Chapter 2
Design Approach for Systems Health Management

2.1 Introduction

Over the last several decades, there has been a wide range of approaches and implementation strategies for performing manual, semiautomated, or fully automated fault diagnosis and prognosis (i.e., health management) on critical systems in commercial and defense markets. Associated with these diagnostic and prognostic systems, designs are an equally diverse number of philosophies and associated architectures used to implement them for particular application.

Following the evolution of diagnostic systems in the modern industry, prognostic initiatives stared to be introduced in order to try to take advantage of the maintenance planning and logistics benefits. However, the early prognostic initiatives often were driven by infield failures that resulted in critical safety or high-cost failures, and thus, retrofitted technology was hard to implement and costly to develop. Hence, diagnostic and prognostic systems developers found the need to analyze and describe the benefits associated with reducing infield failures and their positive impact on safety, reliability, and overall lifecycle cost reduction. This leads to many cost–benefit analyses and ensuing discussions and presentations to engineering management about why the diagnostic and prognostic technologies need to be included in the design process of the system and not simply an afterthought once field failures occur. This had us to the point where many complex vehicle/system designs such as advanced fighter and high-speed train are now developing "*designed in*" health management technologies that can be implemented within an integrated maintenance and logistics system that supports the equipment throughout its lifetime. This "*designed in*" approach to health management is performed with the hardware design itself and also acts as the process for systems validation and managing inevitable changes from infield experiences and evaluating systems design trade-offs, as shown in Fig. 2.1.

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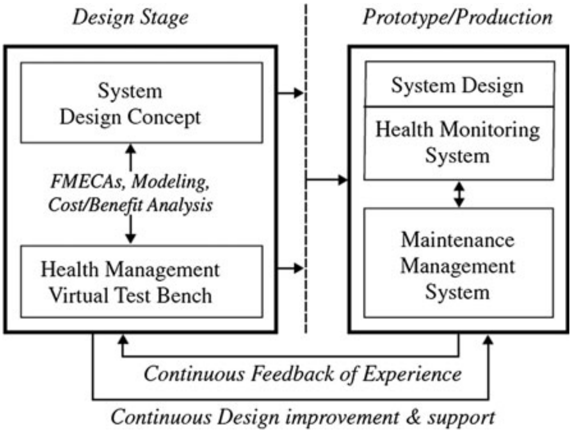

Fig. 2.1 The "designed in" approach to health management (Vachtsevanos et al. 2006)

Realizing such an approach will involve synergistic deployments of component health monitoring technologies, as well as integrated reasoning capabilities for the interpretation of fault-detect outputs. Further, it will involve the introduction of learning technologies to support the continuous improvement of the knowledge enabling these reasoning capabilities. Finally, it will involve organizing these elements into a maintenance and logistics architecture that governs integration and interoperation with the system, between its onboard elements and their ground-based support functions and between the health management system and external maintenance and operation functions.

Condition-based maintenance (CBM) is the use of machinery run-time data to determine the machinery condition, and hence, its current fault/failure condition, which can be used to schedule, required repair and maintenance prior to breakdown. *Prognostics and health management* (PHM) refers specifically to the phase involved with predicting future behavior, including remaining useful life (RUL), in terms of current operating state and the scheduling of required maintenance actions to maintain systems health. Detecting a component fault or incipient failure for a critical dynamic system (aircraft, gas turbine, pump, etc.) and predicting its remaining useful life necessitate a series of studies that are intended to familiarize the PHM/CBM designer with the physics of failure mechanisms associated with the particular system/component. Moreover, the designer must have a thorough understanding of methods for optimal selection of monitoring strategies, tools, and algorithms needed to detect, isolate, and predict the time evolution of the fault, as well as systems approaches for designing experiments and testing protocols, performance metrics, and means to verify and validate the effectiveness and performance of the selected models.

This chapter will introduce the concept of a system, as well as an engineering viewpoint for thinking about systems. The general consideration for systems health management (SHM) life cycle and analysis models is described. Then, two systems-based methodologies for the design of health management systems will be introduced.

2.2 Systems Engineering

Systems engineering is presented as a framework organized around stages of the product development life cycle. We specify a systems health management (SHM) process view of the systems engineering life cycle which provides a basis for understanding the broader issues of SHM and how they fit into the system life cycle. This supports the very important notion that SHM is an essential property of engineered systems that exerts considerable influence on system performance and affordability—it, therefore, must be addressed with an appropriate level of concern early on and throughout the product life cycle.

The term "*systems engineering*" was introduced by Bell Labs in the late 1940s, and by the latter part of the twentieth century, the field of systems engineering was recognized by most engineering organizations as a functional and integral part of the design process.

Systems engineering is concerned with the use of work products, processes, and tools to support and manage the design of complex engineering projects. A systems engineering implementation is typically organized around the system life cycle, addressing the identification and definition of customer requirements, creation, and analysis of alternative design artifacts by performing relevant trade studies, the implementation and integration of selected design approaches, verification and validation of the implementation, and then production support and evaluation/maturation of the embodiment of the design.

