Requirements Specifications for Prognostics: An Overview

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With recent advancements in prognostics methodologies there has been a significant interest in maturing Prognostics and Health Management (PHM) to increase its technology readiness level for onboard deployments. Active research is underway both in industry and academia to address shortcomings in availability of run-to-failure data, accelerated aging environments, real-time prognostics algorithms, uncertainty representation and management (URM) techniques, prognostics performance evaluation, etc., to name a few. At this juncture it is highly desirable to close the loop by connecting the high level customer requirements for mission planning and execution to performance specifications for prognostics methodologies at the lower technical level. This calls for integrating the pragmatics of safety, reliability, cost, and real-time viability into the prognostics methodologies to establish a connection between top-down and bottom-up approaches currently pursued in the PHM community. In this paper we identify key areas that must be addressed to bridge these gaps and provide an overview of how these areas have been addressed in part at various levels. We also discuss on how these issues can be further developed into a comprehensive and more coherent portfolio of technologies that will ultimately lead to specifying guidelines for prognostics performance.

I. Introduction

PROGNOSTICS has become an active field of research in the systems health management community, where the promise is better planning and decision making for an ailing system if a reliable estimate of future system state can be obtained. It is expected that prognostics will make systems safer, more reliable, and longer lasting without incurring significant extra costs. Active monitoring and technologies for predicting remaining useful life are currently being developed and have gained momentum in recent years[1]. While a complete prognostic health management system still does not exist, several examples can be found where this technology has been applied in parts and has been shown to yield benefits[2]. To further improve the Technology Readiness Level (TRL) some challenges that must still be addressed. Active research is underway both in industry and academia to address shortcomings in availability of run-to-failure data, accelerated ageing environments, real-time prognostics algorithms, uncertainty representation and management (URM) techniques, prognostics performance evaluation, methods for verification and validation, etc. to name a few. Another important need is a systematic method to derive specifications for prognostics. Since there have been very few implementations of prognostics for critical systems, prognostics specifications have been very loosely defined. For safety critical system, a process to concretely define

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specifications for prognostics will be extremely important. Industry experts realize that requirements are important for PHM practitioners[3]. From an engineer's point of view there are at least four key parameters driving the requirements for prognostics:

- Maximum allowable Probability of Failure (PoF) of the prognostic system to bound risk,
- Maximum tolerable probability of proactive maintenance to bound unnecessary maintenance,
- Lead time to specify the amount of advanced warning needed for appropriate actions, and
- Required confidence to specify when prognosis is sufficiently good to be used.

However, it is not clear how to derive these requirement specifications. A generalized PHM-Value model has been proposed that defines performance metrics from Original Equipment Manufacturer (OEM)/service provider and customers' points of view and then connects them to high level goals to extract requirements[4]. In a similar spirit this paper takes a systems engineering view towards requirements specification process and attempts to find out what drives performance requirements for a prognostics system. It further identifies various components that must come together to specify requirements and then investigates what has been done in the industry in those areas and whether some or any of it can be reused or enhanced to incorporate prognostics requirement specification process. This work is expected to provide guidance for a more structured approach to connect high level mission requirements to low level prognostic algorithm performance. In this paper we identify key areas that must be addressed to bridge this gap and provide an overview of how these areas have been partially addressed at various levels. We also discuss how these areas can be further developed into a comprehensive and more coherent portfolio of technologies that will ultimately lead to specifying guidelines for prognostics performance.

A. Motivation

As mentioned above, in order to mature PHM and increase its TRL for onboard deployments it is highly desirable to integrate the pragmatics of safety, reliability, cost, and real-time viability into the prognostics methodologies to establish a connection between top-down and bottom-up approaches currently pursued in the PHM community. In an ongoing effort under the Integrated Vehicle Health Management (IVHM) program at NASA, prognostic performance metrics were developed[5, 6]. Figure 1 shows the idea of how performance metrics were envisioned to not only help in developing better prognostic algorithms but also in specifying performance requirements.

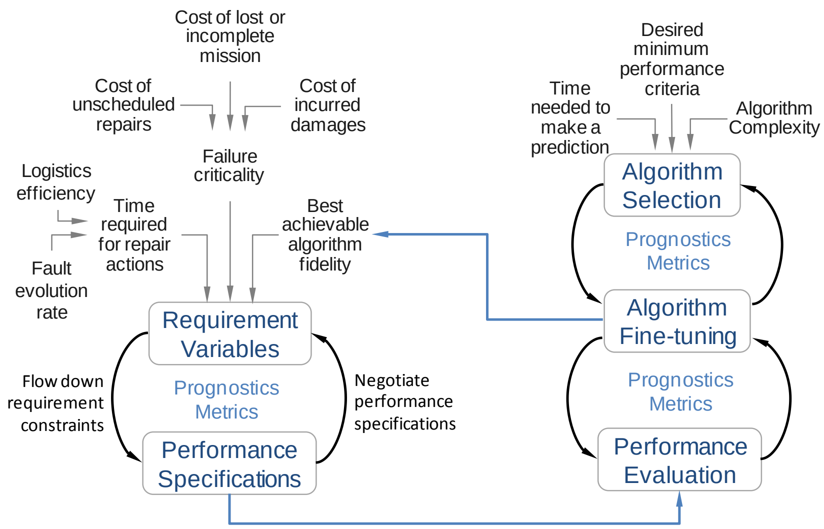

Figure 1. Role of prognostics metrics in the PHM development[6].

These metrics track prognostic performance as it evolves in time and evaluate results with respect to specified performance parameters. These performance parameters were designed with the intention to explicitly connect prognostics performance to practical issues in health management that generate requirements from safety, logistics, and cost viewpoints. Since these issues are most relevant for the customer or the stakeholder, we wanted to study what is important for them and how have they incorporated related ideas into practice. More specifically we were interested in researching ideas about how requirements are dominantly guided by cost-benefit-risk analyses from safety and Return-on-Investment (ROI) points of view. These requirements then ought to integrate systems engineering concepts in order to flow down to performance specification for prognostics methodologies. We believe that borrowing and adapting concepts in disciplines such as systems engineering and actuarial sciences can play an important role in establishing requirement specifications for PHM technologies. It must be noted that URM methods are of utmost importance to establish confidence in the prognostics systems for a successful health management application. Modeling the effects of uncertainties has been challenging and has attracted significant attention as PHM makes headways into real applications. Any decision making or cost-benefit analysis must include the risks of uncertainties[7, 8]. In the absence of well developed URM methods this has been somewhat neglected in most analyses. Therefore, this paper also discusses the latest developments on the URM front and how can they be incorporated into any analysis that results in requirements for prognostics.

