

Strategies For Optimizing The Application Of Prognostic Health Management To
Complex Systems

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Abstract: Contemporary maintenance strategies are focusing on migration to Performance Based Logistics (PBL) and Condition Based Maintenance (CBM). These strategies represent efforts to emphasize evaluating logistics practices in view of impact to system performance measures, and to shift away from time-based scheduled maintenance to a predictive approach. The desired goals of these efforts are to reduce logistics footprint, logistics response time, life-cycle cost, and increase availability. In recent years, Prognostic and Health Management (PHM) technologies have emerged as a key enabler to achieve these goals. Increasing the insight into performance, cost and risk trade-offs early in the product design process is key to identifying and prioritizing where PHM solutions will provide the most significant benefit. This paper explores the challenges and needs of efforts to implement PHM technologies. In particular, this paper identifies and discusses the need for decision support to help characterize the potential impacts of PHM technologies on existing operational and support scenarios, and how to implement those PHM technologies on complex systems in a resource constrained environment.

Key Words: Decision support; anomaly detection; condition-based maintenance; data-derived models; fault analysis; failure modes; prognostics; system health management

What is Prognostic Health Management: System integrators, operators, and original equipment manufacturers are looking for ways to increase system availability, improve system reliability, and reduce the cost of system operations. Maintenance strategies are migrating to Performance-Based Logistics and Condition-Based Maintenance, which seek to extend time between preventive maintenance actions, reduce unplanned service interruptions, and prevent more extensive damage or even catastrophic failure. This includes, for example, efforts to move away from time-based scheduled maintenance, which is based upon the failure characteristics of a *population* of items to a predictive approach, which is based on the failure characteristics of each *individual* item. This also includes efforts to predict failures sufficiently in advance to schedule maintenance to times that result in the least interruption to service. The desired goals of these efforts are to reduce logistics footprint, logistics response time, life-cycle cost, and increase availability. In recent years, PHM technologies have emerged as a key enabler to achieve these goals. PHM technologies essentially take observations of the system (which can include its environment) and provide indications of abnormalities and, in the best cases, make predictions of future failures.

Benefits of PHM: The goal of implementing PHM is to achieve some benefit, which can be quantified in both economic and in non-economic terms. In some cases, it can even be difficult to quantify at all. In addition, benefits should be evaluated from a total enterprise viewpoint.

Economic Benefits of PHM: One of the goals of implementing PHM is the reduced cost of maintaining the system. Maintenance costs of complex systems can be extremely

large, especially for a fleet of systems. PHM can help provide savings in several ways. One such way is through Condition Based Maintenance (CBM) practices. Instead of relying on system reliability information to pick the best time to perform periodic maintenance intervals, a CBM system will rely on maintenance to be performed when the system needs maintenance as predicted by PHM. This will result in longer maintenance intervals, thus decreasing maintenance costs over time. Another way is in reduced spares levels required. Prediction of failures would allow spares to be ordered sufficiently in advance to provide a replacement just in time. This reduces the uncertainty of having replacements in time, which reduces the spares pipelines, and thus their cost.

Non-economic Benefits of PHM: PHM can also provide benefits, which are quantifiable but not necessarily economic. Improved availability is one example. Certainly there are cases where improved availability has a direct economic result. For example, it is essential that wind turbines run continuously in peak seasons for wind. Since it is cost prohibitive to conduct inspection of all wind turbines prior to each peak season, using PHM to continuously monitor them during the off-peak season allows maintenance beforehand of those wind turbines predicted to fail during the peak season. With greater availability of wind turbines during peak season, revenue from generated electricity is increased. In the case of military fighter aircraft, however, availability is measured in terms of sorties (or flights) generated. This metric, while certainly quantifiable, is not easily translated into a cost benefit. Another example is that of preventing catastrophic failures. The use of PHM to predict failures of critical system items can result in avoiding catastrophic failure, such as losing an aircraft engine in the middle of flight. Such a benefit can be quantified in terms of catastrophic events avoided, and is usually argued on the basis of safety rather than economy.

Difficult to Quantify Benefits: Beyond these are benefits of PHM, which are even hard to quantify. One example is the value of the collected data inherent with PHM technologies. Archived data from continuous monitoring can be used for trend analysis, feedback for continuous improvement, potential redesign and re-engineering, or even fix versus buy decisions.

