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Systems Engineering Processes for the Acquisition of Prognostic and Health Management Systems

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

SYSTEM ENGINEERING PROCESSES FOR THE ACQUISITION OF PROGNOSTIC AND HEALTH MANAGEMENT SYSTEMS

by

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September 2012

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Prognostic and Health Management (PHM) systems often experience delayed fielding and lengthened maturation cycles due to their relative immaturity and the fact that they are regarded as non-flight critical systems. The national fiscal crisis and rising debt of the U.S. have each placed increased scrutiny on military systems acquisition and procurement practices. The Defense Department is pushing for greater emphasis on fundamental systems engineering practices earlier in the acquisition phase, with the expectation of fewer schedule slips and budget overruns. The acquisition of PHM systems could also benefit from increased systems engineering rigor early in their development. A 2007 directive from the DoD states that PHM systems be implemented into current weapon systems equipment, and materiel sustainment programs where technically feasible and beneficial. This research examines the definition of PHM requirements and a method for developing a solution neutral architecture for PHM systems. The thesis also identifies software development practices and acquisition processes for military propulsion PHM systems. The conclusion of this research is that the Defense Department can deliver the warfighter a capable PHM system on-time and within budget through the establishment of better procurement and systems engineering practices.

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SYSTEMS ENGINEERING PROCESSES FOR THE ACQUISITION OF PROGNOSTIC AND HEALTH MANAGEMENT SYSTEMS

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ABSTRACT

Prognostic and Health Management (PHM) systems often experience delayed fielding and lengthened maturation cycles due to their relative immaturity and the fact that they are regarded as non-flight critical systems. The national fiscal crisis and rising debt of the U.S. have each placed increased scrutiny on military systems acquisition and procurement practices. The Defense Department is pushing for greater emphasis on fundamental systems engineering practices earlier in the acquisition phase, with the expectation of fewer schedule slips and budget overruns. The acquisition of PHM systems could also benefit from increased systems engineering rigor early in their development. A 2007 directive from the DoD states that PHM systems be implemented into current weapon systems equipment, and materiel sustainment programs where technically feasible and beneficial. This research examines the definition of PHM requirements and a method for developing a solution neutral architecture for PHM systems. The thesis also identifies software development practices and acquisition processes for military propulsion PHM systems. The conclusion of this research is that the Defense Department can deliver the warfighter a capable PHM system on-time and within budget through the establishment of better procurement and systems engineering practices.

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LIST OF ACRONYMS AND ABBREVIATIONS

AT&L	Acquisition Technology & Logistics
BIT	Built-In Test
CBM	Condition Based Maintenance
CBM+	Condition Based Maintenance Plus
CDP	Concept Demonstrator Phase
CONOPS	Concept of Operation
DoD	Department of Defense
EMS	Engine Monitoring System
EVMS	Earned Value Management System
FADEC	Full Authority Digital Electronic Control
FMECA	Failure Mode Effects and Criticality Analysis
FOD	Foreign Object Damage
GAO	Government Accountability Office
HUMS	Health and Usage Management System
IECMS	In-flight Engine Condition Monitoring System
IPT	Integrated Product Team
JSF	Joint Strike Fighter
JSFPO	Joint Strike Fighter Program Office
LCC	Life Cycle Cost
MUIRS	Maintainability Upgradability Interfaces Reliability Security
O&S	Operation & Sustainment
PHM	Prognostics and Health Management
RCM	Reliability Centered Maintenance
SEF	Systems Engineering Fundamentals
SFET	Seeded Fault Evaluation Test
SLOC	Source Lines of Code
SoS	Systems of Systems

TRL	Technology Readiness Level
V&V	Verification and Validation
WBS	Work Breakdown Structure

EXECUTIVE SUMMARY

PHM systems are meant to replace legacy schedule-based maintenance systems and it is important for acquisition professionals to manage customer expectations. The research will show that it is the responsibility of program managers and systems engineers to field capable CBM+ systems early in the weapon system life cycle, such that the system and the overarching CONOPS can be optimized and matured. Some keys to delivering capable PHM systems closer to budget and cost targets are:

1. Incentivize Program Management to focus on Life Cycle Cost Savings
2. Involve the end-user beyond the requirements development phase
3. Manage warfighter expectations to minimize Taguchi losses
4. Plan to support PHM software throughout the weapon system life cycle

This research provides a useful reference to program managers and systems engineers tasked with the implementation of Prognostic and Health Management (PHM) systems. It presents the acquisition of these systems within the framework of systems engineering process and also provides acquisition strategies for PHM hardware and software products.

The establishment of stakeholder requirements for PHM systems is enabled by an understanding of legacy maintenance practices and an assessment of the technologies currently available to replace schedule-based maintenance practices. This research examines these maintenance practices and presents a strategy for evaluating PHM technologies.

The next step in this systems engineering analysis of a PHM system is the establishment of a notional architecture. This solution neutral approach helps us model the system without any pre-conceived notions of how to solve the problem. Once this high-level architecture is presented the research discusses software development. Systems engineering processes and an evolutionary approach to software development are identified as necessary elements to an on-time and on-budget delivery.

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I. INTRODUCTION

A. BACKGROUND

Prior to the F-35 Joint Strike Fighter (JSF) Program, the A-7 Corsair II was the last single engine fighter in the Navy tactical aviation fleet. According to GlobalSecurity.org, “the A-7 began combat operations in December, 1967, and proved to be one of the most effective Navy close support and strike aircraft during the Vietnam War [1].” The A-7 was also the platform that marked the beginning of on-board engine health monitoring for the Navy. A brief given by Andrew Hess at an NDIA Conference in 2001 states, “the engine monitoring system (EMS), developed by Navy engineers, tracked engine parameters and used two vibration transducers to detect anomalies in the mechanical health of the engine. The EMS was a successful technological advancement on the A-7 and eventually reduced engine related accident rates by 90% and reduced maintenance man hours [2].”

The Health and Usage Monitoring System (HUMS) developed for military helicopters greatly advanced the state of mechanical diagnostics. This system architecture was mainly composed of vibration sensors mounted on the propulsion system and throughout rotary wing drivetrains. The current engine monitoring system being developed for the JSF is known as Prognostics and Health Management (PHM). According to their website, “the JSF Program has leveraged advances in sensing technologies and processing capabilities to develop an integrated engine monitoring system with the ability to detect impending failures well in advance, thus increasing fleetwide safety and decreasing operating costs [3].”

The Navy has had an increased focus and commitment to advancing the technological capability of engine monitoring systems in each air system procured since the A-7. Figure 1 loosely illustrates the evolution of diagnostic systems in Navy aircraft since the late 1960s.

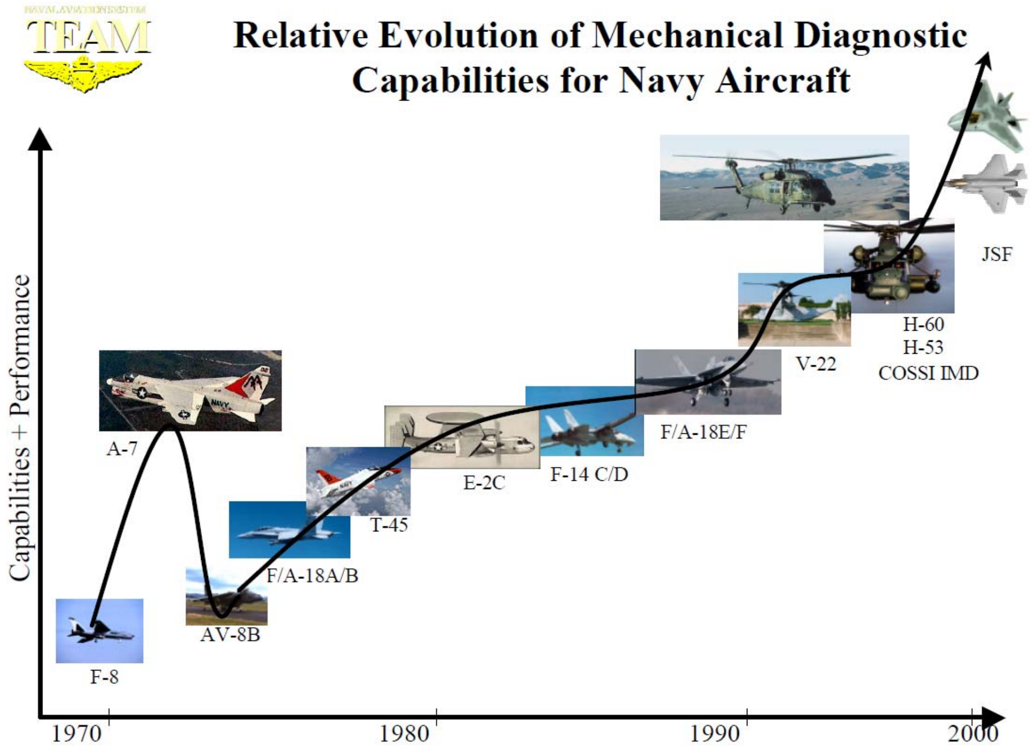

Figure 1. Evolution of EMS in Naval Aviation. From [2]

A DoD Instruction titled *Condition Based Maintenance Plus for Materiel Maintenance* states that "CBM+ is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components [4]." The instruction also mandates that all acquisition programs must implement a CBM+ strategy and concept of operation (CONOPS) "into current weapon systems, equipment, and materiel sustainment programs where technically feasible and beneficial [4]." For the Navy and their aviation propulsion systems, the implementation of this DoD Instruction will eliminate scheduled inspections of turbomachinery and enable the health assessment of components based on their actual usage and life remaining. This, in turn, will lower sustainment costs and increase fleet readiness.

B. PURPOSE

The largest life cycle cost associated with military aircraft is not the unit price or the cost of the multi-year development programs: rather, it is operation and sustainment (O&S) costs. The life cycle of military aircraft varies by model, but it is usually no less than 25 years. The cost associated with operating and supporting these aircraft is usually between 65% to 80% of the entire life cycle cost.

The DoD has recognized the need to control O&S costs and is taking steps to reduce them for future aviation programs. Figure 2 illustrates that O&S comprises the largest portion of the weapon system lifecycle. It is, therefore, the area with the most potential for cost savings.

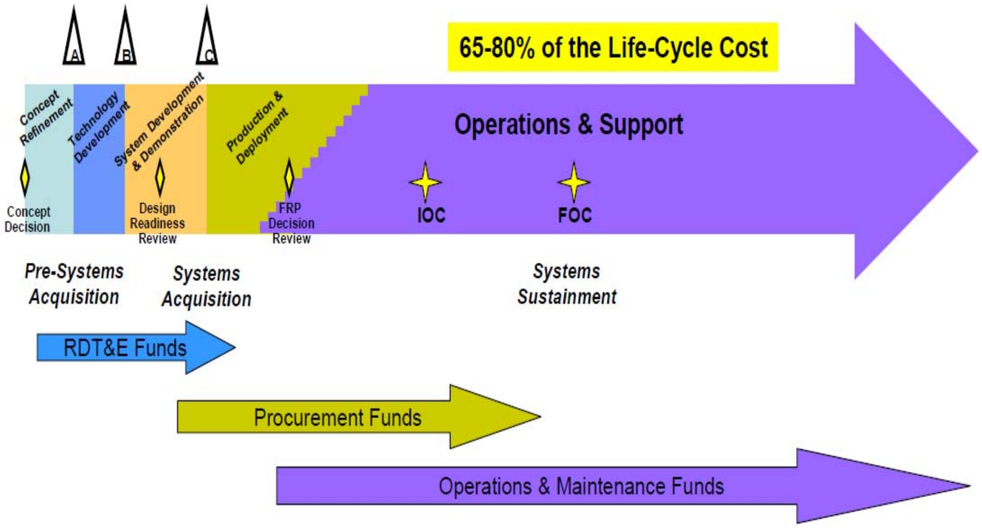

Figure 2. Weapon System Life Cycle Illustrates that O&S Represents a Majority of Life Cycle Costs. From [5]

The DoD mandate to implement PHM technologies and a CBM+ strategy are meant to specifically target cost savings in this area. The benefits of the system go beyond O&S cost savings, however. According to Andrew Hess, "PHM can also enhance mission reliability and aircraft safety, eliminate scheduled inspections, eliminate "cannot duplicates and retest OK's," reduce aircraft downtime, provide opportunistic maintenance, and detect incipient faults [6]."

Over the past decade, there has been a substantial increase in the amount of military spending. Figure 4 illustrates the trend in defense spending since 2001. The large number of new defense acquisition programs has brought with it a greater scrutiny of the cost overruns and schedule delays that have plagued weapon systems acquisition.

