A Reference Stack for PHM Architectures

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ABSTRACT

This paper suggests a reference model for PHM processes that aids the customer of PHM in developing a business case for adopting PHM in his or her supply chain. Various PHM systems have been envisioned and developed in order to produce a prognosis of system or component behavior by collecting physical data from some section of a system, analyzing it and reporting the results to the entity that benefits from it, notably the supply chain that manages the components and receives the resulting cost benefit from PHM. All these systems have varying configurations that involve the collection of different types of data in different ways, the analysis of varying types of physical behavior and have different types of customers (different supply chain configurations). The customer needs to include the cost and complexity of the PHM system in his or her business model but has no formal standard to determine bounds on the complexity of the PHM system. Just as there are reference stacks for service-oriented architectures, this paper proposes a functional stack for PHM that can become a reference architecture for developing or purchasing a PHM system for an organization. The stack of PHM services ranges from the data acquisition layer through analysis functions to supply chain decision support services.

1. INTRODUCTION

There are numerous treatments of the structure of systems that are designed to provide prognostics and health maintenance (PHM) (examples of these systems is described in Section 2). They all deal with sampling data at some rate and analyzing it for some characteristic that indicates that there is a pending system or component failure. Sometimes the designs are focused on a particular aspect of PHM, e.g. a particular type of data analysis, but they all begin to take on similar structures. In addition, regardless of the system, the common goal of the various functions in PHM is to improve lifecycle costs in the supply chain or alternatively, to provide readiness and availability of components in the supply chain. In this effort, it is the business case analysis (BCA) that determines the effectiveness of PHM system functions. The BCA provides requirements for the design of PHM system functions.

A stack architecture would stratify these PHM functions into domains that are orthogonal in their system responsibilities. That is, they involve disjoint sets of activities that produce data that is consumed by the function above it. In this regard, the activities in each layer are opaque to the other layers. This paper presents a stack of functions that can be used as a reference stack architecture for PHM. The reference architecture is driven by the analysis of various existing PHM architectures and the extraction of a commonality from them.

Stacks of functions or responsibilities are used in systems architecture to partition the subsequent design activities and enable reuse of functions. They enable the development of clean interfaces between system functions in that a layer only consumes the information from adjacent layers. The reference stack presented here can enhance the implementation of the BCA requirements because it exposes PHM functions in a way that makes them transparent to PHM system architecture development. There is less of a chance that the PHM system would incur an unforeseen cost due to unnecessary development. Supply chain stakeholders can agree on the functional structure of the system and understand the level of effort that is required to develop the system.

Section 2 surveys a few PHM systems that have been described in the literature in order to extract some common functionality for the discussion in Section 3 that organizes PHM functions into the reference stack.

Clearly there are far more systems than are discussed in Section 2, but the structures are similar. The intent is to develop a motivation for the common stack of system functions in Section 3. For detailed descriptions of these systems and others, the reader is referred to the references and literature. A goal of this paper is to be able to employ its results in evaluating as well as designing PHM systems.

2. BACKGROUND

This section reviews some previous PHM architectures in order to extract some commonality to support the discussion of the reference stack architecture that is appears in Section 3. There have been several approaches to developing PHM systems. They all involve the collection of data (generally data from sensors) from a platform system that is managed, along with its assembled components, by the supply chain. The collected data is analyzed by either a data driven approach, which performs statistical analysis of the data or a model driven approach, which develops a physical model in order to trace the behavior of the data to specific components on the platform (Analysis is discussed in Section 3.2). Both techniques can be employed in an analysis. The results of the analysis are then transmitted to consumers such as the decision process in the supply chain. The results of analysis support maintenance and component management in the supply chain.

Overall, the results of PHM produce several benefits to the supply chain: there is a cost and availability benefit to lifecycle systems management that is driven by the acquired capability to defer maintenance optimally and therefore lower maintenance costs. In addition there are benefits that are orthogonal to life cycle cost such as improved component and system reliability and safety.

The following sections review some of these PHM architectures.

2.1. PHM Architecture Driven by a Systems Engineering Approach

Begin (2012) describes a general architecture that is derived by applying systems engineering principles to PHM. This work develops a methodology for producing a "solution-neutral" PHM architecture. A functional decomposition is given in Figure 1. The various components that are associated with PHM are given but there is no connectivity to the supply chain decision-making services to complete the requirements of the supply chain for lifecycle cost management.

Nevertheless, the simple functional structure in Figure 1 forms a basis for formally defining what a PHM system is. Data acquisition is fundamental and provides, generally, time series data that the other layers consume. Diagnostics obviously looks for failed or faulted components while the more difficult to achieve prognostics might sit on top of diagnostics and use diagnostic services to produce a prediction of remaining useful life of a component. Finally, health management provides overall condition maintenance data to the supply chain, which is not shown. Testability is a function that can be a logical activity that is absorbed into each of the functions.

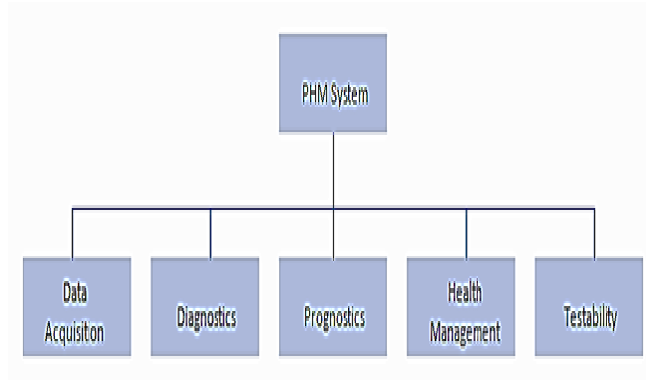

Figure 1. Notional PHM architecture (Begin, 2012).

2.2. Boeing IHVM Reference Architecture

Boeing developed a comprehensive integrated vehicle health management reference architecture (Keller, Wiegand, Swearingen, Reisig, Black, Gillis & Vandernoot, 2001) that is shown in Figure 2.

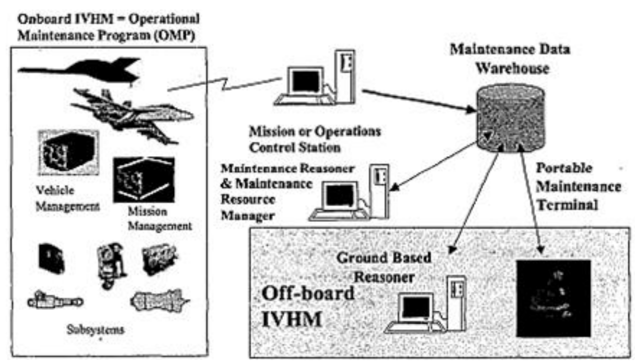

Figure 2. The Boeing integrated vehicle health management architecture (Keller, et. al. (2001)).