Enterprise Benefits of PHM: When PHM is employed on a large number of systems in a fleet, there can be synergistic benefits beyond those for an individual system that is simply multiplied by the number of systems in the fleet. Because PHM systems provide insight into the health status of systems in the fleet, specific decisions can be made to optimize the support of those systems. Deployment of maintenance personnel, quantities and locations of on-hand spare parts and scheduling of opportunistic maintenance are a few of the enterprise support activities, which can be optimized. Issues that need to be considered to realize these benefits include quantifying the number of items, which must have some specified degree of PHM capability in order to effectively lengthen maintenance intervals or avoid service interruptions. The use of PHM, however, has the potential to optimize support, which can in turn result in lower costs and improved system performance.

PHM and Logistics Systems: The value of a PHM system is measured by its ability to effect an improvement in support or safety of a corresponding operational system (system ‘support’ in the context of this paper includes logistics systems, processes and resources). While significant effort is being committed to development of PHM technologies, it is important to remember that ultimately these PHM technologies must be fielded in a complex system within some operational and support scenario. For example, in the case of military fighter aircraft during wartime, sorties are flown during the day and only maintenance of critical items is performed between sorties. At night, maintenance of non-critical items is performed and periodic maintenance is performed less frequently than that. Identifying critical items that need repair in advance could result in higher sortie rates or reduced manpower in the flying window because the repairs could be scheduled to be performed at night (outside of the flying window). In the example of ground radar systems of a satellite control network, downtime to perform maintenance has to be fit into the contact schedule. Limited maintenance is performed locally, while traveling repair crews performs more extensive maintenance. If ground radar failures could be predicted in advance, required maintenance actions could be grouped and scheduled so that the schedule of the traveling repair crews could be optimized. In both of these support scenarios, PHM can provide a benefit, but that benefit is analyzed and characterized quite differently for each scenario, and the tools used for analyzing the benefit can also be quite different.

With the emerging emphasis on Performance Based Logistics, it is even more important to quantify the PHM benefits not only in terms of cost, but also in terms of operational and support measures. Often those measures require system specific models or simulations, which may require modification in order to adequately represent PHM characteristics. Just as important is to consider the impact PHM will have on all logistics elements, especially the less prominent elements such as technical data and manuals, training and training equipment, test, and logistics information management.

PHM Is Diverse: PHM actually encompasses multiple approaches, technologies, and application areas. Some PHM approaches emphasize diagnostics, which can encompass the indication of a failure and the identification of which item has failed (and even why). Prognostics emphasize the prediction of the time remaining before the failure of an item, usually termed the Remaining Useful Life (RUL). Both diagnostics and prognostics are useful for health management, which can encompass the decisions and actions made based on diagnostic or prognostic inputs to address the anomaly and possibly impending failure. PHM technologies can be classified as data-driven [1], Physics of Failure (PoF) [2], or even a combination of them (fusion prognostics) [3]. All technologies rely on input from sensors that monitor the system or the environment or both. Data-driven technologies build empirical models of the component, subsystem, or system that serve to help detect deviations from normal behavior (i.e., detect abnormalities). The input data required to build these empirical models is frequently called the training set, and it must typically come from an item when it is behaving (and being used) normally. Data-driven technologies, however, are not usually good for making predictions of RUL. PoF technologies are based on specific physics-based models of physical phenomena, such as crack growth or dielectric breakdown. PoF models tend to focus on the very basic item

level, and can be difficult to aggregate to higher-level subsystem and system behavior. They can be good, however, for making predictions of RUL. Fusion prognostics attempts to combine the best of both approaches for optimal detection and prediction. Lastly, application areas can be diverse for PHM technology, which can include mechanical, electrical, or thermal phenomena, or any combination of them.

Challenge to PHM Investment – Understanding How PHM Can Help: Most PHM efforts are conducted from a technology perspective, where the primary emphasis is on developing or refining a particular technology and less emphasis on where or how it might actually be applied. Very few efforts are from the use or utility perspective, which involves understanding how PHM technology can be integrated into and benefit a given system. This type of effort starts from a benefit or improvement goal (such as improved availability or reduced support cost), and looks for which subsystems and which PHM technologies might be most effective in accomplishing that goal. From this perspective, there are several questions that naturally arise.