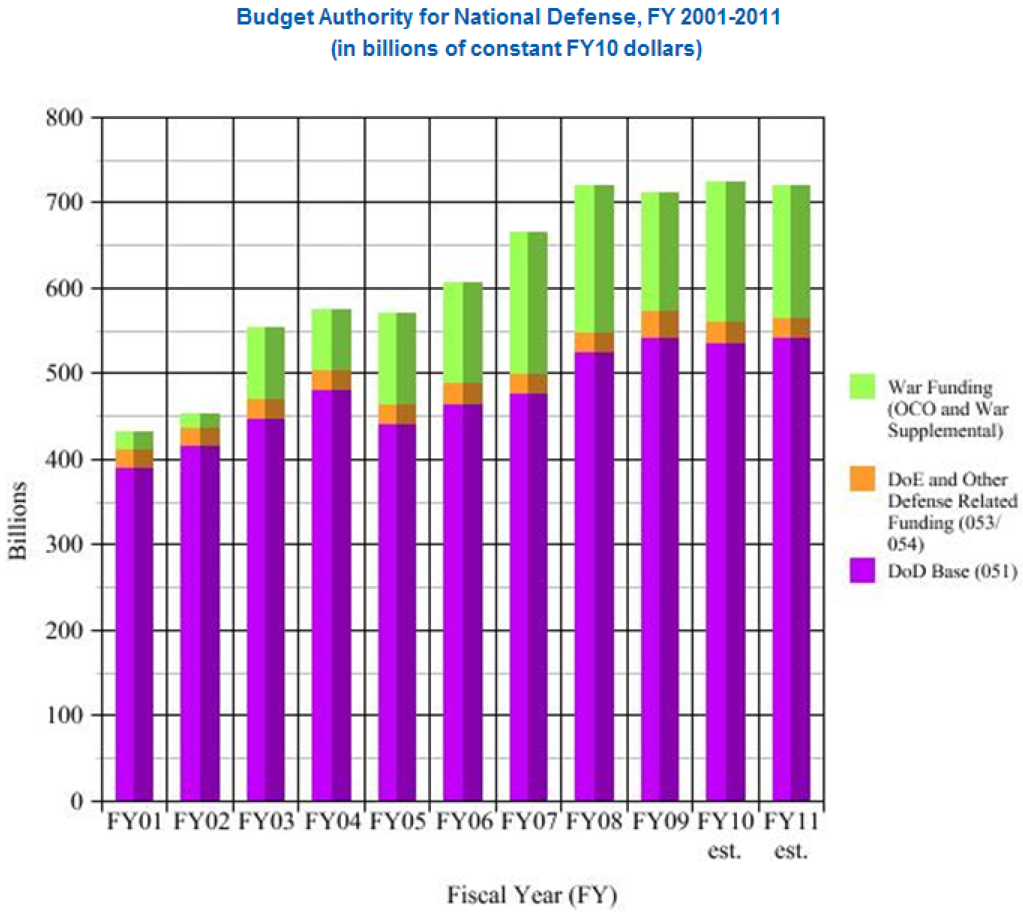

Figure 3. Defense Spending Profile. From [7]

The DoD has placed a greater emphasis on fundamental systems engineering practices earlier in the acquisition phase, with the expectation of fewer schedule slips and budget overruns. Legacy acquisition programs have shown that PHM systems often experience delayed fielding and lengthened maturation cycles. The current acquisition strategies used by the DoD could benefit from increased systems engineering scrutiny and rigor early in their development. The purpose of this research is to investigate how PHM systems and architectures have evolved and identify ways to leverage systems engineering, program management, and systems acquisition practices to procure and field more effective PHM system.

This thesis is meant to provide Systems Engineers and Program Managers a resource for the acquisition of more effective propulsion PHM systems. The research outlines processes for establishing requirements, defining a notional architecture and developing software for PHM systems and presents them within the systems engineering process. It also provides acquisition strategies and lessons learned based on legacy PHM systems. These systems are required for many DoD weapons and improved systems engineering processes tailored for PHM systems acquisition will improve cost and schedule.

C. RESEARCH QUESTIONS

This thesis will examine the systems architecture evolution of military aircraft propulsion diagnostic systems. The analysis will start with early military aircraft diagnostic systems and continue through the current Prognostic and Health Management (PHM) systems currently being developed and fielded. The thesis will also identify heuristics and strategies to improve acquisition strategies for procuring PHM systems. The following research questions will provide a roadmap for answering the overarching research question.

1. How do we establish requirements for propulsion PHM systems?
2. What process can we use to define a high-level solution neutral PHM system architecture?
3. What systems engineering process can be used to develop software for PHM systems?

4. Can the Defense Department deliver the Warfighter a capable PHM system on-time and within budget through the establishment of better procurement and systems engineering practices?

D. BENEFITS OF STUDY

This research will be used to recommend improvements to the acquisition of PHM systems. The research will identify fundamental systems engineering aspects in the procurement of PHM systems and offer ways to field more capable systems earlier in the weapon system lifecycle.

E. SCOPE

The focus of this thesis is limited to propulsion PHM systems for fixed wing tactical fighters. This research will employ systems engineering processes and tools to identify ways to maximize the value and capability of these PHM systems.

F. METHODOLOGY

The needs analysis phase developed by Kossiakoff defines the methodology used in approaching the research. Kossiakoff describes the needs analysis as “part of the conceptual exploration phase;” it was therefore useful in developing an outline for this research [8]. The operational deficiencies and technical opportunities, as illustrated in Figure 5, are inputs to the needs analysis.

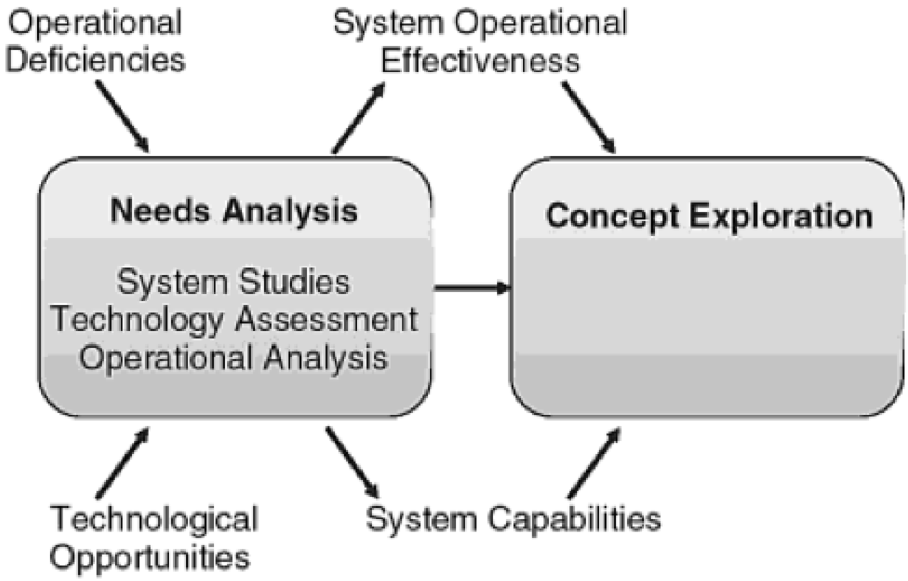

Figure 4. Kossiakoff - Needs Analysis. From [8]

For the purposes of this research, the operational deficiencies represent the legacy maintenance practices used to maintain DoD propulsion systems and the technical opportunities are the CBM+ systems meant to replace them. The legacy maintenance practices are only operationally deficient in the sense that there exists a mandate to replace them with technology driven solutions that whereby the DoD can potentially realize O&S cost savings. This research will identify methods for leveraging these technological opportunities using systems engineering best practices. In Chapter II, a requirements analysis of PHM systems is developed. This section uses System Studies to examine legacy systems that have implemented PHM systems. The research will also perform a Technology Assessment of the PHM sensors and examine how the F-35 program used this assessment to downselect its sensing suite. The synthesis of these concepts provides a foundation to establish some notional requirements for a PHM system. In Chapter III, the architecture for this notional system is developed along with software development. This system architecture represents the output of the needs analysis phase, which then leads to Concept Exploration. The concept in this block is represented by the final research question presented in the previous section: Can the

Defense Department deliver the Warfighter a capable PHM system on-time and within budget through the establishment of better procurement and systems engineering practices? Chapter IV will examine these process and practices and identify some of the issues associated with the acquisition of PHM systems. Chapter V will compile the research and provide heuristics for future acquisition programs.

This research also follows a framework similar to the PD-21 curriculum at the Naval Postgraduate School. The program initially focused on systems engineering principles and concepts, while the latter part was dedicated to the author's chosen concentration in systems acquisition. The first three chapters of this research provide a systems engineering foundation for PHM systems and the overarching CBM+ architecture they are meant to support. The final two chapters integrate these systems engineering concepts, but focus on coursework related to the acquisition concentration. Overall, the research is meant to explore the design, development, and acquisition of PHM systems, while applying the concepts and principles presented during the PD-21 coursework.

II. LITERATURE REVIEW

A. INTRODUCTION

The research in this thesis builds upon concepts presented in various sources. However, the DoD CBM+ guidebook provides the foundation for the requirements and architecture sections of this research. The foreword of the guidebook, provided by Jack Bell, Deputy Undersecretary of Defense for Logistics and Materiel Readiness, states that “it was developed to be an information reference as well as a tool to assist logistics managers with CBM+ project development, implementation, and execution [5].” This thesis is also meant to be an information reference and tool to assist the developers of PHM systems. This research will leverage the processes in the CBM+ Guidebook, present them within the systems engineering process and tailor them to PHM Systems.

According to DoD Instruction 4151.22, “CBM+ is maintenance performed based on evidence of need provided by Reliability Centered Maintenance (RCM) analysis and other enabling processes and technologies. CBM+ uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, sustainment, and operations [4].” The systems engineering approach used by CBM+ is also discussed with greater detail in the CBM+ Guidebook. It states that “systems engineering is the overarching process that a program team applies to move from a required capability to an operationally effective and suitable system. Systems engineering processes are applied early in concept refinement, and then continuously applied throughout the system’s life cycle. Program managers and life-cycle logisticians should consider the effect system development decisions (such as the application of the CBM+ strategy) will have on the long-term operational effectiveness and the logistics affordability of the system. The cost to implement a system change, including supportability enhancements, increases as a program moves further along its life cycle. CBM+ has the greatest leverage in the early stages of development, when the program design is most flexible [5].” This research aims to explore the early stages of development for PHM systems where flexibility provides system developers the opportunity to perform trades on various design criteria. For the purposes of this research, these early stages include the requirements and architecture definition.

The CBM+ guidebook also states that it “presents key elements and implementation strategies for achieving incorporation of CBM+ enablers into the DoD maintenance process [5].” It is important to understand how PHM fits within the system of systems that comprise CBM+. The following sections discuss concepts presented in the DoD CBM+ Guidebook as well as several other related sources to provide a baseline understanding of the maintenance concepts upon which this research builds.

B. CONDITION BASED MAINTENANCE PLUS (CBM+)

The CBM+ guidebook states that “CBM+ is not a single process in itself. It is a comprehensive strategy to select, integrate, and focus a number of process improvement capabilities, thereby enabling maintenance managers and their customers to attain the desired levels of system and equipment readiness in the most cost effective manner across the total life cycle of the weapon system. CBM+ includes a variety of interrelated and independent capabilities and initiatives—some procedural and some technical that can enhance basic maintenance tasks [5].”

A discussion of components of CBM+, as found in Figure 5, provides necessary background for the research presented in subsequent chapters. Reliability centered maintenance is another process used by the DoD to enable informed maintenance practices. The Office of the Secretary of Defense defines RCM as “a logical, structured process used to determine the optimal failure management strategies for any system, based on system reliability characteristics and the intended operating context. RCM defines what must be done to a system to achieve the desired levels of safety, reliability, environmental soundness, and operational readiness, at best cost. RCM is to be applied continuously throughout the life cycle of any system [9].”

In his paper *Defining Requirements for Advanced PHM Technologies for Optimal Reliability Centered Maintenance*, Dr. Richard Millar states that “RCM provides a logical decision process for determining optimum maintenance approaches and establishes the evidence of need for both reactive and proactive maintenance. RCM is used along with the propulsion system FMECA[1] to identify capability gaps in the fault detection. Given a reasonably representative FMECA and a baseline suite of proven PHM tools, a rigorous RCM analysis should yield PHM functional requirements and preferred state of the art technical approaches. If this fails to meet weapon system objectives, we may need to make tradeoffs between safety, availability, initial and recurring costs, and weapon system performance [10].” Figure 5 illustrates the means by which CBM and RCM, combined with systems engineering principles and PHM capabilities, form CBM+.