PHM functions are distributed from the vehicle to analysis activities that are off-platform and a data warehouse. Their partitioning is dependent on the characteristics of the infrastructure such as network bandwidth.

A reference stack of PHM functions is given in Figure 3 where PHM data flow from sensors at the bottom through signal processing of the data, monitoring of component condition, developing a health assessment of the platform and then a prognostic estimate of component lifetime which is a remaining useful component life. Decision Support is the recipient of the analysis results that uses them for lifecycle management in the supply chain. The presentation layer represents peer-to-peer communication with stakeholders in the supply chain.

All of the PHM functions are present in the stack in Figure 3 and the reference stack that is developed in this paper is similar to it and will be discussed in Section 3.

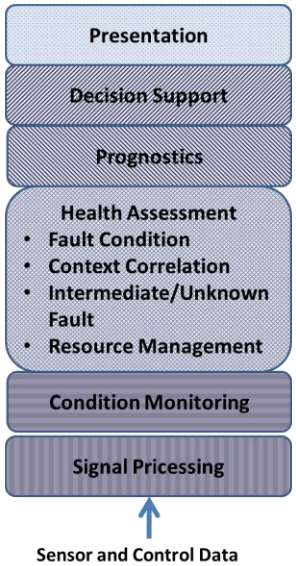

Figure 3. Stack of functions in the Boeing reference IHVM architecture (Keller, et. al., 2001).

2.3. Distributed Prognostic System Architecture

Expanding the diagrams in Figure 1 and Figure 2, the prognostic results of the PHM analysis function can be transmitted to the decision support function via publish and subscribe services. In the architecture in Roemer, Byington, Kacprzynski and Vachtsevanos (2006) that is shown in Figure 4, data flows to logistics decision support at the top. Analysis algorithms are specified to be at the lower level in the stack that is located at the subsystem that is under observation. A reasoner hierarchy isolates fault regions with reasoners placed at the subsystem in addition to the platform so the analysis function can be distributed vertically in the stack.

The functions in Figure 4 begin to look layered and the publish-subscribe mechanism with a data pipe for big data defines clean interfaces that support both the sharing of data and the opacity of the functions that produce the data. Section 3 will organize these functions into a reference stack of PHM architectural functions.

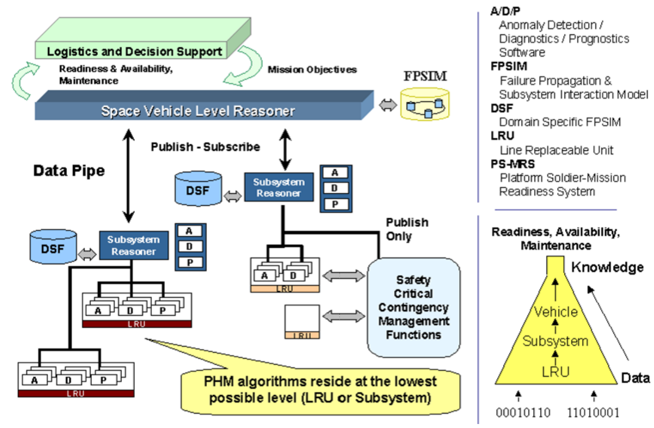

Figure 4. The distributed prognostic system architecture in Roemer, et. al. (2006).

2.4. Distributed PHM Algorithms

Saha, Shaha and Groebe (2009) give a more tightly coupled distributed PHM architecture. In this architecture, shown in Figure 5, the analysis functions are distributed onto sensors with computational elements (CE). The Central Server assists in analysis if there is insufficient remote computational capability, for example in the particle filter algorithm that creates the RUL probability distribution.

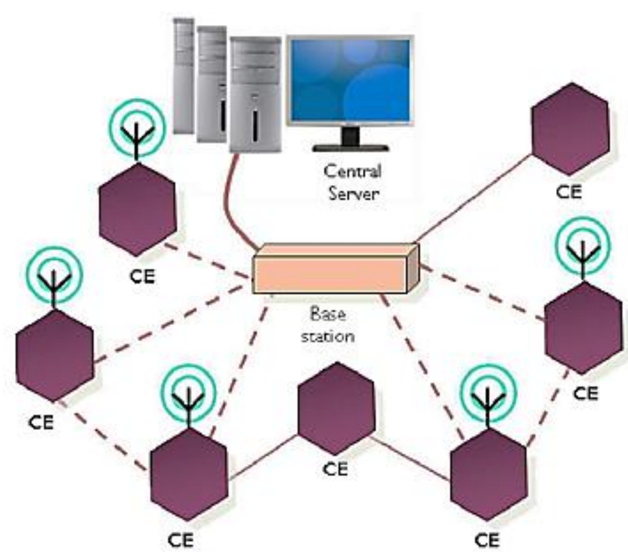

Figure 5. A distributed PHM architecture of sensors with computational elements that perform analysis (Saha, Saha & Groebe. 2009).

Were this architecture to be fit into a stack structure, the analysis function is still layered above data acquisition even though it is distributed. As will be seen in Section 3 the stack is devoid of deployment strategy because it is a logical functional specification.

Again, absent in this architecture is the connection to the supply chain support services in the enterprise that is in Figure 4. In developing a BCA for such an architecture, the supply chain connectivity needs to be considered because it is the recipient of the benefit. Section 3.3 discusses the value of this connection in relation to the BCA. Clearly, this system could be integrated into the supply chain with a services interface because of its computational capability. The connectivity at the level of the CE would be less complex (have a simpler data transfer) due to limitations to computation.

In organizing this architecture in a functional stack, the communications functions to/from the CE can be specified as another interface to the analysis function from the data acquisition function. This will be developed in Section 3.

2.5. F/A-18 Inflight Engine Condition Monitoring Architecture

Hall, Leary, Lapierre, Hess and Bladen (2001) present a PHM architecture for the F/A-18, known as the Inflight Engine Condition Monitoring System (IECMS), shown in Figure 6. The IECMS is an end-to-end system in which the sensor data is retrieved from components on the aircraft in the upper left of Figure 6 and transferred to analysis functions at the ground station that provide results to the pilot, maintainer and maintenance control on the right.