Figure 2 illustrates how, requirements are guided by cost-benefit-risk analyses which then flow down to algorithmic levels. Depending on the application domain and the end goal of an application, different approaches are adopted in industry to carry out these steps. These areas were studied from a PHM point of view and our assessment is presented in subsequent sections.

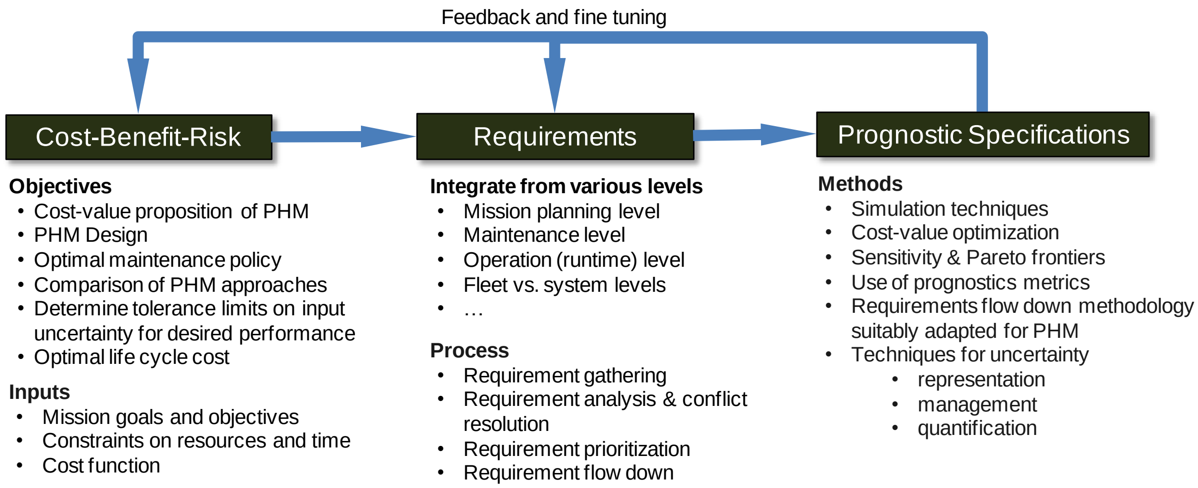

Figure 2. Connecting prognostics performance specifications to customer requirements.

B. What to Expect from the Paper

This paper covers a variety of topics, posed as questions below, that could be brought together as a methodology to generate requirements specifications for prognostics. As a first step, we review the state of the art in each of these topics to identify if there are methods that can be applied for PHM system development. Next, we also attempt to propose how these different topics can be tied together and lay a foundation for a systematic methodology to connect high level requirements to PHM performance at the lower level. This also emphasizes the need to standardize how these concepts are developed and embraced through a common taxonomy and mathematical framework. Specifically, we hope to enhance the understanding of the following topics:

- What are the key drivers that result in requirements for prognostic performance?
- What are various systems engineering processes and methods that are followed for requirements specifications and flow down?
- What are various cost-benefit-risk analyses that are currently involved in the PHM system development and which factors already considered by the industry have a direct relation to prognostics performance?
- To what extent, if at all, do these analyses consider prognostic performance in their equations?
- How can we integrate prognostics performance into these analyses for a more realistic assessment?
- How are the issues related to uncertainties in prognostics currently tackled that can be incorporated in planning and decision making?
- How other domains like actuarial sciences deal with uncertainties and what can PHM borrow?

While answering the above questions we extend our discussions on how prognostics metrics can be used to explicitly connect prognostics performance evaluation at the lower level to performance criteria defined at the higher level. Towards the end we discuss validation and verification (V&V) for prognostics, which is less well developed. Challenges associated with V&V are identified and included to complete the discussion associated with requirements specifications for prognostics.

In the next section we discuss various approaches to cost-benefit analysis. Discussion on methods used in the systems engineering discipline for requirements engineering follows next in section III. We also indicate what could be done for a PHM system development in similar ways. This discussion also includes ideas about how to incorporate uncertainties and risks arising in prognostics. Finally in section IV we discuss challenging issues in PHM that are important for prognostic requirements specification, before presenting our conclusions from this study.

II. Cost-Benefit Analysis (CBA) for PHM

For any system to be implemented it must be justified through a suitable cost-benefit analysis (CBA). CBA helps define requirements on various elements that affect the cost-benefit equation. It also generates a list of alternatives that may be used, under unavoidable constraints, to still maintain an overall benefit situation. Likewise, the PHM community has attempted to make a case for PHM through various CBA approaches. Depending upon who is benefited from integrating PHM into a system's life cycle, approaches to CBA have been different. However, regardless of the approach taken, the results of CBA are directly affected by the performance of diagnostics and prognostics modules, based on which further planning is expected to be carried out. From an extensive literature review of the last decade, it was found that the aspect of prognostic performance was not given sufficient attention for a variety of reasons. First, the methods for uncertainty representation and management are not well developed. This directly affects the performance characteristics of prognostic output. Second, most PHM systems have focused more on diagnostics and not much development has been seen on the prognostics front. This again is partly because prognostics has not yet attained a high TRL and rigorous methods for Validation and Verification of prognostics do not exist[1]. Third, in absence of suitable prognostics metrics it may not have been very clear how to incorporate prognostics performance in such analyses. It is imperative that for a PHM system to realize its intended benefits, specifications for prognostic performance must be met. A CBA that incorporates PHM performance levels is expected to present a more realistic picture for benefits and costs resulting from PHM. This also provides a means to identify minimum performance levels for prognostics to yield an overall benefit scenario. In this section we present a brief summary of various CBA approaches with a discussion on how performance metrics were or may be incorporated.

A. Categories of Cost-Benefit Analyses

Various CBA approaches used to justify PHM can be categorized into the following five broad categories. These categories primarily describe the user's intentions behind specific CBAs.