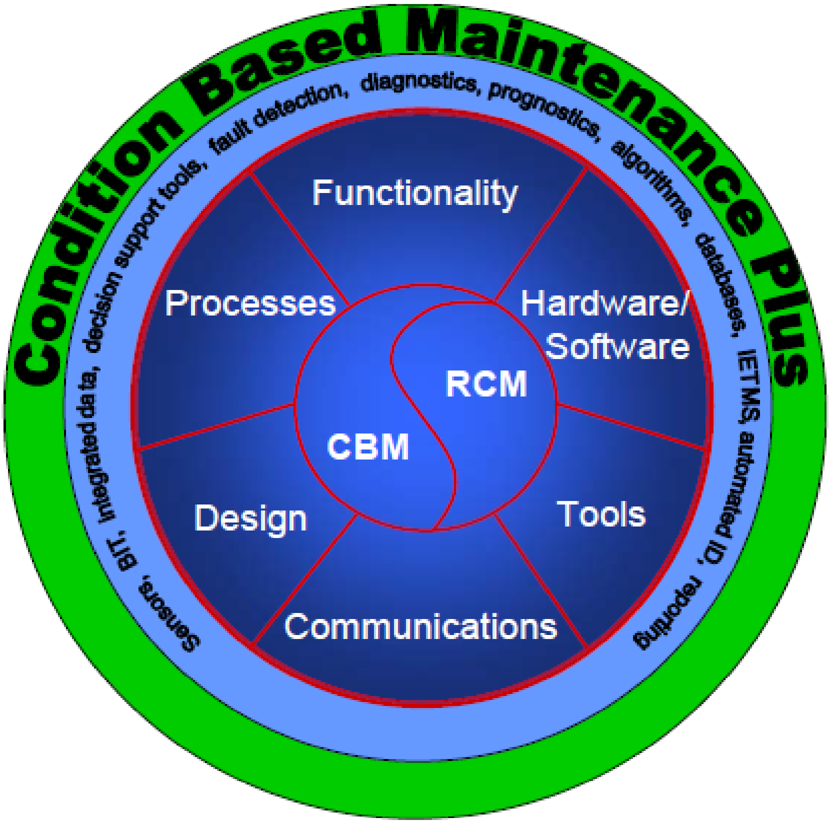

Figure 5. Various Systems and Processes that Comprise Condition Based Maintenance Plus. From [5]

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[1] FMECA—Failure Mode Effects and Criticality Analysis. Process used to determine the functions, functional failures, and failure modes of equipment; and the associated effects, severity, and frequency of each failure modes [11].

The CBM+ guidebook states that CBM+ includes, but is not limited to, the following examples:

- Hardware—system health monitoring and management using embedded sensors; integrated data bus
- Software—decision support and analysis capabilities both on and off equipment; appropriate use of diagnostics and prognostics; automated maintenance information generation and retrieval
- Design—open system architecture; integration of maintenance and logistics information systems; interface with operational systems; designing systems that require mini- mum maintenance; enabling maintenance decisions based on equipment condition
- Processes—RCM analysis; a balance of corrective, preventive, and predictive maintenance processes; trend-based reliability and process improvements; integrated information systems providing logistics system response; Serialized Item Management
- Communications—databases; off-board interactive communication links
- Tools—integrated electronic technical manuals (i.e., digitized data); automatic identification technology; item-unique identification; portable maintenance aids; embedded, data-based, interactive training
- Functionality—low ambiguity fault detection, isolation, and prediction; optimized maintenance requirements and reduced logistics support footprints; configuration management and asset visibility [5].

The Defense Acquisition Guidebook for Systems Engineering states that CBM+ is a system of systems (SoS) that presents a fundamental systems engineering problem: “the integration of various and disparate technologies and concepts [12].” It defines an SoS as a “set or arrangement of systems that results from independent systems integrated into a larger system that delivers unique capabilities. Both systems and SoS conform to the accepted definition of a system, in that each consists of parts, relationships, and a whole that is greater than the sum of its parts [12].”

C. ESTABLISHING REQUIREMENTS AND ARCHITECTURE FOR PHM SYSTEMS

In 2001, the Defense Acquisition University published a Systems Engineering Fundamentals (SEF) book that “provides a basic, conceptual-level description of engineering management disciplines that relate to the development and life cycle management of a system [13].” The SEF provides a roadmap to support the development of requirements definition for PHM systems. The SEF states that “requirements are the primary focus in the systems engineering process because the process’s primary purpose is to transform the requirements into designs [13].” Figure 6 represents the systems engineering process and illustrates how requirements are the basis of design through iterative processes.

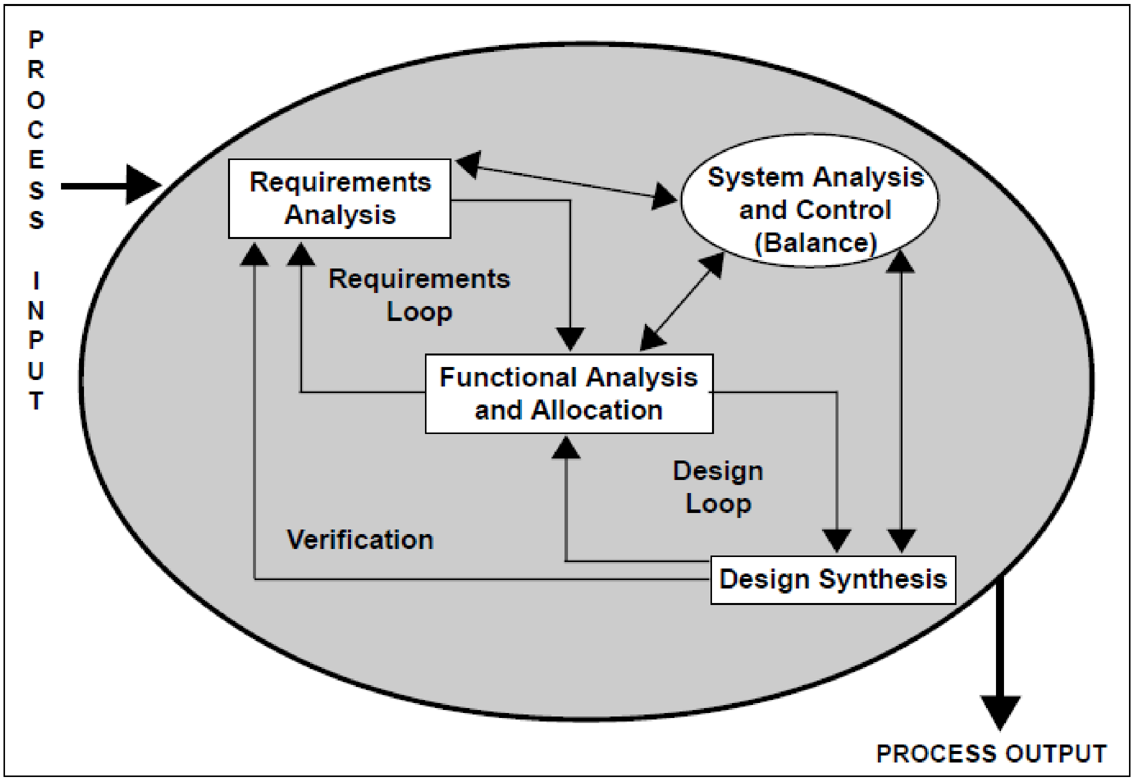
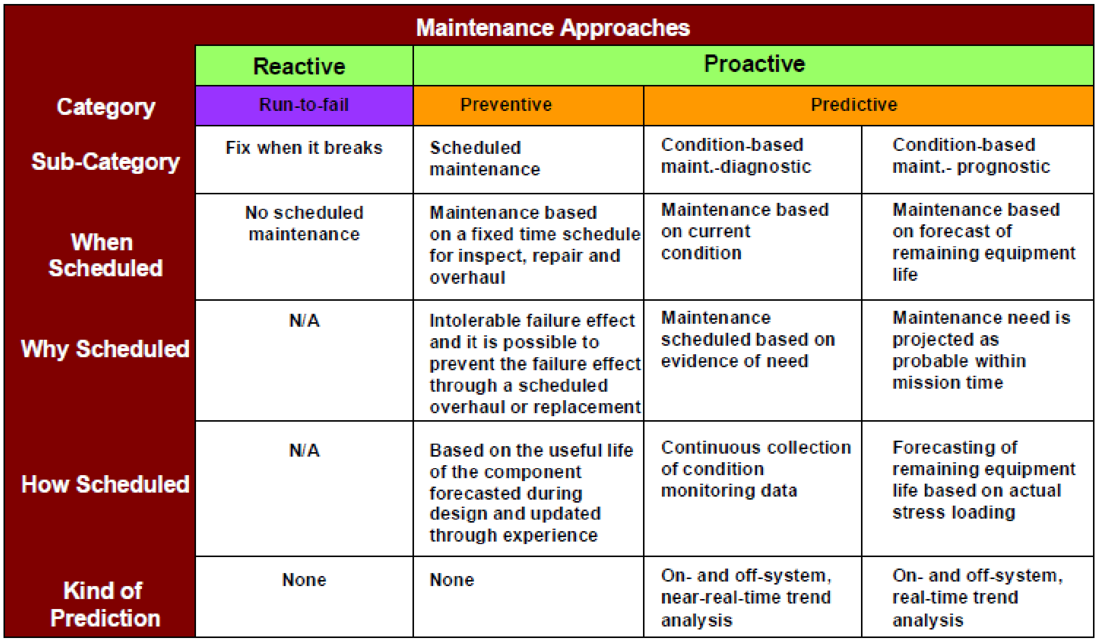


Figure 6. Illustrates the Systems Engineering Process. From [13]

To establish stakeholder driven requirements for a PHM system that will enable a CBM+ conops, program managers and systems engineers must understand the current schedule based maintenance practices. The CBM+ guidebook states that “maintenance can be performed using a wide variety of approaches. Two main categories of maintenance, reactive and proactive, encompass the full range of options available:

- Reactive maintenance (also called corrective maintenance) is performed for items that are selected to run to failure or those that fail in an unplanned or unscheduled manner. An item may be on a schedule for periodic maintenance, but if it fails prematurely, it will require maintenance to fix. Reactive maintenance of a reparable item is almost always unscheduled in the sense the failure occurred unpredictably. Reactive maintenance restores an item to a serviceable condition after the failure has occurred.
- Proactive maintenance is considered either preventive or predictive in nature, and the maintenance performed can range from an inspection, test, or servicing to an overhaul or complete replacement:
    - Preventive or scheduled maintenance can be based on calendar time, equipment operating time, or a cycle (such as number of starts, air vehicle landings, rounds fired, or miles driven). Preventive maintenance may be either scheduled or unscheduled; that is, it is initiated based on predetermined intervals or, alternatively, triggered after detection of a condition that may lead to failure or degradation of functionality of the weapon, equipment, or component.
    - Predictive maintenance can be categorized as either diagnostic or prognostic. Diagnostic identifies an impending failure, while prognostics add the capability to forecast the remaining equipment life. Knowing the remaining life is an obvious benefit to enable optimum mission and maintenance planning [5].”

Figure 7 provides a breakdown of reactive and proactive maintenance approaches. Based on this table, it is obvious that the DoD would want to limit reactive maintenance on costly man-in-the-loop weapon systems. There are, however, many variables within the decision between preventative and predictive maintenance approaches. The predictive systems are complex and expensive, but, as discussed above, the DoD has begun to pursue this approach due to the opportunity for O&S cost savings. The use of reactive and proactive maintenance approaches and how they relate to military propulsion PHM systems is presented later in this research.



	Maintenance Approaches			
	Reactive	Proactive		
Category	Run-to-fail	Preventive	Predictive	
Sub-Category	Fix when it breaks	Scheduled maintenance	Condition-based maint.-diagnostic	Condition-based maint.- prognostic
When Scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on forecast of remaining equipment life
Why Scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance scheduled based on evidence of need	Maintenance need is projected as probable within mission time
How Scheduled	N/A	Based on the useful life of the component forecasted during design and updated through experience	Continuous collection of condition monitoring data	Forecasting of remaining equipment life based on actual stress loading
Kind of Prediction	None	None	On- and off-system, near-real-time trend analysis	On- and off-system, real-time trend analysis

Figure 7. Breakdown of Reactive and Proactive Maintenance Approaches. From [5]

The CBM+ guidebook states that “the most difficult task for the CBM+ implementation team may be to correctly match available hardware, software, and supporting technology solutions to the requirements of the future maintenance process. This task must begin with the documentation of functional requirements [5].” Having established a baseline for legacy maintenance practices, the technical assessment of available capabilities is the next step in establishing requirements for a PHM system. The CBM+ guidebook suggests that a “proof of principle demonstration” is often the best approach to evaluating technologies. The guidebook states that “in light of the time and funding resources required for CBM+ implementation, it is highly advisable for implementers to accomplish small-scale demonstrations of primary CBM+ methods and technologies before full-scale implementation. A short-term pilot test that uses equipment likely to be used for later full implementation can be a low risk approach to ensuring the feasibility and benefits of the desired capabilities. Demonstration of CBM+ planned methods and technologies give managers a higher degree of confidence in the likelihood of future success [5].” In the following chapter, this research explores a PHM acquisition program that used a proof of principle approach to evaluate PHM technologies and discusses how this test enables the informed development of functional requirements.

Once the requirements are defined for the PHM system, the next step in the systems engineering process illustrated in Figure 6 is functional analysis and allocation. The SEF states that “system requirements are allocated and defined in sufficient detail to provide design and verification criteria to support the integrated system design. This top-down process of translating system level requirements into detailed functional and performance design criteria include:

- Defining the system in functional terms, and then decomposing the top-level functions into sub-functions. That is, identifying at successively lower levels what actions the system has to do,
- Identifying and defining all internal and external functional interfaces,
- Identifying functional groupings to minimize and control interfaces (functional partitioning),
- Revisiting the requirements analysis step as necessary to resolve functional issues [13].”

A functional allocation for a propulsion PHM system is performed in Chapter II using methods outlined in the SEF to provide a solution neutral architecture.

The requirements and architecture development in the following chapter will build upon these established concepts presented above. The literature research for the software development and acquisition strategy is woven into Chapters IV and V. Much of the material in these chapters is based on the PD-21 course work and the Author’s lessons learned having worked PHM acquisition at NAVAIR since 2003.

