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Critical Systems Engineering Perspectives for the Development and Implementation of Enterprise Health Management Solutions

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Abstract

The application of Health and Usage Monitoring Systems (HUMS), Prognostics and Health Management (PHM) Systems and Enterprise Health Management (EHM) Systems is becoming increasingly relevant in the new operating paradigm under which advanced military platforms are developed, acquired and sustained. There is also a critical need for the application of health management technologies in existing military platforms. Today's military platforms are required to operate at a higher operating tempo, for longer periods, in a tightly constrained budgetary environment. While it is evident that Health Management (HM) can significantly improve the operational, business and support aspects of the entire Defense Enterprise, it is also becoming evident that the task of managing the development and integration of this capability within the complex set of systems that comprise modern military systems is a key challenge from a systems engineering perspective. This paper examines what the authors consider to be the most critical systems engineering views and perspectives related to the Enterprise, the Capability, the Functions, the Program Organization and Science and Technology (S&T) Development. This paper also treats briefly, in the context of EHM, the application of novel concepts and tools such as the EHM Framework, Strategy Deployment, an Open System Architecture Framework and Model Based Systems Engineering.

I. Introduction

Requirements for Health Management and Condition Based Maintenance (CBM) capabilities are part of almost all major Defense acquisition programs in order to provide a number of benefits in terms of improving system readiness and lowering operation and support (O&S) costs. The authors observe that as this trend continues and Health Management becomes an integral part of the Defense Enterprise, the impact of these capabilities on the enterprise operations will go beyond the traditional expectation-which focused primarily on maintenance improvements.

The overall goal of Health Management is to provide end-users with actionable information to achieve their mission, sustainment and business goals more effectively. Recent work by Dabney et al. [1] and the National Defense Industry Association (NDIA) [2] provides some insight into the key challenges in implementing and deriving these benefits. Dabney et al. propose an approach for technology planning, research and development collaboration and effective transition to health management capabilities to operational programs. The approach provides a Framework for assessing operational needs and business case; identifying technology gaps, roadmaps and collaboration opportunities; and assessing the integration constraints and transition issues. The approach proposed by Dabney et al. not only addresses the importance of understanding the role of technology in meeting the health management requirements in a particular program, but also highlights the need to consider complementary technologies and capabilities in areas such as business processes, architecture, infrastructure and implementation. The NDIA study report validates the benefits and need for such an approach.

Defense policy guidance and guidebooks in the areas of health management and CBM exist, but are often at too high a level to provide detailed design or systems engineering guidance. The policies include:

- Military Flight Operations Quality Assurance (MFOQA)) - [3,4]
- Condition Based Maintenance (CBM+)) - [5]
- Defense Acquisition Guidebook - [6]
- Reliability, Availability and Maintainability – Cost (RAM-C)) - [7]

The following definitions show the Enterprise-wide scope of HM capabilities:

"*EHM is defined as the capability to make intelligent, informed, appropriate decisions about design, logistics, maintenance and operational actions based on health management information, available resources, acquisition strategy, and operational demand.*"[2]

"CBM+ uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, sustainment, and operations…at the operational level, CBM+ brings the ability to meet mission requirements and increase weapon system availability" [5]

These definitions exemplify the need to elevate health management to the status of a systems engineering discipline in order to focus on the development and implementation of the various HM capabilities and functions required to support decision making across multiple stakeholders [1]. This is a highly challenging task since the HM capability may be the most integrated part of the system under development. This paper examines what the authors consider the most critical systems engineering views and perspectives in order to address (systematically) this challenging task. This paper also examines (briefly) novel

approaches and tools such as the EHM Framework, Strategy Deployment, an Open System Architecture Framework and Model Based Systems Engineering.

II. The Enterprise Perspective

Work by Millar [8] has highlighted the need for effective Systems Engineering processes to implement HM especially in an Enterprise context comprised of numerous stakeholders and priorities. The DoD Reliability, Availability, Maintainability-Cost (RAM-C) Report Manual [7] also states this need as follows: "*In the process, the health management and prognostic system must provide timely and actionable information to multiple user communities with distinct needs and priorities*".

Figure 1 shows the three stakeholder communities that are relevant to a complex Health Management implementation in a Defense Enterprise. These broad categories are then further broken down into their key needs, capabilities and priorities.