(1) Optimize planning, scheduling and decision making for maintenance[9-13]
 - For maintenance scheduling by operators of the PHM enabled system
 - For a contract based service provider that relies on PHM to guarantee uptime

(2) Generate a set of alternative solutions given user's flexibility in relaxing various constraints[10, 14-16]
 - Sensitivity analysis to figure out the most critical components
 - Break even curves for various input parameter ranges
 - Define scope for service contracts by assessing which components are most profitable for PHM

(3) PHM Design – for integrating into a legacy system or incorporating into the new system design[16-22]
 - Sensor selection and placement
 - Determine detection thresholds (e.g. on a RoC curve) for cost effective PHM
 - Down select and prioritize list of faults/subsystems/components for PHM capability

(4) Assess effectiveness of PHM to reduce costs and improve reliability[14, 16, 17, 22-32]
 - Evaluate the economic promise of PHM compared to the cost (value) of the system itself
 - Assess safety and reliability benefits of PHM[33]
 - Assess savings in the overall Life Cycle Costs for an asset[10, 16, 30, 34, 35]

(5) Compare various PHM approaches[24-26, 32, 34, 36]
 - Compare based on ROI in a given period of performance
 - Compare payback periods for various alternatives

A variety of CBAs conducted in the above situations also differ in their technical approach. One of the most popular approaches has been to optimize a cost function while honoring the constraints on requirements and resources to arrive at a beneficial maintenance policy[9, 11-13, 21, 22]. An alternative approach aims at finding tolerable ranges of input variables so that CBA still results in a profitable scenario[10, 12, 14, 23, 37]. Further, as shown in Figure 3, most cost benefit analyses can be approached from assessing extra costs or savings resulting from incorporating the PHM. First, additional costs for implementing PHM are calculated that include non-recurring costs of PHM development and recurring costs of maintenance and support. Some studies also include the costs incurred specifically due to implementing PHM. These comprise the loss of unused component lives, costs incurred by unnecessary maintenance due to false alarms, etc. Such costs are assessed based on statistical estimates like probability of false alarms or unused component life calculated based on actual usage and reliability data available from the manufacturer specifications. All these costs are summed up and then weighted against the benefits realized from a PHM system, which primarily are the assessed savings due to reduced frequency of accidents, and reductions in downtime, use of man power, inventory of spares, etc. Several approaches, further, compare the costs for scenarios with and without PHM. This involves assessing the costs of unexpected system failures, downtimes, or even cascaded effects to otherwise healthy subsystems. While the basic computations remain the same, situation specific components of costs and benefits are then added to the analysis for better customizations. For instance, for military aircraft operational environments (war or peace) influence the frequencies of faults and the severity of downtime[19, 23, 28]. For commercial aircraft, intangible benefits such as reputation due to maintenance delays or safety incidents are sometimes factored in[24, 29, 32]. Other benefits such as use of monitoring data for system design improvements and impact of safer public image on reduced insurance costs are also mentioned in the literature[29]. Also, depending on the length of time over which CBA is performed the outcomes differ as fixed cost tends to average out over longer periods. Similarly, costs may be computed on a per system[28] or fleet basis, annually[24, 29] or on per operating hour basis[24], over system life-cycle[19, 24] or per contract period basis[28], etc. Therefore, there is no limit to which different factors, direct or indirect, may be considered in a CBA. A list of such factors was compiled from the literature review and is included in the appendix for a quick reference. This list covers a wide variety of cost and benefit factors but is by no means exhaustive.

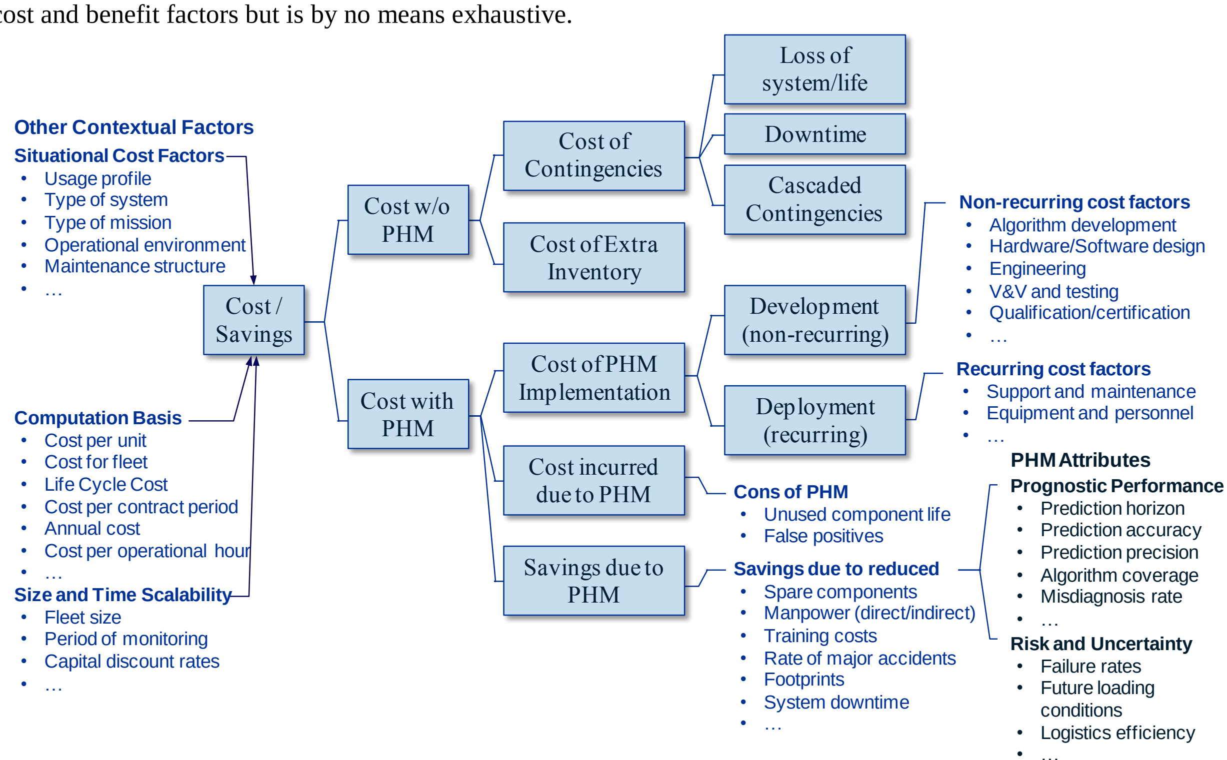

Figure 3. Categorization of Cost-Benefit analyses and important cost factors generally considered.