III. PHM REQUIREMENTS AND ARCHITECTURE

A. INTRODUCTION

This chapter explores the definition of requirements for a propulsion PHM system within a systems engineering process. In order to frame a discussion about systems engineering, it would be useful to start with a commonly accepted definition from Professor Gary Langford at the Naval Postgraduate School:

> Systems engineering is a systematic, disciplined approach to define stakeholder-driven requirements and to satisfy those with the development of functionally driven, synergistic, innovative alternatives [14].

This definition can be decomposed to two basic parts: requirements and functional allocation. In order to define stakeholder driven requirements for a PHM system, it is necessary to examine the legacy maintenance CONOPS. This activity helps bridge the gap between legacy maintenance practices and those needed to enable a CBM+ conops. This chapter examines schedule-based inspections and maintenance actions currently used on legacy propulsion systems. An understanding of these processes and procedures provides a foundation for establishing requirements for a PHM system.

Once the legacy practices are established, this chapter addresses the assessment of PHM technologies. One of the most important and fundamental roles of a Systems Engineer is to understand both currently available and emerging technologies. Situational awareness of emerging technologies will enable a program to incrementally integrate capabilities throughout the development of the weapon system. The integration of the legacy CONOPS and emerging technologies provides a basis for the discussion of requirements and functional allocation for a PHM system.

This chapter also outlines a high-level approach to establishing systems architecture for a PHM system. This solution-neutral approach will apply principles of systems architecting to the design of propulsion PHM system.

B. LEGACY MAINTENANCE CONOPS

As stated in Chapter II, the legacy CONOPS for maintaining tactical fighter aircraft propulsion systems is either reactive or proactive. The redundant and safety critical design of propulsion system components addresses many of the failures that would drive reactive maintenance. However, some system faults that require reactive maintenance cannot be designed out of a propulsion system, such as foreign object damage (FOD)[2] and maintenance induced faults.[3] Despite the occurrence of some reactive maintenance, the vast majority of maintenance performed on aircraft propulsion systems is proactive. These preventive and predictive inspections generally take place at intervals determined by engine flight hours or sorties. Some typical proactive maintenance actions for tactical aviation propulsion systems include: borescope inspections, duct dives, and oil sampling activities. These activities are labor intensive and over the life cycle of an aircraft, these inspections can drive a great deal of O&S costs.

Borescope inspections in legacy aircraft are generally performed based on accumulated flight hours. The inspection can be somewhat invasive and time consuming on some legacy platforms due to the location of the borescope ports and access panels. The inspection uses an optical probe to provide a visual inspection of turbomachinery. It is meant to provide maintainers a means to detect any damage that may have occurred to engine components in the gas path. A CBM+ CONOPS might eliminate the need to perform this inspection based on time intervals and would rely on sensors and parametric data trending to drive this maintenance activity based on the actual condition of the engine. This will enable the maintainers to make informed decisions as to when they should perform borescope inspections.

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[2] FOD can be generated from personnel, airport infrastructure (pavements, lights, and signs), the environment (wildlife, snow, ice) and the equipment operating on the airfield (aircraft, airport operations vehicles, maintenance equipment, fueling trucks, other aircraft servicing equipment, and construction equipment) [15].

[3] Maintenance is essential to aviation safety, yet improper maintenance contributes to a significant proportion of aviation accidents and incidents. This is because a small percentage of maintenance tasks are performed incorrectly or are omitted due to human error. Examples include parts installed incorrectly, missing parts, and the omission of necessary checks [16].

The duct dive is another proactive maintenance inspection used in legacy tactical fighters. During this procedure, the maintenance technician climbs through the aircraft inlet to inspect the inlet guide vanes and the first few stages of the engine fan, as seen in Figure 6. The purpose of the inspection is to visually and tactilely inspect fan blades for cracks that may be propagating in the airfoil. This can also be a time-consuming maintenance check and there is potential for maintenance-induced damage (tools left behind, inlet surface damage, etc.). Similar to the borescope inspection, this time-based maintenance would be eliminated in a CBM+ CONOPS and be driven by some automated means of impending failure detection.

Figure 8. Inlet Inspection of E/A 6B and F-16. From [17]

Propulsion systems on legacy platforms will generally service the lube system after each flight. This procedure involves topping off the oil tank and checking magnetic chip collectors. The chip collectors provide an indication of machine wear, which can be a precursor to component failure (gears, bearings, etc.). Oil samples are also taken at regular intervals and analysis of the lubricant is performed to detect wear material and to determine the condition of the oil. In a CBM CONOPS, these tasks would be performed according to need rather than scheduled intervals. The lube level would be monitored and replenished based on limits set by the system designer, while the chip detection and oil analysis would be replaced by an online oil system monitor.

In addition to proactive inspections, critical propulsion system components will also undergo proactive replacement. Once life-limited parts have reached a particular time on wing, they are replaced regardless of their current state of health. This system management policy often leads to discarding perfectly good hardware. A condition-based maintenance CONOPS, which enables the health assessment of components, based on their actual usage and life remaining, would drive down sustainment costs and increase fleet readiness. In order to implement a CBM scheme, a PHM system would need to sense, detect, and track the health of the propulsion system. PHM would then drive these proactive maintenance actions based on the actual condition of the hardware, as opposed to the length of operation. An automated means of monitoring hardware would need to be implemented in order to drive a condition-based maintenance scheme.

C. PHM TECHNOLOGY ASSESSMENT

As stated above, matching available hardware, software, and technologies is one of the most difficult tasks for systems engineers. The CBM+ Guidebook also states that no combination of technology is likely to provide the “perfect” solution and the team will need to make numerous compromises, trading off required capabilities against cost, time, and implementation difficulty [5].” The proof of principle demonstration discussed above is a useful tool for assessing available technologies for PHM systems and aiding the team in arriving at the right combination of technologies.

The CBM+ guidebook states that “due to time and funding resources required for CBM+ implementation, it is highly advisable for implementers to accomplish small-scale demonstrations of primary CBM+ methods and technologies before full-scale implementation. A short-term pilot test that uses equipment likely to be used for later full implementation can be a low risk approach to ensuring the feasibility and benefits of the desired capabilities [5].”

To assess the available and emerging PHM technologies for the F-35 propulsion system, the JSF Program performed a sensor evaluation during the Concept Demonstrator Phase (CDP). During this test, candidate PHM technologies were placed on an F-100 engine during seeded fault testing.[4] Figure 7 illustrates some of the candidate technologies used during SFET. These technologies were evaluated for their ability to detect various failure modes and seeded fault events during the propulsion system test.

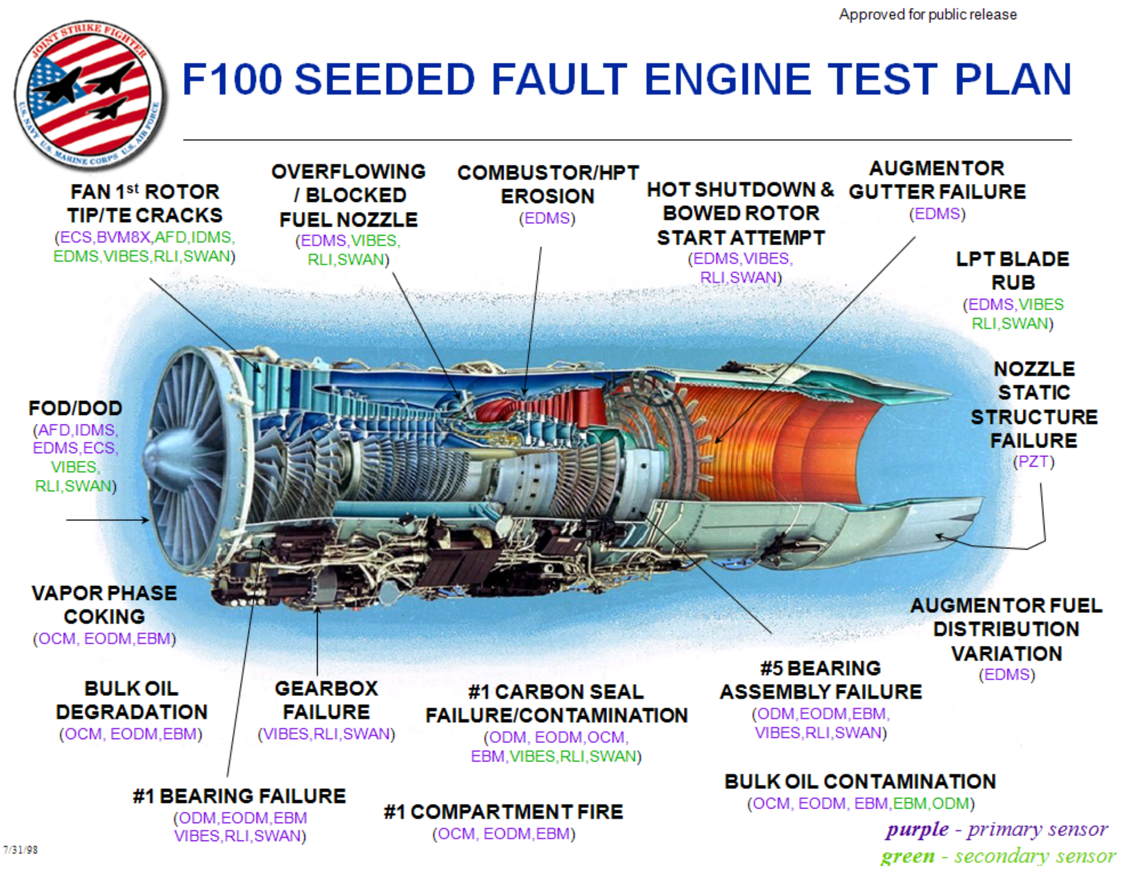

Figure 9. PHM Sensors Evaluated During SFET. From [6]

The results of the test were used to give the systems engineers a baseline understanding of the technologies that were available and the Technical Readiness Level (TRL) of each sensor. Using the data from the SFET, the program was able to establish requirements for the PHM system, requirements that would eventually enable a CBM+ CONOPS. The development and maturation of a PHM system, which enables a CBM+

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[3] Seeded fault testing involves an engine test where failure modes are intentionally excited for the purpose of evaluating detection or accommodation capabilities of the PHM system or control system [6].

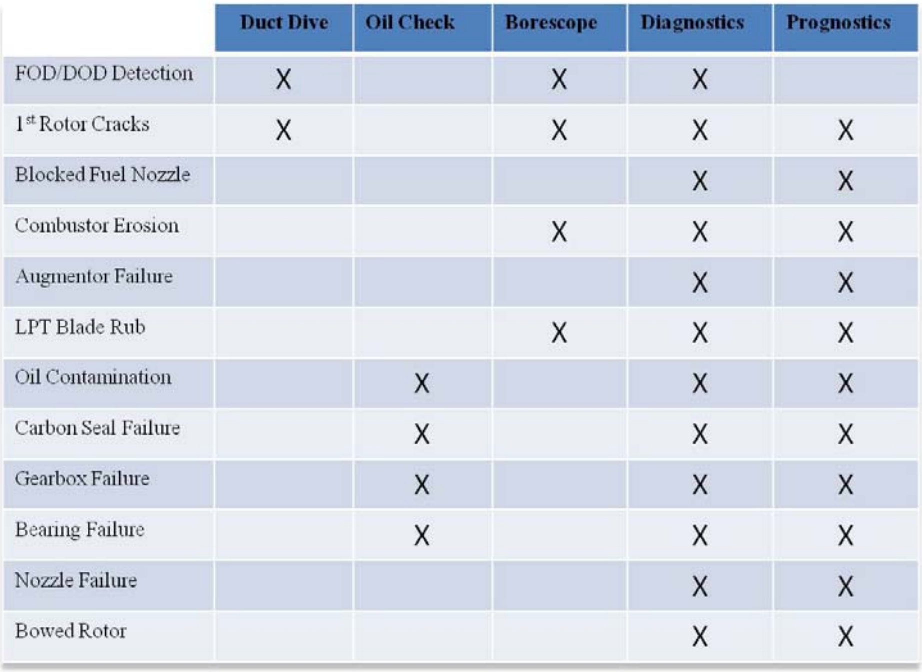
CONOPS, is potentially the longest lead procurement item for modern weapon systems. The SFET testing made Program Management aware of the technologies that could be integrated in the near term, but they still needed to plan and budget for advances in the sensing and computing capabilities that evolve during maturation.

D. STAKEHOLDER DRIVEN REQUIREMENTS

Thus far this chapter has established the legacy maintenance procedures for military propulsion systems and an approach to executing a technology assessment. Systems engineers developing a PHM system can use this information to proceed with the development of stakeholder driven requirements.

There are several different types of requirements identified in the SEF, but since the scope of this research is limited to a notional PHM system, the functional requirements are the most applicable. The SEF defines functional requirements as “the necessary task, action or activity that must be accomplished. It also states that functional requirements must be achievable and must reflect a need or objective for which a solution is technically achievable [13].” To simplify this definition, we need to establish a *necessary task* with an *achievable solution*. Within the scope of this research, functional requirements are deemed necessary tasks by examining the legacy maintenance procedures the PHM system is being designed to replace. This research also examines a technical assessment of PHM sensors used to identify an achievable solution.