The data collection architecture on board the aircraft is further specified, producing a stack of responsibilities from the component that is sensed to the maintenance stakeholders. The functions in this design also support the reference architecture that is developed in Section 3.

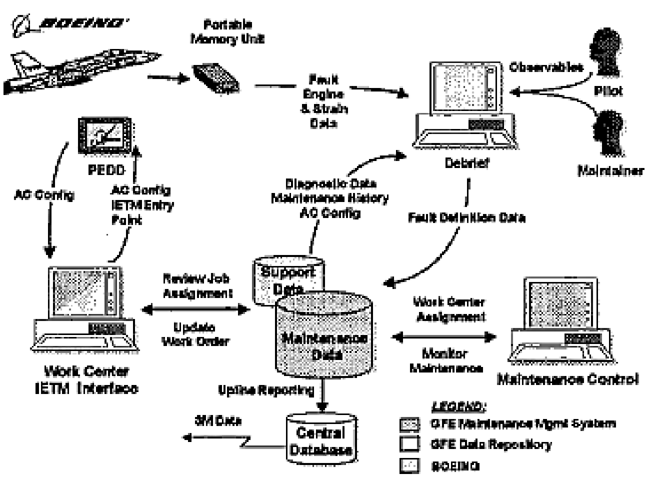

Figure 6. The F/A-18 Aviation Maintenance Environment (AME) Ground Station (Hall, Leary, Lapierre, Hess, & Bladen, 2001).

In Figure 6 the data store is the central part of the architecture. The data types are described in the data transfers between the nodes, for example the fault data from the aircraft and the maintenance data from the data store. The pilot and maintainer on the right form the decision support services (at least part of them) in the supply chain. This architecture conforms to the stack in Figure 3.

2.6. PHM Architecture for Defense

Butcher (2000) presents an architecture that describes a condition-based maintenance system for the Department of Defense. It functionally decomposes into many of the components that are in the architectures that have been presented so far. Figure 7 shows the architecture diagram.

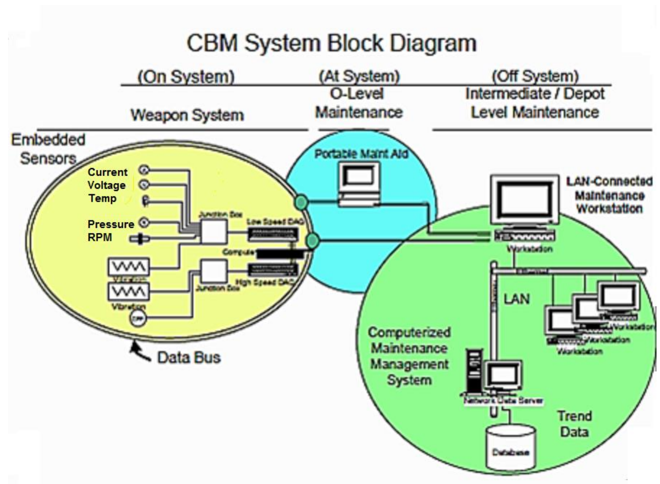

Figure 7. The condition-based maintenance architecture for the DoD in Butcher (2000).

The architecture in Figure 7 defines three domains, On System, At System and Off System. The functions in the stack in Figure 3, Sensor and Control Data and Signal Processing are located on-system. The At-System domain is meant to be the data collection function with the Portable Maintenance Aid shown in the figure. In the operational environment, connectivity can be reduced, hence there is reliance on a physical means of data transfer off the platform; computing capabilities on platform can be reduced hence analysis functions are moved to the right. However, Butcher does discuss the richer on-system computing environment of the Joint Strike Fighter that is diagrammed here in Section 2.8 and conforms to this architecture. Supply chain decision support services are in the Off System domain on the right with the data store. This diagram conforms to the stack of functions in Figure 3.

A similar architecture is developed in Section 3.3.2.

2.7. Condition Monitoring Framework

Another way to partition a PHM architecture is by its ontological elements. There is a description and data hierarchy of what PHM functions do, and Emmanouilidis, Fumagalli, Jantunen, Pistofidis, Macchi and Garetti (2010) develop an architecture by including the knowledge base involved with condition-based monitoring, notably, "Physical Assets, Networking, Knowledge Management, Computational Models and Usage of Information & Operational Technology". The result is Table 1.

Table 1. A condition monitoring relational data table (Emmanouilidis, et.al., 2013).

Physical Assets	Networking	IT/OT	Maintenance Knowledge	Computational Model
System	MAN/WMAN, LAN/WLAN, 3G/4G	ERP, Servers	System class	State
Sub-system	LAN/WLAN	ERP, MES, CMMS, SFCS, Desktop/Server	Sub-system class	Sub-system-level Novelty Detection Diagnostics Prognostics
Unit	LAN/WLAN PAN/WPAN Gateways	Sensors, Actuators, Controllers, DAQ, RFID, PDA	Unit class Unit-level Fault modes Fault mechanisms Fault severity Fault criticality Asset relations Fault symptoms Fault features Measurement characteristics	Collective Models, Single Node Models Unit-level Novelty Detection Diagnostics Fault modelling Prognostics
Component	Serial/Bus PAN/WPAN	Sensors, Actuators, Controllers, DAQ, RFID, PDA	Component class Fault modes Fault mechanisms Fault severity Fault criticality Asset relations Fault symptoms Fault features Measurement characteristics	Single Node Models Novelty Detection Diagnostics Fault modelling Prognostics

In Table 1 there is a stack of physical assets in the left column, but these are quite different from the PHM assets that were described in the architectures in the previous sections, notably the stack in Figure 3.

The functions across the top of Table 1look like they could be organized into a stack that is similar to the one in Figure 3, but there are knowledge areas and models. What is useful in Table 1 is the compilation of the semantic terms for condition-based maintenance. The Maintenance Knowledge column organizes the fault information, which is critical to condition-based maintenance. The Computational Model column has analysis areas. The networking column has the connectivity units. It is as if this architecture could reside on top of the other architectures that are described in this section. As such it is a *semantic* architecture that could reside in a communications stack.

This paper develops a stack of PHM functions in Section 3. It is along the lines of the stack in Figure 3. However, the knowledge base needs to be developed for web services that communicate the PHM analysis results throughout the supply chain. Thus, building a table such as Table 1 creates the PHM ontology for an enterprise. In the stack that is introduced in Section 3, it is viewed that the organization of terms in Table 1 is assembled at the enterprise level where those terms have meaning across the entire PHM system area of operation. Ontologies are discussed later on in Section 3.3.2.