Figure 1 EHM Stakeholder Communities within the Defense Enterprise

As shown in the diagram, the various stakeholders often use HM information in different ways to meet their respective operational goals. This provides an additional challenge to the systems engineer trying to design a suitable architecture and end solution. The ability to produce information for these views and reconcile design elements relevant to each of them is an important consideration. The following paragraphs describe these perspectives in more detail.

Sustainment Operations

The use of HM information to support sustainment operations including maintenance is the traditional area of application. The ability to detect and isolate faults and determine system health state provides the ability to undertake opportunistic or deferred maintenance and logistics actions based on current available resources and operational

needs. The end goal for sustainment is to utilize technology in conjunction with novel sustainment concepts to provide improvements in sustainability and affordability.

The role of HM here is to trigger (autonomously) logistics actions; primarily related to the need for maintenance, supply, and training or for the need to improve the systems monitored by the HM function. The ability to leverage large amounts of data and present actionable information is the key to effective sustainment decision-making. While the need to trigger actions related to maintenance and supply have been well understood, especially in relation to the use of prognostics, the ability to trigger actions related to continuous improvement to improve the overall system performance and maturity are less stated.

Warfighter Operations

The Health Management needs of the Warfighter relate to the ability to provide readily available and serviceable aircraft. Mr. John Johns, Office of the Assistant Deputy Under Secretary of Defense for Maintenance Policy and Programs [9], outlines the challenges in the Warfighter environment with emphasis on the following priorities:

- Rapid deployment
- Quicker readiness refresh
- High Readiness
- Higher level of utilization

These priorities address today's environment where air vehicles deploy for longer periods, face issues with obsolescence, long maintenance lead times and cost growth. In addition, the highly integrated and complex systems under development require greater levels of technology management to ensure they meet Warfighter needs.

From this perspective, the health management system needs to provide a range of capabilities based on the current and projected health of the Air System. These capabilities must also be effective at a number of different levels of management or command. For example, at a local squadron level, HM needs to provide indications of current and future asset availability. The ability of the HM system to declare, with a high level of certainty, an asset as being capable for a given mission is an important decision support function.

Enterprise Business Operations

In today's business environment, the operation and support of Defense platforms involves novel business processes and partnerships between the government and industry. Performance based logistics (PBL) puts new emphasis on delivery of a capability based on cost and readiness imperatives. Therefore, industry OEMs and PBL suppliers need information on how their assets are performing in the field for their continuous

improvement in order to boost system performance and profitability. The need for HM technology to support such concepts at an integrated level is becoming more important.

From this perspective, the HM system must enable a much higher level of integration with not only government and contractor systems but also those of their suppliers and other service providers. It is clear that the ability for HM technologies to provide up to date and accurate health assessments of materiel in the field is an important capability to enable effective business operations and asset management across the entire enterprise.

III. A Health Management Capability Perspective

Health management of engineered systems requires a new perspective in order to deal with the different engineering disciplines and complexities involved. Without the right perspective, most researchers in the field migrate toward complex physics of failure diagnostic models as they attempt to look for *deterministic solutions* to inherently complex systems. The authors observe that a better perspective is to model health management of engineered systems after another science, *medicine*. As in the human body, there are doubtless hundreds (if not endless) different failure mechanisms in an engineered system. Add to this the anomalies due to degraded or failed interconnected systems in a highly complex system-of-systems structure. From this perspective, it is more important to manage the fault progression in a particular component or subsystem, prior to an actual failure, by monitoring the subsystem's "heart beat signals" as opposed to dealing with the failure after the fact (a heart attack).

Using this perspective, there are four key health management principles that form the foundation for the HM capability [10].

- **First-** Health Management is not a "self contained, stand-alone system."
- **Second-** Health Management is both a Function and a Process.
- **Third-**Health Management can be performed on a subsystem, a system, an aircraft, a vehicle, a ship, an entire fleet or an industrial plant.
- **Fourth-**Health Management information enhances the entire "enterprise" which includes business, fleet operations and sustainment infrastructures.

The first principle is the notion that, unlike other platform capabilities, health management is a function designed (inherently) within a system. Second, Health management is both a *function* and a *process; the function that provides users with an integrated view of the health state of the system* and the *processes* used to identify, mitigate and resolve actual and impending faults within the air vehicle.

The notion behind the third principle is that health management is an incremental (tiered) capability that requires insertion and maturation over time. That is, health management involves multiple technology layers (sensors, data acquisition, feature extraction, prognostics, etc.) and application tiers (component, subsystem, system, vehicle, fleet). An example that supports this notion is to recognize that HUMS implementations only cover the data acquisition, data manipulation and, to a limited extent, the health assessment layer, and only for certain life limited mechanical components on rotary aircraft.