How can PHM help accomplish specified goals?: What are the improvement goals in terms of operation of the system and logistics support? What areas would potentially receive the most benefit of implementation of PHM technology? The answers to these questions will also depend on the organization's strategic goals, i.e., whether the goals are to maintain the existing capability (efficiency), enhance capabilities (effectiveness), or phase out certain operations [4].

Which PHM technologies are most appropriate?: If a capability already exists to diagnose cause of failures, but not necessarily a capability to indicate when a diagnosis should occur, then a data-driven approach which detects abnormalities would be very helpful. If a low-level component is identified as a key system driver for failures, and its physics of failure is well understood along with environmental data that facilitates its use for predictions, then a physics-of-failure is most suitable. Each specific situation can require specific capabilities that may be met by a specific technology or mix of technologies.

Where can PHM most effectively be applied?: How is the scope of PHM implementation determined? Which items should be the target of PHM technology insertion or adoption? Possible criteria include high failure rate items, high cost items, or combinations of those or other criteria.

How does PHM fit within the operational and support context?: What changes need to be made to the way the system is operated? For example, PHM could provide the ability for system operators to anticipate problems while they are small and address them in a planned (rather than unscheduled) manner. Prediction of failures can be used to reconfigure a system to properly accommodate the fault or provide an orderly shut down before a catastrophic failure occurs.

Similarly, what changes or improvements can be made to the logistics support system? For example, an automated maintenance and logistics system can be build around PHM

technologies, such as is planned for the F-35 Lightning II fighter aircraft. Such an automated system could allow for a just-in-time maintenance environment where spare parts can be ordered in advance of when they are needed, and maintenance personnel can prepare for maintenance in advance of an aircraft landing due to telemetry download of fault codes [5].

Challenge to PHM Investment – Convincing Others: While PHM holds great promise for operational and economic benefits, the challenge to those planning its implementation has been to quantify the benefits and justify the investment in the technology. Unfortunately, there is often limited experience or expertise among those desiring PHM implementation with actually building and making a case for it. Recent emphasis in Department of Defense policy on implementing Business Case Analysis (BCA), particularly to justify Performance-Based Logistics for current systems [6], demonstrates that this is increasingly becoming a necessary skill. At the heart of BCA is the effort to quantify benefits, especially in terms of cost. An example of an economic analysis of jet engines was provided in a prior paper [7]. Nonetheless, it is important to recognize that not all benefits can be quantified as costs, and that the qualitative aspects of PHM implementation should be considered as well [8]. A discussion of the issues in building a BCA is provided later in this paper.

Need for PHM Investment Decision Support: Due to the complexity of PHM technology, the operational and logistics support system in which it is to be implemented, the many areas in which it could be applied in a given system, and the business case which must be developed to argue its implementation, the decision process for implementing PHM becomes critical. Because of the potentially large number of system items and limited resources, the decision process must identify which items are most suitable for which PHM technologies that will return the largest benefit for an investment made in PHM. The decision process must be structured to ensure that all possibilities have been considered, documented, and traceable to a specific goal. The decision process must also be repeatable, because it is likely that it will be performed for more than one item over time. The decision process must also be integrated, in the sense that the operation and logistics system is considered, so that the decision is not made in isolation. In order to implement a structured, repeatable, and integrated decision process, support for that process needs to be provided.

Elements of PHM Investment Decision Support: The elements of decision support for PHM investment can be divided into four areas: metrics, methods, support scenarios, and resources.

Metrics: The challenge in metrics is to pick the most relevant and useful measures of PHM impacts on operational and support performance, which include PHM characteristics and operational, support, and cost measures.