Based on the legacy schedule-based maintenance practices identified above, the necessary tasks of a notional PHM system are listed across the top of Table 1. These tasks are to eliminate scheduled inspections and to provide diagnostic and prognostic assessments of the health of the propulsion system. The achievable solutions are listed vertically and were taken from the technology assessment outline above in Figure 9.



	Duct Dive	Oil Check	Borescope	Diagnostics	Prognostics
FOD/DOD Detection	X		X	X	
1st Rotor Cracks	X		X	X	X
Blocked Fuel Nozzle				X	X
Combustor Erosion			X	X	X
Augmentor Failure				X	X
LPT Blade Rub			X	X	X
Oil Contamination		X		X	X
Carbon Seal Failure		X		X	X
Gearbox Failure		X		X	X
Bearing Failure		X		X	X
Nozzle Failure				X	X
Bowed Rotor				X	X

Table 1. HM Functions Mapped to Goals

The necessary tasks and achievable solutions identified in Table 1 are not complete, but offer a good basis for the definition of high-level PHM system requirements. The purpose of Table 1 is to provide a mapping of tasks to solutions. This connectivity provides systems engineers with insight to the design interfaces and enables informed decisions regarding requirements. For example, FOD/DOD Detection and Combustor Erosion are each mapped to the goal of Borescope. The identification of this design interface along with a criticality analysis from the FMECA can offer Systems Engineers increased coverage and confidence for the detection of certain failure modes.

E. PHM SYSTEM ARCHITECTURE

As stated in Chapter II, the requirements loop of the System Engineering Process is followed by Functional Allocation. This section will attempt to refine high-level PHM system requirements to into detailed functional and performance design criteria. The principles used for this discussion on PHM architecture are based on course material provided by Professor John Osmundson, Naval Postgraduate School [18].

To explore the development of a PHM system architecture, it would again be useful to frame the discussion with Professor Gary Langford's definition:

> The system architecture model is a cohesive statement of the system's physical configuration in terms of modules, the information flow between them, and interconnects [14].

Professor Osmundson states that "the first step in establishing a system architecture for PHM is to create a high-level and solution-neutral functional decomposition. A solution-neutral characterization of the system will enable the system architect to view the entire problem for what it is and not how to solve it. This approach also allows the architect to identify the proper solution, which may not necessarily be the first solution [18]." Figure 10 illustrates a generic functional decomposition of a PHM system.

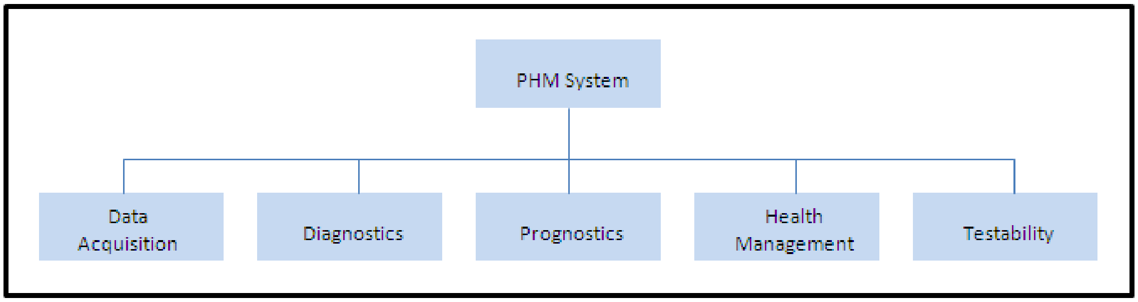


Figure 10. PHM Functional Decomposition

The data acquisition function will be needed to obtain information from the suite of onboard sensors that provides data regarding the health of the engine components. This data will be processed using tailored diagnostic and prognostic algorithms to provide an assessment of the current state of the propulsion system, as well as a prediction of life remaining for all life-limited components. The Health Management module will combine all the various data sources and use them within an overarching logistics system to provide work orders for inspection, repair and replacement of engine components.

Finally, the Testability function will provide the capability for the PHM System to perform an autonomous built-in test (BIT), to provide verification of the functionality of the system.

The functional decomposition in Figure 10 offers no particular means to achieve a system; it is only meant to frame the problem. The next step is to further decompose the solution where it helps to start by modeling the system as a single black box, operating on material, energy, and signal flows. The black box decomposition is shown in Figure 11.

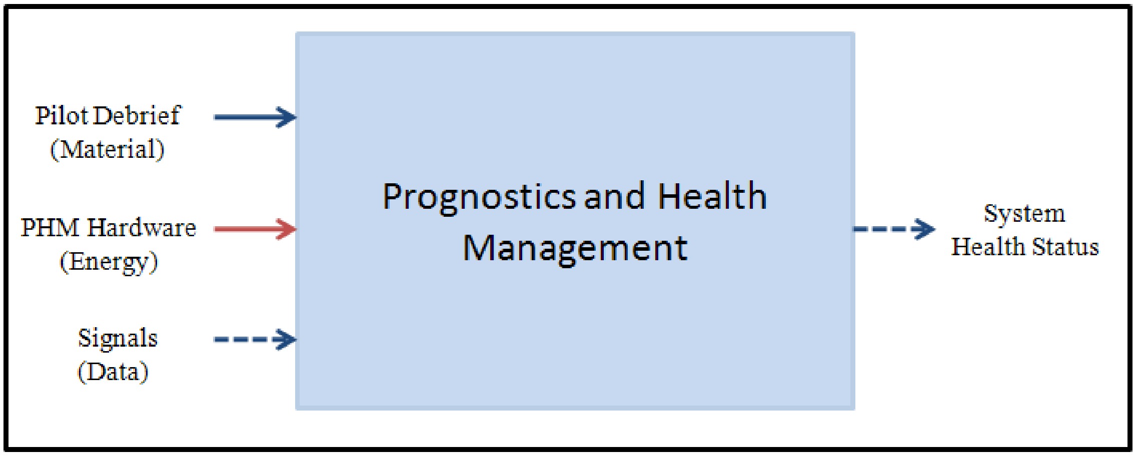


Figure 11. PHM Black Box Decomposition

To further refine the black box model, it is decomposed two more layers. According to Professor Osmundson, this decomposition will "offer insight to the interfaces and functionality" of the system [18]. The illustration in Figure 12 outlines the refined functional decomposition. The colored lines in Figures 11 and 12 represent the transfer of material (blue), energy (red), and data (dashed blue). The material input is represented by Pilot Debrief; after the flight the operator feedback is recorded in the PHM System. The energy input is represented by the suite of PHM hardware. This hardware consists of sensors and electronics used to detect faults in the system, while the data path processes this energy to provide input back to the energy path. This interdependency is represented by a feedback loop between the energy and data inputs. These three inputs flow to the electronics function and result in the system output: System Health Status.

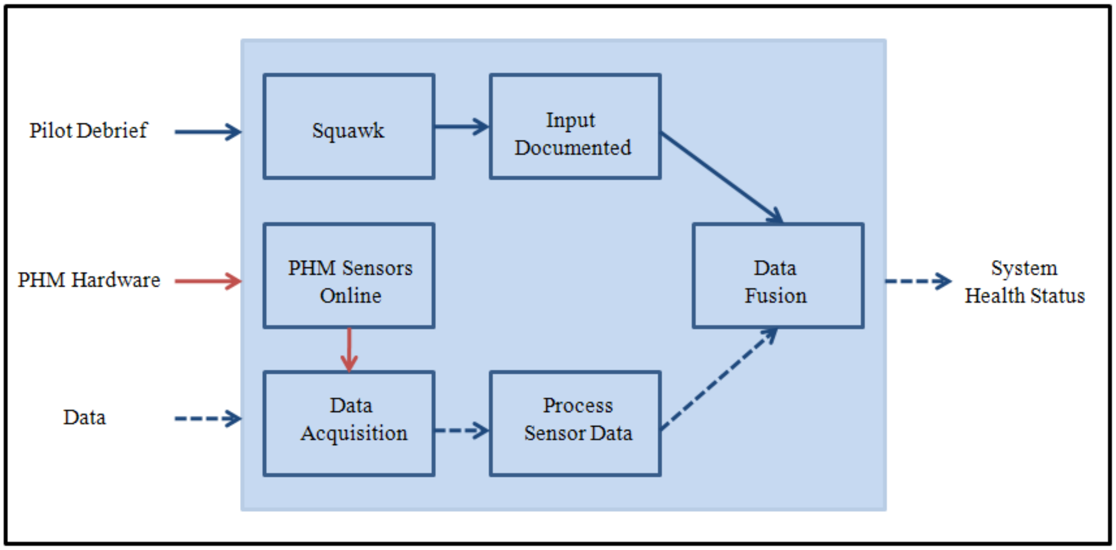


Figure 12. Refined Functional Composition

F. SUMMARY

The intent of CBM+ systems is to replace legacy maintenance practices. Chapter III identified different types of maintenance performed on legacy propulsion systems. The most common routine inspections and proactive maintenance actions for these systems were borescope inspections, duct dives, and oil sampling.

The Seeded Fault Engine Test used by the F-35 Program was presented as a strategy to assess available technologies when establishing requirements for a PHM system. The test designers used PHM technologies to target schedule-based inspections. They also used FMECA information to target specific failure modes. This test gave the Program Managers a baseline understanding of the PHM technologies that were available and the relative reliability and maturity of each sensing system.

As discussed in Chapter II, the CBM+ requirements are based on FMECA analysis and PHM technologies. An understanding of the legacy maintenance practices, along with knowledge of available technologies, will enable acquisition professionals within the DoD to define achievable stakeholder driven requirements. Defining achievable requirements should be the focus of every system designer. Weapon systems that are developed to meet performance levels beyond the current achievable capability often suffer schedule and cost impacts. This concept will be further discussed in subsequent chapters.

The CBM+ Guidebook provides methods for establishing requirements and Professor Osmundson offers a technique for developing solution neutral architectures. These methods were examined and tailored to PHM systems in order provide system developers with a reference and tool for guidance during this critical development stage. The CBM+ Guidebook also offers several questions that CBM+ program managers and systems engineers can use as a checklist for developing CBM+ systems.

1. Do I have sufficient background information on CBM+ to assess the current maintenance program in my organization regarding this strategy?
2. Does the CBM+ implementation team fully understand the reasons for transition from current maintenance approaches to a CBM+ environment?
3. Is additional research needed to familiarize myself and team members with CBM+ background, policies, technologies, or other relevant information [5]?

These questions can be used within the scope of this research to provide a roadmap for developing the requirements for a PHM system. Each of these questions are addressed in this thesis with an examination of legacy maintenance practices for military propulsion systems and in subsequent chapters with a discussion of strategies for gaining program wide support for the implementation of a disruptive technology.

The Propulsion PHM architecture is a highly integrated and complex system designed to enable a CBM+ CONOPS. By its nature, PHM is a system of systems that requires integration across each Integrated Product Team (IPT) within the propulsion system. The development of the PHM system not only falls to the PHM system developers, but also to each component owner across the entire weapon system. The successful implementation of CBM+ requires that the systems architect and systems engineers work to provide a comprehensive overarching architecture and traceability for each requirement throughout every component and IPT. This chapter offered some techniques for developing that architecture through a solution neutral approach consisting of various levels of requirements decompositions and the allocation of functions to system goals.

IV. PHM SOFTWARE DEVELOPMENT

A. INTRODUCTION

Once the system architecture has been established, the software design will represent much of the work remaining to implement a CBM+ capable system. This chapter will discuss the principles of software development related to PHM and identify some common practices and lessons learned.

B. SYSTEMS ENGINEERING PROCESS FOR PHM SOFTWARE DEVELOPMENT

Thus far, the research has been focused on hardware requirements and architecture development for PHM systems. The software development activities for PHM systems, however, can represent the most potential for cost and schedule overruns. According to a GAO report on software acquisition, “a review of five DoD programs found that outcomes were mixed for software-intensive acquisitions. The F/A-18 C/D, a fighter and attack aircraft, and the Tactical Tomahawk missile had fewer additional cost and schedule delays. For these programs, developers used an ***evolutionary approach, disciplined processes, and meaningful metrics***. In contrast, the following programs, which did not follow these management strategies, experienced schedule delays and cost growth: F/A-22, an air dominance aircraft; Space-Based Infrared System, a missile-detection satellite system; and Comanche, a multi-mission helicopter [19].” This section will examine the evolutionary approach and some of the processes and metrics that helped the F/A-18 C/D and Tomahawk missile program deliver software products with fewer additional cost and schedule delays.

The design and development of software products can be characterized as an iterative process. This concept is universally applicable software products for PHM systems. These systems generally take more time to mature, because not all faults will present themselves during testing. While FMECA driven diagnostics systems are often comprehensive, there will always be unknown – unknowns. For this reason, the software systems engineering design process followed for the development of these modules is most often an Evolutionary Systems Engineering Model. This model allows designers to progress through the basic software development life cycle multiple times, adding functionality and lessons learned with each successive release. A DoD memorandum on software development states that “evolutionary acquisition and spiral development area methods will allow us to reduce our cycle time and speed the delivery of advanced capability to our warfighters. These approaches are designed to develop and field demonstrated technologies for both hardware and software in manageable pieces [20].”