Finally, based on the enterprise perspective described in the previous section, it is clear that health management is an integral *function* that enables decision support *processes* across the enterprise. Ultimately, *this is the value added that health management delivers to operational programs.*

IV. EHM Architecture Design

The definition and development of the architecture for EHM solutions is a critical step in the systems engineering process. As stated in the ISO Standard for Systems and Software Engineering [11] "The purpose of the Architectural Design Process is to synthesize a solution that satisfies system requirements. This process encapsulates and defines areas of solution expressed as a set of separate problems of manageable, conceptual and, ultimately, realizable proportions".

The Department of Defense Architecture Framework (DODAF) [12] states: "The value of the architecture is realized through its usage. Architectures support strategic planning, transformation, and various types of analyses (i.e., gap, impact, risk) and the decisions made during each of those processes. Additional uses include identifying capability needs, relating needs to systems development and integration, attaining IT interoperability and supportability, and managing IT investments". In addition, the DODAF framework defines a number of portfolio levels including Enterprise, Mission and Component/Program. These portfolio levels are analogous to the three EHM stakeholder communities identified in this paper.

DODAF also defines a series of viewpoints comprising capability, operational, services and systems. Similarly, other Systems frameworks such as MODAF utilize a series of similar viewpoints, with MODAF introducing an acquisition viewpoint that defines project dependencies and timelines.

Due to the criticality of the architecture and viewpoints involved in the development and implementation of EHM solutions, there is a need to define a generic EHM system architecture framework comprising critical views and perspectives that can guide a program to success. These views will provide guidance for definition of capability, functions, processes, organizational constructs and technology development roadmaps.

V. EHM System Views

Using the DODAF principles [12], this section describes the system views (Figure 2) or perspectives that are critical when developing the EHM system design architecture. These views are derived from the authors' experience in developing and implementing specific HM systems but are described here in generic terms to be useful to any EHM application.

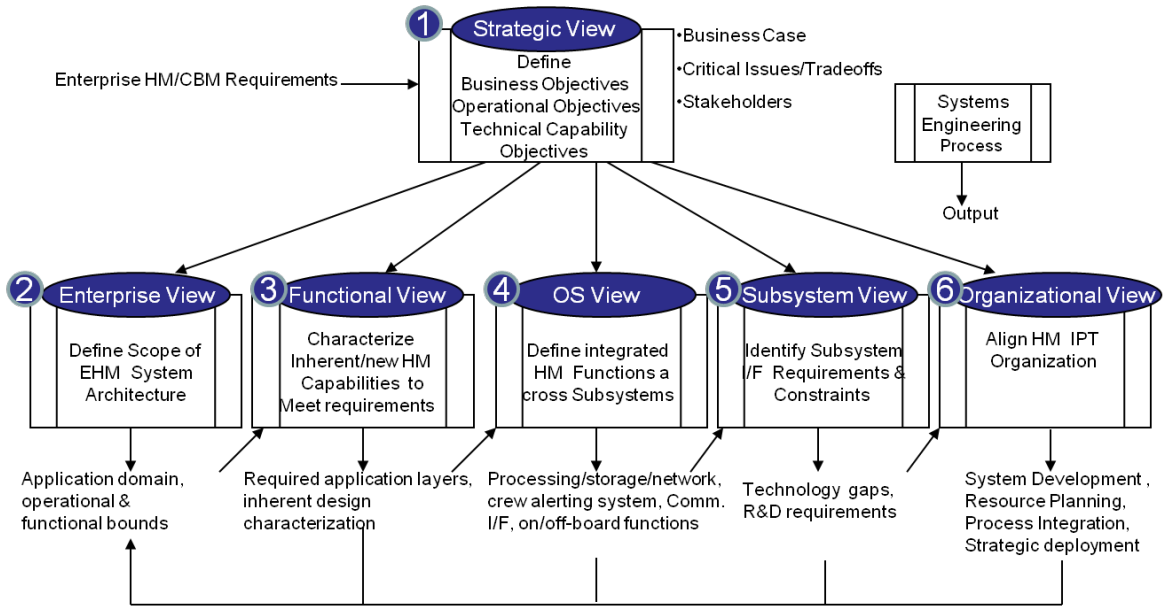


Figure 2 EHM Architecture Development Process

Strategic View

The Strategic View (Figure 3) view provides the overall statement of objectives and ensures that the top-level EHM System strategy is the central driver for development and implementation. This view should drive all priorities and the IPT Lead needs to ensure that the program under development is meeting these objectives.