There is general agreement in the engineering community as to the nature and components of the systems engineering life cycle (ISO 2008). Figure 2.2 illustrates the most atomic stages of the systems engineering life cycle. These stages should not be construed as discrete events in a timeline, but rather as evolutionary phases with a necessary order of evolution, including the parallel utilization and support stages.

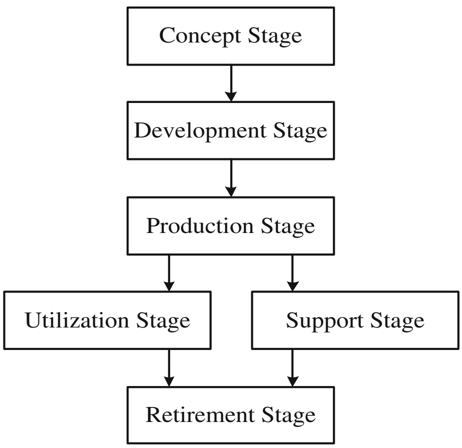

Fig. 2.2 The components of the systems engineering life cycle (Stephen et al. 2011)

2.3 Systems Engineering, Dependability, and Health Management

The creation of systems involves the application of methods from a variety of disciplines, coordinating and controlling the system creation process, and performing these functions under the influence of a number of external factors. Creating dependable systems requires that systems engineers develop an awareness of the holistic, interdependent nature of these processes and their effects on the dependability of the systems being created.

Dependable systems are those that perform their intended function when called upon to do so within their expected lifetime while not performing any unintended functions (Campbell et al. 1992). Dependability does not mean perfect, and while experienced engineers will tell you that you cannot build a perfect system, it is generally a critically important requirement that the system must be able to survive and recover from a failure condition (*mission-critical function* of SHM). This simple requirement has far-reaching implications, however, because systems of this nature typically do not exist in isolation. Engineered systems are generally hierarchical in nature, interact freely with each other, and in general exhibit behavior of an extremely complex nature. A less critical requirement may be that system failures be predicted or detected and isolated in a manner that supports efficient maintenance processes (*support-critical function* of SHM).

The notion of health management (HM) in complex systems, therefore, transcends engineering, management, and social processes and can only be obtained as an emergent property of a system that accounts for all of these issues. This "health" property is best viewed as the result of a dynamic process that changes based on the context of the lifecycle phase in which one is operating, the scale and complexity of the system being created, and the social interactions that take place between the individuals and organizations involved in the overall task of creating the system. The multi-organizational nature of the product development process adds a considerable degree of difficulty in understanding, analysis, and mitigation of system failures.

This systems engineering perspective provides us with a convenient framework for representing the SHM process. This perspective supports representation of the roles and interactions of system management methods, engineering activities, and cross-functional teams in the planning, implementation, and evaluation of the SHM process. SHM can be treated as a specialized view of the systems engineering process (ISO 2008). In this specialized process view, one can represent the HM design for a system as a system in its own right. In this view, HM system influences and interactions cut across multiple subsystems, serving to integrate the SHM perspective at each of the levels of hierarchy, as shown in Fig. 2.3.

Figure 2.3 expands upon the composite system view by including the notion of a health management system that encompasses all of the aircraft system components. This implies that each of the vehicle/system components participates in the health management system and that the health management system is itself hierarchical in

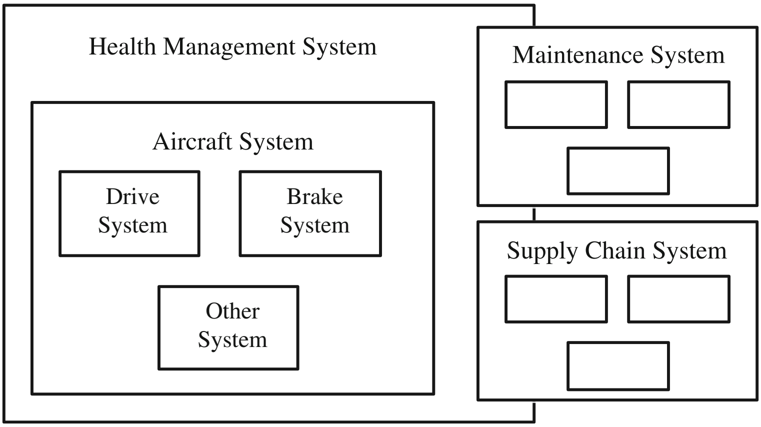

Fig. 2.3 Integrated SHM perspective (Stephen et al. 2011)

nature. The figure also shows that the health management system encompasses elements of the maintenance and supply chain systems. Health management system functions provide critical decision support functions to maintenance and supply chain systems, and in some applications, maintenance and supply chain system states may inform the health management systems. As described above, there are numerous other (unrepresented) internal and external elements, not shown here, which may influence all of the elements in this SHM hierarchy in unanticipated ways, providing significant challenges to the overall system designers and operators.