B. Prognostic Performance Metrics and Risk in CBA

In the last section we saw that while most CBA approaches do not take prognostics performance into account while assessing the benefits from PHM, some slightly touch upon this issue. These approaches consider performance (mostly diagnostic) by specifying probabilities of false positive or false negatives[10, 21, 22, 27, 32]. Prognostic Horizon[11, 13, 26, 32, 36], and some notions related to prognostic accuracy[10, 19, 22, 23] and prognostic precision[29, 36] are also indirectly considered. For instance, in one of the studies on quantifying the effect of prognostic errors on system performance a discrete event simulation is used where prognostic error and variance are stochastic input parameters[38]. The authors show that while in general PHM improves system performance (reliability, availability, and maintainability) there is an upper bound on prognostic errors beyond which PHM is no longer cost justified either due to too many missed detections or too many false positives. Another study in the context of a Maintenance Repair and Overhaul

(MRO) network explores the effects of Prognostic Horizon on the performance of a logistics system[39]. Except for a few cases where levels of accuracy or precision are considered, in most cases a perfect prognostic outcome is generally assumed. It was pointed out earlier that there are few challenges that must be overcome before it becomes clear on how to incorporate and assess benefits of prognostics in a true sense. First, rigorous methods for uncertainty representation and management need to be developed. Methods to interpret this uncertainty as risk and then quantifying that risk are needed. Further, contingency management schemes based on suitable post-prognostic reasoning must be devised based upon which a more realistic CBA can be performed.

It is clear that aiming at a fully functional PHM system requires assurance of availability of information/data from various levels of the product lifecycle management. This has been a rather elusive piece that is hard to come by in the early stages of research and development, particularly because several needed technologies have not matured yet (e.g. uncertainty management for prognostics) or various industrial entities keep their data proprietary. Some researchers have overcome this difficulty by performing simulations and then identifying the bounds on key parameters that affect the outcome of PHM activities on the system of their interest. These methods also use reliability history data to obtain estimates for stochastic parameters[7, 40]. In the absence of analytical solutions numerical simulation approaches provide a means to evaluate a range of possible scenarios based on which a decision may be based. Generally, uncertainty in the system is represented in terms of stochastic variables. In such situations, CBA is formulated as Monte-Carlo type simulations to obtain probabilistic results based on uncertain inputs[12, 26, 28, 36]. While simulations do not necessarily solve the entire problem it certainly overcomes the roadblocks in conceptualizing a practical PHM system and brings one closer to clear visualization of how such a system should look. This also paints a preliminary picture of how these simulation studies can play a constructive role in connecting the two worlds of requirements and specifications.

III. Prognostic Requirements Specification

Requirements specification guides system design and development. No matter how well a specific subsystem performs in isolation if it does not contribute towards meeting overall goals of a system it is of limited value. Similarly, prognostics algorithm performance should be viewed from a system level perspective. For instance, an algorithm with very high prediction accuracy that does not run fast enough or is hard to certify for onboard applications may not be an attractive proposition. A prognostic system can be considered a supporting system whose functions are defined by whatever facilitates uninterrupted operation of the monitored system. Furthermore, it is expected that in the event of a contingency further decisions and re-planning will be based on prognostic outlooks. Therefore, it becomes imperative to be able to guarantee a minimum level of prognostic performance, which can be specified only if there are guidelines or methods to specify these performance levels.

Systems engineering is the discipline that deals with questions like these during a product development phase. There is an enormous amount of literature on methodologies for requirements specification and the role of requirements engineering in product development. Here we briefly present various methods used in the requirements engineering field and then suggest how these methods can be applied towards prognostic system development. It should be noted that while most of the general concepts still carry forward, there are several PHM specific issues that must be accounted for while using these methods.

A. Systems Engineering for Requirements Flow down

There are a number of systems engineering approaches that have been used for large scale system design and development by agencies like NASA and DoD. These approaches offer a methodical way of organizing and executing various steps that are needed to realize a system from its initial design. NASA uses a Systems Engineering Engine (SE engine) for its projects in engineering system products[41], which follows a "top down" approach for design of each product in the system structure and a "bottom up" product realization process. A technical management process controls the two branches through planning and technical decision making. Technical requirements are flown down from top level to lower levels and translated into specifications for various sub-systems. Other approaches are also followed by agencies like DoD that have a slightly different approach by partitioning the product design and development life cycle into separate program phases[42]. Traditionally health management has not been an active part of the system development but DoD provides guidelines (DoD 5000.2 instruction) to include health management into the design of a system from the very beginning rather than introducing it at a later stage through FMECA (Failure Modes Effects and Criticality Analysis), Fault Tree Analysis (FTA), Probabilistic Risk Analysis (PRA), or HAZOP (Hazard and Operability Analysis)[7, 40]. More critical components and fault modes are identified upfront and corresponding baselines and thresholds are then determined to ascertain a minimum desired performance level. Other similar approaches[43] are also followed in industry where topological models and functional allocations are identified during the system design phase to formulate HM strategies. However, such integrated approaches may not be feasible in many cases. For instance, many existing aircraft were not designed and built incorporating health management components. However, as they age and require efficient prognostics, such measures need to be retrofitted at a later stage. For such cases, an approach like "plug and play toaster model" may be used[44], where PHM is developed for prioritized sub-systems preferably using the existing infrastructure or through slight modifications that may be possible. However, the add-on strategy usually turns out to be less cost effective than an integrated PHM solution.

Requirements Engineering (RE) is a sub discipline of SE that systematically determines the goals, functions, and constraints of hardware and software systems such that top level mission requirements are met within specifications[45]. RE involves several processes that assist in specifying respective requirements for every sub-system/component at lower levels. Specifically it includes[46]:

(1) *Requirements Definition and Gathering*: involves interactively interfacing with the customer (stakeholder) to determine top level requirements. It is a key step that includes defining the scope of the health management system by
   a. defining needs, goals, mission, constraints, schedules, budgets, and responsibilities,
   b. determining operational concepts that cover scenarios for how the health management system might behave and be used,
   c. identifying a suitable interface between the health management system and rest of the world,
   d. generating health management design requirements and a corresponding rationale for each requirement,
   e. assigning requirements to the right levels,
   f. verifying each requirement,
   g. providing proper documentation for all requirements, and checking requirements for completeness and correctness.

(2) *Requirements Analysis*: involves determining whether the stated requirements are unclear, incomplete, ambiguous, or contradictory, and then resolving these issues. This involves further interactions with the customer though interviews (formally known as requirements workshops), prototyping, and/or use-cases. Requirements must be categorized so they can be appropriately prioritized. They can be broadly categorized[42] into customer requirements (mission objectives), functional requirements, non-functional requirements, performance requirements (e.g., quantity, quality, coverage, timeliness or readiness, etc.), design requirements, derived requirements (implied or transformed from higher-level), and allocated requirements (by dividing a high-level requirement into multiple lower-level requirements).