The use of Strategy Deployment techniques such as the Hoshin System [13] provide a structured approach to identifying top-level strategic goals and to identify gaps, barriers and opportunities. The approach utilizes metrics and incorporates regular plan, do, check and adjust (PDCA) cycles to ensure progress. The approach also includes a 'catchball' process that seeks to provide consensus among stakeholders and ensures that potentially conflicting program decisions or initiatives are avoided. Strategy deployment is a useful tool to provide ongoing support to the systems engineering process. It facilitates the management of the highly integrated nature of HM and keeps the EHM project team focused achieving the EHM strategy of the particular program.

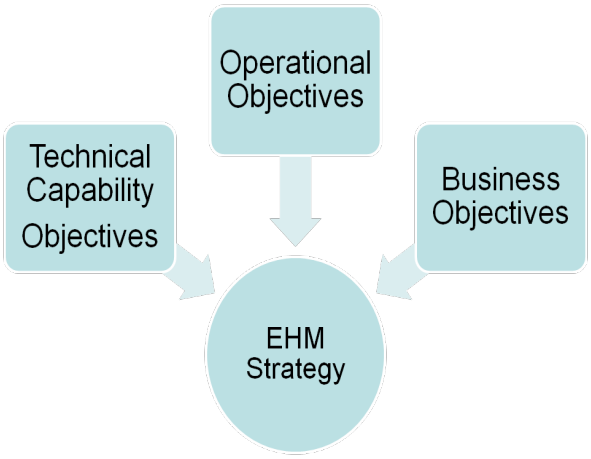


Figure 3 Strategic View

Enterprise View

The Enterprise View (Figure 4) shows the top-level system and the key stakeholders. It is important to show all stakeholder interactions at an Enterprise Level to ensure that requirements derivation takes into account the expected capabilities and benefits of each of them. These stakeholders need to be intimately involved in the system architecture development process. The design and any impacts or workarounds need to be well defined and documented. Legacy systems have traditionally focused on providing benefit to the maintenance and servicing stakeholders. This can limit the range of opportunities for HM to deliver benefits to other stakeholders including:

- Fleet Management
- Depot Servicing
- Reporting system performance to OEMs
- Logistics Support
- Business support for performance evaluation and PBL
- Continuous Improvement Initiatives

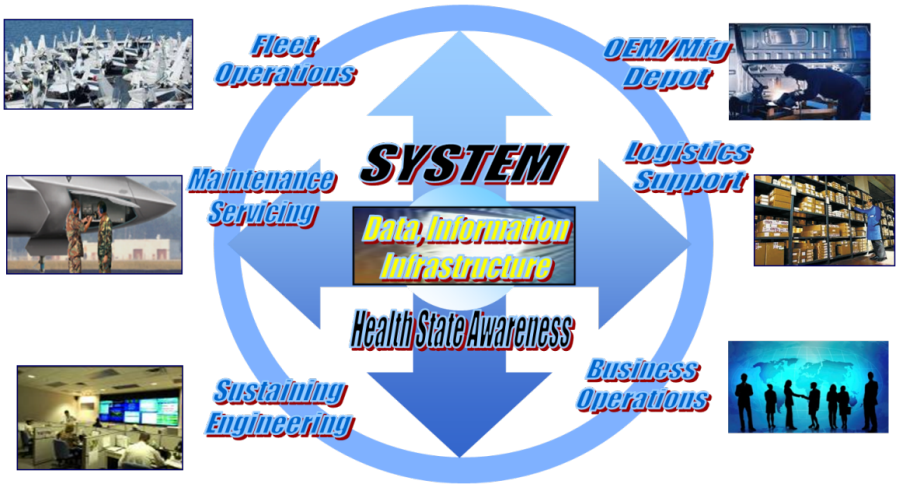


Figure 4 Enterprise View

Functional View

The EHM System Functional View (Figure 5) shows the functions that comprise the HM capability. This capability is a functional build-up based on the system's inherent data collection, diagnostics and health reporting which leads to the ultimate goal of Health Management. The idea is to use the existing capabilities as the basis for integrating new functionality into the platform's systems or subsystems that are suitable candidates for the health management capability. This approach allows for incremental gains and non-intrusive improvements to existing functions—setting the foundation for development and integration of the new advanced functions (e.g. prognostics). It is important to note that the delivery of these functions is dependent on the system architecture, interfaces, processes and tools. A clear definition of the interface between the existing and new design functions is developed using traditional systems engineering processes.