2.8. JSF Autonomic Logistics Architecture

The F-35 has the most recent and complete PHM system for a complex operating environment, having to monitor the F-35 and its F135 engine. The system detects faults and predicts component lifetimes, the results of which are transmitted to the maintenance activities on the ground where aircraft components can be managed autonomously. That is, some maintenance activities are replaced by the PHM results.

The development of prognostic functions is ongoing, but the supply chain is able to respond more quickly to aircraft maintenance needs than was previously possible (McCollom & Brown, 2011). There is a concept of operations for delivering analyzed data autonomously from the aircraft to the supply chain in order to reduce supply chain inefficiencies. There is a stack of responsibilities from data collection at the aircraft to the decision support functions in the supply chain.

The layers of the architecture are shown left to right in Figure 8. Again, each of the areas of responsibility can be broken down into detailed stacks of functionality. The Air Vehicle has analysis and fault detection functionality and a function that manages that data. Fault data from the aircraft is then reported directly to the Decision Support Maintenance Planning Condition-based Maintenance node on the right, in the spirit of the stack in Figure 3.

The following section suggests a structure that generalizes all the architectures that were discussed in this section.

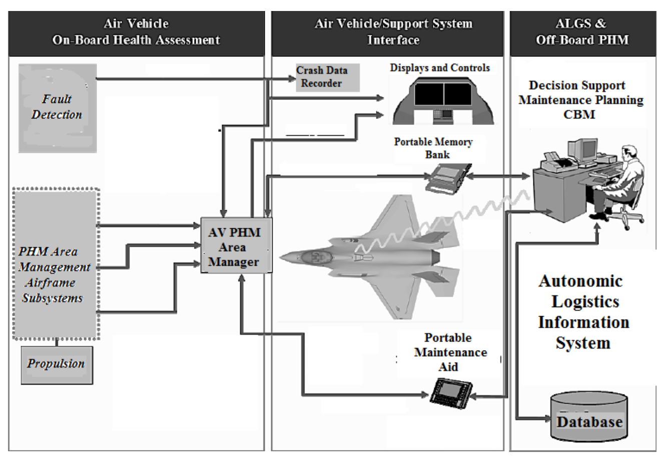

Figure 8. F-35 Autonomic logistics system deployment (McCollom & Brown, 2011).

3. THE PHM REFERENCE STACK

This section synthesizes the discussions of the architectures in Section 2 into a general reference stack of PHM functions.

The development of PHM architecture is based on requirements for integrating PHM into the supply chain. The requirements are generated by a business case analysis (BCA) that justifies the cost of developing a PHM system against the cost of managing the traditional supply chain for a particular system (Beyer, Hess & Fila, 2001, OSD(ATL), 2010).

From the discussion in Section 2, functional layers can be identified that reflect the activities in the various architectures that meet some need for PHM in a supply chain. The stack in Figure 9 is an architectural response to the requirements for PHM and defines the functions that produce the required return-on-investment (ROI) or increased availability. The BCA-generated requirements are the input on the left.

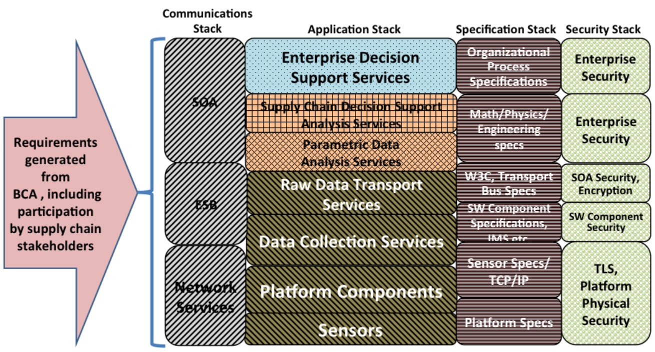

Figure 9. Functional reference stack of PHM Services.

Figure 9 organizes the architectural functions into function-type areas in the columns. In the beginning, a set of requirements is generated from a process that builds a business case analysis for the system, shown in the arrow on the left. Such a process includes interaction with suppliers, integrators and the other stakeholders in the supply chain. This process is beyond the scope of this paper, but provides the motivation and formal requirements for developing the system that delivers PHM functionality.

The central area is the Application Stack that delivers the system functionality. Other stacks support the Application Stack: A communications structure is on the left. The Specifications Stack provides technical requirements and standards that are levied on the system. The Security Stack on the right satisfies the information assurance requirements of confidentiality, availability, integrity, auditing and so forth.

In discussing the architecture in Figure 9, it is best to start at the top, because the motivation for developing a PHM system is to improve the cost of managing the supply chain that supports systems in use by an organization. Every logistics organization has Enterprise Decision Support Services at the top layer where supply chain activities manage parts and services for the systems that an organization deploys. The bottom layers produce the information that enhances supply chain activities.

The following sections discuss the elements of the stack in more detail.

3.1. Enterprise Decision Support Services

The decision support services in the enterprises are the ultimate recipient of PHM data. As mentioned above, the goal is to create a greater efficiency in the supply chain that improves its operating costs by streamlining the management of the systems that are under its control. Decision Support that consumes the products of the Analysis Services that are located beneath is shown at the top in Figure 9.

Following the information flows from the architectures that were described in Section 2, Figure 10 abstracts the flow of the PHM analysis products to the Supply Chain Customers that are in the upper right who receive analysis results from the PHM functions that are in the bounded region.

The Data Collection Services in Figure 9 can produce a large amount of data, such as time-series data, to be analyzed. The analysis *results* are greatly distilled from the raw, parametric, data that is produced by the Data Collection Platforms that are shown on the platforms within the bounded region in Figure 10. For Data Collection–Platform 1, mid-left in Figure 10, the analysis function is actually on the platform and analysis results are pushed up into the enterprise, as in Figure 4 above.

It is important to note that Figure 9 is a logical structure; the functions are logical and are deployed in the implementation phase, thus can be located where the system design dictates. For example, the architectures of Roemer, et. al. (2006) in Figure 4 and Saha, et. al. in Figure 5 distribute Analysis Services to remote elements in the design.