(3) *Requirement Prioritization*: deals with resolving conflicting requirements, mostly through cost-value approach[47]. Requirements can be rated based on type (functional vs. non-functional, primary vs. secondary), estimated benefit to the stakeholder, estimated size of software that embeds the requirement, estimated cost of building what embeds it, priority and requirement dependencies. Methods like Analytic Hierarchy Process (AHP)[48] have been employed to prioritize various requirements, where a pair wise comparison among all requirements is made according to a standard scale and then normalized aggregates are used to indicate relative order of priority (value).

(4) *Requirement Flowdown*: once all relevant requirements are gathered and organized they are flown down to lower levels and the steps 1-3 may be repeated at each level as needed.

Conceptually RE follows an intuitive flow of process steps but for large systems it can be significantly overwhelming by growing out of proportions if not managed properly. Therefore, the key is to preserve interrelationships and constraints while translating the requirements to other levels. We now look into models and tools for carrying out the above steps that identify the relationships between the various components/sub-systems and their priorities if any. Tools like "*Strategic Dependency (SD) Diagram*" have been used to capture the dependencies between different modules of a system and "*Strategic Rationale (SR) Diagrams*" to capture individual goals and processes of stakeholders and systems[49]. *Scenarios*[50] and *use-case*[51] modeling describe required interactions between a proposed system and its environment in order to achieve an intended purpose by decomposing the functional requirements of a system into smaller steps to be performed by the system or a sub-system. While *scenario* modeling may be generic, *use-cases* model customer's view point in describing these relationships. One of the most popular methods for requirements analysis is through the use of Quality Function Deployment (QFD), first introduced in the late 1960s[52, 53]. QFD has been used in a variety of applications of which the Joint Strike Fighter (JSF) is one of the examples where prognostics was embraced under it health management plan[54]. JSF and the US Navy's Common Support Aircraft (CSA)[55] programs used QFD for requirements development[54]. QFD technique helps in analyzing the important requirements and provides a step-by-step transformation method to convert these requirements into process/functions in the system as well as required system design parameters. Various tools employed to carry out QFD are:

- *Affinity diagrams*: help finding relationships between ideas to organize and gain insight into a set of qualitative information, such as voiced customer requirements.
- *Relations diagrams*: also known as interrelationship di-graphs show cause-and-effect relationships and are used to discover priorities, root causes of problems, and unstated customer requirements.
- *Hierarchy trees*: illustrate the structure of interrelationships between groups of statements built top down in an analytical manner.
- *Process decision program diagrams*: systematically identify what might go wrong in a plan under development and hence are used to study potential problems of new processes and services.
- *Analytic hierarchy process*: a structured technique for dealing with complex decisions. It uses pair-wise comparisons on hierarchically organized elements to produce an accurate set of priorities.
- *Blueprinting*: a tool used to illustrate and analyze all the processes involved in providing a service
- *House of Quality*: a collection of tables, matrices and deployment hierarchies that aids in translating a set of customer requirements – drawing upon market research and benchmarking data – into an appropriate number of prioritized engineering targets to be met by a new product design. This is one of the most popular methods and comprises of customer and technical requirements tables, planning, interrelationship, and technical correlation matrices, and keeps track of technical priorities, benchmarks, and targets.

QFD can be conducted using simple spreadsheets if the problem is relatively straightforward and it has been shown that application of QFD analysis to small subsystems has resulted in significant efficiency improvement for the overall product design[53]. However, for large and complex systems, direct use of QFD can lead to unwanted complications. Various commercial tools have been developed to handle large systems but also several modifications have been made to the QFD analysis itself over the years. For example, an extension of QFD analysis has been proposed to incorporate links between the system engineering process, the concurrent engineering process, the robust design process, and the costing processes[56]. Another significant model for requirements analysis is called the Kano model developed in the 1980s[57]. The Kano model is based on the concepts of customer quality and provides a simple ranking scheme to distinguish between essential and differentiating attributes. The model provides a\powerful way of visualizing product characteristics and stimulating debate within the design team and can be used in conjunction with other tools such as QFD. It classifies customer requirements into five categories, namely;

Attractive, One-Dimensional, Must-Be, Indifferent, and Reverse. Another analysis method, Critical-To-Quality (CTQ) trees, that stem from SixSigma concepts, provide yet another way to analyze customer requirements by decomposing broad requirements into more easily quantified ones[58].

As touched upon briefly earlier, while most of the approaches for RE follow a logical intuitive set of steps, practical problems arise due to the growing number of requirements for a complex system. Various software tools have been designed for efficient requirements management that implement some of the RE elements discussed above. Some representative examples of such tools include: Cradle from 3SL, Kollabnet, MatrixOne from Telelogic and SmarTeam CSE from Dassault Systèmes[59]. Most of these tools help in organizing the projects; importing and exporting of various design documents with support for multiple file types and organizing them. They also provide support for maintaining links between documents that could indicate various priorities, dependencies and/or importance levels. Many also aid in identifying requirements from design specification documents and structure them using conditional links and rules. Other tools like inteGREAT Requirements Studio and Ravenflow RAVEN™ provides a whole suite of functionalities for RE and result in visual models and specification documents[60]. Yet almost all of these software tools also aid in understanding and constructing high-level requirements specifications. They still lack capabilities which allow technical requirements to be systematically translated from top-level specification to component level design parameters. The ability to keep track of technical constraints along with identified requirements would perhaps help in more systematic specifications generation by simultaneously allowing a quantitative flow down of requirements.

B. Requirements Flow down for Prognostics Specifications

In previous studies[61, 62] it has been argued that requirements for diagnostic and prognostic systems should be related to performance specification from end user's perspective. Furthermore, performance measures should be derived by an integrated product development team that accounts for all expected user groups and a common health management infrastructure must be used to integrate across subsystems[62, 63]. This derivation of requirements should be guided by cost-benefit-risk analyses such that a critical balance is established between these three competing elements. In these studies a thorough analysis was conducted to identify different user groups and their respective requirements at various stages of the life cycle of a system. These requirements were then mapped onto specific tasks within health management and the corresponding performance metrics[62]. While a comprehensive discussion on "what" must be done was presented very little light was shed on "how" to do it.

Common sense and insights emerging from research and field experiences states that it may neither be wise nor possible to implement a comprehensive and generic PHM system for all possible failure modes for all components and subsystems of a system under health monitoring[64]. Use of prioritization analysis tools like FMECA (Failure Modes Effects and Criticality Analysis) or HAZOP (Hazard and Operability Analysis) coupled with cost-benefit analysis are used to determine which parts of the system will be monitored to improve a global economic performance. Several extensions to FMECA for PHM have been suggested in the literature that add PHM specific features to the analysis[22, 64, 65]. Ideally, PHM should be integrated into the system life cycle early on from the design phase; most PHM efforts are focused on extending the lives of existing legacy systems.