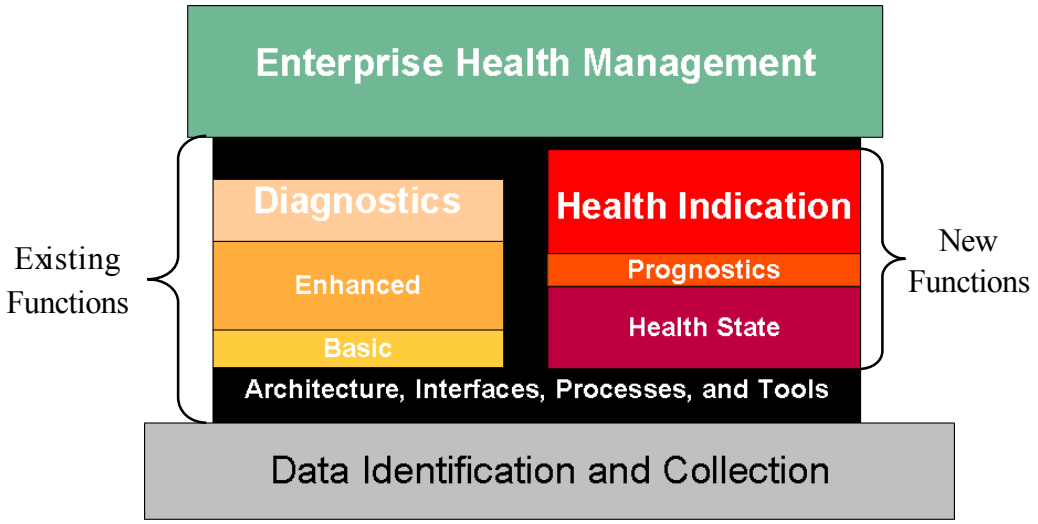


Figure 5 Functional View

Operational Systems View

The Operational Systems View (Figure 6) describes build-up of the health reporting which begins at the sub-system level and ultimately provides actionable information to all stakeholders. As described in the diagram, the idea is to group aircraft subsystems into functional groups. Each aircraft subsystem (propulsion, power, mission systems, avionics, structures, etc.,) has its own subsystem health management (SHM) function (Tier 1). Ideally, each subsystem SHM function should produce a health state determination or the data to produce one for its health enabled components. The integrated health state determination is then derived from the health state data produced by the individual subsystems in an aircraft (Tier 2). Once obtained, the integrated health state data can be used by a variety of decision support applications throughout the enterprise, including crew alerting, vehicle maintenance and logistics systems, mission planning, and fleet operations to name a few (Tier 3). It is in this way that health management truly enhances the enterprise operations.