The illustration in Figure 11 depicts an evolutionary systems engineering model. The process begins with user requirements and progresses from design through test. At the end of each cycle, feedback or lessons learned from Operations are documented and the iteration process begins. After each iteration, the evolutionary process is followed while adding functionality and correcting issues identified in previous versions of the logic.

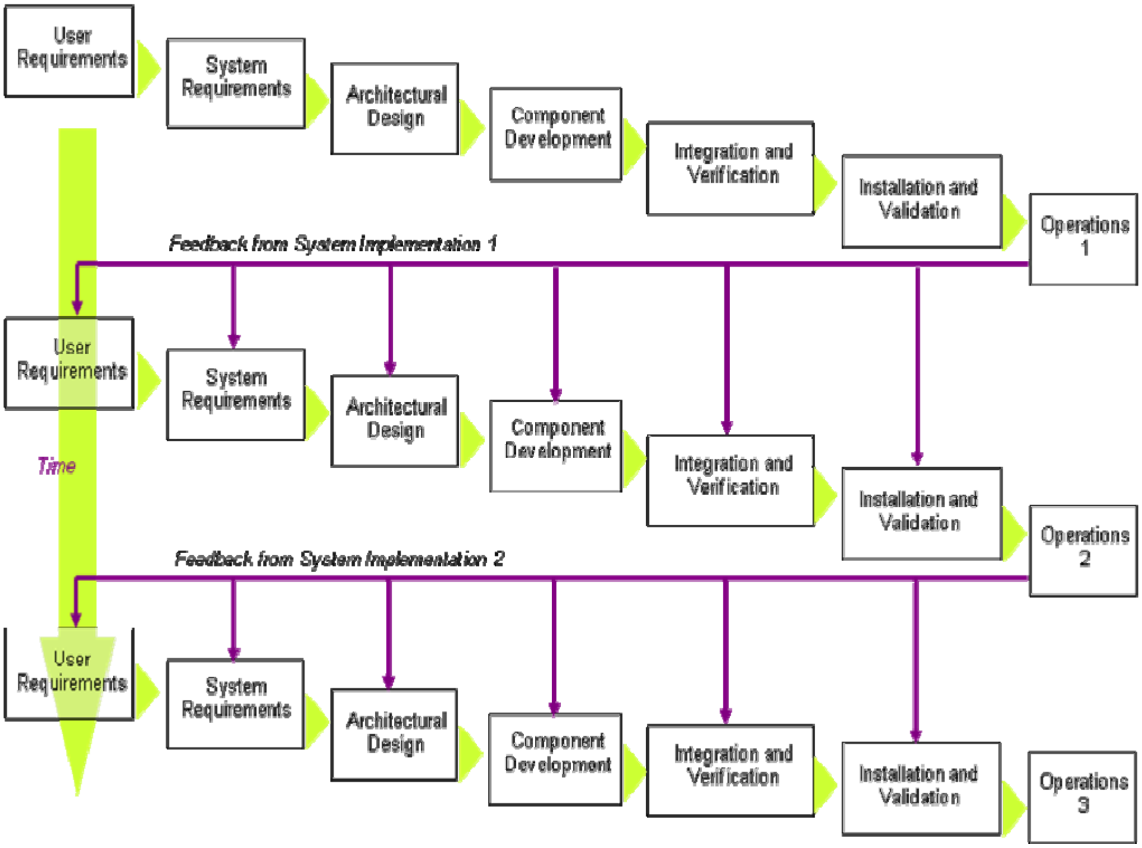
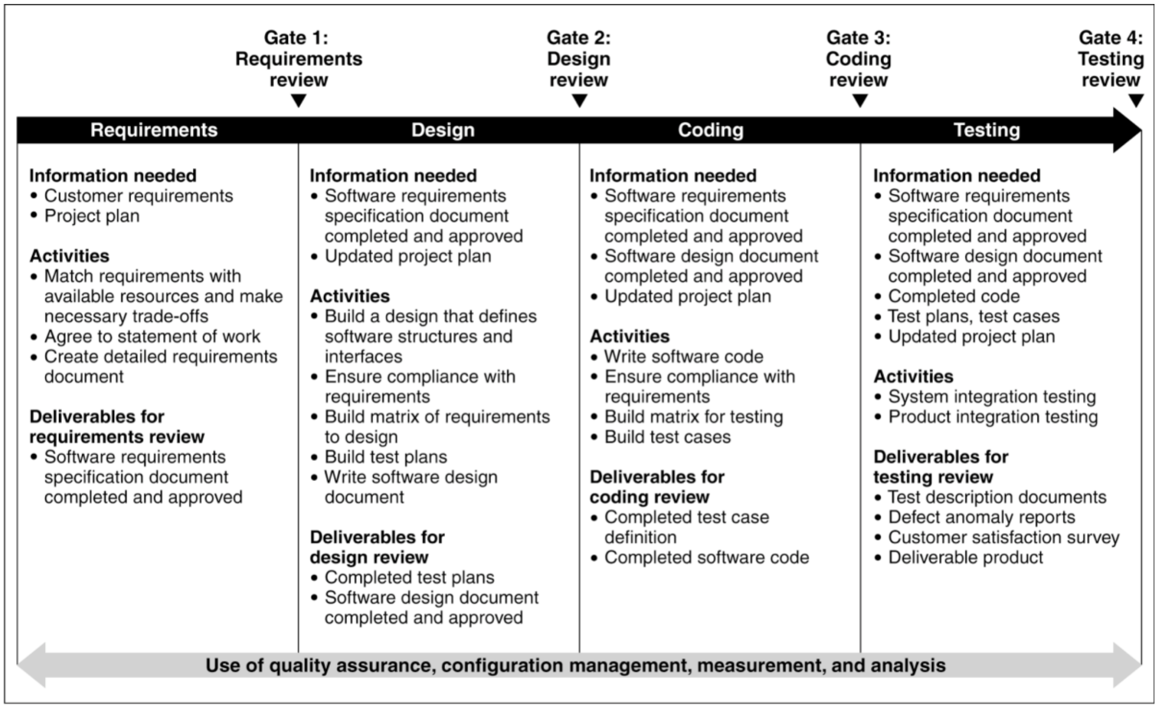


Figure 13. Evolutionary Systems Engineering Model. From [14]

The GAO met with industry software developers to “identify disciplined approaches to software development [19].” Figure 12 highlights the four-gated reviews often used during the software development activity. The processes outlined in this chart exist within the evolutionary approach outline in the previous section. According to the GAO, “within each phase are key activities that must take place and knowledge, or information, that must be attained to pass a review and move to the next phase of development [19].”



Source: GAO's analysis of leading companies' software development practices.

Figure 14. Knowledge Based Software Development Process. From [19]

The system requirements are established and approved at Gate 1. As discussed in Chapter II, the systems engineering process can be decomposed to requirements and allocation. Therefore, this is a critical review that will establish the scope of the entire project. There will likely be some changes to requirements during the development of most software development projects, but the Gate 1 review should establish the expected level of effort for the entire program. The GAO states that "software developers typically devote about 20% to 30% of their software development time to requirements-setting activities. Doing so ensures that developers will be able to provide managers with key knowledge at the requirements review gate and show that requirements have been properly vetted with the acquirer and that they are achievable and well written [19]."

The software design review occurs at Gate 2. Figure 14 shows that at this stage the software design documents and test plans are completed and reviewed. The GAO states that “as with typical hardware reviews, Gate 2 is often broken down by preliminary and critical design review. A stable design ensures that all requirements are addressed and that components and interfaces are defined [19].”

Once the software has passed the design reviews the coding begins in preparation of Gate 3. The GAO states that “at this stage, the design documents are used for logic development by software engineers. The success of this stage often relies upon the ability of the software engineer to interpret the requirements established during design. Ambiguous design requirements will often lead to re-work and result in added cost and schedule delays at this stage [19].”

The final stage of the process is testing. In their report the GAO states that “testing is then performed to uncover defects or gaps in the code. Leading software companies we visited develop test plans after requirements are stable and take steps to ensure that there are one or more tests for each requirement [19].”

Another software development process used by DoD is the Work Breakdown Structure (WBS). The Military Standard 881A states that “the WBS identifies the product to be developed and/or produced. It relates the elements of work to be accomplished to each other and to the end product. A WBS can be expressed to any level of detail; however, the top three levels are the minimum recommended any program or contract needs for reporting purposes unless the items identified are high cost or high risk [21].” The illustration in Figure 13 represents a generic WBS for a PHM Software IPT. The elements are identified for three levels to gain perspective on the scope of the project.

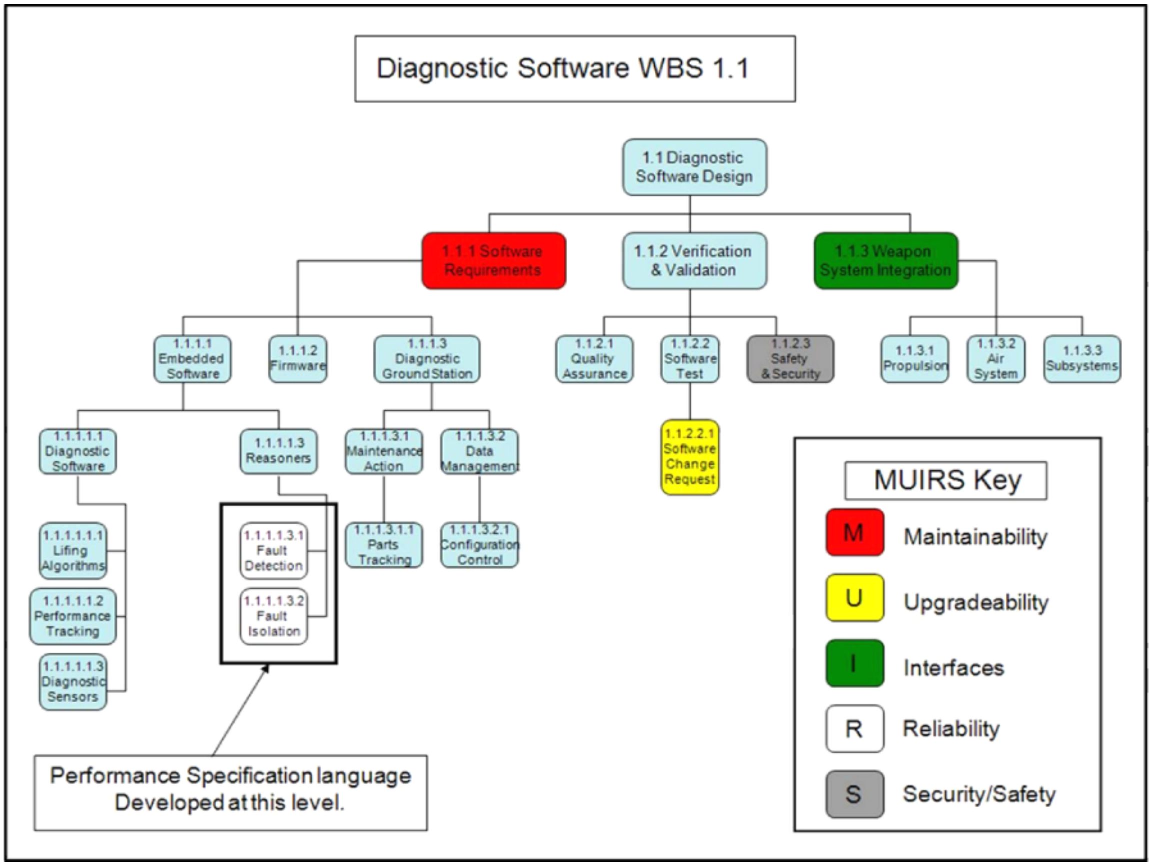


Figure 15. Notional PHM WBS

The MUIRS analysis is another software procurement process used by the DoD. Professor Dave Matthews states that "a MUIRS analysis is performed using the WBS to identify critical support functions within the software [22]." The MUIRS Key in Figure 13 identifies the WBS elements according to their supportability functions. The Maintainability function will be the responsibility of the Software Requirements element. This element will ensure that all software maintenance requirements are established to support the product throughout its life cycle. All upgrades to the software will reside within the Software Change Request element. This element will need to establish a protocol for new development, testing, and implementation of all new software requirements. The Weapon System Integration element will manage all software interfaces. There are only a few interfaces listed in the example WBS, but, in reality, the

Propulsion PHM software will have many interfaces and any changes to the product could have a cascading effect across the weapon system. The software reliability function of the MUIRS analysis is identified within both the Fault Detection and Fault Isolation WBS. At this level, the performance specification language is developed. For example, the Fault Detection and Fault Isolation requirements for reliability could be established at 90% and 75%, respectively. Finally, the Security & Safety element of the WBS provides these functions during development and throughout the sustainment of the diagnostic software.