PHM characteristics are measures of the PHM system itself and how well it diagnoses and predicts future failures. While up to 18 possible PHM metrics have been identified [9], there are four basic metrics that are fairly representative: false alarm rate, accuracy,

precision, and prediction lead time. *False alarm rate* is the number of times a PHM system indicates there is a failure or impending failure when there is not. High false alarm rates cause the support system to overreact and waste resources responding to failures that have not occurred, and can breed distrust of the system by those using it. *Accuracy* is how close the prediction is to the actual failure. The most accurate prediction is exactly at the same time when the failure occurs. A prediction that occurs after the failure is considered a failed prediction. *Precision* is the spread of uncertainty around the prediction. If predictions always occur at the time of failure, the spread of uncertainty is essentially zero. Otherwise, there is some distribution that predictions will take around the actual failure. It is most desirable to have a highly accurate *and* highly precise prediction. *Prediction lead time*, also called prognostics distance, is the time between the predicted failure and the time the prediction was first made. Longer prediction lead times allow greater time for planning a response to the failure before it occurs. Planning a response, such as a replacement of a part, to occur before the prediction can help mitigate poorer accuracy and precision. This is equivalent to shifting the distribution of the prediction away from the actual failure, helping to increase the likelihood that a response will occur before actual failure.

Operational and support measures are measures of operation and logistics support performance, which typically are identified as a program's technical performance measures (TPM) or key performance parameters (KPP) for the system. For example, for Joint Strike Fighter Lightning II, these measures are sortie generation rate (SGR), direct manpower spaces per aircraft (DMSpA), and logistics footprint. Support measures could also include standard reliability, maintainability, and availability measures, such as mean time between failure and maintenance, mean corrective and preventive maintenance times, mean delay times, labor-hour factors, and inherent, achieved, and operational availability [10]. Particularly for operation and support, the measures must be chosen to accommodate specific scenarios with and without PHM technology for comparison purposes. With the emphasis in performance-based logistics on technical performance measures, these measures are particularly important in supporting PHM implementation decisions.

Cost measures can include definition and quantification of Life-Cycle Cost (LCC), Return on Investment (ROI) or breakeven point. There can be up to nine different analysis approaches with corresponding cost measures [11]. For PHM, there are generally two types of costs [12]. The first is PHM implementation cost, specifically, the cost of buying or developing, integrating, and sustaining a PHM technology in a new or existing system. These costs involve standard cost elements for acquisition and sustainment, and can be categorized as recurring, non-recurring, or infrastructural (which can include data, maintenance of PHM, decision support, documentation, and training). The second type of cost measure for PHM is savings, or cost avoidance. These costs are directly related to how the PHM technology will work with the operation and logistics system, so relevant cost elements should be selected based on established operation and support scenarios. For example, these costs could focus on avoided failures (and avoided loss of system or system function) or improved efficiency (extending maintenance intervals). Avoided costs can include indirect or secondary costs as well, which include

impacts not directly related to the failed equipment. Examples of formulation of avoidance costs are provided in [7]. Net Present Value (NPV) of costs must be used based on a planned implementation schedule if costs occur over time. The implementation costs, cost savings, and planned schedule can then be used to produce LCC, ROI, the breakeven point, and any other desired cost measures.

Methods: The challenge in methods is to determine the most efficient way to find the most promising candidate items and technologies for PHM investment. The methodology should take into account system complexity, existing analysis methods, and utilize sufficient resources (including subject matter experts) to obtain credible estimates of benefits of PHM investment. The simpler the system complexity, the simpler the analysis methods (e.g., for alternatives analysis) can be. For more complex systems, however, more sophisticated analysis methods would be required. Two basic avenues of analysis are possible: requirements analysis and assessment. Requirements analysis would attempt to identify what minimum requirements a PHM technology would have to achieve in order to accomplish stated operation or support goals (such as availability or reduced manpower). Assessment analysis addresses what impacts a PHM technology would have in an existing or proposed support system. Comparing assessments of different PHM technologies or uses of a given PHM technology comprises alternatives or tradeoff analyses, which can form the basis for a business case analysis for PHM investment. An outline of a proposed methodology for this second type of analysis (assessment) is provided later in this paper.

Operation and support scenarios: Since PHM investment takes place in the context of a proposed or existing logistics system, the challenge is to define one or more maintenance concepts and support scenarios that take advantage of the PHM technology. Careful development of such concepts and scenarios with operations and maintenance personnel is a necessary element in accurately characterizing both requirements for PHM and how PHM will be integrated into an overall support concept. For example, a support concept may allow an item to run to failure, but use PHM to order a spare in time to replace the item when it fails (to eliminate backorders and reduce spares pipelines). PHM might also be used to schedule the fix of an item at an off-hour to improve availability, or to group fixes for several items to make optimal use of a high-cost support resource (such as a traveling maintenance team or a crane in a wind turbine field).