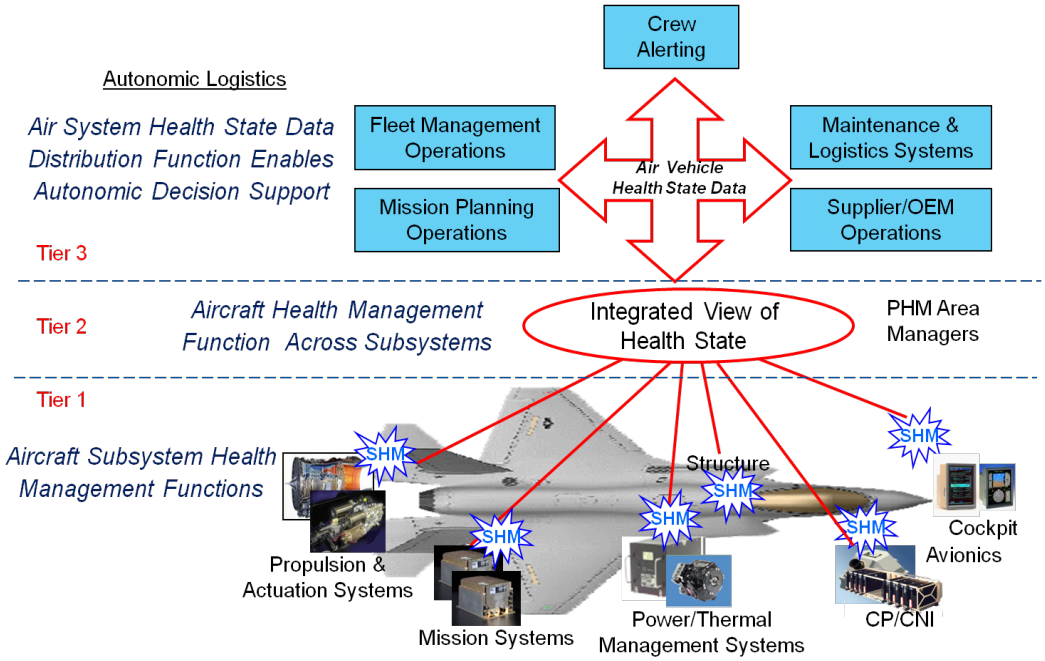


Figure 6 Operational Systems View

Subsystem/Component View

The Sub-System or Component View (Figure 7) defines the key performance characteristics of each sub-system or component that is part of the HM capability. These performance characteristics should be included in system design and performance

assessments to ensure that requirements are met and that the overall HM approach meets the defined strategic goals.

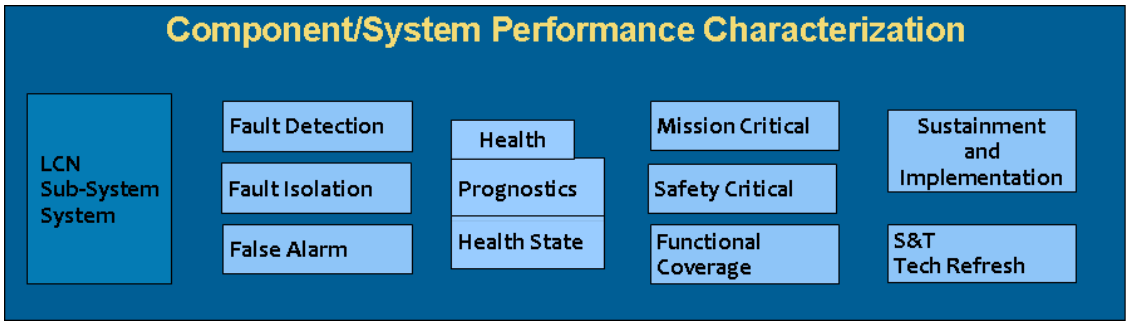


Figure 7 Subsystem/Component View

Organizational View

The Organizational View (*Figure* 8) shows the key roles and functional organization to support the development of a successful EHM system. The EHM Integrated Project Team (IPT) Lead provides overall strategic guidance to the development and implementation activities and takes ultimate responsibility for the delivered system. It is important to note that the EHM IPT must have the support and advocacy of the enterprise leadership. EHM solutions involve significant complexity, cross-functional disciplines, and a high degree of technology integration - requiring alignment and collaboration across multiple stakeholders. As shown in the diagram, the organization consists of four functional areas comprising:

- **Design and Integration:** This covers the design aspects of all systems and sub-systems and their integration. This covers all hardware and software elements both on the vehicle and those located on ground systems.

- **Operations and Business:** This team examines operational and business strategies and shows how the EHM system will provide applicable decision support. The team also examines metrics and performance to evaluate the effectiveness of the system.

- **Sustainment:** This team develops the strategy to sustain the EHM system and to identify how to best integrate health state data within the system logistics and support concept.

- **Systems Engineering:** This team carries out the systems engineering process to define system requirements, the architecture to meet those requirements and provide a strategy to execute verification and test activities.