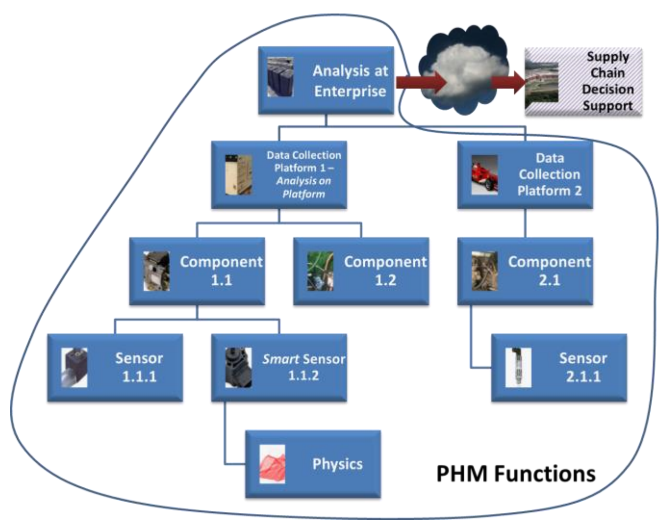

Figure 10. Injection of PHM analysis results from two platforms into the supply chain.

The analysis results that are pushed to the supply chain, or, to which the enterprise subscribes in the case of a cloud-based Services Oriented Architecture (SOA), can have some governed ontology that deals with components, fault modes and prognostics such as that described by MIMOSA (2009) and ISO 13374-3:2012 (2012). Section 2.6 described a semantic architecture, and the use of a SOA is further discussed in Section 3.3.2.

MIMOSA is a stack-oriented data architecture. Figure 11 shows its stack of functions, starting from a layer that deals with the acquisition of data, through layers that further refine the data. Analysis occurs in the HA and PA layers, the results of which generate an advisory in the AG layer.

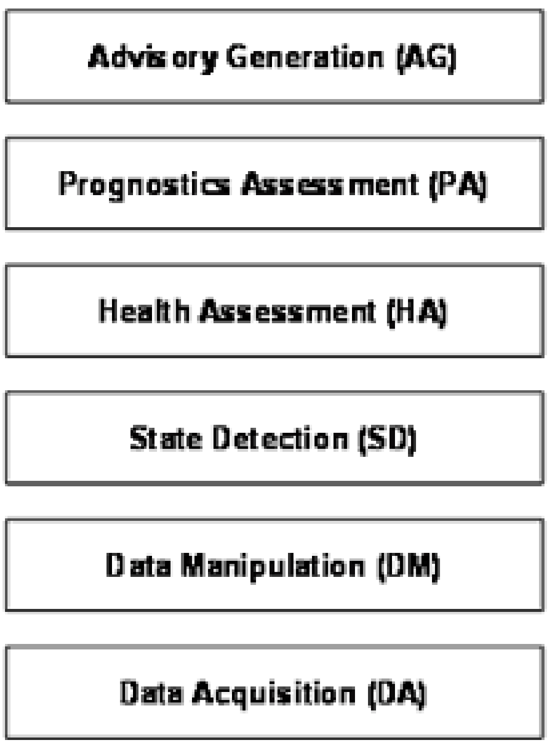

Figure 11. OSA CBM functional blocks (ISO 13374-3:2012).

Figure 11 is suggestive of functions in the PHM stack that is shown in Figure 9, and it is used in a *data architecture* that defines the interfaces between these PHM functions. The functions in in Figure 9 are *system* functions. The data that is generated in its layers can conform to the stack that is shown in Figure 11 but the functional organization of a PHM system is not mandated to conform to the functional organization that is shown in Figure 11.

An advantage of the ISO 13374 standard is that a schema can be built from its data stack. This is described in Section 3.3.1 for tagging the data and in Section 3.3.2 for developing an ontology for PHM web services.

Figure 10 indicates that there might be some sort of service-level agreement (SLA) between the supply chain decision support and the analysis services and governance over the analysis results that are created and its users if data is shared over a SOA. There is a cost to providing the SOA transport. Design costs as well as operating expenses of the SOA need to be factored into the BCA. The SLA includes requirements for quality of service (QOS) which involves the required bandwidth for data transfer. In Figure 4 above, a data pipe is inserted for a higher level of performance for more massive data amounts such as time-series data. Section 3.3.1 discusses the QOS requirement for raw data transport.

There is a central notion to this paper that the creation of a PHM system should not require the refactoring of supply chain functions in a dramatic way, as this would lead to additional cost. Most supply chains today operate within some sort of enterprise resource planning framework that is connected via a SOA. Thus, it is convenient to publish the PHM analysis results without having to retool the data transport mechanism. Section 3.3.2 discusses the SOA in stack.

The functions in Figure 9 and Figure 10 are to be used in the complete deployment of PHM technology to the platform and can used in a BCA to develop the cost basis for the PHM system (Sandborn & Wilkinson, 2007, and Kent & Murphy, 2000)).

3.2. Analysis Services

The Analysis services process the raw, parametric, data received from the Data Collection layer that collects data from the critical components that were identified in the BCA and provide supply chain decision support for life cycle management of components. The following two sections discuss these modes of analysis.

Analysis activities can be broken out into a stack of functions once the target components are identified. A good discussion of the analysis process is given by Roemer, et. al. (2006) and there are numerous approaches.

3.2.1. Parametric Data Analysis

The result of the analysis process in PHM is generally some sort of estimation of remaining useful life of the components from a trend in the data that indicates the *future* behavior of the component. The well-known idea is to predict a remaining useful life of a component, among other analysis products, that is injected into Supply Chain Decision Support to expedite its product stockage and provisioning functions, as is shown in Figure 10.

The notion really is that there is some stochastic process in state space which is therefore non-deterministic, but were the process known, would show a path to failure where the operation of a component passes into a region of inoperability. The time from the detection of this path, t_c, say, to the time of failure, t_f, is the component's remaining useful life or RUL. Figure 12 illustrates the path in state space of some measured parameters from a component. Multiple parameters are more difficult to correlate, so generally, papers on RUL deal with only one parameter. Figure 12 reminds us of the underlying physical complexities of the problem by plotting a multi-dimensional state space.

The broadened paths indicate that the parameters are really described by a probability density function with some statistical moment, such as average, indicated by the narrow path curve. Thus, the remaining useful life calculation is some probability distribution function. Examples of stochastic treatments of RUL are in Saha, Goebel, Poll and Christophersen (2007), Tang, Kacprzynski, Goebel and Vachtsevanos (2009) and Sankararaman and Goebel (2013).

If we *knew* the entire path for all time, we would see that somewhere along the permissible operating range the path bifurcates into a course that leads it to failure at some point in the future. In Figure 12 that point is the red statistical ball, the "failure occurrence volume", where the failure curve penetrates the operating volume at time t_f.