Resources: Resources for a PHM investment decision process can include data, tools, and experts.

Data required for the decision process includes data not only for the PHM system itself (PHM characteristics as well as logistic element data of the PHM technology), but also for the item that is the subject of the monitoring and operation, and support system in which it is to be deployed as well. Item data can include reliability and maintainability data, including failure mode effects and criticality analysis (FMECA) and maintenance task analysis (MTA) data. Operation and support system data can include turn-around time requirements, spares levels, and manpower requirements not only for the item, but for all the other system items as well (to put the PHM investment in the context of the

overall support scenario). When data is unavailable, alternative sources of data need to be examined (e.g. from historical or similar systems) and the estimated differences quantified and accounted for in the final analysis.

Decision support tools, including models and simulations for analysis, used in the PHM investment decision process, need to be able to define and quantify the support system both with and without the PHM technology. Cost and logistic/support models are required to determine the impacts of the PHM investment. While for any item there may exist cost and logistic/support models, the challenge is to assess whether they can adequately represent the PHM technology. The challenge of performing trade studies or alternatives analysis, particularly for complex systems with large numbers of items, highlights the need for a tool to facilitate such studies.

Experts are also required for decision support in the areas of PHM technologies, cost, logistics and operation of the system, design/engineering, and in cases of large integrated systems, subsystem suppliers.

Tools for PHM Investment Decision Support: This section describes tools that can comprise a decision support infrastructure for PHM investment. These tools include tradeoff tools, cost models, and supportability models.

Tradeoff tools: Because there can be many quantitative and qualitative factors to consider in selecting a particular PHM implementation, the use of tradeoff tools to identify and prioritize those factors is important. Such tools can be used to compare alternative PHM technologies, selected system items for PHM implementation, or both. For example, tools that support Cost As an Independent Variable (CAIV) analysis, as shown in Figure 1, can be utilized to conduct tradeoffs of the PHM investment decision