Given a wide variety of approaches for prognostics and a number of possible user objectives, careful analysis should be conducted during the PHM system design phase. Standard approaches from systems engineering may be applicable if we regard the PHM design as any other system development. From the system designer's point of view the V-Model is a standard approach in systems engineering. A V-model for PHM system design is suggested[64] where first the choice and specifications for prognostics metrics as the system level design requirements is identified, followed by identification of a subset of failure modes (components of a PHM system) of interest as the item level design requirements. We take a broader view of this approach and suggest the following V-model; as shown in Figure 4. User requirements (safety, availability and costs) are first gathered from the customer, that are then converted into system health requirements and constraints (failure thresholds, acceptable cost in terms of false positives and false negatives, logistics constraints, etc.). Thorough analyses like FMECA, HAZOP, or domain experts from the customer side then identify a subset of subsystems/components and corresponding critical failure modes that must be monitored. Accordingly, henceforth, a PHM system architecture is created that includes a choice of sensors, algorithms, fault models, etc. Depending on available information (sensors), noise levels, and uncertainty management techniques, a set of performance metrics is identified keeping in mind high level user requirements. Once a set of performance metrics is selected, system health requirements are quantitatively translated into specifications for metrics, and successively into performance parameters for a specific monitored subsystem/component.

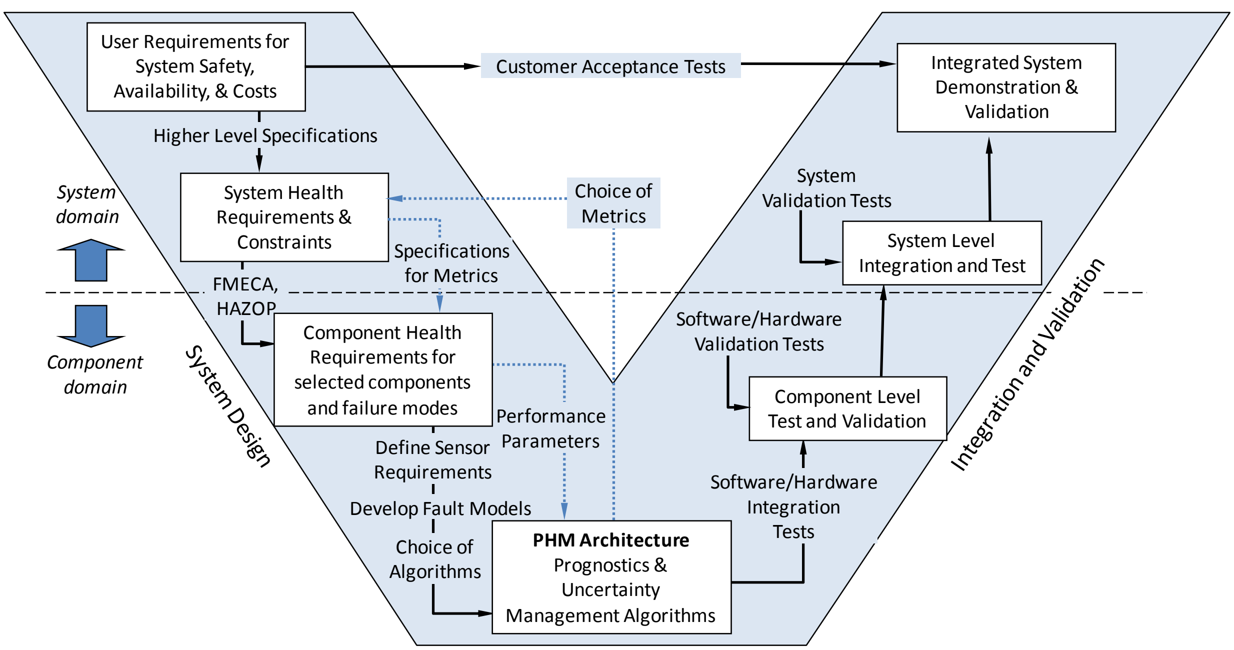

Figure 4. V-Model for PHM system development: Choice of metrics and requirements specification is an iterative process.

It must be noted that the choice of metrics and performance specification is an iterative process that negotiates between user requirements guiding the performance requirements and capabilities (maturity level) of the PHM system with respect to uncertainty management and real-time response. Once implemented, the integration and validation branch of the V-model is executed through various methods established for each level. The methods for integration and validation are separate topics in themselves and out of the scope of this paper.

From a PHM system point of view requirements are generated from customer expectations that help meet mission goals and objectives. They must consider operational distribution or deployment (i.e. where the monitored system is deployed), mission profile or scenario (how the system is expected to meet mission objectives), performance and related parameters (critical parameters to accomplish the mission), utilization environments (how will specific subsystems/components be used), effectiveness requirements (how effective the PHM system should be), operational life-cycle (how long the system is intended to be in use), operational environment, etc. A popular model for classifying software requirements is FURPS+, which establishes requirement classifications for software systems[66]. It classifies requirements based on functionality (feature set, capabilities, generality, security), usability (human factors, aesthetics, consistency, documentation), reliability (frequency/severity of failure, recoverability, predictability, accuracy, mean time to failure), performance (speed, efficiency, resource consumption, throughput, response time), and supportability (testability, extensibility, adaptability, maintainability, compatibility, configurability, serviceability, installability, localizability, portability) while considering design, implementation, interface and other physical requirements. This model directly ties in prognostic performance in the requirements specification step. Also, it must be noted that RE is expected to be an iterative process irrespective of the tool that is employed for this analysis. Every time one moves to a lower level, more details about the allocated requirements are needed that often times suggests going back to the customer or even reconsidering earlier design parameters.

In our review we did not surface detailed examples of how such a process can be worked out specifically with respect to quantitative requirement flow down. However, in a study on a solar telescope the authors show a technical requirements flow and analysis[67]. The study systematically shows how high level specification for a telescope such as wavelength coverage, lifetime, adaptability, etc. can be converted to individual component requirement specification such as lens aperture, polarimetric sensitivity, field of view and so on. A similar framework could be suitable for flow down for prognostic performance metrics as well.