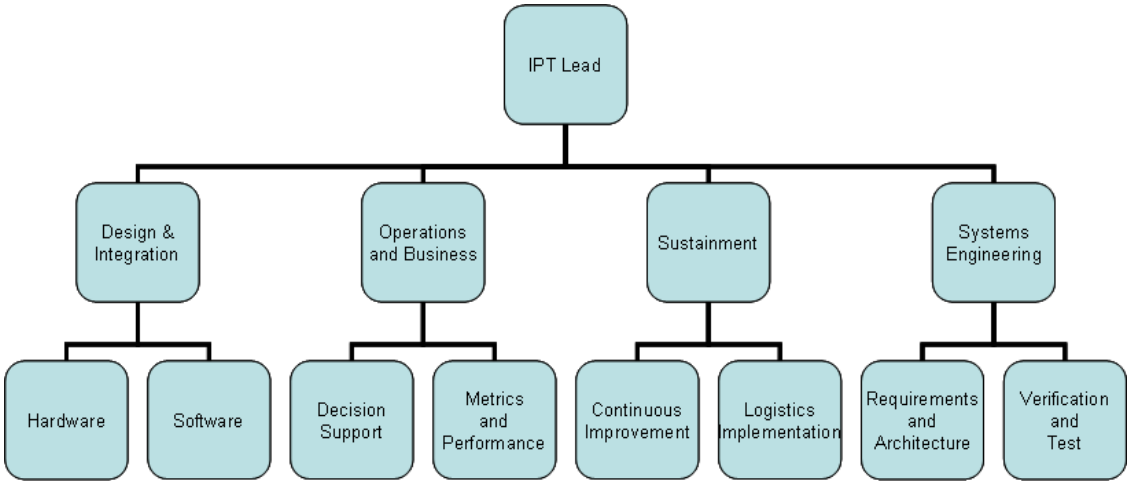


Figure 8 Organizational View

Framework for S&T Development and Transition

Figure 9 shows a framework developed by Dabney et al. [1] and the National Defense Industrial Association [2]. As shown in the diagram, the framework provides a useful means to aid in the systems engineering process and production of roadmaps to facilitate technology planning, R&D and transition. The framework process elements are grouped into five key pillars; Business, Architecture, Science & Technology, Infrastructure, and Implementation. Within each pillar, specific process elements produce technology capability gaps and implementation barriers using a clear descriptive term.

As shown in Figure 10, this framework provides an approach for assessing operational needs and business case, identifying technology gaps, roadmaps and collaboration opportunities, assessing enterprise integration constraints and S&T transition issues. The objective is to avoid the "S&T valley of death" and to avoid producing "orphan technologies" with no clear transition path. That is, in addition to the need to develop the S&T capability, the development and transition strategy needs to address a solid business case and needs to be enabled by a compatible architecture and supporting infrastructure. The implementation of the technology also needs to be considered early in development to ensure that it is consistent with the stakeholders' concept of operations and sustainment implementation plans.

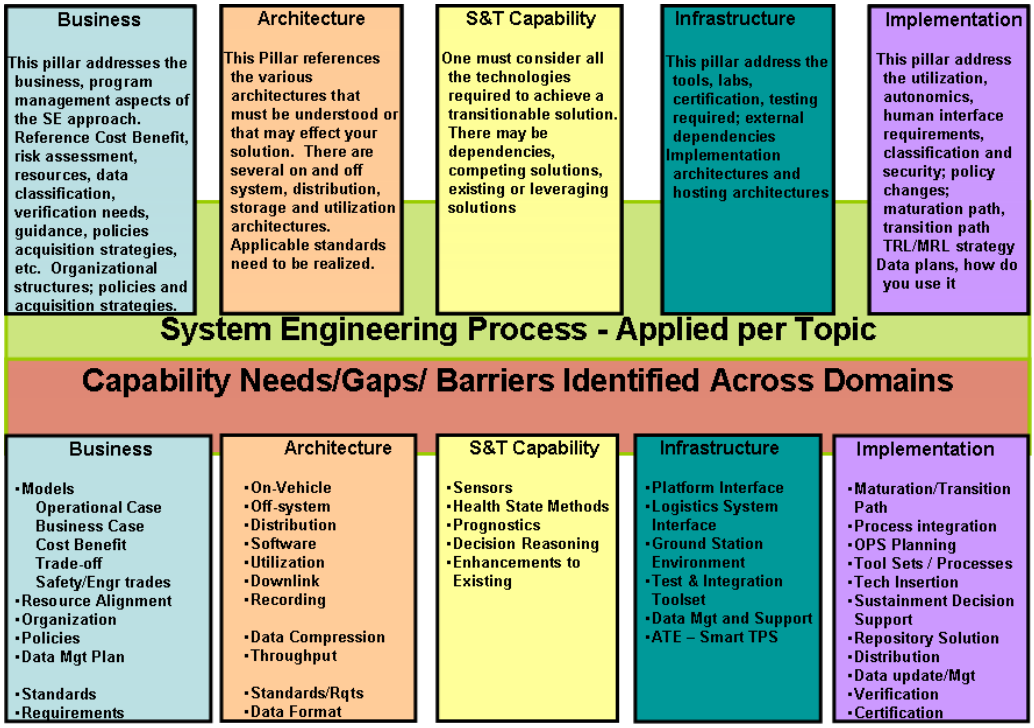


Figure 9 Framework for S&T Development and Transition

VI. Emerging Systems Engineering Tools

Systems Modeling Tools

The use of systems modeling tools can be particularly useful in developing, integrating and managing multiple systems views and perspectives. A number of systems modeling tools and templates are available for this purpose including Unified Modeling Language (UML) and frameworks including DODAF, MODAF and UPDM. Model Based systems engineering (MBSE) is an approach which integrates many aspects of systems-engineering processes in an environment which is based on integrated models rather than documentation. The MBSE approach allows a consistent and integrated model to be developed and maintained. This model includes requirements, structural and behavioural models as well as parametric models to capture system performance. This approach can provide a basis to select candidate architectures and to define applicable verification and test approaches.