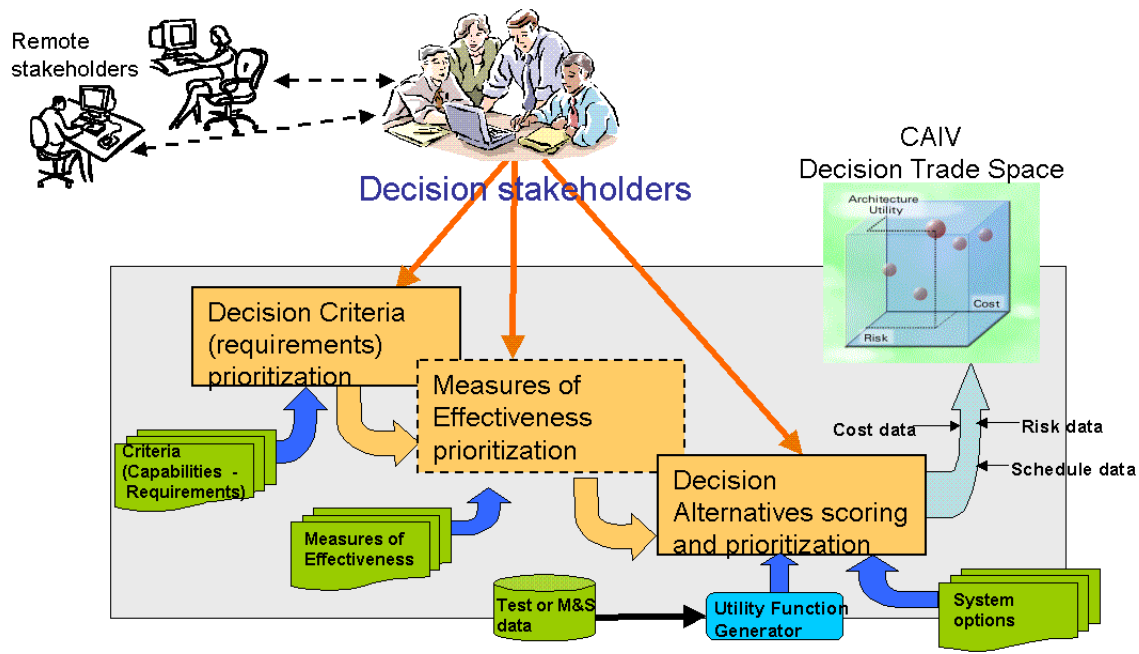


Figure 1: Process for Analysis of Alternatives

space. Such tools could help to identify item and technology candidates for PHM investment based on what is important to the stakeholders (which could include operators, maintainers, managers, and engineers), goals in terms of performance and cost, and even subjective inputs such as possible changes to the maintenance culture. A tool with a well structured process could lead participants through the decision process, prioritizing capabilities and alternative selection criteria based on a number of factors which could include probability of failure, severity of consequence if the item fails, likelihood that the PHM technology will be able to detect and unambiguously identify failure modes, as well as overall utility. The calculation of utility and risk assessments and integration of costs and schedule in the decision space would be beneficial to the decision support process. Also beneficial would be features which allow end results to be traced to original capabilities, metrics which are understandable to the decision maker to support conclusions, and the ability to integrate cost, utility, risk, and schedule parameters into a single decision. A capability to allow remote participation over time in the decision process would increase flexibility for participants so that they do not have to be in the same room at the same time.

Cost models: Cost models that could be integrated to support a cost benefit analysis would be a necessary element of PHM implementation decision support, as shown in Figure 2. These models would need to be able to estimate LCC and ROI of PHM investment for future systems, modifications, enhancements, or technologies. The ability to show the cost difference between one system alternative and another (such as with PHM investment and without) and facilitate changing system parameters for quick trades

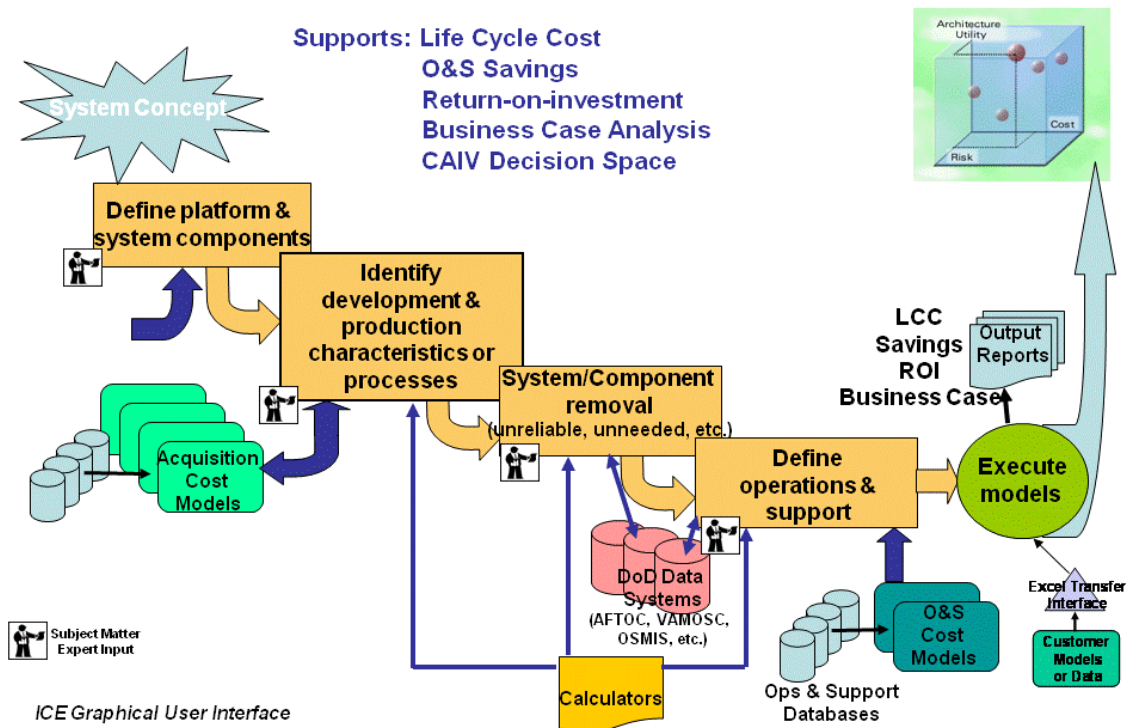


Figure 2: Cost Analysis Process

would also be beneficial. Also beneficial would be easy, graphical access to detailed cost models, the ability to save multiple concepts to compare alternatives, and ease in integrating additional models or databases (e.g. for item specific proprietary models and data).