IV. Challenges in Prognostics Performance Specification

A. Uncertainty and Risk in Prognostics

Uncertainty representation and management is still a challenge in PHM. Steve Engel, an industry expert in PHM, puts it "The hard part about prognosis is quantifying this uncertainty to enable risk based decisions". He suggests several methods to create and validate verifiable requirements for accurate and safe prognostic predictions[68]. Specifically, the research is focused on uncertainty representation and quantification methods[69-73]. In most cases a probabilistic representation is adopted using various methods such as particle filters[71,74, 75], relevance vector machines[76]. Other methods such as principle component analysis[77] or prognostic fusion[78] have been used for uncertainty reduction. Quantification of uncertainty from various sources in a process was investigated and a sensitivity analysis was conducted to identify which input uncertainty had the most contribution to the output uncertainty in prognostics for fatigue crack damage[79]. In another application authors considered future load profile uncertainties and sensor sensitivities as major sources of uncertainties in failure prognosis for fatigue cracking on a bolt hole in a turbine disc on military combat aircraft[80]. Their probabilistic simulations indicate that a usage variability of magnitude x can result in 6x variability in fatigue life, and 10x to 100x variability in probability of failure at a given life. They then show how specifications on sensor sensitivities can be derived for a desired mission requirement specified in terms of Probability of Detection (PoD) through simulations. This study clearly shows the trade-off between frequency of interrogation and sensor sensitivities, and how specific values of desired sensitivities depend on requirements on the minimum crack size that should be detected for safe operation. The specifications thus derived were used to design a thin film sensor for that specific application.

While URM deals with accounting for uncertainties in diagnostic and prognostic algorithms, these uncertainties can be incorporated into decision making through the concept of *Risk*. Risk, once identified, can be quantified probabilistically and then through monetary concepts incorporated into a cost-benefit equation[7]. Other fields such as actuarial sciences seem to focus on risk for the insurance industries in a similar way as we envision for PHM. Due to similarities between actuarial science and PHM where (cost-effective) decisions are required to be made for the future under various sources of uncertainties, we expect to find some relevant formalism that can be re-used. For instance, in PHM we can consider a system as an *asset*, which, if *lost*, will result in a monetary or human *loss*. An asset can be an aircraft, a fleet of aircraft, spacecraft, key equipment in a manufacturing process, etc. Failure of its function can result in total material loss, catastrophic failure, unsuccessful mission, etc. Although loss function resulting from human safety is harder to express in monetary terms, there are approaches that can be used for analysis purposes[7]. PHM will in principle reduce the risk of loss associated with an existing system and if a new system is being designed PHM should be aimed at reducing this risk of loss. Therefore, the problem now reduces to computing the loss function due to probabilities of undesired events under various uncertainties. Techniques like PRA have been employed for such tasks[40]. In addition to system level efforts on assessing the risk, some researchers have also incorporated the notions of risk at a low algorithmic level. For instance, it has been shown that the use of Risk Sensitive Particle Filters (RSPF) tackles the situation of low probability/high risk events that would otherwise be neglected as outliers[81]. This method reduces the risk due to uncertainty from outlier data. In the literature, one of the most widely used concepts to measure risk is that of Value at Risk (VaR) that quantifies the value of losses that can be expected in a given time horizon and at a specified confidence level. A similar concept of Fault Value at Risk (FVaR) has been adopted for PHM perspectives and is being used to incorporate prognostics in automated contingency management methods. Most of these methods primarily aim at uncertainty management and reduction to yield a narrow RUL distribution and not many methods currently exist that incorporate these distributions into the decision making process for PHM.

B. V&V for PHM

Another key challenge for prognostics is the lack of formal V&V methods. While this does not limit our ability to develop a requirement specification methodology, in the absence of such V&V methods (and to some degree also certification methods) there are no clear guidelines for specifications. Indeed, V&V for prognostics has been identified as an area that needs to be urgently addressed for prognostics to find a way into fielded systems. Feather *et al.*[82] list a comprehensive list of hurdles that have been identified in the literature to V&V for prognostics. They list "barriers" that span a wide range of topics, including for example lack of ground truth, absence of statistically significant number of run-to-failure data, potential difficulty to adapt to design changes, lack of standardized performance evaluation metrics, etc. The authors also list a set of potential solutions that address the barriers for a particular application[82]. While the enumeration of problem areas does not per se solve the V&V problem, it does aid in the identification of bottlenecks for a particular application. It may also motivate research into formal methods for V&V which will ultimately lead to completing requirements specification for prognostics.

V. Conclusion

A comprehensive review of various approaches taken for cost-benefit analysis was conducted. These approaches have been grouped and categorized to emphasize priorities of different end users based on the nature of their applications. This helped in abstracting key cost parameters that are of interest in general and then connect them to specifications for the prognostics performance metrics. A review of various tools for requirements flow down that are already established in industry was conducted. These tools have been described vis–à–vis key components such as requirement definition and gathering, requirement prioritization, and requirement flow down. Preliminary ideas have been proposed to adapt these tools and methods, keeping in mind PHM specific characteristics. A more rigorous methodology is under development that will then enumerate various steps to carry out such transfer of information from one level to another. Overall this paper describes key elements that should be incorporated and embraced in a unified framework for a fully functional PHM system that connect user requirements to performance parameters via prognostics metrics. We have identified findings from literature reviews conducted for each of these elements to enhance the reader's knowledge about the current state-of-the-art in these respective areas, point them to relevant sources in the literature, and also help identify key areas that still stand as a challenge. Last but not least, this paper highlights various aspects of PHM technologies that need to be viewed in a more unified fashion as they work their ways towards technology maturation.

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Appendix

The table below lists various parameters that were incorporated into CBAs for PHM applications. These parameters were categorized under various groups. It can be seen that prognostics performance related inputs are very limited in number and do not offer much flexibility in allowing risk and uncertainty in their current form.