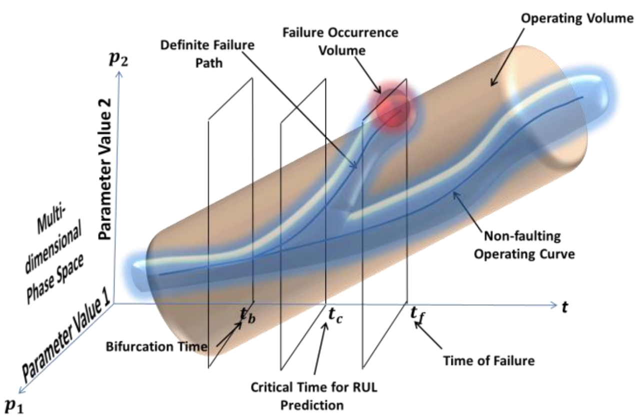

Figure 12. Paths, operating and failure, of measured component parameters in phase space.

The program in PHM is to recognize that the system is operating on this failure path soon enough to get the information back into Supply Chain Decision Support so that it has time to provision stockage and provide maintenance and part management functions before the actual failure, as is well known. In Figure 12 the time t_c is the time before the failure time t_f that the prediction of failure occurs, and the knowledge of which enables the supply chain to act on the predicted failure cost-effectively.

Analysis services that produce prediction of failure, or remaining useful life incur cost in the BCA. There is an open ended-ness to the analysis process because new failure modes or behavior characteristics can be discovered by continued analysis, but this is difficult to budget in a BCA. The identification of *specific* analysis algorithms that are attached to specific failures enables a turn-key system. Such algorithms would be deployed in distributed systems such as that is shown in Figure 4 and Figure 10 where analysis is distributed to the sensor locations. It may be necessary to update the remote CEs in Figure 4 with new algorithms (updating algorithms in regards to the stack in Figure 9 is discussed in Section 3.6). The identified analysis algorithms could conform to standard measures that are implemented in libraries in analysis tools. Standards are discussed more in Section 3.5.

In regards to the stack in Figure 9, the interfaces to the Analysis layer need to be defined so that they are useful to the subscribers in the Enterprise Decision Support Services above. Clearly, the schematic analysis result in Figure 12 is *opaque* to the enterprise that is looking for extracted information from it such as RUL. The RUL is to be injected into the level of analysis that is at the enterprise that requires a greatly reduced and far more descriptive set of data than is raw data. Section 3.6 discusses these analysis results in relation to the orthogonality of the functional layers in the stack and the next section discusses analysis at the enterprise.

Another aspect of Analysis Services is identifying an approach to the analysis. As was mentioned in Section 2, analysis methodologies involve data-driven and/or model driven analysis processes (Bernstein, Hauske & Hermann, 2014, Byington, Roemer & Galie, 2002). In including the analysis strategy in the Analysis Services in Figure 9, it should be understood that the analysis methodology can impact the supply chain and the BCA because there can be added cost to developing a dynamical physical behavioral model for a component which is a requirement of the model driven approach.

Detecting the data signature of a failure mode and associating it with a component is generally done with a model because it is difficult to run a statistically significant number of components to produce a failure signature for the data-driven approach and run the components to failure. Therefore, a model can simulate the data that is produced by deployed sensors and trace it to a fault condition.

However, the data-driven approach can *also* incur inordinate costs if a seeded-fault approach (Hess, A. (2002)) is used to identify failure signatures because system run time is required to associate the faults with data signatures. A problem with data-driven analysis is the uncertainty of achieving a logical connection between the analysis results and the physics at the data collection point.

In reality, there is a model that is developed from behavioral equations that describe the physical behavior that produces the sensor data. This is a complex, boundary value problem to develop and solve. Therefore, a data-driven approach appears attractive, but the sensors were applied to the critical component with some understanding of the underlying physical behavior of the system which causes the component to fault. To resolve these issues, the discussion of how the analysis process of a proposed PHM system affects the BCA for the system needs to occur with the engineering community as well as supply chain managers.

3.2.2. Supply Chain Decision Support Analysis

In Supply Chain Decision Support Services (DSS), another level of analysis occurs to determine the best plan of action for managing a component's total life cycle given the results from the PHM analysis in the previous section, as is shown in Figure 9. Thus, in developing a BCA for PHM, the Supply Chain analysis activities need to be taken into account in order to estimate the impact that PHM has on component life cycle management in the supply chain.

Such a supply chain analysis model is done in Feldman, Jazouli, and Sandborn (2009) who consider the costs of integrating PHM into the supply chain in their stochastic model for a Boeing 737 display, and Banks and Merenich (2007) develop a trade-space tool that calculates the cost benefit analysis for a PHM system for batteries in vehicle power systems.

Tsoutis (2003) simulates the effect of the autonomic logistics system for the F-35 that is shown in Figure 8 on supply chain management. He incorporates existing maintenance data for the F/A-18E/F F-414 engine (F-35 maintenance data was of course not yet available). His work compares a baseline of the traditional logistics system for the F-414 engine with a set of *modified* repair activities that are streamlined by the injection of prognostic information from a PHM system in the autonomously enabled aircraft in Figure 8. Tsoutis was able to perform a sensitivity analysis of the effects of increased component (module) reliability and prognostic accuracy, among other parameters. This type of work enhances the development of the BCA and produces a clearer understanding of the effect of introducing a new PHM system into a supply chain. The cost of restructuring a supply chain must be included in the BCA, and simulation of supply chain activities can demonstrate a cost benefit of the PHM system.

It is clear that the Analysis Services function occupies an important area for the BCA. The stack in Figure 9 can be used to partition the types of data, components and types of analysis to determine how much effort is required to reach a result from the analysis function.

3.3. Logistics Data Transport

The transport mechanisms for PHM data are shown in Figure 9 on the left as the Communications Stack and below the Analysis layer as Raw Data Transport Services. Raw Data Transport Services provide primitive data ("raw data" or parametric data), principally sensor data that can be voluminous due to high sampling rates, to the services that analyze and transform it. Discussion of their mechanisms of transport is treated separately for this reason in the next section.

The general Communications Services provide higher level communications functions such as a web services stack that includes semantic information and can be governed by an ontology. They are discussed in Section 3.3.2.