Supportability models: These models and simulations are used to model the operation and support of a given system, including logistics system resources and tasks. Such models would need to be able to assess how PHM would impact (or improve) support in terms of operation and support measures. Modeling and simulation of PHM in the logistics process, however, is still somewhat in its infancy. Community-accepted logistics and support models used within the DoD and the commercial realm that can be used to validate PHM benefits need to be identified. One such model is the USAF Aeronautical System Center's Logistics Composite Model (LCOM), which is a comprehensive discrete-event simulation application that has started to address the positive contribution of PHM in the logistics environment for the Joint Strike Fighter Program.

Methodology Outline for Candidate Assessment, Selection, and Analysis: An outline of a methodology for performing assessment of PHM technology investment is provided below. This outline is oriented toward logistics support (versus safety analysis, for example), and seeks to emphasize the tasks unique to PHM versus those for general technology insertion.

1. Identify system/item which is to be examined and the corresponding operational and support context – for Joint Strike Fighter, for example, this could be Communication, Navigation, and Identification (CNI) systems, in the context of the Joint Strike Fighter operational and support scenario.
2. Define goals – what improvement is sought, or, what impact is the PHM technology intended to have? There may be multiple goals, in which case a tradeoff of those goals for a fixed cost may need to be conducted. Make sure to include alternatives that exist for meeting those goals that might not include the use of PHM technology, especially to support the development of a business case analysis.
3. Define metrics that will help define how the goals can be met (both with and without PHM technology) – especially for effectiveness (e.g. meeting operational and support performance goals) and efficiency (e.g. fewer resources, lower cost). These would include operational metrics (such as sortie generation rate for military aircraft), support metrics (such as expected backorders or maintenance man hours per operational hour), and cost metrics (such as LCC and ROI). Choose metrics that are used by the decision-makers. For example, a specific set of cost-benefit metrics may be needed, such as ROI or benefit to cost ratios. These metrics can help determine which analysis tools are most appropriate.
4. If more than one candidate item, collect data for ranking candidate items, e.g. reliability, maintainability, cost, and other data. Identify top drivers in a selected category or combination of categories (e.g. list of most frequent failures comprising 80% of total failures, list of highest cost items comprising 70% of total cost, or items common to both lists). If there are a large number of factors in determining the most desirable candidates, a tradeoff of driver factors may be desired. It may be

determined at this point that a reasonable set of candidates for further analysis do not represent a sufficient percentage of the driver. For example, if 10 candidates only represent 10% of the failures, and 100 candidates represent 80% of the failures, it may be determined that improving the 10 will not sufficiently improve reliability, or that reliability improvements to 100 candidates is not feasible.