Factors considered in CBA	Comments
Category 1: Maintenance and Operations	
1.1 Distributions – Reliability data or maintenance history data	
Failure Rate (MTTF) distribution	For all component with PHM support, e.g. rate per million engine flight hours (EFH)
Self recovery time distribution	
Vehicle recovery time distribution	
Part order time distribution	expresses logistics efficiency
Field diagnoses distribution	
Repair rate or Repair Time (MTTR) distribution	includes time for fault isolation + parts lead time + repair actions + repair validation
Additional repair time distribution	assessed from past history record whenever there was an incomplete maintenance action
Mix of different types of scheduling tasks and corresponding cost factors	Information about the mix of unanticipated corrective actions (due to unanticipated failures) + scheduled corrective actions (for components without PHM) + PHM scheduled maintenance tasks
1.2 Probabilities – FMECA, HAZOPs, Expert opinions, etc.	
prob(on mission)	probability of system being deployed
prob(field repair)	to express possibility of field repair
prob(self recovery)	chances of self-recovery
prob(incomplete repair)	assess from past track record of maintenance operations
prob(diagnostic capability)	assess for each component if it can be suitably diagnosed
prob(prognostic capability)	assess for each component if a failure can be predicted, also called *Prognostic Potential*
prob(sensor failure)	chances of PHM sensor failing
prob(faults propagation to downstream components)	established through an extended FMECA or system models
prob(parts available for repair)	availability of parts, facilities, schedule etc.
1.3 Cost estimates	
Cost of false positive	due to unnecessary replacement, inspection or maintenance operation
Cost of Could Not Duplicates (CND)	includes cost of maintenance man-hours for component removal/replacement, transportation of part etc.
Cost of false negative	follows from the consequential cost of a failure mode going undetected
Cost of Operational Unavailability	losses due to downtime or unavailability, e.g. flight delays or cancellation
Penalty for not being able to provide promised availability	similar to previous factor for contract based services
Consequential cost of a failure mode	includes costs of fault propagation downstream (collateral damage), may also include the costs of repair
Cost of safety	includes cost of human and system loss
Repair Cost	includes material, inspection and labor cost estimates
Average cost of spares	used to assess costs of maintaining inventory levels
Lifecycle costs for PHM system	for upkeep and maintenance of PHM system hardware and software
Cost of PHM sensor validation and maintenance	considered in cases where customized instrumentation may be developed
Cost of post-prognostic reasoning and decisioning	to implement post-prognostic decision making process – optimization and re-planning
Cost (risk) of certification due to PHM related modifications to the systems	more applicable to military and aerospace systems where modifications lead to high certification costs
Cost of redundant systems in the absence of PHM	generally used to assess savings in a CBA
Cost of maintaining inventory levels	used to assess reductions in inventory levels by using PHM
System operational costs	Specific to a system, e.g. cockpit crew cost + Fuel cost + Maintenance costs + depreciation + insurance costs for a commercial airline, needed to evaluate relative costs of PHM & benefits from PHM
Cost of planned scheduled maintenance activities	generally used for comparison purposes in a CBA
1.4 Constraints	

Constraints on availability of resources	resources such as manpower, parts, support equipment, and facilities. This is useful for the run-time decision making case
Constraints from Criticality of various failures	critical failures need to be addressed immediately, they may be more expensive to repair, may have more expensive (computationally, resource wise, etc.) repair process
Category 2: PHM Algorithmic Performance Attributes	
prob(Misdiagnosis - false negative)	for prognostics FN is the situation where failure occurs before predicted time
prob(Misdiagnosis - false positive)	for prognostics FP is the situation where failure doesn't occur until after the predicted time
Prediction Horizon	time available for a maintenance operation after a prediction with desired confidence
Prediction Accuracy and Precision	accuracy and precision for logistics planning – combined metrics like Mean Predicted Failure with Confidence (MPFWC) may be used as well[12]
PHM Algorithm Coverage	in a portfolio of several algorithms, ones with higher coverage may or may not be the most cost effective. depending on the cost of their implementation may prefer broad-spectrum sensors that cater to a wider group of faults with suboptimal performance
PHM Algorithm TRL	helps integrate Technical Risk into the CBA equation in terms of prob(success)
Timeliness	may employ an asymmetric cost function for errors (cost) computations
Category 3: Situational Scenarios for CBA	
Projected usage profile of the system (operational hours over system lifecycle)	Operational profile may alter CBA equation, e.g. war or peace time for combat vehicles, or total flight time/yr vs. total ground time
Type of system/platform (vehicle)	Depending on platform type integration costs vary and require development of appropriate interfaces, e.g. M1A2 Abrams (critical) or HMMWV (not mission critical)
Type of mission	combat or tactical
Mission length	single mission length during which the vehicle is unavailable for repairs
Maintenance Scenarios: e.g. before mission, during mission and after mission	different maintenance scenarios may be considered where the costs of repair may vary. e.g. 1. Access> FDI> Remove and Replace > Checkout > closure, 2. Access > Inspect > Repair > Closure, 3. Position of the aircraft > Tie down > Engine Run > Remove & Replace > Chcekout > Closure
Type of operational structure available for maintenance	e.g. for commercial airlines: in house vs third party maintenance, Hub-spoke vs. point-to-point maintenance, etc.
System deployment schedule	hrs/system/year - for the flexibility of reconfiguring the operational schedule when needed
Category 4: Direct upfront costs for PHM Development and Implementation	
4.1 Cost estimates: these estimates typically scale by the size of target system	
Labor overhead rates and fees	costs in addition to direct labor (man-hour) charges
Hardware costs	material costs for sensors, cables, DAQs, and computers
Software costs	cost of algorithm development
PHM sensor development costs	where special sensor may be needed
Weight & power requirement cost of a sensor	weight increases fuel costs
Training costs	costs for training personnel for PHM system
Documentation costs	costs for documentation and subsequent maintenance and updates
IT infrastructure costs	PHM system requires an IT infrastructure that must be developed if did not already exist
4.2 Constraints	
Number of sensors permissible	weight and volume constraints
Observational quality of a sensor	a function of sensor placement and correspondingly ability of a sensor to detect a particular fault mode
Labor hour estimates	for assembly, integration and testing or qualification (for military standards)
Category 5: Time and Size window for CBA on PHM	
Number of systems to be monitored (Fleet Size)	cost scales with number of monitored systems and types of monitored systems. e.g. costs for 10 batteries + cost of 5 bearings + costs of gears and shafts, etc.
Period of monitoring to evaluate costs	life time of a system, during a mission,
Capital discount rates with time	used to compute NPV of the cost-benefit at present
Category 6: CBA computation/comparison basis factors	
LCC - over the estimated life of a system	Life Cycle Costs (LCC), total ownership costs
Phase in - Phase out schedule of a LRU (aircraft)	per program length
Phase in - Phase out schedule of a squadron	per program length
Annual cost of operation for a system	

Cost of operation during the planning period	per aircraft or per squadron
Cost per LRU or LRU group	
Cost per contract period	for contract based PHM services
Cost per flying hour(s)	e.g. EFH - per Million Engine Flight Hours
Category 6: PHM Scenarios for how maintenance service is structured	
Contract based	service contracts: e.g. to guarantee up time through PHM by OEM
Product based	PHM system as a product with a service bulletin that can be used by the customer
On-demand third party services based	purchase maintenance services as they are needed - e.g. car mechanic for oil change

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