The creation of the SHM process then can be thought of as a HM-specific view of the systems engineering process, with its own lifecycle stages mapped to those of the systems engineering process. The SHM lifecycle stages are shown in Fig. 2.4. Note that the SHM systems engineering process stages exhibit the notion of iteration and feedback between stages and reference a function common to each stage labeled “Monitor and Control.” This is because the SHM development process is highly distributed; elements of an integrated SHM solution are provided from the distributed elements of multi-disciplinary, multi-organizational teams. Suppliers and systems integrators must work together to achieve the most affordable and safe SHM solution possible for the system under development. Therefore, one of the primary functions of any SHM development team is to monitor these disparate process inputs, in order to coordinate and control the timing and quality of the various work products across both internal and multi-organizational design teams.

The mapping of the SHM process to the core systems engineering process also implies that there is a rough correlation in time between the two lifecycle views of system development. For example, when the primary system (or delivered product) is being manufactured, the SHM system may be in the design synthesis and integration stage. These mappings are given in Table 2.1, and we describe the HM systems engineering lifecycle phases in the following sections.

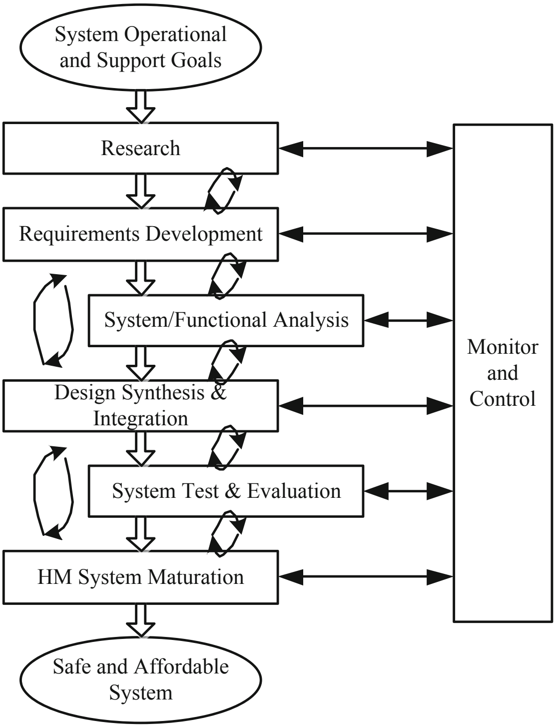

Fig. 2.4 The components of the SHM systems engineering life cycle (Stephen et al. 2011)

Table 2.1 Mapping of the SHM systems engineering process stages to core systems engineering process stages

Core systems engineering stages	Health management lifecycle stages
Preconcept	Research
Concept	Requirements development
Development	System/functional analysis
Manufacturing	Design synthesis and integration
Utilization	System test and evaluation
Support	Health management system maturation
Retirement	N/A

2.4 SHM Lifecycle Stages

2.4.1 Research Stage

The primary activity in the research stage is the identification, selection, and refinement of technologies or methods to meet customer operational needs. This is generally applied scientific research, based on more generic basic research executed by the participating organizations and the supporting academic community. This includes research in topic areas leading to product discriminators—those system features that are novel or so advanced compared to the competition as to provide some competitive advantage—as well as research performed to advance the maturity of technologies for use in the product line under development. A number of pure research centers, academic institutions, nonprofit centers, system providers, and integrators may be engaged in separate or coordinated research activities.

The initial selection of technologies and processes can have a significant effect on overall system dependability: "Numerous retrospective studies indicate that uncertainties often constitute a central consideration in the performance of engineering systems". Uncertainty can be managed in part by the selection of proven, well-developed technologies that are understood and have historical performance data available that allows the system creator to assess their dependability. Where newer technologies are anticipated for inclusion in the system proposal, careful planning of trade studies and other technology integration activities supporting risk reduction is essential. While it is not always the case that experimental or new technologies have greater chances of failure, they are less understood and inject a greater degree of uncertainty into the system creation process. The system goals and objectives will determine whether the development or use of new technologies is required. They may also place limits on the selection of existing technologies.

In addition to research into the dependability of advanced product features, this phase also is characterized by the development of advanced HM capabilities aimed at providing improved support for operational and safety goals compared to current product generations.

2.4.2 Requirements Development Stage

The purpose of the SHM requirements development stage is to define a complete set of system requirements that can be effectively used to manage the HM development process and assure that the end product will satisfy all customer needs and expectations.

From the system developer (or integrator) point of view, the primary activity in this stage is the requirements analysis leading to the development of a system concepts. These requirements define what the system must do to meet customer needs; the analysts must also consider requirements for how the building, testing, and operation of the system will be conducted.

Some of these activities relate to the management and administration of the system creation process. Budgets and schedules are developed. The management team is created, usually consisting of a project manager, systems engineers, technical experts, and administrative personnel. Legal and reporting requirements are determined. The effectiveness of these organizational and management structures has a profound influence on the dependability of the system being created. Shenhar and Bonen state: "both project management and systems engineering practice differ with each specific system [being created] and that management attitudes must be adapted to the proper system type" (1997).

This is also the time to integrate SHM into the total system design. Including consideration of SHM methods in all phases of the system life cycle and defining requirements for their implementation result in increased system dependability. It is during the requirements development phase that system development process leaders must arrive at a consensus which balances initial system delivery costs with overall system lifecycle costs.