3.3.1. Parametric Data Transport

A central activity in the BCA for PHM is generally based on identifying high cost components that are expensive to manage (Banks, Reichard, Hines & Brought, 2008). Failure characteristics of these components are identified through a failure modes, effects and criticality analysis (FMECA) that leads to a root-cause analysis of the failure. The process identifies a characteristic of the component that can be monitored by sensing a region on the component that produces data that identifies that characteristic (See also the discussion in Section 3.2.1). The sensed data quantity can be large due to the results and recommendations of the FMECA and root-cause analysis. As the stack in Figure 9 and flow diagram in Figure 10 show, the resulting collected data needs to be transported to the analysis services that detect the failure characteristics.

Sensors generally sit on buses such as the well-known SAE J1939 and MIL-STD-1553 buses. Determination of what bus to use is dependent on the particular connectivity with the sensor. The Data Collection Services in Figure 9 define the data collection protocols. The cost for PHM systems on new equipment or retrofits includes the technology in this layer. These standards would be included in the standards in the specification stack, Section 3.5

The communications protocols for raw, parametric, data need to provide enough quality of service (QOS) to support large data streams. The protocol for transporting the data might not be the internet, but some physical mechanism such as a local lap top computer or portable maintenance aid. This configuration eliminates the bandwidth bottleneck but lessens real time data collection. However, the Analysis Services could be deployed on the local laptop. Thus, the stack in Figure 9 is useful for partitioning the functions of the PHM to the deployed areas in the system. Figure 13 shows a possible deployment. QOS in regards to data transport to the enterprise is discussed in Section 3.1.

Using the Stack to Reduce Bandwidth Requirements

Sensor data is generally a time series that is obtained at regular intervals at a specified sampling rate. The physics of the problem determines what rate is required to discover the data signature that indicates pending failure, as was discussed in Section 3.2.1. As such, the data can be large and hence require high bandwidths. The cost of managing big data needs to be integrated into the BCA for the PHM system. The stack in Figure 9 is helpful because it can be used in conjunction with the *deployment* of PHM services in the supply chain, such as that shown in Figure 10 and those that were discussed in Section 2.. A tradeoff analysis of the location of Analysis Services can reduce the cost of bandwidth. For example, Figure 5 distributes the analysis function to local computational elements that is a measure that greatly reduces the burden of having to supply a high-bandwidth transport for sensor data.

Describing or Tagging Sensor Data

An ideal is to publish this raw sensor data in the context of a services-oriented architecture. Sensor data can then flow up the left SOA stack in Figure 9.

There are formats that tag sensor data in order to develop a publish/subscribe mechanism at the parametric data level. This adds overhead to the sensor data but for large data transfers the headers are relatively small. One well known format is in the NASA CDF applications library (CDF User's Guide, 2012). A data tagging standard was built on top of that for PHM systems by the US Army known as Army CBM Bulk Data (ABCD) format (US Army PEWG, 2011). The tagging in ABCD format respects the data layers that are found in the MIMOSA standard (MIMOSA, 2009) and in ISO 13374-3:2012 (2012).

All these standardization activities need to be included in developing the BCA for PHM. The advantage is that developed standards such as NASA CDF come with functional software applications programmer interfaces that eliminate the cost of new software development. The Standards Stack in Figure 9 is useful to organize the standards at each level of the architecture. Standards are discussed in Section 3.5.

3.3.2. Communications Services

Communications services transport logistics information throughout the supply chain. The stack diagram in Figure 9 and data flow diagram in Figure 10 illustrate that these are the communications services that inject derived analytical information into the supply chain.

It is also envisioned that there is a Services Oriented Architecture (SOA) to provide the transport. An enterprise service bus (ESB) (Chappell, 2004) that provides connectors and messaging services as well as other functions in the SOA stack enables the SOA.

Enterprise Services Bus

The services stack in Figure 9 is meant to be integrated into an existing SOA that is provided by the supply chain that requests PHM technology. Adding the additional cost of developing a SOA to the PHM BCA would be excessively costly. Furthermore, it is a distinct advantage to be able to publish PHM logistics data to *existing* supply chain services that already make use of enterprise services technology.

Web Services (SOA)

Web services itself provide a stack of functions (W3C, 2004), but the configuration varies widely with providers. The supply chain would have a services architecture with governance and provisioning already determined. Thus, the PHM system should be able to publish the analysis results to the supply chain that subscribes to it. Again, it is meant to require minimal effort to connect to the supply chain. Section 3.1 discussed the role of a SOA in communicating PHM analysis results.

Figure 13 illustrates a possible deployment of a SOA architecture for PHM data transport in a military environment. Here, an ESB is located at each of the nodes in the Tactical, Operational and Enterprise areas and implements a SOA stack. Data collection on the Vehicle Platform in the tactical environment involves both the SOA for analyzed data, which can be generated on-platform, and a fast pipe, such as that in Figure 4 for parametric data transport. There is data analysis on platform as in Figure 4 and Figure 5. Raw/Parametric data is transferred to the operational node via a maintenance support device, such as a laptop or PDA over the high bandwidth link to support the bandwidth requirements. Decision support services (DSS) exist at the Enterprise node where the analysis is the decision support analysis that is discussed in Section 3.2.2 for lifecycle support. Note that the functions in the stack in Figure 9 are deployed in Figure 13 and the deployment looks like that in Figure 10.

The SOA makes the sharing of data seamless, but the diagram indicates that there has to be a common understanding of terminology of data types in the supply chain. In this environment, the ISO 13374 tagging (See Section 3.3.1) is useful for sharing the raw, parametric, data.

The ontology produces a common knowledge base throughout the supply chain and between enterprise domains; the ontology can be used to communicate diagnostic, health and prognostic information from one logistics domain to the next. The data schema, such as parametric data from the Tactical node in Figure 13, is governed by the MIMOSA standard (MIMOSA, 2009) as shown in Figure 14. The enterprise is the locus of domain expertise and has a *domain-specific* ontology that is developed by stakeholders.

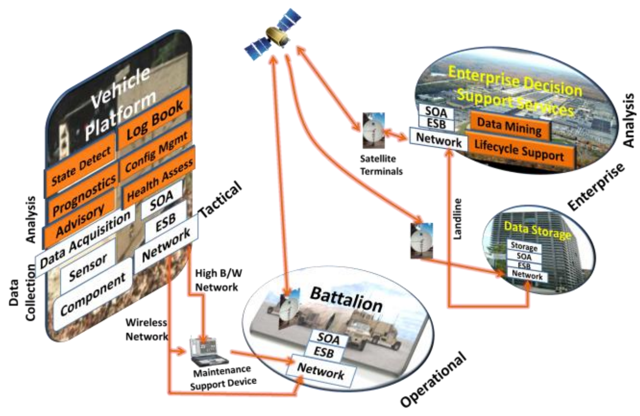

Figure 13. Notional deployment of a PHM system incorporating a SOA with corresponding ESB.