The Systems Modelling Language (SysML) approach [14,15] was utilized to develop a model of a generic EHM system. A number of diagrams were developed including requirements, functional breakdown, state machines and use cases (Figure 10). The MBSE approach using SysML has a number of advantages in that it can tie these elements together within the same model and allows verification and test activities to be identified. This provides an excellent solution to managing the complexity and highly integrated nature of EHM solutions. In addition, the model can provide a number of

views of the same model that can cater to different stakeholders. The re-use of model elements and the ability to maintain internal model consistency is a benefit to both small and very large EHM implementations.

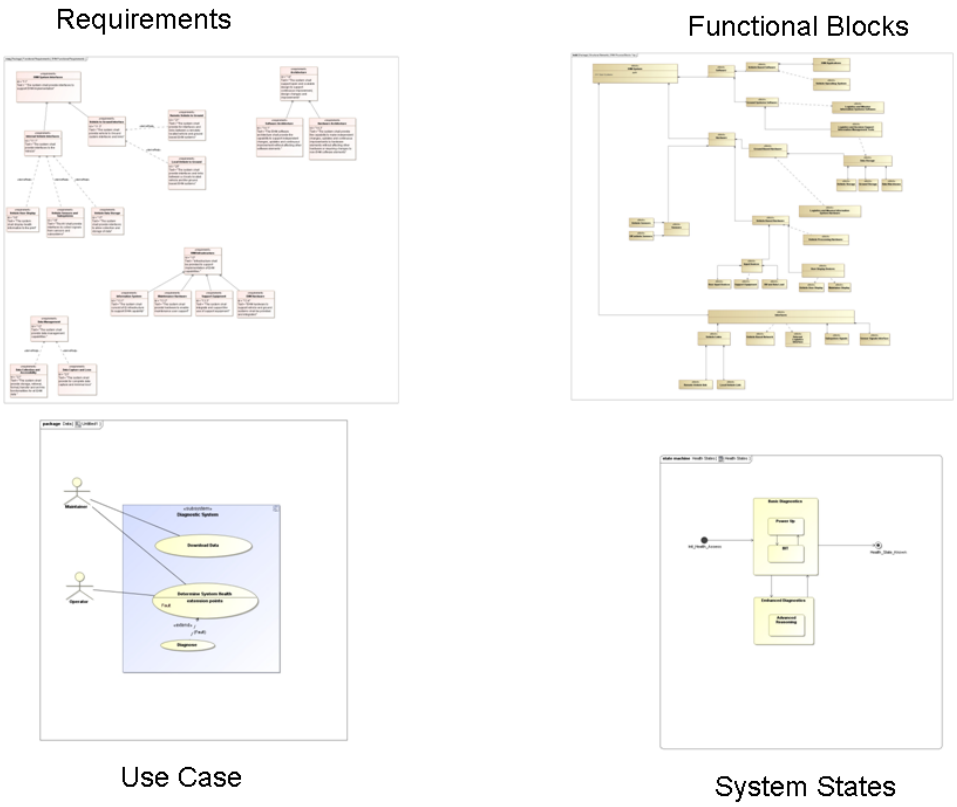


Figure 10 Representative SysML Diagrams for an EHM Solution

VII. Conclusion

The development and implementation of CBM or health management solutions for use in the modern acquisition and support environment presents a challenge to the systems engineer and architect. Health management systems involve highly integrated capabilities throughout the operational, support and business Enterprise. Successful solutions need to cater adequately to the various stakeholders. There is a need for a set of generic systems views or perspectives that can guide the complex systems engineering process to define suitable architectures, capabilities, organizational constructs and strategic approaches. This paper provides a series of views that have proved to be useful in developing EHM solutions. Model Based Systems Engineering tools such as SysML can provide an effective means for capturing and integrating these views and generating model perspectives suitable for each stakeholder. The use of a framework for S&T development and transition can provide an effective means for identifying technology gaps, roadmaps

and collaboration opportunities, assessing enterprise integration constraints and S&T transition issues.

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