Many, but not all, elements of SHM are developed by multi-organizational teams. As a result, much of the HM requirements definition occurs within the framework of the initial contractual process; that is, operational requirements for the system are defined as part of the published request for proposal (RFP) and are the basis for supplier selection and subsequent contracting. During this phase, supplier requirements may be further tailored as necessary to capture system technical details and programmatic constraints. The RFP typically includes formal procurement documents such as performance specifications, statements of work, supplier data list, and bidder's instructions. This information is distributed to prospective suppliers, who then submit proposals. During the source selection process, these items may be further tailored to each potential supplier based on how they propose to do business.

The goal here is to try and arrive at a clear understanding of the requirements for the multi-organizational system development team to provide the most cost-effective solution supporting systems operational and safety requirements. To that end, the procuring organization typically identifies and performs operational and support system trade studies to determine the system architectural and development features that have the greatest impact on these goals. The initial SHM concept may include elements detailing the architecture of distributed HM system elements (within either the platform boundaries, or extending to off-platform components), hardware and software configuration identification and management plans (an understanding of specific system configuration is crucial to effective HM), and HM system interfaces and data collection mechanisms—again, both on- and off-platform.

Definition of a detailed concept supported by architectural trades as just described will support the development of a cross-functional and interorganizational program management plan to support the execution of an effective SHM program and help initiate the development of another critical program element, the risk management plan.

SHM program risks can originate from numerous areas; a few notable sources to initiate the development of a SHM risk management plan could include the HM performance of similar systems in relevant field environments, knowledge of technical performance or business practices of potential system development partners, and anticipated issues with proposed customer HM requirements specifications. Customer requirements are allocated to subsystems and incorporated into the RFPs for each specific subsystem component procurement document. Specific targets for failure prediction, failure detection, and fault isolation, as well as criteria such as false alarms (FAs) and cannot duplicates (CNDs), are allocated and distributed to potential partners, as well.

Anticipation and worst-case analyses of systems performance in anticipated field conditions are a critical part of the requirements analysis process, and as these are performed, mechanisms for collecting relevant field data should be postulated and work initiated to ensure that such mechanisms are deployed to adequately support the HM systems maturation stage (as is discussed in that upcoming section of this chapter).

Another important part of initial communication with potential system development partners is to make expectations known for program information exchange, analytical tool and metric considerations, and the relationship of the delivery of data elements, analyses, and metric pass/fail criteria and expectations to proposed program schedules.

Ultimately, the goal of the requirements development stage is to determine the most affordable manner in which each product development partner can contribute to an acceptable overall technical systems design and then to enact an effective organizational infrastructure to manage the product development process. A satisfactory conclusion to this stage includes a well-formed design team with a clear understanding of mutual goals, the establishment of program management criteria as well as documented processes and tools to help ensure successful systems deployment and satisfaction of customer goals and requirements.

2.4.3 System/Functional Analysis

The purpose of the SHM system/functional analysis stage is to develop a preliminary functional design that allows all SHM program requirements to be satisfied. To do this, a system functional analysis is performed, in which the system is decomposed into the relevant top-level functions and lower-level subfunctions required to meet system performance goals. Alternative mechanisms to perform these functions are assigned and assessed by design teams, and means to assess or potentially guarantee the performance of system functions are postulated and analyzed. This is a matter of assessing the inherent system dependability from a standpoint of system reliability and developing operational health assessment and failure mitigation strategies that support contractual and operational goals. During the systems engineering development stage, requirements developed during the conceptual stage are translated into conceptual product architectures, and alternative designs for specific and tangible elements that will execute the system functions are postulated. These activities may vary significantly based on the type of system being created. Aerospace systems, software, and nuclear power plants, for example, have different approaches and methodologies for system design. The common factor is the goal of designing the product to meet the established systems operational requirements. From the SHM standpoint, however, during the corresponding system/functional analysis stage, engineers and system analysts perform detailed modeling and analyses that support the system designers' requirements and concepts through an integrated approach to system condition monitoring, failure prediction, detection and isolation, and correlation of system health effects across hierarchical system boundaries.

From a top-level functional perspective, SHM design is derived from an assessment of the needed dependability of each function in the system decomposition, and then a decision as to whether failure prevention provides sufficient reliability, or whether active operational failure mitigation methods will be required to achieve the needed reliability of each function. Put another way, every function in the system must be considered from the perspective of its failure and the consequent effect of that failure on the system. Completeness of the SHM design derives from complete coverage of SHM failure preventions or operational failure mitigations across all branches of the "function tree decomposition." Note that failure mitigation may include the possibility of doing nothing at the time of failure, if the failure is not safety or mission-critical, until a later time when proper maintenance can address the failure.

