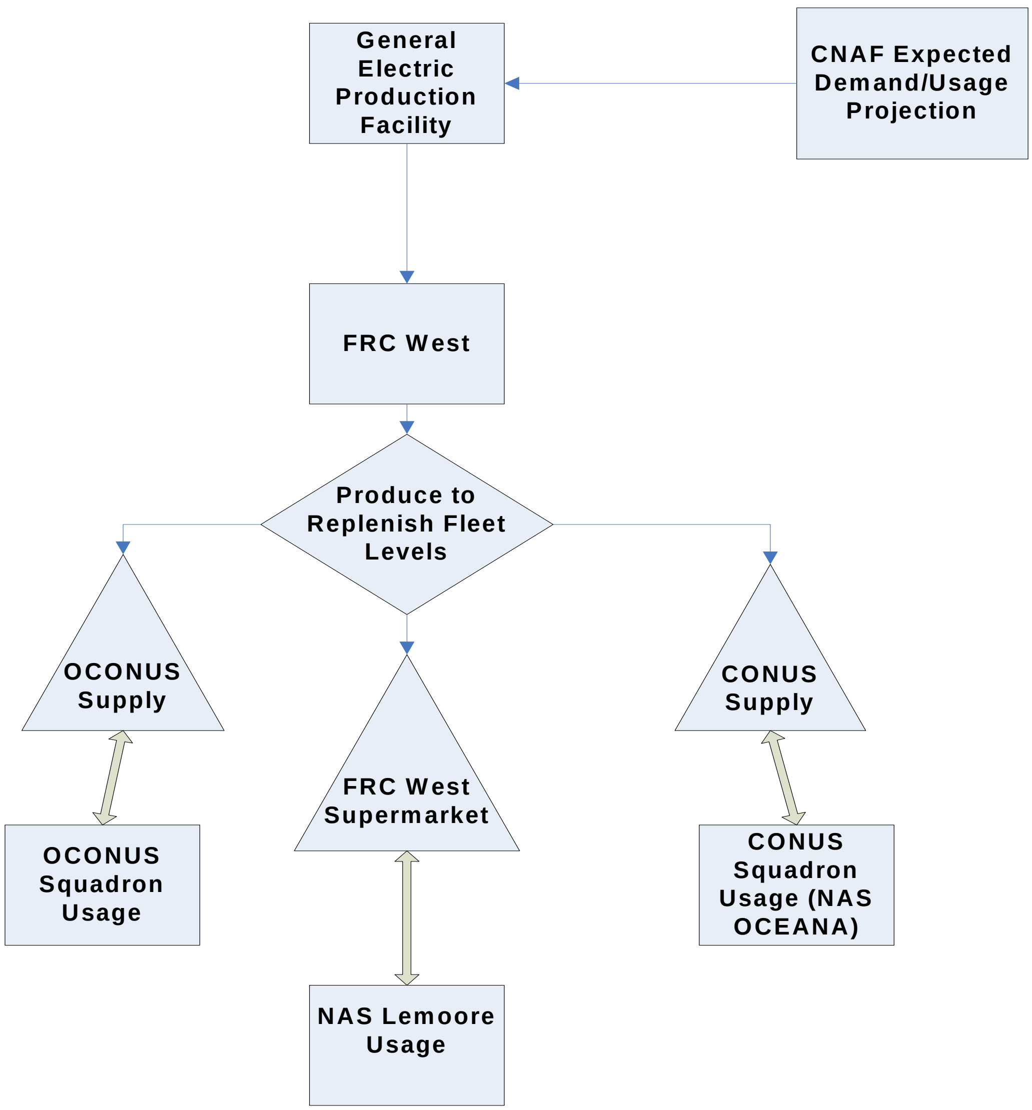
Appendix A. Macro Level Flow Chart for F414-GE-400