The Maintainability portion of the MUIRS analysis could be considered to be the most critical for PHM software development. Software support is by far this biggest life cycle cost driver and the most significant component of system risk. The ability to support major software intensive systems is a paramount mission requirement. According to Professor Brad Naegle "the future capability of major systems in a net-centric warfare environment is totally dependent on the ability to cost-effectively maintain them [23]." As stated in Chapter I, the DoD has targeted O&S costs through better systems engineering practices and acquisition training. The O&S costs for weapon systems represent the 65% to 80% of the life cycle costs of weapon systems. Professor Naegle also states that "within that percentage of O&S costs, the cost to maintain software is typically between 60% and 80% of the software component total life cycle cost (LCC) [23]." Software maintenance, therefore, has the potential to provide tremendous LCC savings to the DoD if the acquisition practices and development can be improved. Software maintenance costs will improve if we are able to develop and initially field more mature software products. The responsibility for delivering mature systems, as previously stated, remains with the Program Managers and Systems Engineers within the DoD.

The final characteristic of successful software acquisition programs identified by the GAO was the proper use of metrics. The GAO interviewed several commercial software development firms to understand the metrics commonly used by industry. They identified the following seven metrics for managing software development activities:

Cost, Schedule, Size, Requirements, Tests, Defects, and Quality. Using metrics for cost and schedule is pretty common in the DoD. Large acquisition programs now require some sort of cost and schedule control and reporting system. The Earned Value Management System (EVMS) is used by many government agencies and the private sector. Program Managers need to be very familiar with EVMS and lean on their Budget and Finance Managers for insight.

The size metric is often referred to as Source Lines of Code (SLOC). SLOC is the number of lines of text within source code. SLOC overruns have the potential to drive a great deal of cost into a program. The processing and throughput requirements for electronics (i.e., FADEC) are partly based on SLOC estimates. The redesign of this hardware due to requirements creep and SLOC overruns is very costly. This is an area where the evolutionary concept differs for hardware and software, because you cannot necessarily evolve hardware incrementally the way you can with software.

Establishing requirements metrics early in the acquisition phase is an essential component of meeting cost and schedule targets. This requirement metric is used not only to track the addition of new requirements, but also their timing. This is important because changes are easier and less costly to implement in the early stages of development. New requirements that arrive late in development will drive greater cost into the program. The metric can be used to alert Program Management of these potential cost drivers.

The final metrics identified by GAO were tests, defects and quality. These metrics provide management with feedback regarding the software that is in the latter stages of development. Issues identified by these metrics could impede the evolutionary development cycle and cause delays with subsequent versions of code and additional capabilities.

C. SUMMARY

This chapter also discussed the principles of software development related to PHM and identified some common practices and lessons learned. The GAO identified three industry best practices for the development of software systems: an evolutionary approach, disciplined processes, and meaningful metrics. The evolutionary approach employed basic systems engineering process to establish requirements, design, build, and test the software. The disciplined process included use of gated reviews at each stage of software development. This research also identified and explored the use of the WBS and MUIRS analysis as a necessary process for software development and sustainability. The metrics commonly used by industry for software development were: Cost, Schedule, Size, Requirements, Tests, Defects, and Quality. The F/A-18 C/D and Tomahawk Missile were identified as two DoD acquisition programs that were able to deliver their products near cost and schedule targets by using these industry best-practices.

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V. PHM ACQUISITION STRATEGY

A. INTRODUCTION

This chapter will identify some strategies for acquisition managers regarding the procurement of PHM systems. These highly integrated and complex systems are a relatively recent requirement for implementation on DoD propulsion systems. This chapter will discuss a legacy program that was able to field and upgraded PHM system and identify some of the lessons learned and best practices related to this successful acquisition program. Chapter IV will also examine some of the obstacles facing the program managers that procure PHM systems with the DoD. Finally, the chapter will wrap up with a discussion of the maturation process for a PHM system.

B. F/A-18 E/F IMPLEMENTATION OF PHM

The Innovator’s Dilemma written by Clayton Christensen introduces the concept of sustaining and disruptive technologies. An MIT website offers a summary of the book and states that “sustaining technologies are technologies that improve product performance. These are technologies familiar to most large companies; technologies that involve improving a product that has an established role in the market. Disruptive technologies are innovations that result in worse product performance, at least in the near term. Disruptive technologies occur less frequently; when they do, however, they can cause the failure of highly successful companies that are only prepared for sustaining technologies [24].” Christensen’s theories were developed based on the application of new technologies by businesses competing for market share, but using an abstract interpretation of these concepts, the principles of sustaining and disruptive technologies can be applied to the implementation of CBM+ systems within the military.

For the purpose of this interpretation, sustaining technologies are analogous to the legacy CONOPS for aviation maintenance, i.e., schedule-based inspections, schedule-based removals, etc. The technologies that enable these maintenance practices have consistently been developed and improved over time. The Navy F/A-18 E/F Super

Hornet acquisition program is a good example of a sustaining technology improvement for Propulsion PHM and can serve to put the application of this theory in context.

Figure 16. Super Hornet approach aboard CVN 72. Photo taken by Author.

The US Navy and Boeing collaborated on a paper about the upgrade of the F/A-18 propulsion monitoring system. The paper states that "under Navy direction, GE and Boeing have enhanced the proven performance of the F/A-18 C/D F404 In-flight Engine Condition Monitoring System (IECMS) and produced an Advanced IECMS for the F/A-18 E/F tailored for the F414 engine. The advanced IECMS system is fully integrated between the engine and airframe and effectively uses available avionics computers and interfaces, which contributes to low system weight. This advanced system includes many improvements, including:

- Better aircrew displays and additional cautions/advisories,
- Additional mission computer resources,

- Reliable, new FADEC[5] with outstanding fault detection and isolation capabilities,
- Improved monitoring hardware installation and signal processing,
- Expanded memory unit data recording,
- Addition of an engine-mounted master electrical chip detector, and
- Additional maintenance codes

Each of these capabilities contributes to reduced pilot workload and reduced aircraft/engine maintenance. The bottom line is that aircraft readiness is improved with fewer engine runs, less down time required for troubleshooting, and rapid turnaround through onboard diagnostics [25]."

There were substantial improvements made to the IECMS during the development of the Super Hornet propulsion system. The improvements were largely based on advances in computing resources and sensor capabilities that were developed as sustaining technologies. These technologies gave the maintainers better fault detection and isolation capability, but did not substantially change the procedures for maintaining the propulsion system. In other words, the improvements were not substantial enough to bridge the gap between the legacy maintenance CONOPS and CBM+, but were an important step in that direction.

While the F/A-18 E/F IECMS upgrade was an important step toward the implementation of CBM+, it did not represent a paradigm shift in the way the Navy maintained the propulsion system. The implementation of a CBM+ system could be characterized as a disruptive technology. For CBM+ to become a reality, the Navy will still need to rely on advances in sustaining technologies, but the implementation and reliance upon these technologies will be disruptive. The greater reliance on new sensing technologies could result in degraded performance in the near term, as the systems are matured. DoD maintainers are accustomed to performing schedule-based inspections and removals. And while the next generation of maintainers that will learn to perform condition-based maintenance and value the disruptive technology, the more experienced

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[5] FADEC—Full Authority Digital Electronic Control.

maintainers will likely resist the change, particularly in the period during which the system is being matured and product performance decreases, i.e., false alarms, missed detects, etc.

The MIT review of Christensen's work states that "disruptive technologies cause problems because they do not initially satisfy the demands of even the high end of the market. Because of that, large companies choose to overlook disruptive technologies until they become more attractive profit-wise [24]." This is illustrated in Figure 17.

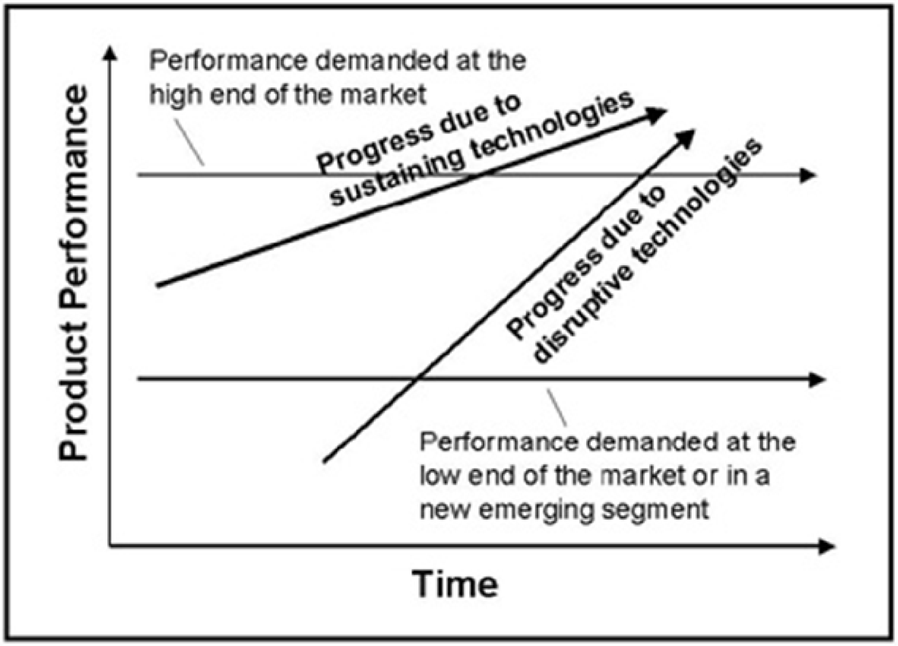


Figure 17. Disruptive Vs. Sustaining Technologies. From [24]

The Taguchi definition of quality and his theories regarding losses to society are relevant to this discussion of CBM+ as a disruptive technology. Taguchi defined quality as "the loss a product causes to society after being shipped, other than losses caused by its intrinsic function [26]." This theory is analogous and applicable to the development of CBM+ systems within the military. These systems are fundamentally designed to enable maintainers, but when not properly implemented or designed, they can be burdensome and unreliable. As previously stated, the use of PHM systems to drive all maintenance is a huge paradigm shift within the DoD and change is not always welcome. There is a natural reluctance and skepticism within the maintenance community to rely on automatic fault detection systems to drive maintenance actions. Unsuccessful attempts in the past to implement these systems have led to a perception among some maintainers (society) that condition-based maintenance may not be an attainable goal. It is the responsibility of Program Managers and Systems Engineers to field capable CBM+ systems early in the weapon system life cycle, such that the system and the overarching CONOPS can be optimized and matured.

C. PHM MATURATION PROCESS

PHM design, development, and maturation is a unique process and different than all other components on the propulsion system. The PHM System and the associated logistics infrastructure that it supports are, potentially, the longest lead development items associated with the acquisition of military propulsion systems. The diagnostic sensors and other hardware associated with the PHM system is designed, developed, tested, and matured along with all of the propulsion hardware. However, this hardware only provides a source of data. The software and algorithms that enable a CBM+ system are developed through an iterative process long after the propulsion system has gone into production.

As discussed previously, the technologies that enable a CBM+ CONOPS are relatively immature. The propulsion system FMECA provides designers with insight as to the failure modes the system should target, but the verification and validation of the ability to detect these actual failures could, in some cases, occur long after the system is fielded. Ideally, PHM system designers would like to perform seeded fault testing to validate their capability to detect faults throughout the propulsion system, i.e., the F100 SFET testing discussed in Chapter II. However, this testing is cost prohibitive in that it often leads to damaging expensive hardware for the sake of maturing a non-flight critical system. Therefore, this is an implausible approach for most acquisition programs. The normal timeline of verification and validation for fault detection and fault isolation software extends beyond the development phase and well into production. Although this involves delivering an immature product to the field, many of the failures that the PHM system is designed to detect will present themselves during the course of normal operation. It is also critical to update and maintain a current and valid FMECA as hardware changes occur. The validity of this data is essential for RCM and CBM+ systems.

The Taguchi loss analogy cited in Chapter II stated that delivering an immature PHM product to the Services could have an ill effect on the perception and customer satisfaction with PHM. However, due to the unique requirements and long lead maturation of the PHM system, the end users actually become part of the design team. Once initially deployed, these maintainers will be able to provide the system designers with feedback regarding the operation of the system and areas for improvement. It is, however, critical that the Program Manager and PHM designers deliver a baseline product that is representative of the final product with intermediate functionality. If the system is deemed unreliable by the end user, the end-user will revert to legacy maintenance procedures and the feedback loop necessary to correct inherent system design flaws will be gone.

D. PROGRAM MANAGEMENT DILEMMA

Professor Dave Matthews stated that "the number one responsibility of a Program Manager is to make a program viable from a cost and schedule perspective [22]." History has shown that weapon systems acquisition budgets and schedules often suffer due to the unknown unknowns. The DoD procures some of the most technically complex systems designed by man, and there are inevitable flaws that will present themselves throughout the design, build, and test phase of the acquisition programs. This concept can be applied broadly to weapon systems or specifically to the development and maturation of Propulsion CBM+ systems.