Proposed failure prevention and mitigation design mechanisms are allocated for each function and analyzed using historical and analytical techniques to determine whether the needed reliability can be achieved for that function. If failure mitigation is selected, then the proposed failure mitigation design mechanism must be able to detect the actual or potential loss of functionality and respond quickly enough so that it successfully completes before the critical failure effects that it is attempting to mitigate and propagate to cause functional failure. If the mechanism does not operate quickly enough, then it is usually true that the mitigation mechanisms must be driven further down the function tree into lower-level components, which are closer to the originating fault, thus detecting the problem faster and providing more time for the response actions to complete. System reliability is estimated by statistical summation of all component reliabilities to determine whether the system's overall dependability goals are achieved. If the system reliability does not meet these goals, then the SHM design must be improved in one or more components: The system's operational concept must be changed, or the system's dependability goals must be relaxed, or a combination of these actions must be taken to satisfy the design goals. System dependability estimates must include estimates of the potential failure of the SHM design mechanisms, which prominently include interactions between SHM detection and response mechanisms with each other, with the mission sequences, and with the system's control system. Specific activities in the SHM system/functional analysis stage include allocation of HM requirements to responsible subsystem design teams, discussions of architectural issues with strategic and technology partners, and trade studies to optimize architectural partitioning decisions (e.g., on-platform vs. off-platform, distributed vs. centralized, diagnostic vs. prognostic approaches). SHM approaches are selected from best-of-class technology resources that will satisfy operational and technological health requirements and then optimized on cost, safety, reliability, and diagnostic characteristics using a variety of engineering analysis tools.

System partners work with system integrators to ensure that distributed development schedules are all integrated into program management plans and schedules, and specific trade studies supporting HM development activities around the evolving SHM architecture are agreed to and planning initiated. Plans, schedules, and trade studies all support the requirements and functional areas covered in the requirements development stage.

Preliminary reliability, safety, and diagnostic analyses are performed using models derived from initial system design data, anticipated system operational usage, and system support specification. System failure modes are analyzed for their probability of occurrence and potential detectability. Failures with relatively low probability of occurrence or minor consequential effects are considered with respect to the resources required to detect them. Specific cost–benefit studies may be initiated in this SHM development stage—as initial product design begins to evolve from a functional architecture into a physical manifestation, evaluations of the cost-effectiveness of predictive versus diagnostic or scheduled maintenance solutions, as well as on-platform versus off-platform trades— and can be evaluated. These trade studies, besides targeting individual system drivers, can be evaluated as a whole in order to determine the most cost-effective overall approach to the overall SHM solution. In general, the cost ramifications of each design decision are considered against the projected lifecycle cost targets, and the implementation risks are evaluated against systems risk management plans initiated in the previous stage.

At the conclusion of this stage, the preliminary SHM design approach and proposed concrete implementation should be specified and supported by detailed functional analytical studies as system design becomes concrete.

2.4.4 Design, Synthesis, and Integration

The purpose of the design synthesis and integration stage is to develop and integrate a detailed design solution that meets all SHM program requirements. Implementation of selected SHM approaches is initiated, and analytical models are further refined with details of selected approaches and design knowledge as system and subsystem designs mature.

Complex systems are often characterized by two notable characteristics: (1) incorporation of an increasing number of functionalities that increase the integration of the number of parts and components (multi-component) as well as services and (2) incorporation of a number of maturing technologies (Dosi et al. 2003). Verification of the capability of these maturing technologies (providing product differentiation or other advanced capabilities to support system design goals) to support the requirements for which they are intended is performed in this stage. Partner design instantiations are verified by analysis and benchmarking against the agreed-to system performance metrics, and interfaces are evaluated for compatibility.

This stage initiates the process of verification and validation (V&V) of the SHM system. Verification is the process of ensuring that the system has metal of the developed requirements. Validation is the process of ensuring the correct system to meet customer needs has been constructed. Verification activity in the design synthesis and integration stage is strongly connected to the requirements development and system analysis stages, on one the hand, and with the validation activities in the system test and evaluation stage on the other hand. During the requirements phase, system objectives and goals are translated into requirements. These are further elaborated via the design process to greater levels of detail in the system. These requirements determine system specifications and impact the selection of materials and components; they further provide a basis for additional development of requirements and specifications and criteria for the verification of system performance and dependability.

Requirements verification is usually based on analytical approaches begun in the previous stage. Trade studies of the proposed SHM approaches are finalized and analyzed to assess the potential effectiveness of selected SHM approaches and system design decisions. Detailed reliability, safety, failure detection, fault isolation, and verticality verification analyses are performed based on specific schematic diagram and part information to support the understanding of the chosen SHM approach and ongoing assessment and management of requirements compliance.

It is usually not possible to have a "perfect" approach to detection and remediation of all failure modes as they exist in the initial design concept. At this point, in the design process, the areas that may be deficient are addressed through alternative approaches to system design, modification of the operations concept, or supplemental support procedures that may be outside the scope of initial design considerations. The coordination of this effort can be challenging because of the number of partners that may contribute to the development and production of any complex system. The close relationships of these partners in the design and production process are reflected in the coupling of the information flow and analysis required to support verification. At the completion of the design synthesis and integration stage, the SHM detailed design approach should be integrated with overall system design in a way that satisfies SHM requirements and is fully supported by interorganizational hardware design and analysis data.

Throughout the functional analysis and design synthesis stages, trade studies are continually performed that evaluate the efficacy of the proposed failure detection, isolation, prediction, and mitigation approaches with alternatives. This process continues until a satisfactory SHM approach has evolved that meets system design goals.