Macro Level Flow Chart for F414-GE-400



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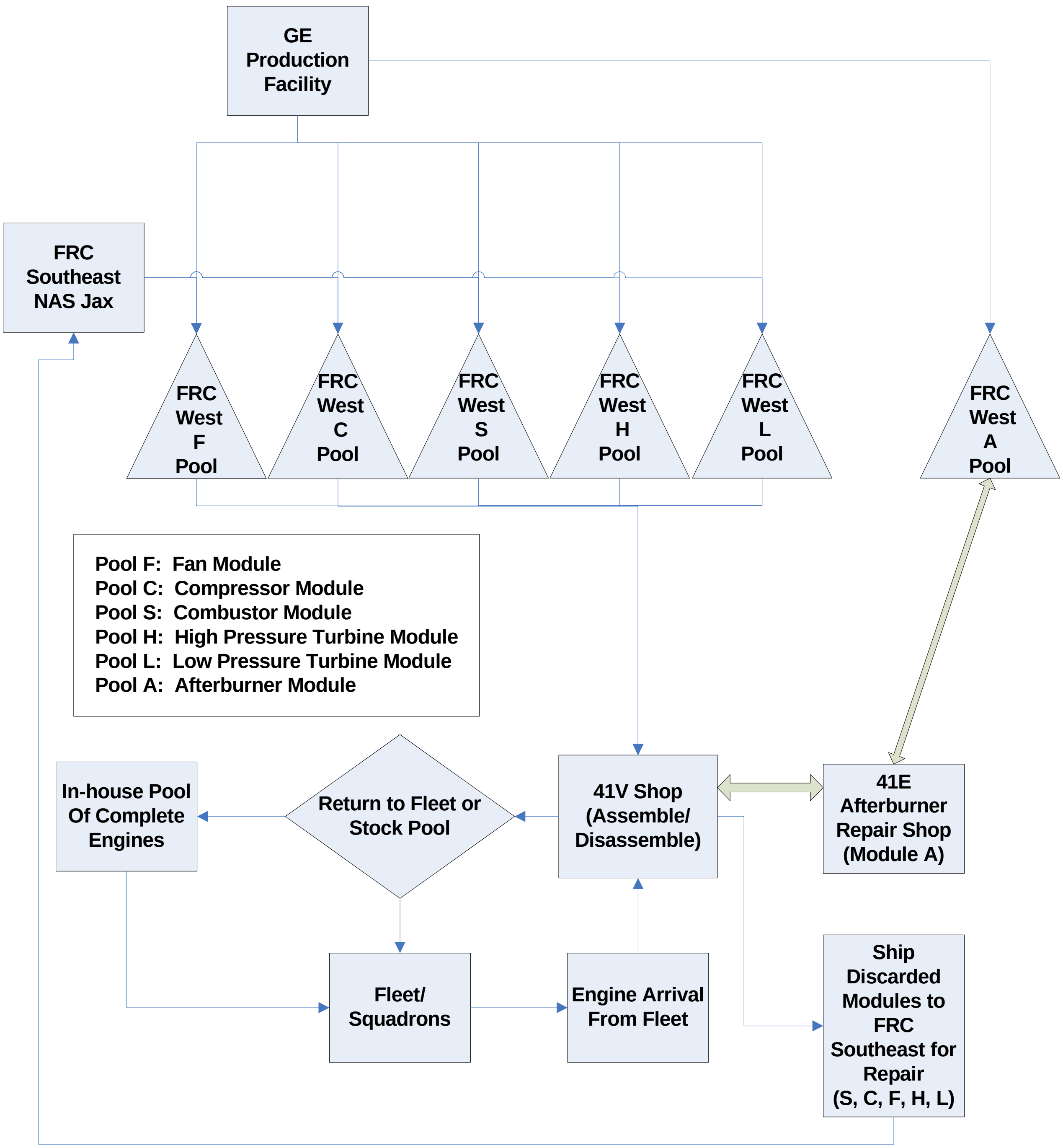
Appendix B. FRC West Flow Chart

FRC West Flow Chart



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Appendix C. TAT

TAT 7 Days

	Percentage MD/ID		
	90/10	85/15	80/20
AD3	34	34	34
AD2	6	6	6
AD1	2	2	2
Engine Repair Capacity	40	40	40
Slack, Maintenance	35.7	39.1	18.4
Slack, Inspection	41.45	38.1	58.8
AD3M Used	34	34	34
AD2M Used	0	1	4
AD1M Used	0	1	0
AD2I Used	6	5	2
AD1I Used	2	1	2

TAT 9 Days

	Percentage MD/ID		
	90/10	85/15	80/20
AD3	34	34	34
AD2	6	6	6
AD1	2	2	2
Engine Repair Capacity	31	31	31
Slack, Maintenance	53.7	44	34
Slack, Inspection	43.4	53	62.4
AD3M Used	34	34	34
AD2M Used	4	2	0
AD1M Used	0	0	0
AD2I Used	2	4	6
AD1I Used	2	2	2

TAT 12 Days

	Percentage MD/ID		
	90/10	85/15	80/20
AD3	34	34	34
AD2	6	6	6
AD1	2	2	2
Engine Repair Capacity	23	23	23
Slack, Maintenance	131.9	119.2	82.5
Slack, Inspection	25.3	38	74.8
AD3M Used	34	34	34
AD2M Used	2	0	0
AD1M Used	2	2	0
AD2I Used	4	6	6
AD1I Used	0	0	2

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