The program management dilemma with regard to the procurement of PHM systems pertains to incentive. With all of the pressure placed on Program Managers to make a program viable, there is often no sense of urgency or incentive to focus on systems that are in place to provide LCC savings many years into the program. Although this research has cited numerous reasons for providing PHM capabilities as early in the program as possible, it has become the norm for Programs to mortgage non-flight critical systems to make their Program viable. The justification for doing this is perfectly reasonable. There are political pressures that surround defense acquisition programs and the technical challenges that the programs often face drive program realignment activities that focus on the near-term must haves. However, deferring PHM capabilities comes at the cost of both LCC and increased development costs, due to the fact that added capabilities are always more expensive to implement later in a program life cycle. The DoD is currently focused on these sustainment cost savings, but these savings will never be realized for PHM systems without programmatic incentives for acquisition managers to focus on LCC. Without some kind of incentive, the costs that any Program Manager will focus on are the here and now costs to solve today's technical issues. The LCC savings realized by the implementation of a CBM+ system will likely not be realized until well after the Program Manager has moved on or retired. These LCC savings should be tracked and pursued from day one; currently, they are not. Program Managers are forced to be near-sighted with regard to cost and schedule; this comes at the detriment of CBM+ systems.

At the program management level, supportability and logistics issues are often deferred until later in the acquisition program due to limited resources and the redesign of more critical hardware and software systems. The prioritization of CBM+ through programmatic incentives will not be a trivial policy to implement for the DoD, but it needs to be a priority if the LCC savings associated with these systems are to become a reality.

E. SUMMARY

PHM systems are often introduced with a performance degradation compared to the legacy maintenance practices they are meant to improve. Disruptive technologies have the potential to transform the way an organization operates and they offer a great deal of upside potential with respect to O&S costs. The acquisition professionals must learn to manage not only the effective procurement of these systems, but also the expectations of the end user. These expectations were also explored in a discussion of the Taguchi Loss Theory. The acquisition managers must also prepare a mitigation strategy for the potential perceived quality losses during the introduction of a disruptive technology.

The maturation and software maintenance of the PHM system is likely to last as long as the weapon system on which it resides. The end user becomes an integral part of the design loop throughout this lifecycle of this product. Once again, the Taguchi losses experienced with this disruptive technology must be managed by developers and Program Managers.

If the Life Cycle Cost savings associated with PHM system are to be realized, the DoD must incentivize Program Managers to actively attack the enabling technologies. These technologies are often an afterthought due to the need to address more immediate technical concerns.

VI. CONCLUSION

A. INTRODUCTION

The purpose of this research was to provide Systems Engineers and Program Managers a resource for the acquisition of propulsion PHM systems. The thesis outlines processes for establishing requirements, defining a notional architecture and developing software for PHM systems and presents them within the systems engineering process. It also provides acquisition strategies and lessons learned based on legacy PHM systems. The goal of the research is to enable the system developers to use this reference to improve cost and schedule delivery of capable PHM systems throughout the acquisition life cycle.

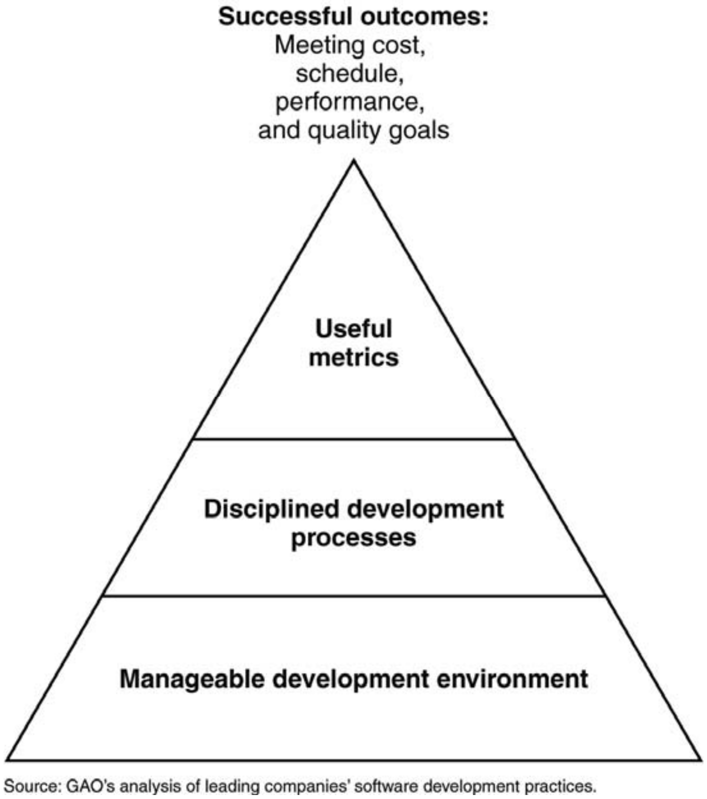
B. RESEARCH SUMMARY

The research began with a background examination of military propulsion PHM systems and the their evolution from the diagnostic systems first fielded on the A-7 Corsair to the CBM+ systems being developed for the F-35 JSF. It also identified the DoD directive that mandates the implementation of CBM+ strategies. This mandate was an important step in the evolution of CBM+, but in order to be successfully implemented, there must be a sense of ownership throughout each level of the program. PHM is unique in that it touches each and every IPT within the weapon system. Its development, therefore, is a program wide responsibility.

There are many different systems engineering process models, but, generally speaking, they each start with the establishment of system requirements. In the DoD, requirements for weapon systems are commonly defined by the user community. For PHM systems, it is important to focus on requirements related to the schedule-based maintenance actions we are seeking to transition to a condition-based CONOPS. The logical first step was to examine current schedule-based maintenance actions. This activity provides a baseline understanding for the requirements analysis needed to be performed by any program planning to implement CBM+. The use of RCM tools and the FMECA also provide an important resource for identifying capability gaps and addressing them with available PHM technologies.

The definition of requirements was followed by a high-level approach to establishing an architecture for a generic PHM system. This method provides a solution neutral characterization of the problem rather than a way to solve the problem. Once the high-level architecture is identified, it is decomposed to the basic elements, which add resolution by establishing flows material, energy, and data.

There is no one-size-fits-all approach to software development and acquisition. This is particularly true for the PHM software procurement. It is important to focus on the established processes and metrics that have been established and proven by previous successful acquisition programs. Research performed by the GAO established some lessons learned for software development. The report suggests some methods the DoD could employ to leverage industry best-practices for delivering quality software products within time and cost constraints. The use of an evolutionary approach, disciplined processes, and meaningful metrics were identified as key enablers to successful software acquisition programs, such as the F/A-18 C/D and Tomahawk Missile Program. Figure 18 highlights these management practices and how they relate to program goals.



Source: GAO's analysis of leading companies' software development practices.

Figure 18. Key Management Practices. From [19]

PHM was presented as a disruptive technology that has the ability to revolutionize the way the military maintains weapon systems and provide significant LCC savings. However, as with any disruptive technology, there will be a period of learning and a need to overcome the perceived or actual quality loss by society, as outlined by Taugchi. The period of transition from design and development to initial demonstration is critical for PHM technologies to be matured. It is important for Program Managers within the DoD to defend PHM systems and to manage expectations within the user community.

Most large companies are adept at turning sustaining technology challenges into achievements, the F/A-18 E/F IECMS upgrade is a good example of this. IECMS was a sustaining tech upgrade that improved the F404 engine, which had an established role in the market. Each of the acquisition programs discussed in this chapter used a systems engineering approach to the establishment of requirements for a propulsion PHM system.

The difference in the way that the F/A-18 and F-35 programs approached their respective evaluation of candidate technologies is obviously much different. The F/A-18 E/F was an established platform that was upgrading their current diagnostic capabilities based on needs established by the user, whereas the F-35 program used the SFET program to build a CBM+ system from the ground up. The JSF Program had a need to establish an understanding of the technologies available at that time.

In each case, the respective Programs started with a customer need and followed the systems engineering process to deliver a product. Figure 19 identifies a basic systems engineering process V- model commonly used for the development of weapon systems. The discussion of the Super Hornet and F-35 Programs focused on the first two stages of the model, the Problem Decomposition phase and the System Design phase, respectively.

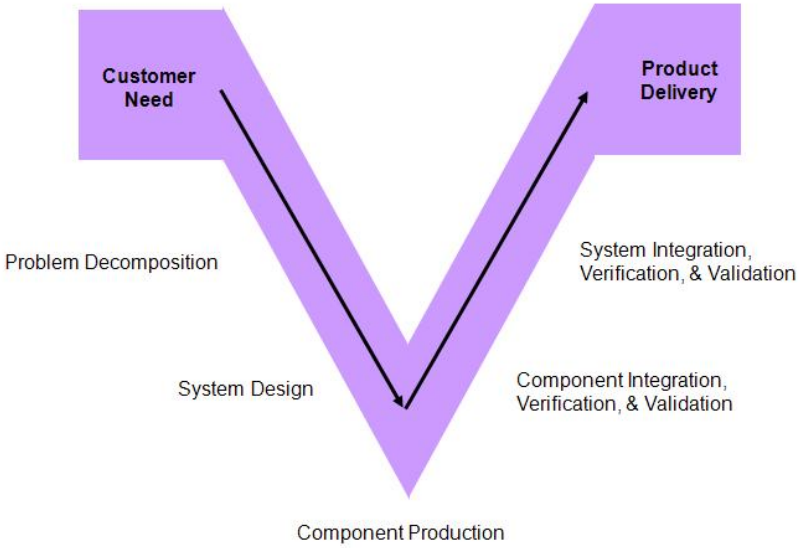


Figure 19. Systems Engineering Process V-Model. From [14]

The F/A-18 discussion focused on the Problem Decomposition step in the V-model. The team identified maintenance issues in the fleet that could be eliminated or improved with the IECMS upgrade. They interviewed the users to identify improvements and establish requirements to increase maintainability and reliability of the F414. The F-35 example was focused on the Systems Design phase of the V-model. This phase occurred after the Problem Decomposition had been performed and systems engineers had identified the maintenance actions they wished to target. To begin the systems design phase, they performed the SFET to provide an analysis of alternatives and an assessment of the TRL of existing PHM technologies.

Once the PHM system is fielded, the maturation process begins. The support of the PHM software will last as long as the weapon system on which it resides. The maturation of this system is unique and will often involve the end user more than other systems. Care must be taken to manage the Taguchi losses experienced by maintenance personnel with regard to immature software products.

The DoD is aggressively looking for ways to reduce its budget and weapon system life cycle costs are a prime target. CBM+ systems are designed to provide LCC savings, but the technology is still relatively immature and often not the focus of Program Managers. The DoD needs to incentivize its Program Managers to focus on the implementation of CBM+ systems earlier in the weapon system development life cycle in order to capitalize on the LCC savings they provide.

C. CONCLUSION AND LESSONS LEARNED

The development of PHM will not succeed without commitment from all levels of the Program. The Program Management must be willing to defend the system during the inevitable cost-cutting exercises. The system developers must have a sense of responsibility for the design and integration activities that cross all IPT’s. All of the IPT’s have a stake in the development of the PHM system. The hardware and software configuration management and integration activities are extremely complex and errors will have a cascading effect across the weapon system.

Program Management and system developers are responsible for not only designing systems according to the warfighter’s requirements, but also managing their expectations, particularly when delivering a disruptive technology with intermediate functionality. Programs must also account for the budget necessary to maintain PHM systems throughout their lifecycle. The Program could consider the establishment of a Software Maintenance IPT at some point during the acquisition phase.

The program manager and logic designers should be aware of and identify risks related to the development of PHM software. The following are some common risks associated with the PHM software development activity:

- There is an inherent risk in developing software for safety critical control components. The risk is especially high when working with airborne weapon systems. The fault detection and accommodation logic must be tested, verified and validated to a high standard.
- Cost and schedule are always significant risk factors during software development. The WBS for these programs is such that one IPT depends on a product from another IPT. There is a risk of creeping requirements. The evolutionary model is used to mitigate this risk, but a large change in project scope cannot be absorbed or accommodated by any systems engineering model.
- Staffing issues and the learning curve associated with developing complicated software systems can place a large amount of risk on programs.
- The test benches used for Verification and Validation (V&V) testing will often run at 100% capacity during peak times. A shortage of equipment to test the logic will create a backlog and eventually schedule delays.
- Configuration control boards will have their own set of priorities. For example changes to the Control logic will get higher priority than changes to the Diagnostic logic. Excessive development issues with higher priority modules will often delay the development of less critical modules.

Tight collaboration between the customer and the developer is a critical aspect of controlling requirements, cost, schedule, and quality during software projects. A customer presence at the development site can provide autonomy and a fast turn-around when challenges inevitably present themselves. For example, derived requirements will often have some ambiguity and leave room for interpretation. This interpretation could impact project cost and schedule. However, having a government representative with decision making authority integrated with the development team can provide timely guidance and potentially eliminate costly rework and delays.

As stated above, the DoD is in the business of making the difficult seem easy. Schedule delays and cost overruns associated with developing high-tech weapon systems are nearly inevitable. These vast and complex systems are bound to experience shortfalls and unexpected failures that drive redesign activities. However, it is not unreasonable to expect better performance from the DoD and the contractors that develop the weapon systems.

This research provided examples of acquisition and development programs that have used systems engineering processes and industry best practices to achieve better results. Along with these documented improvements used on legacy programs, the research also identified several other success oriented criteria for delivering capable PHM systems closer to budget and cost targets, such as:

- Incentivize Program Management to focus on Life Cycle Cost Savings
- Involve the end-user beyond the requirements development phase
- Manage warfighter expectations to minimize Taguchi losses
- Plan to support PHM software throughout the weapon system life cycle

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