2.4.5 System Test and Evaluation

The purpose of the system test and evaluation phase is to qualify the implemented SHM solutions for delivery to the customer as part of the overall system. Activities in this stage will:

(1) Verify that the detailed design solution, which was previously verified by analysis to assure compliance with specification requirements, will actually achieve all SHM requirements upon delivery. As is the case in fundamentally sound software testing, system requirements are mapped to a collection of tests that will formally verify those requirements (answering the question "is the system built right?"). This can be perceived as a "bottom-up" approach that will provide traceability of the system design and development work performed to the specified requirements.

(2) Validation methods in this stage use demonstrable measures of reliability, availability, and dependability in conjunction with detailed system simulations of SHM system performance to determine whether the system is capable of achieving its goals as expressed in the system concepts—a "top-down" approach to functional verification that thoroughly exercises safety- and performance-critical HM functionality. This will provide a level of confidence that the system design is both correct and will satisfy customer goals and expectations. So, while verification determines whether the system has been built right, validation determines whether the right system has been built.

SHM verification and validation (V&V) activities include fault insertion, qualification, integration, and operational testing. Failure detection and fault isolation predictions and methodology are verified, and susceptibility to unexplained anomalies (UAs), false detections or false alarms (FAs), and cannot duplicates (CNDs) is assessed and their risk mitigated through various means. It is also possible at this point to identify and develop supplemental test and other support system elements.

The central model to the implementation of the SHM failure mitigation approach—the failure detection and fault isolation model(s)—can be verified analytically, but V&V of the SHM system requires that a fault insertion approach be employed, as diagnostic software is opportunistic (i.e., it only performs its intended job in the presence of failures). The implemented SHM approach can therefore be validated using one or more of the following approaches, depending on the criticality of the application and the corresponding stringency of customer requirements:

(1) Detailed simulation models of the subject system can be built and exercised in conjunction with the implemented SHM approach. System component faults can be inserted and the performance of the SHM system validated based on the response of the simulation models. This would require detailed validation of the simulation model itself.

(2) The system could be validated in a laboratory setting, where an actual system is placed in a simulated representative environment on a test bench, and then, system component faults can be inserted and SHM system response in the presence of failures can be verified. The simulation environment will again need to be verified to some degree, but this “hardware in the loop” approach does have the advantage of exercising the actual system.
(3) Finally, failures could be inserted in an actual operational environment (e.g., flight test of an aircraft system) and the SHM system then validated under actual operating conditions.

In practice, a mix of the three methods just described is typically employed based on factors such as availability of system hardware, operational parent systems or laboratory hardware, and cost considerations. Regardless of the methods used, as deficiencies are discovered, corrective actions are implemented and validated before the demonstration is considered successfully completed.

FAs and CNDs are undesired design characteristics that cannot truly be predicted or systematically tested, so there is no true validation possible. However, there is risk reduction activities that can be performed in conjunction with other program validation efforts to reduce the likelihood that FA/CND programs will occur during system operation. The only way to observe these system anomalies is by exercising the system in conditions as close to operating conditions as possible. There is a great deal of uncertainty associated with the design, development, and deployment of a HM system, and often, its performance cannot be accurately predicted due to emergent “metasystem” behaviors deriving from the interaction of the engineered system and its operating environment (as discussed early in this chapter). The more the system is exercised, and particularly if it can be exposed to operational conditions that may exceed the envelope considered during initial design, the better the chance one has to observe and then correct the root cause of the issue prior to actual deployment.

As the validation phase draws to a close, any system failures identified as sufficiently probable and consequential to warrant inclusion in the SHM detection, prediction, isolation, and mitigation strategy that remain undetectable should be addressed by an alternate means in accordance with customer requirements or other remedial action (redesign, additional testing, support system workarounds, etc.). Any additional support system requirements should be documented as part of the evolving requirements for the support infrastructure. Any potential impacts to customer requirements must be coordinated prior to delivering hardware and software to the customer. At the conclusion of the system test and validation stage, the SHM system is a fully qualified, production-ready integrated hardware and software design.

2.4.6 HM System Maturation

The purpose of the system maturation process is to effectively measure actual SHM system performance and to identify/implement corrective actions as required to satisfy all customer needs and expectations. The system maturation stage actually overlaps with system test and evaluation and continues throughout product deployment (corresponding to the core systems engineering utilization and support stages). The maturation process in brief consists of these major activities: (1) collect system operational (including performance and maintenance) data; (2) identify anomalous or unwanted SHM performance issues; (3) perform root cause analysis; (4) identify potential corrective actions; and (5) implement identified changes within formal closed-loop corrective action processes. Corrective actions may include physical system design changes, SHM system design changes, additional supplemental tests, or other support system element or process changes. Another way of viewing the closed-loop corrective action process is that it is just the iteration in the evolution of the SHM system within the product life cycle.

The operation phase of the systems engineering life cycle is where the system actually performs its intended functions. Operations typically involve environmental and human–machine interactions that can have a significant effect on system dependability. Interaction of the system with its operational environment has been, until deployment, a matter of engineering conjecture—actual interactions with the environment may provide significantly different outcomes than those anticipated in system design. This is because the development of effective SHM solutions requires prediction of complex systemic interactions and the effect of presupposed external stimuli. It is nearly always the case that unforeseen emergent behaviors (those that result from unpredicted system interactions) of fielded systems within their operational context create deviations from anticipated SHM system performance. Similarly, the operational infrastructure (including human, facility, and supply chain resources), details of process definitions, extent of operator training, and the functionality of human–machine interfaces are all critical influences on system dependability and may often not be accurately assessed until the system has been deployed within the support infrastructure, and interactions between these elements can be observed.