5. Characterize the link between observations and failure predictions - for each PHM technology being considered for a given item, assess the link of observations (e.g. type of sensor input, such as temperature or vibration sensors) to analysis inputs. This involves several important and diverse steps. First, the number and type of sensors to be used need to be identified (both for cost estimating and for assessing potential PHM effectiveness). This can vary depending on the PHM technology. For physics of failure PHM technology, this involves careful analysis to determine the relevant models corresponding to targeted failure modes/mechanisms. These models require predefined inputs, which must be mapped to sensors as data sources. Processing of sensor input to feed the physics of failure models must also be considered. These models in turn must be linked to specific reliability and maintainability parameters, which in turn are related to the specified metrics via supportability and cost models. For data-driven PHM technology, inputs from potential sensors are used to detect deviations from normal behavior (i.e. detect abnormalities). Analysis must then be performed which links abnormalities which can be observed to specific failure modes to link in turn to the reliability and maintainability parameters. In simpler cases, detection of abnormalities may be able to link directly to maintenance actions. For fusion PHM technology, which combines elements of both data-driven and physics of failure models, some combination of the two must be performed. Regardless of the PHM technology, the reliability and maintainability parameters that link to supportability and cost models must be identified. The result of this step is the qualitative or quantitative rating of the degree to which the PHM technology can take observations and provide output that can be used to predict failures. It may be determined as a result of this step that there does not exist a strong enough link between what the PHM technology is able to observe and what it is able to predict.
6. Determine how PHM characteristics relate to logistics and cost inputs – Characteristics of the PHM technology that represent the effect of the PHM technology in support and cost models must be identified and determined. These characteristics can include false alarm rate, missed indication, precision, accuracy, and prognostics lead time. False alarm rate and missed indication can be used to determine costs of PHM not performing as expected, as well as potential support actions taken that were not necessary and which may impaired effectiveness. Precision and accuracy can influence how much a scheduled maintenance interval can be extended. Prognostics lead time can influence how effective support actions in advance of the impending failure can be. PHM characteristics may vary by item.
7. Perform ‘as is’ analysis – determine baseline operation, support, and cost metrics without PHM investment for candidate item(s) under consideration.
8. If a number of risk areas have been identified, especially with multiple items and multiple PHM technologies or ways to implement a given PHM technology (such as number or type of sensors), it may be desirable to perform tradeoffs – A tradeoff of

risks of the candidates could be conducted to prioritize candidates based on perceived risk and potential benefits.

9. For each selected candidate (which is a unique PHM technology/item pair), perform detailed assessments with cost and supportability models. For example, cost models could be used to quantify implementation and avoidance costs and ROI of each candidate. Use supportability models to address questions of implications for logistics elements (e.g. support planning, personnel, training and training support, supply support, computer resources, technical data, facilities, logistics information, test, packaging and handling).
10. Develop the business case.

Building the Business Case: With increasing emphasis on performing business case analysis (BCA) in connection with performance-based logistics, and as a means of obtaining approval for PHM implementation, a BCA needs to be developed as part of the PHM implementation decision process. A BCA must primarily address economic benefits, but can also address non-economic benefits and qualitative arguments, such as sensitivity and risk analysis. Use of tradeoff analyses can provide a means for relating quantitative and qualitative benefits. A plan of action and milestones (POA&M) must also be provided. The focus of the BCA should be on whether PHM should be implemented versus non-PHM alternatives, and if so, which PHM alternative is the best. A summary of what constitutes a BCA, derived from [4] and [13], is outlined below.

General BCA Outline: A BCA begins with an executive summary, which captures the key assumptions, results, and conclusions and recommendations. This is typically followed by an introduction, with background and statement of the problem or objective. Methods and assumptions can also be addressed [13]. A description of the baseline system and alternatives is then presented (in “business case analysis” section in [4] and “business impacts” in [13]). This is followed by the economic analysis and comparison of alternatives. Risk and sensitivity analysis can also be performed [13]. Finally, conclusions and recommendations are provided.

PHM BCA: The baseline system against which PHM alternative(s) are to be compared is the system without the PHM alternative(s) under consideration. Each PHM alternative must be described in terms of impact on cost and performance, and these impacts quantified. Detailed supportability analysis may also need to be conducted. The results of these analyses must then be fed into selected cost elements or key supportability metrics. Economic analysis of alternatives can then be conducted. Risk and sensitivity analyses can be separately presented in the BCA, or used with cost metrics in a trade-off model to identify the most desirable alternatives.

Final Thoughts: It is a challenge to identify and evaluate specific applications of PHM technology in terms of identifying items and technologies that will return the largest benefit if an investment is made in PHM technology. Factors that can and should influence this decision concern not only the PHM technology itself, but also its applicability in its intended application and the operation and support context in which it will operate. Increasing the insight into performance, cost and risk trade-offs early in the

product design process is key to identifying and prioritizing where PHM solutions will provide the most significant benefit. This paper described different aspects of decision support that should be considered in PHM implementation efforts, ending with discussion of business case analysis as the key milestone in the decision process. An outline of a methodology to perform an assessment of the benefits of PHM technology was provided and discussed. This outline is evolving, with an ultimate goal of developing a more detailed methodology and set of models that can help ensure that application of new maintenance strategies represent the best use of available resources and the optimum investment in PHM technology.

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