The organization might further develop an ontology to enable semantic structure to the data (W3C Semantic Web, 2014). An ontology is developed by Emmanouilidis, et. al., (2010) which was shown in Section2.6; the domain structure is shown in Figure 14. It is at this point that a table such as Table 1 can be developed at the enterprise to identify the semantic elements in the PHM system that is to be designed.

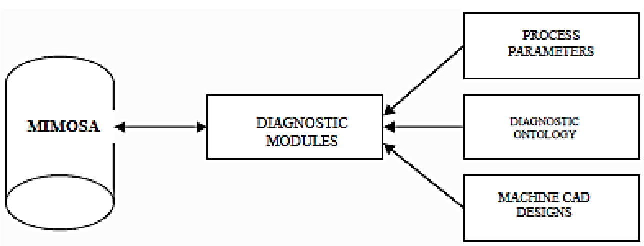

Figure 14. Diagnostic ontology of Emmanouilidis, et. al., (2010).

Including the cost and effort of developing a PHM system ontology in a BCA is a complex task. It is of course better to incorporate existing ontologies such as MIMOSA and the data stack that is described by ISO 13374. In developing a domain-specific ontology, the BCA should investigate existing ontologies in the organization and look to expand them with PHM terminology. Barring that, the effort needs to be closely monitored and costs need to be estimated as early on as possible. Ontologies are best restricted to systems of common functionality in order to bound the effort.

3.4. Security Stack

The architectures that are discussed in Section 2 are shy of data security measures, in part because PHM is the central function of the architectures and in part, because the data is not mission-critical data. For example, on an aircraft there is system control data, which is of course critical, while PHM data is produced in order to monitor the operation of the controlled system.

Data streams of time-series data such as that shown by the data pipe in Figure 4 can be protected by link encryption while services that produce higher level semantically governed information can be protected by implementing standards such as WS-Security (OASIS, 2004).

The stack on the right in Figure 9 addresses the security for the layers in the Applications Stack. What would be filled in here for the implementation are the specified security standards that are going to be used to provide information assurance to the stack. In developing the BCA for the particular PHM system that is under consideration, the cost of security may be relevant.

In developing PHM for military systems (Butcher, 2000), there are well-defined directives and procedures that need to be followed, indeed, *required* to be followed, such as *Net Ready Key Performance Parameter*, (NR KPP)CJCSI6212, 2012) and *Information Assurance Certification and Accreditation Process (DIACAP)*, (DoDI 8510.01, 2007). The implementation of DIACAP requirements requires additional time and obtaining a formal authorization to operate the system.

Collocating PHM data services with secure areas could incur a cost, possibly a cross-domain solution that would have another form of certification (DISN, 2004). The stack in Figure 9 is useful for identifying *where* data is produced in order to identify the security boundary of the originating systems (NIST 800-18, 2006), a primary task in information assurance.

3.5. Specification Stack

As mentioned at the end of Section 3.3.1 that discusses tagging sensor data by using specifications for various PHM functions, the stack in Figure 9 organizes standards and exposes them to the developer community for evaluation of their effectiveness. In Figure 9, the Specification Stack is to be augmented with the specifications that the design incorporates.

The specification stack begins at the top where decision support activities occur to support lifecycle systems management. These standards will already be in place, as PHM architecture does not refactor the supply chain architecture; it would be difficult to justify a cost for doing so. *However*, the JSF autonomic logistics architecture in Section 2.6 *does* affect some of the organizational structure of maintenance because its autonomic prognostic notification of faulty parts on the aircraft can remove a maintenance inspection step. A discussion of a simulation of this effect was given in Section 3.2.2.

The employment of standards can affect the BCA for the PHM system; the decomposition in Figure 9 can be factored according to the envisioned and simulated cost model for the PHM system. The use of standards over custom specifications more confidently reduces the cost of the PHM system. An example is the use of standard analytical methods for analyzing sensor data (See Section 3.2). While a lot of analysis work is specific to a particular system, the BCA can require that standard analysis libraries and tools be employed to conduct the search for failure precursors in the sensor data.

3.6. Orthogonal Property of the Stack Layers

As discussed in the Introduction, the functions in the layers in Figure 9 are isolated from adjacent layers. In good systems architecture, each layer contracts with the services from the layer below it via a well-defined interface and has no knowledge the internal functionality of its neighbors. Services do not get data from the service layers above them. One could ask if a lower layer receives data from a higher layer in the case of Figure 5, where new analysis algorithms are distributed to the remote CEs (this update process was mentioned in Section 3.2.1). However, this would be a transaction *within* the *analysis* layer in the stack in Figure 9 and would not violate the read-down-only principle. Recall, the stack in Figure 9 is *not* a deployment diagram that specifies where services physically reside.

An example of functional separation between layers is the analysis layer: the Supply Chain Decision Support Analysis Services and the Parametric Data Analysis Services layers in Figure 9. Supply Chain Decision Support Analysis Services would have no access to the raw, parametric data from the Parametric Data Analysis Services below it. Instead it subscribes to an agreed-upon analysis result, possibly component RUL, through a contractual interface. It does not have the same analysis functions or purposes of analysis as are in the Parametric Data Analysis Services layer. In terms of a BCA, this means that there is no duplication of effort between the layers and there is no confusion of functions in the layers. The argument is the same for all other layers.

4. Conclusion

Figure 9 presented a reference stack of functional areas that would comprise a reference architecture for a PHM system. Its development was motivated by the analysis of several existing PHM architectures in Section 2. Closely attached to this stack is the business case analysis (BCA) that provides a motivation for developing a PHM architecture. The reference stack in Figure 9 supports the BCA by making the functional composition of the proposed PHM system transparent to the cost and availability requirements that are generated by the BCA.

Included in the stack in Figure 9 are additional stacks that track the specifications to which the PHM system is designed. They are constraints on the cost of the system. Choosing existing specifications of services can reduce the cost of the system. On the other hand, security requirements can be a burden on the cost and availability of a PHM system. The communications stack describes the data transport functions for the PHM system but is also meant to identify open-source transports and a SOA that can be integrated easily into the existing supply chain enterprise services structure.

The PHM architectural reference stack is an effective way to communicate PHM system functions to the stakeholders in the supply chain who have commissioned the PHM system to reduce the lifecycle costs of the components that they manage.

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