Initial test and maintenance solutions that are deployed to support new complex systems are therefore generally imperfect (by definition) and are initially liable to contribute substantially to system ownership costs. This suggests a need for processes and tools to (1) monitor the effectiveness of produce HM solutions in their application domains, (2) collect data that validate and document system performance, and (3) pinpoint and analyze relevant patterns that can help mitigate the issues that arise. The ability to mature the effectiveness of fielded system test, diagnostic, and maintenance procedures is a critical factor in an overall system operational and support posture. The process of identifying and implementing corrective actions as required to satisfy customer SHM requirements is known as the health management maturation cycle. A maturation cycle should primarily be initiated as a function of system supportability performance monitoring; however, customer requests and other internal investigations can also trigger a cycle.

Another important consideration is the feedback connection between the requirements, design synthesis/integration, and maturation stages. System requirements are the drivers that guide the designer and ensure that the system does what it is intended to do. The operation of a system in its fielded environment provides the ultimate integration testing (or validation) of system requirements. Observation of unanticipated behaviors can often trigger a new cycle through the SHM system life cycle (or its corresponding product system engineering life cycle).

If the developers who are writing requirements in the planning phase do not understand what the actual operational conditions are, then they cannot write good requirements.

2.5 A Systems-Based Methodology for PHM/CBM Design

A systems-based methodologies have a direct impact on the design of PHM/CBM systems: a formal framework to conduct trade studies that are intended to compare alternative options for the selection of components, sensors, and algorithms and to assist in the selection of "best" alternative technologies according to specified requirements. Failure modes and effects criticality analysis (FMECA) forms the foundation for good PHM/CBM design. In concert with reliability-centered maintenance (RCM), a FMECA study decides on the severity of candidate failure modes, their frequency of occurrence, and their testability. For each failure mode, it considers fault symptoms and the required sensor suite to monitor their behavioral patterns. In advanced versions, FMECA studies also may list the candidate diagnostic and prognostic algorithms that are best suited to address the identified failure modes. New fault data may be required in most cases that are essential for training and validating diagnostic and prognostic routines if historical data collected through on-system monitoring or test bench testing are not sufficient or nonexistent. Means, therefore, must be sought to devise and design a test plan, execute it, and assess the statistical significance of the collected data. Technical and economic performance metrics must be defined to guide the design process and evaluate the effectiveness and performance of the overall PHM/CBM system and its individual modules.

Figure 2.5 depicts the main modules of an integrated approach to PHM/CBM system design with the systems-based components of the architecture described. The schematic indicates feedback loops that are intended to optimize the approach and complete the data collection and analysis steps that are essential inputs to the development of the fault diagnostic and prognostic algorithms.

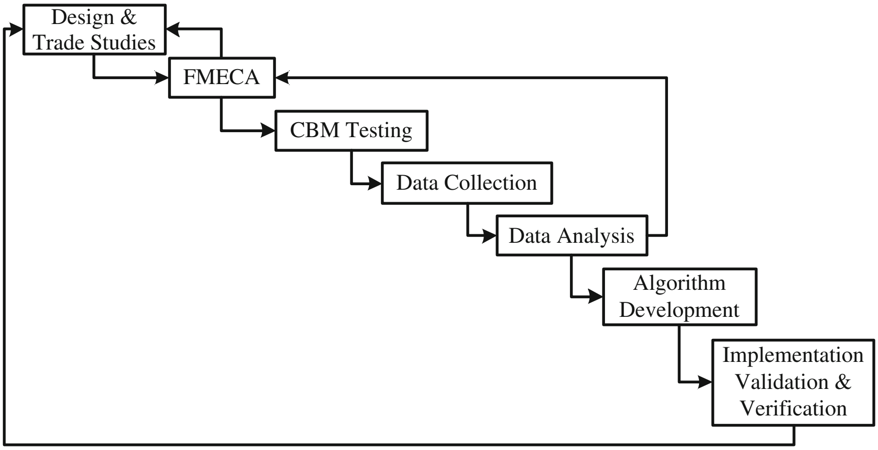

Fig. 2.5 An integrated approach to PHM/CBM design (Vachtsevanos et al. 2006)

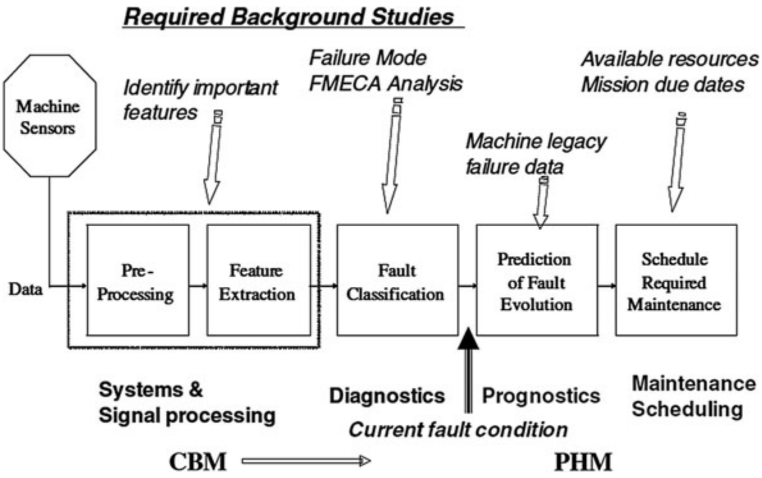

Fig. 2.6 The CBM/PHM cycle (Vachtsevanos et al. 2006)

In Fig. 2.6, one can identify a preliminary off-line phase and an online implementation phase of PHM/CBM. The online phase includes obtaining vehicle/system data from sensors, signal preprocessing, extracting the features that are the most useful for determining the current status or fault condition of the system, fault detection and classification, prediction of fault evolution, and scheduling of required maintenance.

2.6 A Proposed PHM Design Approach for Rotary Machinery Systems

To conduct step-by-step design and deployment of a PHM system, 5S approach is adopted to convert multivariate data to abstract prognostics information, utilizing different computing tools for different steps (Lee et al. 2013). 5S, as shown in Fig. 2.7, stands for Streamline, Smart Processing, Synchronize & See, Standardize, and Sustain.

The *first* "S," Streamline, focuses on identifying critical components and prioritizing data to ensure the accuracy of the second "S," which is Smart Processing. Identifying the critical components for which the prognostics should be performed is the first key step of smart processing by determining which components' degradation or failure has the most significant impact on a system in terms of performance and/or cost of downtime. In real-world applications, data collected from multiple sensors are not necessarily in a readily usable form due to issues such as missing data, redundant data, noise, or even sensor degradation problems. Therefore, it is necessary to sort, filter, and/or prioritize the raw data before processing it.

The *second* "S," Smart Processing, focuses on utilizing computing tools to convert data into information for different purposes, such as health degradation evaluation, performance trend prediction, and potential failure diagnosis. Currently, most manufacturing, mining, farming, and service machines (e.g., elevators) are actually quite "smart" on their own; many sophisticated sensors and computerized components are capable of delivering data concerning status and performance. In many situations, a large amount of data is available, but it is often not known which prognostics technologies should be applied. A systematic methodology for the design of a PHM system should include a means of selecting and combining a set of data-to-information conversion tools to convert machine data into performance-related information to provide real-time health indicators/indices for decision makers to effectively understand the current performance and make maintenance decisions before potential failures occur. This would prevent waste in terms of time, spare parts, and personnel and ensures the maximum uptime of equipment, resulting in significant cost-savings.

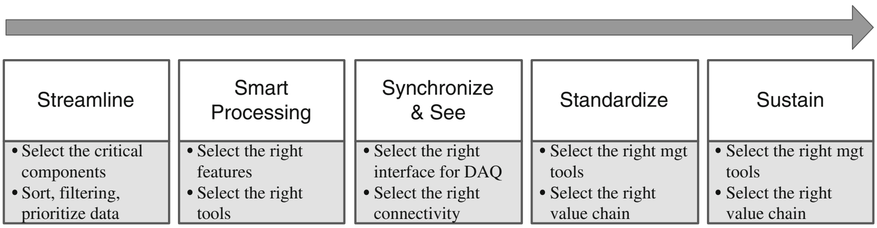

Fig. 2.7 5S approach (Lee et al. 2013)

Synchronize & See is the *third* "S" of the 5S methodology. It integrates the results of the first two S's (Streamline and Smart Processing) to enable the selection of the right hardware solutions and software platforms to most effectively facilitate data-to-information conversion and information transmission. Advanced technologies, such as embedded agents and tether-free communication, are considered to realize prognostics information transparency between manufacturing operations, maintenance practitioners, suppliers, and customers. Prognostics information is demonstrated using information visualization tools. These tools allow decision makers to use decision support tools, based on the delivered information, to assess and predict the performance of machines in order to make the right maintenance decisions before failures can occur. Prognostics information can be further integrated into an enterprise asset management system, which can greatly improve productivity and asset utilization by providing a direct link between machine status and support availability.

The *fourth* "S," Standardize, has great impacts for enterprises, especially in terms of deploying large-scale information technology applications. The interface for acquiring prognostics information from the Synchronize & See stage and importing the information into enterprise business systems, such as supply chain management (SCM) and enterprise resource planning (ERP) systems, needs to be constructed. The implementation of those applications can benefit from a standardized open architecture, information sharing interface, and plant operation flow, which brings cost-effective information integration between different systems that can aid in realizing the implementation of e-manufacturing.

The *fifth* "S," Sustain, aims to technically enable a sustainable closed-loop product life cycle. To accomplish this, management tools need to be selected and value chains need to be defined. Product information, such as product usage profiles, historical data, and middle-of-life (MOL) and end-of-life (EOL) service data, can be provided as feedback to designers and lifecycle management systems.

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